Investigation of high-speed optical transmission in the presence of fibre nonlinearities

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Abstract

This thesis investigates the impact of nonlinear effects on optical transmission in wavelength-multiplexed (WDM) and optical time-domain multiplexed (OTDM) systems up to 40Gbit/s. The degradation due to cross-phase modulation (XPM) in multi-channel WDM systems is analysed and the increase of error-free transmission distance is shown for optically regenerated OTDM systems.

The high powers needed to maximise inter-amplifier span lengths in high bit-rate multi-channel WDM transmission systems result in increased signal distortion and bit error-rate due to fibre nonlinearities. One of the dominant multiwavelength nonlinearities is XPM causing a variation of the optical phase due to power fluctuation in the other channels. This phase fluctuation is subsequently converted into amplitude distortion by the residual system dispersion leading to eye closure. This thesis focuses on the investigation of XPM distortion as a function of fundamental systems parameters using a straight line and recirculating loop fibre transmission system. A technique is proposed to minimise the residual dispersion of the fibre links by adding lumped dispersion at the receiver, efficiently reducing the impact of XPM on multi-channel transmission.

Another important aspect addressed in this thesis is the validation of the laboratory measurements: the simplicity of the pump-probe configuration allows the comparison with analytical calculations. The first field experiment investigating XPM distortion of the installed fibre in the BT LEANET network between Ipswich and Norwich, UK is described. The impact of XPM on transmission is assessed in additional Q-factor measurements and compared to the pump-probe measurements of signal distortion. A technique is proposed to accurately estimate XPM penalty in WDM optical fibre transmission experiments.

In the second part of the thesis, an application of fibre nonlinearities is shown for a single channel OTDM transmission at 40Gbit/s. Self-phase modulation (SPM) can compensate the dispersive broadening of the RZ pulses and thus increasing the error-free transmission distance. An all-optical semiconductor-based regenerator using a unidirectional nonlinear interferometer (UNI) configuration is described and its capability to operate at 40Gbit/s is demonstrated. A recirculating loop is used to operate this regenerator in a multi-span link and cascading of the regenerator up to 20 times effectively increases the error-free transmission distance.
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Chapter 1

Introduction

A Growth of optical communications

There has been a phenomenal growth in optical communications over the last decade with little evidence of saturation. This development has led to the availability of enhanced communication with the arrival of multimedia services. Trends show that the nature of traffic is shifting from voice to data due to the rapid growth of internet-protocol (IP) based services [FER99]. Driven by the need of increased bandwidth and globally expanding networks, research in optical fibre systems has responded to this development by the continuous increase of transmission capacity. Several new technologies were implemented enhancing the state of the art of current systems such as digital transmission, optical fibre, single mode optical fibre, optical multiplexing and optical amplification.

The first optical communication systems used only a single channel and relatively complicated and costly electronic repeaters were needed to increase the transmission distance. The key development for extending transmission over long distances was the development of the erbium-doped amplifier (EDFA) in 1988 following advances in fibre doping [POO88]. The bit-rate of a single channel is limited by the speed of electronic components to typically 10-40Gbit/s. Two different approaches added a new dimension to the transmission capacity in optical communications: Time-division multiplexing (TDM) and frequency/wavelength-division multiplexing (FDM/WDM). TDM combines $N$ channels on a single optical carrier. This can be done electrically (ETDM) or optically (OTDM) by interleaving the channels in time, thus creating a data stream with $N$ times the bit-rate of the base channel. OTDM bit-rates up to 640Gbit/s have been reported recently [YAM00]. FDM/WDM systems show a different approach taking advantage of the huge bandwidth (>50THz) of optical fibre defined by the low loss transmission windows. The data is transmitted in $N$ channels at different frequencies. A special case is sub-carrier multiplexing (SCM) where data is frequency-multiplexed in the electrical domain and transmitted on a single optical carrier. FDM and WDM are identical although FDM usually refers to coherent systems with narrow channel spacing $\Delta \lambda$. WDM systems are used to carry the information in $N$ distinct optical channels.
where the maximum bandwidth $N \cdot \Delta \lambda$ is dictated by the gain bandwidth of the EDFAs. The gain spectrum could be extended to longer wavelengths creating a 43nm transmission window in the L-band [SRJ98]. To date, terabit-capacities have been achieved and the channel number has been substantially increased with 10000 channels reported in a combined SCM/WDM experiment [OGA00]. Table 1.1 summarises the current trend in optical communications towards higher bit-rates and longer distances since the first terabit experiments in 1996 [YAN96]. The results are categorised according to the total bit-rate distance product. In addition, the bit-rate per channel and the number of channels are also listed. WDM systems exhibit many channels with a relatively low bit-rate whilst OTDM systems carry the full capacity in a single channel. The spectral efficiency in (bit/s) per Hz quantifies the bandwidth utilisation, an important factor in dense WDM transmission.

<table>
<thead>
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<td>640</td>
<td>92</td>
<td>58.9</td>
<td>-</td>
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Table 1.1 Bit-rate–distance products for some recent record single- and multi-channel experiments, according to [BAY00]

However, to maximise transmission capacity at a given bit-rate for WDM systems, narrow channel spacing is required, to increase the number of channels. In addition, the increase of the system length and longer inter-amplifier distances require higher launch power into the fibre spans. As a result of high optical power and narrow channel spacing nonlinear effects in the fibre significantly decrease the achievable error-free transmission distance. One of the most important multiwavelength nonlinearities in dense WDM is cross-phase modulation (XPM) [CHR90, AGR95]. XPM causes a modulation of the optical phase through the refractive index variation of the fibre when other channels are intensity modulated. This phase modulation is converted into amplitude distortion of the signal by fibre dispersion and leads to eye closure and timing jitter. The interaction of phase modulation with fibre dispersion and
the involvement of many channels result in a complex nature of this effect. For a given transmission capacity, the combination of bit-rate and number of channels is highly important when nonlinearities are considered [FOR96]. Although XPM is highly relevant for WDM transmission, at the start of this work, little has been published on the nature of XPM-induced impairments or the understanding of XPM in combination with different fibre dispersion schemes. Therefore, the work in this thesis is focused to develop an understanding of the key nonlinearities in optical transmission systems which allows to minimise the detrimental effect of XPM on transmission. The aim of this research was to undertake a systematic investigation of XPM distortion in IM-DD systems as a function of system parameters to develop a detailed understanding of the physical nature of the XPM process. The experimental results must also be compared with analytical calculations, numerical simulations and can be further verified in field experiments over installed fibre. The final goal of this work is a simplified description of XPM enabling the prediction of penalties in more complex transmission experiments.

The OTDM format is an alternative to WDM transmission since only a single channel is used with no detrimental XPM distortion. However, nonlinearities such as self-phase modulation (SPM) still occur for a single channel and lead to signal distortion limiting the transmission distance. However, when balancing SPM against the other limiting factor of fibre dispersion, both effects can compensate each other leading to error-free transmission. This nonlinearity-supported regime is confined to a narrow range of parameters and soliton-like pulses can be transmitted over thousands of kilometres [SUZ98]. The transmission distance is still limited by timing jitter, amplifier noise and pulse distortion at high bit-rates. However, OTDM systems offer the advantage of all-optical regeneration due to the digital nature of the RZ modulation format. All-optical regeneration at 40Gbit/s has attracted high interest as it allows to increase the bit-rate – distance product of OTDM systems. This thesis focuses on the aspect of all-optical regeneration, investigating a 3R-regenerator which compensates for the effects of nonlinearity, distortion and noise. The experimental investigation presented in this thesis also includes the aspect of cascading multiple regenerator units as this important issue determines the suitability of the regenerator for networks and long-haul applications.

### B Overview of thesis

The thesis is structured as follows: In chapter 2 the theory of multiwavelength optical fibre transmission is reviewed. In the first part, the linear effects of fibre attenuation and dispersion are considered. In the second part, a summary of nonlinear effects in optical fibre is given and the XPM effect is described in detail introducing the concepts of nonlinear phase shift, channel walk-off and residual dispersion. Analytical work is discussed which allows the exact and rapid calculation of XPM distortion in dispersive fibres.
An overview of existing research on XPM is given in chapter 3. This allowed to place the new results of this thesis in context with previously published experimental and theoretical results. After a review of early work, results reported from investigations of XPM in transmission experiments are discussed, including the impact of XPM on bit-error rate and system penalty and techniques for XPM suppression. This chapter concludes with a detailed summary of aspects requiring further investigation.

The next two chapters are devoted to the results obtained in this Ph.D. research. XPM distortion and XPM-induced penalties are both investigated. In chapter 4 the concept of pump-probe experiments is briefly presented to isolate XPM from other nonlinearities. Initially, XPM is investigated in single-span pump-probe experiments for different fibre types, channel spacing, bit-rate, pulse shape and launch power. The validation of these laboratory experiments is essential. Firstly, the results are compared with numerical simulations using the split-step algorithm and analytical calculations. Secondly, XPM experiments carried out over the installed fibre in the BT-LEANET network are discussed. The recirculating loop based experiments used to extend the investigation to variable link lengths are described to study the accumulation of XPM distortion with distance.

The aim of this work was to relate XPM-induced penalties to transmission system parameters. This is described in chapter 5. A technique is presented which allows to determine the Q-factor by scanning the decision threshold of the bit-error rate analyser. This method is applied to measure the Q-factor for single span links as a function of channel spacing. Similar to chapter 4 a recirculating loop is used to investigate the decrease of the Q-factor with distance, and the relationship between the pump-probe and the transmission experiments is described. It is shown that the measured or calculated amount of XPM distortion can be used to accurately estimate the penalty due to XPM in the system.

The impact of nonlinearities and dispersion on transmission is investigated in a single channel OTDM system and described in chapter 6. A mode-locked external cavity laser and source based on electro-absorption modulators are introduced for 40Gbit/s signal generation. A PLL-based receiver is discussed and the experiments are carried out using a 3-span recirculating loop. The error-free transmission distance is shown as a function of wavelength and the results are in agreement with numerical simulations. The second part of this chapter investigates 3R all-optical regeneration as a solution to improve the transmission performance. A summary of different 3R concepts is given and a unidirectional nonlinear interferometer (UNI) is investigated at 40Gbit/s for regeneration and demultiplexing. The work is completed with transmission experiments operating the UNI inside the loop.

Chapter 7 provides a summary of results of this research, a comparison with the aims of this work and possible areas for further research.
C Original contributions

The following original contributions to the field of XPM were made in the course of this research:

- Detailed investigation of XPM in pump-probe experiments, dependence of XPM distortion on channel walk-off, enhancement of XPM distortion near $\lambda_0$ for DSF
- First study of XPM for different pattern sequences, pulse widths and formats
- Identification of enhanced XPM distortion by filter misalignment
- First distance-dependent analysis of XPM distortion using recirculating loop
- Closest channel spacing (0.2nm) reported for length-dependent XPM pump-probe experiments at 10Gbit/s
- First and only field experiment reported to date investigating XPM distortion in the BT-LEANET network over installed fibre
- 2-span interference of XPM contributions showing a high sensitivity to dispersion map and wavelength fluctuations
- Wavelength dependent measurement of Q-factor for XPM-limited link
- Q-factor versus distance measurement using a recirculating loop: impact of number of pump channels and optical power on Q-factor
- Proposal of new technique to predict XPM penalties by simple pump-probe measurements or analytical calculations

The following original contributions to the investigation of nonlinear effects in OTDM transmission were made:

- First all-optical 3R regeneration using an ultrafast nonlinear interferometer (UNI) at 40Gbit/s with long PRBS pattern ($2^{31}-1$)
- Error-free transmission of regenerated signals and first cascading of a UNI in a recirculating loop at 40Gbit/s with only 0.1dB penalty per stage
D Publications and conference presentations

Refereed papers and conferences:


Other publications and presentations:


Chapter 2

Theory of optical fibre transmission

In this chapter the theory of the mechanisms governing the propagation of optical pulses in optical fibre is discussed. The interaction of the signal with the propagation medium through linear and nonlinear processes results in attenuation and distortion of the pulses. In section 2.1 linear effects in fibres such as attenuation and dispersion are discussed and in section 2.2 nonlinear effects in fibres are described. Finally, cross-phase modulation (XPM), which is the main subject of the investigation in this thesis, is introduced in section 2.3.

Introduction: The propagation of light in optical fibres is described by the nonlinear Schrödinger equation (NLSE), whose derivation is presented in appendix C [AGR95]. This equation describes the linear and nonlinear effects experienced by electromagnetic (EM) waves in dielectric media. In particular, the terms on the left hand side of equation (2.1) describe the linear mechanisms during transmission, namely the fibre attenuation and dispersion. These effects are independent of the optical power in the fibre and will be described in section 2.1.

\[
\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i\gamma |A|^2 A
\]  

(2.1)

\( A(z,t) \) denotes the complex EM field, \( \alpha \) is the linear attenuation, \( \beta_1 \) the inverse group velocity and \( \beta_2 \) the group velocity dispersion. The term on the right hand side will be discussed in section 2.2 and includes nonlinear effects with the coupling factor \( \gamma \) characterising the nonlinear properties of the optical fibre.

Assessment of transmission performance: As a result of linear and nonlinear effects the signal described by \( A(z,t) \) is degraded after transmission. In this thesis, different parameters are used to characterise the transmission quality. The pulse width is used to investigate the impact of fibre dispersion on isolated pulses. In general, a pseudo-random bit sequence
(PRBS) is used for the transmitted data. In this case, the signal distortion can be described by the horizontal and vertical eye-opening penalty (EOP) [AGR92]. The optical signal-to-noise ratio (SNR) is used to describe the quality of the transmitted signal in the presence of ASE noise and is measured as the ratio of '1'-level of the signal to the background noise. The Q-factor or the electrical SNR provides a more detailed assessment of the transmission by taking into account the broadening of '0' - and '1'-level due to noise and distortion shown in Fig. 5.1. The Q-factor is described in chapter 5. When investigating the '1'-level alone, the vertical broadening can be characterised using standard deviation $\sigma$. In chapter 4 the special case of time-averaged signals is considered where $\sigma$ only describes the broadening due to distortion alone. The parameters described above provide insight into the physical processes leading to degradation of transmission. Alternatively, transmission performance can be directly characterised using the bit-error-rate (BER). It is conventional to consider transmission as error-free for BER<$10^{-9}$. The power penalty indicates the necessary adjustment of the optical receiver power as a result of transmission degradation to maintain BER=$10^{-9}$ [BER93].

2.1 Linear effects in optical fibres

2.1.1 Linear attenuation

In a dispersion-free linear medium the NLSE is reduced to a first order differential equation.

$$\frac{\partial A(z,t)}{\partial z} = -\frac{\alpha}{2} A(z,t)$$

(2.2)

The optical power evolution $P(z,t) = |A(z,t)|^2$ in the fibre, can then be found as

$$P(z,t) = P_0(0,t) \cdot \exp(-\alpha z)$$

(2.3)

where $P_0(0,t)$ is the launch power into the fibre link and $\alpha$ is defined as the attenuation constant, usually in logarithmic units dB/km. The constant $\alpha$ can be converted into linear units as $\alpha_{lin} = \alpha(dB)/4.343$ and takes into account scattering losses, fibre bending losses and ion absorption due to excitation of vibrational modes in the infrared (IR) region. One common absorption peak at $\lambda=1.4\mu m$ is a result of OH impurities from the fibre manufacturing process and limits the spectral usability of the fibre. However, in new fibre types such as the Lucent-Allwave fibre this peak could be suppressed joining the second and third telecommunications window [KUM00]. For standard fibre (SSMF) the absorption reaches a minimum of $\alpha=0.2dB/km$ in the widely used 1.55$\mu m$ range, the third telecommunications

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1 Other fibres used in this thesis were dispersion-compensating fibre (DCF) with $\alpha=0.5dB/km$ and dispersion-shifted fibre (DSF) with at $\alpha=0.22dB/km$ at $\lambda=1.55\mu m$. 

window, as shown in Fig. 2.1. The second window at 1.3μm shows minimum group velocity dispersion (GVD) but a loss of about 0.4dB/km for SSMF. This increase of α towards shorter wavelengths is due to Rayleigh scattering which varies as λ⁻⁴. This intrinsic scattering is due to random fluctuations in the refractive index of the fibre setting the ultimate limit of fibre propagation. Other losses in real systems are bending losses and splicing losses. All linear losses can be compensated in a repeatered system using optical amplifiers.

\[ \frac{\partial A(z, \omega)}{\partial z} = i \frac{\beta_2 \omega^2}{2} A(z, \omega) \]

Equation (2.4) describes, for a particular frequency component ω, a distance- and frequency-dependent phase shift where β₂ determines the magnitude. Therefore, different spectral components travel with different velocity along the fibre leading to pulse broadening. The quantity β₂ is given by
As can be seen from (2.5) $\beta_2$ is dependent on the second derivative of $n(\lambda)$ of the silica fibre and becomes zero at the turning points of $n(\lambda)$. Equation (2.5) also shows that $\beta_2$ can be interpreted as the group velocity dispersion (GVD) since it is a measure for the variation of $v_g$ with $\omega$. For silica fibre at $\lambda_0=1.3\mu m$, the GVD is zero ($\beta_2=0$) and pulses do not broaden due to zero dispersion. $\beta_2$ is commonly expressed by the dispersion constant $D$ which gives the dispersive delay in picoseconds for a wavelength change of $\Delta\lambda=1nm$ after propagation over $L=1km$ of fibre.

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2$$

In the region of $\beta_2>0$ higher-order effects of dispersion must be taken into account described by the dispersion slope $D'=dD/d\lambda$. Typical values for SSMF fibre are $0.06-0.07ps/(nm^2-km)$ where the dispersion away from $\lambda_0$ can be written as $D(\lambda)=D'(\lambda-\lambda_0)$. For $\lambda<\lambda_0$, $\beta_2$ is positive and, hence, $D$ negative which is referred to as normal dispersion. The blue-shifted components of the pulse spectrum propagate slower than the red shifted components leading to a time-dependent frequency $\omega(t)$ of the pulses which is known as chirp. For longer wavelength $\lambda>\lambda_0$, as in the case for SSMF at $\lambda=1550nm$ in the third telecommunication window, $\beta_2<0$, $D>0$ and the leading edge of the pulse is blue-shifted whilst the trailing edge is red-shifted resulting in the opposite chirp. This wavelength region is important in nonlinearity-supported transmission as the dispersive broadening can counteract the nonlinearity-induced pulse distortion and support soliton-like pulses as shown in chapter 6.

In an optical fibre the additional waveguide dispersion, dependent on the geometrical dimensions of the core and cladding, must also be taken into account modifying the total dispersion experienced by the signal. For different $\lambda$ and a given core diameter, the ratio of light travelling in the core and cladding regions changes and, hence, so does the overall dispersion due to the different refractive indices of the inner and outer region of the fibre. Increasing $\lambda$ therefore increases the mode area and reduces $D$. The combination of material and waveguide dispersion can be used to shift $\lambda_0$, the region of zero GVD, to longer wavelengths to combine low loss with low fibre dispersion as indicated in Fig. 2.2. An example is dispersion-shifted fibre (DSF) with $\lambda_0$ around $1.55\mu m$ or non-zero DSF with $\lambda_0$ around $1.52\mu m$. 

$$\beta_2 = -\frac{1}{v_g^2} \frac{d^2 \omega}{d\omega} = -\frac{\lambda}{c} \frac{d^2 n(\lambda)}{d\lambda^2}$$

(2.5)
Chapter 2: Theory of optical fibre transmission

2.1.3 Dispersion management

Limitation of transmission distance: The dispersion of SSMF at \( \lambda = 1550\text{nm} \) of approximately \( \beta_2 = -21.7\text{ps}^2/\text{km} \) [AGR95] results in signal distortion limiting the transmission distance due to pulse broadening and intersymbol interference (ISI). For single Gaussian pulses the broadening can be described by the full width half maximum \( T_{\text{FWHM}} \). After propagation over a distance \( z \) its width increases and becomes \[ T_{\text{FWHM}}(z) = T_{\text{FWHM}}(0) \sqrt{1 + \left( \frac{z}{L_D} \right)^2} \] (2.7)

where \( L_D = T_{\text{FWHM}}^2 / (4 \cdot \ln(2) \cdot |\beta_2|) \) is defined as the dispersive length and the pulse broadens by \( \sqrt{2} \) after \( z = L_D \). This is equivalent to the distance where the pulse peak power is reduced to 50% of its initial value corresponding to EOP=3dB. For \( T_{\text{FWHM}}=100\text{ps} \), the dispersion limited length is 166km and is reduced to 10.4km for \( T_{\text{FWHM}}=25\text{ps} \).

Improving transmission with pre-chirping: In Fig. 2.3 the relative broadening \( T_{\text{FWHM}} / T_{\text{FWHM}}(z=0) \) is plotted as a function of distance for Gaussian pulses with \( T_{\text{FWHM}}(z=0) =100\text{ps} \). These results are compared with the pulse shape used in experiments and simulations of this thesis. For Gaussian pulses the broadening can be calculated analytically [AGR92] where \( C \) denotes the chirp factor, \( T_{\text{FWHM}}(z=0) \) the initial width and \( \beta_2 \) the fibre dispersion. For

![Diagram of normal and anomalous dispersion](image)

Fig. 2.2 Above: Influence of material and waveguide dispersion on \( \lambda_c \) and \( D \) for SSMF fibre, according to [AGR92]. For DSF fibre the waveguide dispersion results in a shift of the total dispersion curve with \( D=0 \) in the \( \lambda=1.55\mu\text{m} \) region.
C>0, the instantaneous frequency increases from the leading to the trailing edge, called up-chirp. The chirp is defined in equation (2.21).

\[
\frac{T_{\text{FWHM}}(z)}{T_{\text{FWHM}}(0)} = \sqrt{\left(1 + \frac{C \beta_2 z}{8 \ln(2) \cdot T_{\text{FWHM}}(0)}\right)^2 + \left(\frac{8 \ln(2)}{8 \ln(2) \cdot T_{\text{FWHM}}(0)}\right)^2} \tag{2.8}
\]

It is shown in Fig. 2.3, that for \(L<100\text{km}\) of SSMF the pulse broadening \(T_{\text{FWHM}}/T_{\text{FWHM}}(z=0)\) is reduced by a positive chirp (\(C=2\)). This is due to the interaction with fibre dispersion where the linear chirp counteracts the broadening induced by the SSMF. For distances \(L>100\text{km}\), however, unchirped pulses show the smallest broadening. In the simulations Bessel-filtered rectangular pulses were used. The evolution of this unchirped pulse shape is also plotted in Fig. 2.3.

**Fibre-based dispersion compensation**: Pre-chirping of pulses can reverse their dispersive broadening and the original pulse shape is restored after transmission. The necessary chirp can also be achieved with a dispersive element of opposite dispersion. In general, DSF exhibits low dispersion in the interval ±2ps/(km·mn) around 1550nm which does not require dispersion compensation in some cases. However, the low dispersion results in enhanced nonlinearities such as four-wave mixing (FWM) and cross-phase modulation (XPM) \([AGR95, CHR90]\) due to phase matching and low channel walk-off, as discussed in detail in section 4.14. The introduction of moderate dispersion of approximately 3-5ps/(km·nm) in nonzero dispersion-shifted fibre (NZ-DSF) can reduce this detrimental effect yet keep the accumulated dispersion \(D \cdot z\) low \([CHR95, GAR96]\). The concept of dispersion management was proposed nearly two decades ago by \([LIN80]\). To date, a number of schemes have been suggested based on using optical fibre with an opposite sign of dispersion to reduce the total link dispersion \([NIS96]\). In particular, alternating sections of positive and negative DSF were
used in transmission systems [MAR91b], negative DSF followed by SSMF for compensation [CHR93] and highly negative dispersion compensating fibre (DCF) [IZA92]. The advantage of DCF is the short length required for compensation due to a typical dispersion $D = -100\text{ps/(km-nm)}$. However increased loss of 0.5-0.8dB/km and nonlinearities due to a small effective area of 25μm$^2$ have to be taken into account. In this thesis, dispersion managed links of DSF and SSMF were mostly used. For very high bit-rates of 100Gbit/s special continuous dispersion-managed fibre has recently been reported [ANI99]. Unlike conventional fusion-spliced fibre links of opposite dispersion this fibre contains alternating sections of positive and negative dispersion with a short periodicity of 0.5km.

Other techniques for dispersion compensation include chirped fibre Bragg-gratings (FBGs), first reported in 1987 [OUE87]. In contrast to fibre-based compensation a chirped FBG exhibits a lower spectral bandwidth due to a typical length of 10cm. More recently, this length could be increased to 1m to compensate nearly 630km NZDSF ($D=3.2\text{ps/(km-mm)}$) over a 4.8nm bandwidth [IPS97]. The bandwidth limitation of FBGs can be overcome by applying either mechanical stress or controlling the temperature resulting in tuneable dispersion compensators [NIE00b]. Exact dispersion compensation was also demonstrated by mid-span spectral inversion up to 40Gbit/s [STE99]. This process is based on optical phase conjugation resulting from the four-wave mixing process [YAR79].

For a dispersion-managed link with SSMF of length $L_{\text{SSMF}}$ and dispersion $D_{\text{SSMF}}$, the required amount $L_{\text{DCF}}$ of DCF fibre with $D_{\text{DCF}}$ for compensation of linear distortion can be obtained as

$$L_{\text{DCF}} = \left| \frac{D_{\text{SSMF}}}{D_{\text{DCF}}} \right| L_{\text{SSMF}} \quad (2.9)$$

For 60km SSMF commonly used in the experiments described in chapter 4 and 5, about 10km of DCF with $D_{\text{DCF}} = -100\text{ps/(km-mm)}$ are needed. The slope is typically $-0.1\text{ps/(nm}^2\cdot\text{km)}$ for DCF and $0.07\text{ps/(nm}^2\cdot\text{km)}$ for SSMF. Therefore, the link is exactly compensated only at a single wavelength. However, using fibre with additional slope compensation can exactly compensate for dispersion over the entire wavelength range as was recently shown for a 32 channel WDM system using slope-compensating SCDCF and reverse dispersion fibre (RDF) [TAN99, TSU00]. The slope compensation of $\beta_2$ is becoming increasingly important for short pulse widths in high bit-rate transmission. Alternatively to slope compensation, new fibre with reduced slopes has been developed such as Lucent RS-Allwave fibre with $0.045\text{ps/(km-mm}^2\) [LUC00].

**Dispersion map:** In dispersion-managed fibre links there is a distinction between (a) compensation on a per span basis where the compensation interval coincides with the amplifier spacing in the link or (b) lumped compensation at the receiver or transmitter for the entire link. For fibre-span based compensation, 3 different configurations are typically used.
• **Post-compensation**: In every span, the compensating fibre follows the transmission fibre, e.g. SSMF+DCF

• **Pre-compensation**: On a per span basis the compensating fibre is located before the transmission fibre, e.g. DCF+SSMF

• **Symmetrical compensation**: a combination of pre- and post-compensation where the transmission fibre is located between the compensating modules (DCF1+SSMF+DCF2)

Fig. 2.4 Exactly pre- and post-compensated spans calculated using 60km SSMF and 10.2km DCF at 10Gbit/s, eye diagrams for 10Gbit/s PRBS modulated channel before and after transmission, only linear effects are considered ($\gamma=0$).

The dispersion map for pre- and post-compensation is shown in Fig. 2.4. The eye diagram for a 10Gbit/s PRBS signal is calculated at the output and after the first fibre subsection in the case of linear transmission. Due to the accumulated dispersion, the pulses are significantly distorted but are completely restored after using fibre with the opposite dispersion. In the presence of nonlinearities these compensating schemes are no longer equivalent and are further discussed in section 2.2.5 and chapter 4, sections 4.3 and 4.4.

The benefit of increased transmission distance due to dispersion compensation is demonstrated in Fig. 2.5. For a noise-free PRBS-modulated channel at 10Gbit/s eye-opening penalty is shown as a function of span length. The EOP increases exponentially for the uncompensated SSMF reaching 3dB after approximately 80km. This is due to dispersive pulse broadening alone shown in Fig. 2.3 before. The EOP can be reduced using DCF in pre-compensation. The length of 10.2km DCF is chosen to exactly compensate for 60km of SSMF. As a result, the EOP reaches zero after $L_{op}=(10.2+60)$km since the linear chirp of the DCF compensates the distortion generated in the SSMF subsection. The EOP reaches 3dB after 150km span length, a significant improvement over the uncompensated span of similar length. In the post-compensated configuration the system remains fully compensated after $L_{op}=(60+10.2)$km and exact compensation results in EOP=0dB. This observation is different in systems where nonlinearities such as self-phase modulation (SPM) have to be taken into
account. It will be shown in section 2.2 that the additional nonlinear chirp of the pulses requires to reduce the length of the compensating fibre for minimum EOP.

![Diagram showing EOP versus distance for 10Gbit/s PRBS signal over different fibre spans. (a) bold line: SSMF only, (b) solid line: DCF + variable amount of SSMF, (c) dotted line: 60km SSMF + variable amount of DCF, (d) dashed line: as in (c) but for 20mW launch power into the SSMF.]

**Fig. 2.5** Eye-opening penalty (EOP) versus distance for 10Gbit/s PRBS signal over different fibre spans. (a) bold line: SSMF only, (b) solid line: DCF + variable amount of SSMF, (c) dotted line: 60km SSMF + variable amount of DCF, (d) dashed line: as in (c) but for 20mW launch power into the SSMF.

### 2.1.4 Phase-to-intensity conversion

The linear effect of phase to intensity (PM-IM) conversion due to fibre dispersion is important in combination with nonlinear effects such as self-phase and cross-phase modulation as it results in intensity distortion, limiting the transmission distance. The origin of this phase modulation can be either of a linear nature, such as the chirp of directly modulated light sources [COL95], or modulators [GNA91] or originating from nonlinear processes in the fibre [POT87] as discussed in sections 2.2 and 2.3.7. According to Wang et al. [WAN92] a matrix can be derived for a fibre span relating the output power $P_{\text{out}}(\omega)$ and phase $\phi_{\text{out}}(\omega)$ to their input values $P_{\text{in}}(\omega)$ and $\phi_{\text{in}}(\omega)$. For propagation over a distance $L$ and fibre dispersion $D$ it was shown, assuming only a small conversion $\Delta P \ll P$ along $L$, that

$$
\left( \begin{array}{c} \frac{\Delta P_{\text{out}}(\omega)}{2\langle P_{\text{out}} \rangle} \\ \phi_{\text{out}}(\omega) \\ \end{array} \right) = \left( \begin{array}{cc} \cos \left( \omega^2 \frac{\lambda^2}{4\pi c} D \cdot L \right) & -\sin \left( \omega^2 \frac{\lambda^2}{4\pi c} D \cdot L \right) \\ \sin \left( \omega^2 \frac{\lambda^2}{4\pi c} D \cdot L \right) & \cos \left( \omega^2 \frac{\lambda^2}{4\pi c} D \cdot L \right) \\ \end{array} \right) \left( \begin{array}{c} \frac{\Delta P_{\text{in}}(\omega)}{2\langle P_{\text{in}} \rangle} \\ \phi_{\text{in}}(\omega) \\ \end{array} \right)$$

(2.10)

where $\langle P \rangle$ is the time-averaged power of the channel. For a given signal, the square matrix in (2.10) represents a rotation in the $(P, \phi)$ plane mixing intensity modulation and phase modulation. In the case of an input CW signal ($\Delta P_{\text{in}}(\omega)=0$ at $L=0$) with phase modulation
\( \phi_\omega(\omega) \), the intensity distortion \( \Delta P_{\text{out}}(z) \) along the fibre is obtained from equation (2.10) as a single matrix element.

\[
\Delta P_{\text{out}}(\omega, z) = -2\langle P_{\text{out}} \rangle \sin \left( \omega^2 \frac{\Delta^2}{4\pi c} D \cdot z \right) \phi_\omega(\omega, 0)
\] (2.11)

Equation (2.11) shows that for \( z \ll 4\pi c/(\Delta^2 D) \) the intensity distortion \( \Delta P_{\text{out}} \) increases linearly with distance. This is due to the GVD of the fibre leading to different velocities of the spectral components generated by the phase modulation \( \phi_\omega(\omega) \). The sine-function indicates that phase modulation is periodically converted into amplitude distortion with the propagation distance where the period of the oscillation between states of complete amplitude and phase distortion is determined by the fibre dispersion. Equation (2.11) was used to calculate the PM-IM conversion for different amplitudes of \( \phi_\omega(\omega) \) using the small signal approximation, and the results are shown in Fig. 2.6. This approximation is used by several authors [BEL98, CAR98] in combination with XPM to calculate analytically the intensity distortion due to PM-IM conversion. In the following, PM-IM conversion was investigated for 60km of SSMF, a span length used in the single span experiments described in this thesis.

The propagating channel is phase-modulated at 5GHz, corresponding to a 1010... bit-pattern at 10Gbit/s for the non return-to-zero format (NRZ). The results for the normalised power fluctuation \( \Delta P(\omega)/\langle P \rangle \) obtained with equation (2.11) are compared with the exact numerical simulation using equation (2.4) in Fig. 2.6. For a small phase amplitude \( \phi_{\text{in, max}} = 0.2 \) radian, good agreement between the analytical and the simulated results is obtained. Increasing the amplitude to \( \phi_{\text{in, max}} = \pi/2 \) radian, the accuracy of equation (2.11) is reduced due to the small signal approximation. This calculation demonstrates that analytical techniques allow the
estimation of PM-IM conversion. In combination with nonlinear effects this approach allows us to calculate the signal distortion as described in section 2.3.7.

In addition to PM-IM conversion in dispersive fibres optical filters can also increase the amplitude distortion of the signal. The limited filter bandwidth results in partial attenuation of frequency components associated with the phase-modulated signal. The removal of frequency components from the signal has the same effect as the different velocity due to dispersion. This effect is experimentally investigated for XPM in chapter 4, section 4.1.8.
2.2 Nonlinear effects in optical fibres

The nonlinear effects in optical fibre can be separated into two categories. One group of nonlinear effects, known as Kerr nonlinearities, such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM), is governed by the $\chi^{(3)}$ susceptibility of the fibre. Another group of nonlinear effects originates from the stimulated inelastic scattering between the electrical field and phonon modes in the silica fibre. These are stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). Most of the work in this thesis is related to the investigation of the interaction of XPM and SPM with dispersion and, hence, these are the effects which are described in detail. Other nonlinearities are described in the appendices E and F.

2.2.1 Kerr nonlinearities

The Kerr-effect gives rise to an intensity dependent refractive index $n$ of the fibre given by

$$n(I) = n_0 + n_2 I$$  \hspace{1cm} (2.12)

with $n_0 = n(I=0)$ and the nonlinear coefficient $n_2$ defined as the real part of the first tensor element of $\chi^{(3)}$. In the case of linearly polarised light only one component of the fourth-rank tensor $\chi^{(3)}(\omega)$ contributes to the nonlinear polarisation $P_{nl}(\omega)$ [HAN95]:

$$n_2 = \frac{3}{8n} \text{Re}(\chi^{(3)}_{1111})$$  \hspace{1cm} (2.13)

Typical values for silica fibres are $n_2 \approx 2.2-3.4 \times 10^{-20} \text{ m}^2/\text{N}$, depending on the core composition [AGR95]. In the following, a system with two channels at $\omega_1$ and $\omega_2$ is considered and the resulting nonlinear source terms due to $\chi^{(3)}$ are discussed. The combined electric field $E_i(\omega_i) + E_2(\omega_2)$ is substituted into the expression for $P_{nl}(\omega)$ (given in appendix C) and the arising nonlinear contributions are according to their frequency

$$P_{NL}(\omega_1) = \chi_{eff} \left[ E_1(\omega_1)^2 + 2|E_2(\omega_2)|^2 \right] \cdot E_1(\omega_1)$$

$$P_{NL}(\omega_2) = \chi_{eff} \left[ E_2(\omega_2)^2 + 2|E_1(\omega_1)|^2 \right] \cdot E_2(\omega_2)$$

$$P_{NL}(2\omega_1 - \omega_2) = \chi_{eff} E_1^2(\omega_1) E_2^*(\omega_2)$$

$$P_{NL}(2\omega_2 - \omega_1) = \chi_{eff} E_2^2(\omega_2) E_1^*(\omega_1)$$  \hspace{1cm} (2.14)

where $\chi_{eff} = \frac{3}{4} \cdot \omega \cdot \chi_{1111}$. The last two expressions show terms oscillating at new frequencies $2\omega_1-\omega_2$ and $2\omega_2-\omega_1$. This is a result of the four-wave mixing (FWM) process (discussed in
appendix F) in which power is transferred from the original channels into new spectral sidebands. The first two expressions in equation (2.14) are symmetrical in $\omega$ and have a structure similar to the first order polarisation.

$$P_{nl}(\omega_i) = e^{NL}_i E_i(\omega_i)$$

The coupling factor $e^{NL}$ between the electrical field and the polarisation is dependent on the intensity in the channel itself and on the intensity in the neighbouring channel. The first coupling term in $P_{nl}(\omega_1)$ and $P_{nl}(\omega_2)$ is due to self-phase modulation (SPM) discussed in section 2.2.3 and describes the optical phase modulation due to power variation in the channel itself. The second coupling term results from cross-phase modulation (XPM) discussed in section 2.3 and describes the phase modulation due to power fluctuations in the neighbouring channels. In Fig. 2.7 the different nonlinear effects are categorised. This thesis focuses on the investigation of the Kerr effects SPM and XPM whilst SBS, SRS and FWM are described in appendix E and F.

![Fig. 2.7](image-url) Overview of nonlinear effects in optical fibres

### 2.2.2 Coupled Schrödinger equation for self-phase modulation and cross-phase modulation

An expression for the SPM and XPM effect in a WDM system with $N$ channels can be derived from the NLSE. In a single channel approach, the electric field $A_s(z,t)$ of channel $s$, ($s=1,\ldots,N$), is separately evaluated and the nonlinear term on the right hand side of equation (2.1) includes the coupling between particular channels due to XPM in a similar way as the
source terms in equation (2.14). This method is in contrast to the total field approach where
\( A(z,t) = A_s(z,t) + A_p(z,t) \) represents the combination of all channels (channel \( p = 1, \ldots, N, p \neq s \)) and only a single equation needs to be solved. In the following, a link with low dispersion is assumed, hence, the shape of the envelope \( A_s(z,t) \) is not affected by the fibre dispersion and \( \partial^2 A_s / \partial t^2 \approx 0 \). However, the channels still propagate with different group velocities \( v_g \).

Therefore, the NLSE can be written as

\[
\frac{\partial A_s}{\partial z} + \frac{1}{v_g} \frac{\partial A_s}{\partial t} + \frac{\alpha}{2} A_s = i \gamma \left[ |A_s|^2 + 2 \sum_{p \neq s} |A_p|^2 \right] A_s
\]

with \( A_p(z,t) \) denoting the interfering channels. The solution has the following form:

\[
A_s(z,t) = A_s(0, t - \frac{z}{v_g}) \exp\left(-\frac{\alpha}{2} z\right) \exp\left(i \phi_s(z,t)\right)
\]

which describes a plane wave with exponential decay due to \( \alpha \) and additional phase modulation expressed by \( \phi_s(z,t) \). The phase modulation in channel \( s \) is given by

\[
\phi_s(z,t) = \gamma \frac{1 - e^{-\alpha z}}{\alpha} \left[ |A_s(0, t - \frac{z}{v_g})|^2 + 2 \sum_{p \neq s} \int_0^t A_p(0, t - \frac{z}{v_g} + d_{wp} \zeta) |A_p|^2 e^{-\alpha \zeta} d\zeta \right]
\]

where the parameter \( d_{wp} = D \cdot \Delta \lambda = D \cdot (\lambda_s - \lambda_p) \) describes the walk-off between the channels at \( \lambda_s \) and \( \lambda_p \) and is discussed in section 2.3.2. The factor \( L_{\text{eff}} \) is defined as

\[
L_{\text{eff}} = \left(1 - \exp(-\alpha L)\right) / \alpha
\]

Expression (2.19) indicates the fibre length over which nonlinearities are significant. In Fig. 2.8, \( L_{\text{eff}} \) is shown for different attenuation \( \alpha \) and specifies the distance where the power is reduced to \( 1/e \) of the input value. For \( \alpha \cdot L \gg 1 \), it can be approximated as \( L_{\text{eff}} \approx 1/\alpha \) corresponding to 20.6km for SSMF.

![Fig. 2.8 Nonlinear length \( L_{\text{eff}} \) for different fibre types used in this thesis (\( L=60\text{km} \))](image)
The first term of equation (2.18) describes the SPM effect resulting in a phase shift \( \phi_s^{SPM} \) proportional to the optical power \( |A_s|^2 \) in the same channel. The second term is due to XPM taking into account the contributions of all channels including the relative difference of these channels in their group velocities. In the case of the same propagation speed of all channels, \( d_{sp}=0 \), the phase shift induced by each of the neighbouring channels due to XPM is twice that resulting from SPM alone.

### 2.2.3 Self-phase modulation (SPM)

The SPM effect was first investigated in optical fibre by Stolen et al. [STO78]. The interaction of SPM with dispersion results in pulse distortion due to PM-IM conversion of the phase distortion \( \phi_s^{SPM} \). The phase shift due to SPM in equation (2.18) is given by

\[
\phi_s^{SPM}(z,t) = \gamma L_{\text{eff}} \left| A_s \right| \left( 0, t - \frac{z}{v_g} \right)^2
\]

with \( L_{\text{eff}} \) defined in (2.19). The nonlinear phase shift \( \phi_s^{SPM} \) is dependent on the intensity profile of the pulses and is proportional to the optical power. In a medium with negligible dispersion the pulse shape remains unaffected and phase variation across the pulse results in a time-dependent carrier frequency, known as chirp

\[
\delta \omega(t) = -\frac{\partial \phi_s^{SPM}(t)}{\partial t}
\]

The chirp generates new frequency components leading to spectral broadening in dispersive media, increasing for fast pulse transitions since the shape of \( \phi_s^{SPM}(t) \) is proportional to \( P=|A_s|^2 \). In response to the SPM phase shift the leading edge of the pulses experiences a frequency reduction (red shift) and the trailing edge a frequency increase (blue shift). Fig. 2.9 illustrates the typical chirp for Gaussian pulses compared with super-Gaussian pulses of the form \( P(t)=P_0 \exp\left[-0.5\left(t/T_0\right)^m\right] \) where \( T_0 \) is the 1/e-pulse width and \( P_0 \) the peak power. Pulses with \( m>1 \) have steeper rising/falling edges than regular Gaussian pulses and therefore produce more localised chirp at the pulse edges. The pulse shape of single pulses at 10Gbit/s used in the experiments could be approximated by \( m=1.3 \). For the Gaussian pulses \( m=1 \) the chirp in Fig.2.9 is linear across the central region. In the limit of rectangular pulses the variation of \( \phi_s^{SPM}(t) \) for the centre of the pulse approaches zero with localised chirp at the pulse edges.
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2.2.4 SPM and dispersion

In dispersive optical fibre the spectral components of a chirped pulse propagate at different speeds. As already shown in section 2.1.2, an increase of the optical frequency results in an increase or decrease of velocity of a particular spectral component in the fibre with anomalous and normal dispersion, respectively. The different velocities of the spectral components results in a break-up of the pulses and distortion due to PM-IM conversion. In the 1550nm spectral region, DCF fibre exhibits normal dispersion ($D<0$) and, therefore, the velocity of the red-shifted leading edge of the pulse is increased and the velocity of the blue-shifted trailing edge is reduced leading to enhanced broadening. SSMF exhibits anomalous dispersion ($D>0$) and, therefore, blue-shifted components travel faster than red-shifted components. Instead of the dispersive broadening observed for transmission over SSMF in the linear regime, the interaction of SPM and dispersion can compress the pulses in the nonlinear regime. The distortion due to nonlinearity and dispersion is investigated for a PRBS-modulated channel at 10Gbit/s over 60km of SSMF and the equivalent DCF link with the opposite dispersion, and the results are shown in Fig. 2.10. The pulses, initially unchirped, are 6th-order Bessel-filtered square pulses similar to the pulse shapes used in the experiments described in chapter 4 and 5.
In agreement with the results in Fig. 2.4 the linear distortion of unchirped pulses in the SSMF and the DCF link with exactly the opposite dispersion is identical. The total broadening of the individual pulses only depends on the absolute value of the accumulated dispersion after propagation and the difference between the two fibre types is the reverse sign of the chirp induced by the dispersion. As described above, one can distinguish between SSMF and DCF when additional, dispersion-independent chirp due to SPM is induced on the pulses and the initial symmetry is lifted. Fig. 2.10(b) shows significant recompression enhancing the pulse edges in comparison to Fig. 2.10(a). In Fig. 2.10(d), however, SPM and dispersion broaden the pulses and reduce the pulse amplitude. In section 2.2.6 and chapter 6 the special case of solitons is discussed. Propagation of time-stable pulses is achieved since the broadening due to anomalous dispersion is exactly compensated by the SPM nonlinearity.
2.2.5 Modulation instability

In the presence of nonlinearity and dispersion a constant waveform can be self-modulated, a phenomenon known as modulation instability (MI), initially investigated by Hasegawa [HAS70]. In the region of anomalous dispersion ($D > 0$) MI has been shown to result in a break-up of continuous wave (CW) pulses into a train of ultrashort pulses. Fig. 2.11 shows the calculated PRBS waveform at 10Gbit/s as a function of distance for a link of 100 exactly post-compensated spans of 80km using low dispersion fibre ($\beta_2 = -1ps^2/km$). After 80 spans with 20mW launch power a fast oscillation is visible on the pulse on the right hand side increasing its magnitude in subsequent spans. At the same time the onset of MI on the left pulse can be observed after $n=100$ spans. MI normally becomes relevant for long distances $L > 5000km$, however, this distance can be reduced to less than 500km in the presence of ASE noise seeding the MI process [SAU97].

![Fig. 2.11](image)

**left:** Distortion due to modulation instability (MI) as a function of distance, $n$: number of post-compensated spans, $\beta_2 = -1ps^2/km$, 10Gbit/s PRBS, NRZ format, 20mW launch power, no ASE, **right:** oscillation due to MI after $n=100$

2.2.6 Solitons

There are two principal approaches to overcome the limitations due to nonlinearity and dispersion: in the first, which can be called 'linear', chromatic dispersion and fibre nonlinearity are considered to be detrimental factors while in the second the nonlinear and the dispersive effects are counterbalanced. Nonlinear effects can be used to improve the transmission characteristics of optical communication systems resulting in nonlinearity-supported transmission. One important example is the use of solitons in optical fibre initially predicted by Hasegawa and Tappert [HAS73]. Solitons describe a special solution of the
Chapter 2: Theory of optical fibre transmission

NLSE found using the inverse scattering method [TAY90]. For the first time, solitons were experimentally observed in optical fibre by Mollenauer in 1980 [MOL80] using a mode-locked laser at 1.5μm. In the case of anomalous dispersion (D>0) SPM can compensate for the pulse broadening due to dispersion. Solitons maintain their pulse shape during transmission and are thus very attractive for long-haul transmission. The envelope amplitude of the solitons is described by a hyperbolic secant

\[ A(0,t) = \sqrt{P_0 \text{sech}(t/T_0)} \]  

(2.22)

where the required peak power for the soliton is given by

\[ P_0 = \frac{|\beta_2|}{\gamma T_0^2} \approx 3.11 \frac{|\beta_2|}{\gamma T_{\text{FWHM}}^2} \]  

(2.23)

where \(T_{\text{FWHM}}\) describes the width of the first order (fundamental) soliton pulse. Soliton transmission over a link of standard fibre has been demonstrated [CHR93b] but this requires a high launch power, e.g. 27mW for \(T_0=40\)ps and \(\lambda=1550\)nm. This power level can be further reduced in DSF since, due to the reduced dispersion, less SPM induced chirp is needed to counteract the dispersive broadening. Pulses of different shape evolve during transmission to a stable \(\text{sech}^2\) form. Solitons strictly exist only for \(\alpha=0\). In the presence of fibre loss the influence of SPM reduces as the pulse propagates over the fibre and dispersion broadens the pulses. For narrow pulse width \(T_{\text{FWHM}}\approx 1\)ps dispersion-decreasing fibre (DDF) can be used which has a distance-dependent local dispersion following the loss profile of the fibre [MOS97]. This allows to counteract pulse broadening by balancing dispersion and nonlinearity at all points along the fibre according to equation (2.23). Periodic amplification after each fibre span overcomes loss and, if a constant dispersion is used, results in stable pulses referred to as ‘average solitons’ [BLO91]. For these pulses, SPM dominates at the beginning of each span and GVD at the end offsets the effects of nonlinearity.

A fundamental limit to soliton transmission is ASE introduced by the EDFAs in the link resulting in small variations of amplitude and phase of the solitons. The amplitude fluctuation leads to variation in the pulse width according to (2.23) whilst the phase fluctuation leads to a random change of the soliton frequency converted into timing jitter by the GVD. This effect introduces timing jitter known as Gordon-Haus jitter [GOR86]. It can be reduced by using optical filters to remove the ASE or periodic dispersion compensation creating dispersion managed (DM) solitons [DOR96, SUZ95]. Dispersion managed solitons were also transmitted with 8 WDM channels at 20Gbit/s over 4000km [MOR99]. The first implementation of commercial fiber-optical networks based on DM soliton has recently been reported in [ROB98].
For transmission of soliton-like pulses it is necessary to use the return-to-zero (RZ) format. RZ pulses have a well defined shape, independent of the bit-pattern as shown schematically in Fig. 2.12. In contrast to the pattern-dependent pulse length found in NRZ systems, all RZ pulses are affected in the same way by nonlinearity and dispersion. However, for a given bit-rate, RZ pulses are shorter than the bit-period since they return to zero within each bit slot. At 10Gbit/s the pulse width is typically 100ps for the isolated 'one' in NRZ and less than 50ps in RZ. The transmission performance for RZ and NRZ has been compared in experiments [CAS99] and theory [ENN96, FOR97] by several authors. Recently, it was also shown that nonlinear effects such as intra-channel XPM (IXPM) and intra-channel FWM (IFWM) are relevant for single channel RZ transmission at 40Gbit/s [ESS99, KILO0]. This is due to the temporal overlap of the chirped frequency components of neighbouring RZ pulses during transmission over dispersive fibre. IFWM and IXPM between the different frequency components results in shadow pulses and jitter, respectively.

In this thesis, experiments investigating XPM distortion of NRZ signals were used to analyse the transmission impairments due to nonlinearities (chapter 4 and 5) whilst RZ signals were used to investigate improved transmission by all-optical regeneration (chapter 6).

![Fig. 2.12 Comparison of RZ and NRZ format, left: RZ format, right: NRZ format](image)
2.3 Cross Phase Modulation (XPM)

XPM is a result of a power-dependent phase shift in analogy to the SPM effect discussed in section 2.2.3. SPM describes the phase variation due to power fluctuation in the same channel, whilst XPM extends this phenomenon to a multi-channel system where the optical phase is influenced by the power of the neighbouring WDM channels.

2.3.1 XPM phase shift

The optical phase shift due to XPM can be derived from the nonlinear Schrödinger equation and is given by equation (2.18) as

\[ \phi_{XPM}(z,t) = 2y L_{eff} \sum_{p=1}^{N} \int_{0}^{z} A_p \left( 0, t - \frac{z}{v_g} + d_{sp} \zeta \right)^2 e^{-\alpha \zeta} d\zeta \]  

Unlike the expression for SPM, the phase shift \( \phi_{XPM} \) depends on the power \( P_p = |A_p|^2 \) of the neighbouring channels \( p \), increasing with channel number \( N \). Due to the different velocity of each channel, the bit-pattern of the interacting channels is shifted after the propagation as illustrated by Fig. 2.13. This time-dependent alignment of the channels is characterised by the walk-off. The walk-off parameter \( d_{sp} \) is the most important parameter characterising XPM and is a result of different group velocities \( v_g(s) \) and \( v_g(p) \) of the channels \( s \) and \( p \). Low channel walk-off results in enhanced XPM due to the build-up of nonlinear phase modulation. It is defined as

\[ d_{sp} = \frac{1}{v_g(s) - v_g(p)} = \int D(\lambda) d\lambda \]  

![Fig. 2.13](image)

Fig. 2.13 Walk-off \( d_{sp} = D(\lambda_s - \lambda_p) \) between 2 PRBS-modulated channels at \( \lambda_s \) and \( \lambda_p \) over SSMF, \( d_{sp}<0 \): the detected channel is faster (this example), \( d_{sp}>0 \): the interfering channel propagates faster than the detected channel.

In the case of constant dispersion within the interval \( \Delta \lambda_{sp} = \lambda_s - \lambda_p \), expression (2.25) is given by \( d_{sp} \approx D \cdot \Delta \lambda_{sp} \) [CHI96]. For \( d_{sp}=0 \) the phase shift reaches a maximum \( \phi_{XPM} = 2\phi_{SPM} \). For channels with orthogonal polarisation states, \( \phi_{XPM} \) is reduced to a third of this value as described in section 2.3.4.
The chirp acquired during the interaction of the two channels is due to transitions in the interfering channel. A rising edge in the interfering channel causes a red-shift towards longer wavelengths as a result of an increased refractive index for the signal under intensity, according to equation (2.12), whilst a falling edge results in blue-shift. However, the shape of the associated intensity distortion of the detected channel at $\lambda_n$ depends on the sign of the dispersion as shown in Fig. 2.14.

(a) Generation of XPM chirp

(b) Generation of distortion for given pulse at $\lambda_n$

Fig. 2.14 Impact of XPM on intensity modulated channels. (a): introduction of chirp at $\lambda_n$ due to pulse transitions in the neighbouring channel at $\lambda_p$ (b): PM-to-IM conversion due to fibre dispersion resulting in pulse distortion. Red-shifted chirp is introduced by a rising edge and blue-shifted by a falling edge of the pulses at $\lambda_p$.

After the nonlinear interaction, the chirped frequency components of the pulse propagate with different velocities in the dispersive fibre. The two consequences are timing jitter and amplitude distortion leading to horizontal and vertical eye-closure, respectively. Firstly, timing jitter occurs because of the different arrival time of pulse components. This is a result of the relative delay the chirped components experience during propagation over the fibre following the nonlinear process. Secondly, amplitude distortion occurs due to PM-IM conversion in the fibre. It has been shown in simulations that the impact of jitter on the BER
is low for NRZ signals compared to amplitude distortion, although both processes occur simultaneously [EIS99b]. However, timing jitter is expected to be significant for RZ pulses due to the shorter pulse width. It was also confirmed in experiments which are presented in chapter 4 of this thesis that intensity distortion dominates jitter for NRZ signals. XPM distortion due to PM-IM conversion, therefore, is the key topic of this thesis work and is discussed in more detail in section 2.3.5.

The early quantitative analysis of XPM in optical communication systems has only focused on the phase distortion $\phi_{i}^{XPM}$ in equation (2.24) taking into account GVD [CHI94, KAG94]. A model described in [CHI96] can be used to derive $\phi_{i}^{XPM}$ as a function of fibre length, dispersion, $\Delta \lambda$ and modulation frequency without solving the NLSE. The calculation presented by the authors was restricted to a sinusoidal modulation of the interfering pump channel at $P_{p}(t)$. The probe channel $P_{s}(t)$ is initially CW, so that

\begin{align}
P_{s}(0, t) &= |A_{s}(0, t)|^2 = P_{s0} \\
P_{p}(0, t) &= |A_{p}(0, t)|^2 = P_{p0} + P_{p} \cos(\omega t)
\end{align}

Equation (2.26) is substituted into the general expression for $\phi_{i}^{XPM}(t)$ given by (2.24) and the XPM phase modulation of the probe at $\lambda_{i}$ is obtained as

\begin{align}
\phi_{i}^{XPM}(L, t) &= \gamma (P_{s0} + 2P_{p0}) L_{eff} + \Delta \phi_{i}^{XPM} \cos \left[ \omega \left( t - \frac{L}{v_{gap}} \right) + \phi \right],
\end{align}

where $\phi$ is a phase retardation factor dependent on $\omega$. It is of importance when contributions of several sinusoidal components add up to $P_{p}(t)$. $\Delta \phi_{i}^{XPM}$ is the amplitude of the XPM-induced phase shift and can be simplified in the case of low walk-off $|\omega d_{wp}| \ll \alpha$, $\ll 1/L$ as

\begin{align}
\Delta \phi_{i}^{XPM} &\approx 2\gamma P_{p} L_{eff}
\end{align}

This expression is constant in $\omega$ and only dependent on the power in the modulated pump channel. In a long fibre with strong walk-off $d_{wp} = D \Delta \lambda$, equation (2.28) can be approximated as

\begin{align}
\Delta \phi_{i}^{XPM} &\approx \frac{2\gamma P_{p} \alpha L_{eff}}{\omega D \Delta \lambda}
\end{align}

The resultant amount of phase modulation is inversely proportional to the modulation frequency $\omega$ or walk-off $D \Delta \lambda$ since both parameters increase the averaging effect between the bit-pattern in both channels preventing a build-up of phase modulation. Therefore, the XPM process can be understood to act as a low-pass filter with a $1/\omega$ or $1/d_{wp}$-characteristic for the input intensity $P_{p}(\omega)$ of the co-propagating channel. In a similar way, $\Delta \phi_{i}^{XPM}$ decreases when increasing the channel spacing.
The walk-off $d_{sp}$ is a result of fibre dispersion and leads to wavelength-dependent group velocities of the two interacting channels as described by equation (2.25). The parameter $d_{sp}=D\Delta \lambda_{sp}$ increases with channel spacing and dispersion resulting in a time-dependent channel alignment. The physical process of XPM is directly influenced by the sign and the absolute value of $d_{sp}$. The sign of $d_{sp}$ determines the relative shift between the bit-patterns of the two channels. In this thesis, $d_{sp}>0$ indicates that the interfering channel at $\lambda_p$ propagates faster than the detected channel at $\lambda_r$. The absolute value of $d_{sp}$ determines the degree of averaging during the nonlinear interaction between the two channels. For $d_{sp}=0$ the interfering channel is shifted with respect to the detected channel and pulse transitions, thus, induce both positive and negative chirp on a given pulse section of the detected channel. As a result of the interference between opposite chirp components, the build-up of XPM phase modulation can be prevented. This averaging effect is also evident in equation (2.24). For $d_{sp}=0$ the phase modulation $\phi_{s,\text{XPM}}(t)$ can be directly expressed as a function of $A_p(t)$. However, for $d_{sp}=0$ the argument of $A_p(t)$ is time-shifted by a factor determined by $d_{sp}$ during the nonlinear interaction. In this case, an integration over the pulse sequence of $A_p(t)$ must be performed to determine $\phi_{s,\text{XPM}}(t)$. The walk-off can be normalised to the bit period $T_0=1/B$ when different bit-rates $B$ are considered. In Fig. 2.15 the normalised walk-off $d_{sp}/T_0$ is plotted for 2 channels at 10Gbit/s as a function of $\Delta \lambda$ for 60km of fibre with different dispersion values. The walk-off increases linearly with $\Delta \lambda$ reaching 10 bits at $\Delta \lambda=1$nm in the case of SSMF ($D=16\text{ps/(km\cdotnm)}$). In contrast, DSF exhibits a low walk-off of less than a bit over the entire interval of 3nm suggesting a significant build-up of XPM phase modulation. The slope $d_{sp}/(\Delta \lambda T_0)$ is determined by the fibre dispersion $D$, however it can also be reduced at lower bit-rates.

**High walk-off and linear attenuation:** The attenuation $\alpha$ during the walk-off determines the build-up of XPM since the amount of nonlinear chirp is power dependent. For an idealised case of $\alpha=0$ and $d_{sp}=0$ it can be shown that at some distances no phase modulation is generated as the chirp introduced by a rising edge in the pump channel is completely cancelled by the opposite sign of chirp associated with a falling edge [EVA99]. For 1010-modulation in the interfering channel, the nonlinear chirp of the detected channel is compensated every multiple of $2\cdot T_0$. However, in the case of attenuation $\alpha \neq 0$ the absolute value of the chirp components generated by two subsequent pulse transitions of opposite chirp is different and exact cancellation will no longer exist. A simple model was derived by
Marcuse [MAR94] to determine the minimum required channel spacing $\Delta \lambda$ so that the walk-off along the effective length $L_{\text{eff}}$, necessary for averaging, is at least twice the pulse width $T_0$.

$$\Delta \lambda > \Delta \lambda_{\text{min}} = \frac{2T_0}{DL_{\text{eff}}} \quad (2.30)$$

For SSMF ($D=16\text{ps/(km}$-$\text{nm}$)), $L_{\text{eff}}=20\text{km}$, $T_0=100\text{ps}$, the required spacing is at least $\Delta \lambda_{\text{min}} = 0.62\text{nm}$. The minimum channel spacing $\Delta \lambda_{\text{min}}$ for SSMF, DSF ($0.5\text{ps/(km}$-$\text{nm}$)) and NZ-DSF ($4\text{ps/(km}$-$\text{nm}$)) according to equation (2.30) is included in Fig. 2.15. In the single-span experiments described in this thesis $\lambda_{\text{min}} \approx 1\text{nm}$ for SSMF and $>5\text{nm}$ for DSF. Equation (2.30) therefore only provides an estimation of $\Delta \lambda_{\text{min}}$. One limiting assumption is a constant channel power over However, according to (2.19) the power is reduced by the factor $1/e$ after $L_{\text{eff}}$ resulting in incomplete compensation of the chirp. In addition, this model does not take into account the additional chirp due to SPM and the PM-IM conversion.

![Figure 2.15](image)

**Fig. 2.15** Normalised channel walk-off $d_{\text{wp}}/T_0$ as a function of $\Delta \lambda$ over 60km fibre span at 10Gbit/s. SSMF: $D=16\text{ps/(km}$-$\text{nm}$), NZ-DSF: $D=4\text{ps/(km}$-$\text{nm}$) and DSF: $D=0.5\text{ps/(km}$-$\text{nm}$), minimum channel spacing $\Delta \lambda_{\text{min}}$ to suppress XPM calculated according to equation (2.30), grey area: low walk-off $<2$-$T_0$ within $L_{\text{eff}}$

**Low walk-off and linear attenuation:** In [SHT00] the effect of small walk-off $d_{\text{wp}} \approx 0$ on XPM is discussed. The walk-off length was introduced by Shtaif and is defined as $L_{\text{wp}} = \Delta t/d_{\text{wp}}$ where $d_{\text{wp}}=D\Delta \lambda_{\text{wp}}$ and $\Delta t$ denotes the 10-90% rise time of the pulse transitions. For narrow channel spacing $\Delta \lambda_{\text{wp}}$, the walk-off length $L_{\text{wp}}$ increases due to the small difference in velocity between the two channels. As experimentally shown by the authors and indicated by equation (2.28) the amount of XPM generated becomes independent of $d_{\text{wp}}$ for $L_{\text{wp}} > L_{\text{eff}}$, i.e. the amount of XPM does not vary with $\Delta \lambda$ in low dispersion fibre such as DSF or NZ-DSF (moderate dispersion). In the experiments described in chapter 4 of this thesis this effect was observed for $\Delta \lambda < 0.5\text{nm}$ in DSF. Therefore, both $\Delta \lambda_{\text{wp}}(2T_0/D=L_{\text{eff}})$ and $\Delta \lambda_{\text{wp}}(L_{\text{wp}}=L_{\text{eff}})$ are important.
parameters characterising the impact of XPM in WDM systems in the case of high and low channel walk-off.

2.3.3 XPM efficiency

It is convenient to estimate the amount of XPM generated for a given set of system parameters or walk-off with respect to the maximum amount possible at $d_{sp}=0$. For this analysis, the XPM phase shift in a 2-channel system is considered and the analysis is simplified assuming sinusoidal modulation with frequency $\omega$. In [CHI96] an expression for the XPM efficiency was derived for the first time. The efficiency is independent of channel power and polarisation and is defined as the ratio $\eta_{XPM}=\phi_{XPM}/\phi_{XPM}(d_{sp}=0)$.

\[
\eta_{XPM} = \frac{\alpha^2}{\omega^2 d_{sp}^2 + \alpha^2} \left[ 1 + \frac{4 \sin^2(\omega d_{sp} L / 2) \exp(-\alpha L)}{(1 - \exp(-\alpha L))^2} \right] \tag{2.31}
\]

With this expression the integral in equation (2.24) can be simplified to

\[
\Delta \phi_{XPM} = 2 \gamma L_{eff} P_p \sqrt{\eta_{XPM}} \tag{2.32}
\]

This expression corresponds to the maximum XPM phase shift for a given channel power $P_p$ scaled by $\eta_{XPM}$. It is a generalisation of equation (2.28) for arbitrary walk-off. However, this expression still does not take into account the impact of XPM on signal distortion described in section 2.3.5. Although the important aspect of PM-IM conversion is not included in equation (2.31) the factor $\eta_{XPM}$ provides insight into the fundamental process generating XPM phase modulation. The efficiency factor $\eta_{XPM}$ is similar in its form to equation (F.3) in appendix F describing the FWM process where the walk-off expression $\omega d_{sp}$ is substituted by the phase matching parameter $\Delta \beta$. Fig. 2.16 compares $\eta_{XPM}$ as a function of $\Delta \lambda$ for a 60km span of DSF ($D=1\text{ps/(km}\cdot\text{nm})$) with SSMF ($D=16\text{ps/(km}\cdot\text{nm})$). The XPM efficiency for DSF fibre is almost unity for $|\Delta \lambda|<3\text{nm}$ due to the low walk-off of 0.8bits over $L_{eff}$. This is a factor of 16 smaller than $d_{sp}$ for the corresponding SSMF link with $\eta_{XPM}<0.05$ for $\Delta \lambda>2\text{nm}$. Therefore, DSF fibre is ideal to study the physical properties of the XPM effect but detrimental for transmission.
2.3.4 Polarisation dependence of XPM

In the previous sections parallel polarisation of the interacting channels was assumed. The magnitude of $n_2$ and thus the amount of $\phi_{\text{XPM}}$ for a given fibre type is determined by the tensor elements of $\chi^{(3)}$ selected by the state of polarisation of the electrical fields. In [AGR95] it is shown for two orthogonally polarised channels that $\phi_{\text{XPM}}$ is reduced to 1/3 of the value given by expression (2.25). Therefore, XPM even occurs within a single channel between the different components of the EM wave. This is called degenerate XPM. The study of the polarisation dependence of XPM requires a defined state of polarisation during propagation achieved by the use of polarisation maintaining (PM) fibre.

In [KAT95] the above mentioned factor 1/3 for orthogonal polarisation and 2/3 for random polarisation were experimentally confirmed. The authors were using a heterodyne detection technique for a 2-channel system enabling the direct analysis of the phase change due to XPM. The power of the detected channel was 3 orders of magnitude lower than the interfering channel to minimise the phase shift due to SPM. In addition, the nonlinear refractive index $n_2$ for different fibre was obtained measuring the XPM phase shift due to depolarised light [BOS96]. The advantage is increased accuracy for random polarisation which naturally occurs in fibre without polarisation control. In [CER96] it was shown that the factor for depolarised light is independent of the input polarisation and totals 8/9 for both SPM and XPM in the case of elliptically polarised light. In addition to different states of polarisation, XPM was also observed between distinct modes in multimode fibre [LOU91].
2.3.5 XPM and residual dispersion

Similar to SPM, the fibre dispersion leads to pulse distortion due to PM-IM conversion of the XPM-induced phase distortion $\phi_{XPM}$. Unlike SPM, however, this phase distortion or chirp is of more complex nature, since it is introduced by pulse transitions in the neighbouring WDM channels carrying independent bit-sequences. For two uncorrelated channels the chirp introduced by XPM is independent in the bit-pattern of the detected channel. In modulated channels the chirp components due to SPM and XPM interfere and create the resulting intensity distortion. This distortion is dependent on the relative channel delays and can be enhanced or reduced by adjusting $\Delta t$, as shown in Fig. 2.17. In chapter 4.1 the combined distortion due to XPM and SPM is investigated experimentally and in chapter 5 its impact on the Q-factor is analysed.

As discussed in section 2.1.3 exact dispersion compensation can compensate for pulse distortion. This statement is only valid in the absence of nonlinearities such as SPM or XPM since additional chirp due to Kerr nonlinearities occurs within the effective length of the span where the optical power is high. The PM-IM conversion of the nonlinear chirp results in pulse distortion even for the exactly compensated fibre span. In the following, the residual dispersion of the link $D'_{res}(z)$ is used as a parameter for minimising the nonlinear distortion. This parameter was introduced for XPM distortion by Killey [KIL99] and Bellotti [BEL98]. For a given span length $L$ it is defined as
Equation (2.33) must not be confused with the accumulated dispersion of the span calculated over the interval $0 < z' < z$. However, $D_{\text{res}}(0)$ corresponds to the accumulated dispersion for the total link $L$. In an exactly dispersion compensated span the residual dispersion is zero at $z=0$. Therefore, only the chirp components generated at $z=0$, e.g. due to SPM or XPM, will be compensated at $z=L$ with no remaining amplitude distortion. However, for chirp components generated at $z>0$ the residual dispersion increases because the remaining link appears to be overcompensated and, therefore, pulses are no longer perfectly restored after transmission. The residual dispersion reaches a maximum after the first subsection of the span since PM-IM conversion for the respective chirp components takes place over the entire length of the second fibre of the compensated link as shown in Fig. 2.18. Since SPM and XPM occur in the range given by $L_{\text{eff}}$, complete cancellation of this nonlinear distortion is not possible by adjusting the compensator length and hence the residual dispersion. The total dispersion of the link can only be minimised [BEL99] but not compensated. One aim of this thesis is to show how residual dispersion can be optimised to allow maximum transmission.

![Residual dispersion](image)

Although the chirp components due to SPM and XPM experience the same residual dispersion, the channel walk-off must be considered when investigating XPM. In this section, the effect of residual dispersion on nonlinearities is illustrated for a single channel whilst the impact of residual dispersion on XPM is investigated in section 4.4 of this thesis. Fig. 2.19 illustrates the effect of residual dispersion on the eye-opening. A span of 60km SSMF was chosen, post-compensated with a variable amount of DCF. This configuration is typical for the experiments described in this thesis. A Gaussian pulse with a FWHM width of 40ps was launched into the fibre, equivalent to a single ‘1’-bit in 10Gbit/s return-to-zero (RZ) transmission. The shorter pulses in comparison with non return-to-zero (NRZ) transmission ($T_{\text{FWHM}}=90\text{ps}$) resulted in greater sensitivity of the pulse shape to dispersion. The maximum
eye-opening for the launch power $P_{in} = 1\text{mW}$ is reached for 10.4km of DCF, the amount necessary for exact dispersion compensation of the SSMF span. However, for $P_{in} = 20\text{mW}$ the maximum eye-opening occurs at shorter length of DCF. In this example, the length of the DCF had to be reduced by 15%. This is due to additional SPM counteracting the initial dispersive broadening of the SSMF and, therefore, less DCF is needed for recompression of the pulses [YU98]. Also, the pulses are not completely restored and the maximum eye opening is only 92% of the linear case, which is a result of incomplete compensation of nonlinear pulse distortion. In Fig. 2.18 the residual dispersion is shown as a function of distance for under-compensation. The minimum $D_{\text{res}}(z') = 0$ is shifted from $z' = 0$ in the linear case to larger values $0 < z' < L_{\text{eff}}$ minimising PM-IM conversion of the nonlinear phase modulation generated within the effective length. It is evident, that $D_{\text{res}}(z') = 0$ only applies to a single value $z$ and, therefore, the total PM-IM conversion can only be minimised. Fig. 2.20 shows the required amount of under-compensation as a function of launch power into the SSMF fibre.

![Fig. 2.19](image)

**Fig. 2.19** Impact of variable length of DCF fibre, $D = -95\text{ps/(km.nm)}$, on eye opening for single post-compensated span of 60km SSMF, $D = 16.5\text{ps/(km.nm)}$, input: Gaussian pulses, $T_{\text{FWHM}} = 40\text{ps}$

![Fig. 2.20](image)

**Fig. 2.20** Calculated under-compensation in post-compensated link of $L=60\text{km}$ SSMF, necessary for maximising the eye opening, Gaussian pulses, $T_{\text{FWHM}} = 40\text{ps}$, $P_{in} = \text{peak power}$
For 100mW peak power, the length of the DCF was reduced by almost 40% to compensate for 60km of SSMF. In analogy to this case, the pre-compensated link must be over-compensated to achieve maximum eye opening when SPM is present. In the experiments investigating XPM as a function of transmission distance in section 4.4, lumped under-compensation of a link with post-compensated spans was successfully used to recompress the pulses after transmission increasing the transmission distance.

The impact of dispersion on XPM is summarised in the following. For $L > L_{\text{eff}}$ the channels can be considered as independent and only linear effects such as PM-IM conversion are relevant. However, for $L < L_{\text{eff}}$ nonlinearity and dispersion must both be taken into account and XPM distortion and pulse walk-off occur simultaneously. Dispersion therefore influences the generation of XPM distortion in three ways:

- Firstly, the channel walk-off $d_{\text{eff}} = D \Delta \lambda$ increases with fibre dispersion, and averaging over chirp contributions from rising and falling pulse edges reduces the amplitude of $\phi_{\text{XPM}}$. This effect is characterised by the XPM efficiency introduced in section 2.3.3. It suggests that the amount of XPM generated is lower in SSMF than DSF for the same channel spacing and bit-rate.

- Secondly, higher dispersion increases the resulting distortion of the optical signal due to higher PM-IM conversion as indicated by equation 2.11. From this point of view, SSMF is expected to result in more XPM distortion than DSF due to the higher dispersion.

- Finally, the total amount of intensity distortion depends on the residual dispersion following the generation of XPM phase modulation. XPM-induced intensity distortion can only be minimised since complete cancellation of the nonlinear distortion is not possible by adjusting the compensator length and hence the residual dispersion.

In conclusion, XPM-induced distortion is likely to have a strong dependence on parameters affecting both phase and amplitude distortion. These are dispersion map, channel spacing and bit-rate which are the focus of the research described in this thesis and, in particular, of the experimental investigation described in chapter 4.

### 2.3.6 XPM measurement techniques

In general, XPM can be studied in the time or in the frequency domain. The investigation in the time domain has the advantage that XPM distortion can be directly related to the Q-factor, eye-opening penalty and pulse broadening. The analysis of the XPM-distorted waveform also provides detailed insight into the physical process of XPM as it can be easily linked to
experimentally measured parameters such as channel walk-off, bit-rate and bit-pattern. Time-
domain measurements form the basis of experimental techniques used in this thesis. In the
following, different measurement techniques for XPM are described:

**Frequency domain:** Spectral effects of XPM were initially studied for single pulses in a
fundamental paper by Agrawal [AGR89]. Spectral measurements are commonly used to
investigate XPM in subcarrier-multiplexed (SCM) systems [LEE99, PHI99, WAN95].
However, only a few authors investigated XPM in WDM transmission measuring the optical
spectrum. Recently, the spectral broadening due to XPM was analysed as a function of
wavelength spacing and channel power in [HO99] or in transmission experiments using a
high resolution Fabry-Perot filter [MIK99]. In [HUI99] the power fluctuation \( dP_s(\omega) \) due to
XPM distortion was investigated as a function of modulation frequency \( \omega \) for a multi-span
link. In the frequency domain the RMS spectral width and spectral power \( dP_s(\omega)/d\omega \) are
commonly measured using an optical spectrum analyser (OSA) or RF spectrum analyser.
Spectral measurements allow a high detection sensitivity (less than -60dBm) and dynamic
range of more than 100dB [HP99]. However, it is not possible to relate these measurements
directly to XPM distortion and eye-closure.

**Time domain:** The XPM-induced phase shift \( \phi_{XPM}(t) \) can be directly measured in coherent
communication systems using PSK or FSK modulation where the phase is detected at the
receiver [BET95]. Using intensity modulated direct-detection (IM/DD) the influence of XPM
can only be indirectly measured detecting the distorted probe waveform \( P_d(t) \). The effect of
XPM on BER and power penalty has been studied in transmission experiments [MIY95,
KIK96], and more recently in [BIG99]. A pump-probe technique can be used for a more
fundamental investigation of XPM distortion as described in chapter 4.1. First measurements
were reported in [RAP97] and more recent work was reported in [SHT00, THI00]. A common
parameter for a pump-probe characterisation is the XPM index \( m_x \) introduced in [RAP97].
The XPM index is quantified by the peak-to-peak distortion normalised to the time-averaged
channel power \( \langle P_s \rangle \) with \( P_s(t) = \langle P_s \rangle + \Delta P_s(t) \) so that

\[
m_x = \frac{P_{s,\text{max}} - P_{s,\text{min}}}{\langle P_s \rangle},
\]

where \( \Delta P_{s,\text{max}} = \max(\Delta P_s(t)) \) and \( \Delta P_{s,\text{min}} = \min(\Delta P_s(t)) \). In the case of a PRBS pattern the XPM
distortion is no longer uniform and the standard deviation \( \sigma \) is more appropriate to
characterise this distortion. In Fig. 2.21 the parameters \( m_x \) and \( \sigma_{XPM} \) are shown for a typical
XPM-distorted probe signal.
2.3.7 Analytical techniques to calculate XPM distortion

The key advantage of analytical methods is the fast calculation of XPM distortion in comparison with simulations using the full split-step Fourier algorithm. Moreover, the transparency of analytical expressions provides insight into the physical process of XPM. However, XPM distortion can be analytically calculated only for a subset of systems, in particular a set-up based on a pump-probe configuration with one CW channel and one or more modulated channels. In recent publications three, at first sight, different approaches were used to calculate XPM distortion, from Bellotti, Cartaxo and Shtaif. The main results are summarised in the following.

Cartaxo: In this approach the XPM phase distortion of an infinitesimal element $dz$ is taken since XPM and PM-IM conversion occur simultaneously [CAR98]. From equation (2.24) it follows that

$$d\phi_{XPM}(z, \omega) = -2\gamma P_p(0, \omega) \cdot e^{\cdot a(L-z)} \cdot e^{-i\omega(L-z)/\nu_e} \cdot \sin[b(L-z)] \cdot d\phi_{XPM}(z, \omega)$$

(2.35)

This contribution to XPM at $z$ is converted by GVD in the remaining section $(L-z)$ of the fibre into amplitude distortion. Taking into account PM-IM conversion, $dP_s(z, \omega)$ is calculated for the probe channel as

$$dP_s(z, \omega) = -2P_s(0) \cdot e^{-a(L-z)} \cdot e^{-i\omega(L-z)/\nu_e} \cdot \sin[b(L-z)] \cdot d\phi_{XPM}(z, \omega)$$

(2.36)

where $b = \omega^2 \chi^2 D / 4\pi c$. The total distortion $\Delta P_s(\omega)$ is obtained by integrating over the entire fibre length $L$ as

$$\Delta P_s(\omega) = 4\gamma \langle P_s(0) \rangle \cdot P_p(0, \omega) \cdot e^{-aL} \cdot e^{-i\omega L/\nu_e} \frac{1}{a^2 + b^2} \cdot \left[ a \sin(bL) - b \cos(bL) + be^{-aL} \right]$$

(2.37)
where \( a = \alpha - i\omega d_{sp} \). Equation (2.37) describes the spectral components of XPM due to modulation of the pump at frequency \( \omega \). The temporal intensity fluctuation can be obtained by inverse Fourier transformation. In table 2.1 the phase distortion (section 2.3.1) and the corresponding relative intensity distortion according to equation (2.37) are compared in the case of low and high channel walk-off.

<table>
<thead>
<tr>
<th>Case</th>
<th>( \Delta \phi_{XPM}(\omega) )</th>
<th>( \Delta P_s(\omega)/&lt;P_s(\omega)&gt; )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega d_{sp} \ll \alpha )</td>
<td>( 2\gamma P_p L_{\text{eff}} )</td>
<td>( \gamma P_p e^{-aL}e^{-i\omega L/v_g} \frac{D\Delta^2L}{\alpha \pi c} )</td>
</tr>
<tr>
<td>( \omega d_{sp} \gg \alpha )</td>
<td>( \frac{2\gamma P_p \alpha L_{\text{eff}}}{\omega D\Delta \lambda} )</td>
<td>( \gamma P_p e^{-aL}e^{-i\omega L/v_g} i\omega \frac{D\Delta^2L}{d_{sp} \pi c} )</td>
</tr>
</tbody>
</table>

Table 2.1 Analytical expressions for XPM phase and intensity distortion, \( P_p \): pump power, \( P_s \): power of detected channel, \( L \): span length, \( v_g \): group velocity

For small \( d_{sp} \), due to low dispersion or narrow channel spacing, power fluctuations \( \Delta P_s(\omega) \) increase with \( \omega^2 \) solely due to PM-IM conversion. In the case of large \( d_{sp} \), intensity distortion only increases linearly with \( \omega \) due to pulse averaging reducing XPM phase modulation at higher bit-rates. The analysis of XPM distortion was generalised for arbitrary modulation and multiple fibre spans [CAR99]. For transmission over \( M \) spans the distortion is found to increase with \( M^2 \) in the case of low channel walk-off since the XPM contributions from all spans are in phase. Equivalent calculations for the phase distortion \( \Delta \phi_{XPM}(\omega) \) show a linear increase with \( M \) in the low walk-off regime [CHI96]. The general solution for XPM intensity distortion for multiple spans is a combination of contributions from all spans. The extension of equation (2.37) to \( M \) fibre spans is described in [MAR96, CHI96, CAR99].

**Bellotti:** The calculation of intensity distortion \( \Delta P_s(\omega) \) described in [BEL98] is similar to the approach in [CAR98]. The GVD-induced distortion of the pump channel could also be included in this model to increase the accuracy of the results [SCH99]. In contrast to (2.38) an exponential notation is used for \( \Delta P_s(\omega) \) in [BEL98, BEL98c, VAR98]. This simplifies the calculation of XPM for multiple spans by reducing the complexity of the expressions. Another significant aspect of this work is the introduction of the XPM transfer function discussed in section 2.3.8.

**Shtaif:** In this analysis only a single fibre span with one interfering channel is considered [SHT98, SHT98b, SHT98c]. The following assumptions are made:
• Firstly it is assumed, that the nonlinear interaction between the pump and the probe signal occurs only within the first walk-off length \( L_{\text{wo}} = \Delta t / d_p \) where \( \Delta t \) is the duration of a pulse transition. For SSMF with \( D = 16.5 \text{ps/}(\text{km}\cdot\text{nm}) \), \( \Delta \lambda = 1 \text{nm} \) and \( \Delta t = 50 \text{ps} \) rise time (10Gbit/s) \( L_{\text{wo}} \approx 3 \text{km} \). XPM is also generated for \( L_{\text{wo}} < L < L_{\text{eff}} \), however, it is assumed that the XPM chirp introduced by the following pulse transitions is negligible due to fibre loss [SHT98].

• The second assumption is a small GVD-induced distortion for \( L < L_{\text{wo}} \). Similar to the split-step algorithm (described in appendix D) the calculation of XPM intensity distortion is divided into two parts: nonlinearity is taken into account for \( 0 < z < L_{\text{wo}} \) whilst dispersion acts on the signal over the remaining span length \( L_{\text{wo}} < z < L \).

With only the intensity fluctuations due to the first transition considered the phase is given by

\[
\phi_{\text{c}, \text{XPM}}(\omega) = -2\gamma P_p(0, \omega) \cdot \frac{1}{\alpha - i \omega d_p} \quad (2.38)
\]

In this case, the XPM intensity distortion can be written in the frequency domain as

\[
\Delta P_s(\omega) = -2\langle P_s(0) \rangle e^{-\alpha L} \sin \left[ \omega^2 \frac{\lambda^2}{4\pi c} D(L - L_{\text{wo}}) \right] \cdot \phi_{\text{s}, \text{XPM}}(\omega) \quad (2.39)
\]

Fig. 2.22 summarises the different approaches for calculating XPM distortion. The calculation of XPM in the frequency domain by Bellotti and Cartaso is very similar. Nonlinearity and dispersion are considered simultaneously. Due to the good agreement with simulations, this technique was used to calculate XPM distortion in chapter 5 for the estimation of XPM penalties. Although equation (2.39) describes XPM in the frequency domain, Shtaif calculates XPM distortion in the time domain which is more convenient for the subsequent analysis of waveforms since no inverse Fourier transform is required. However, this results in a more complicated calculation. This approach also limits the effect of nonlinearity to the walk-off length \( L_{\text{wo}} \) with dispersion acting on the pulses over the remaining span length. As shown in [SCH99] this approach was only accurate for a single span of SSMF.

### 2.3.8 XPM transfer function

The impact of a modulated pump channel on XPM distortion can be analytically described by a linear transfer function \( H_{sp}(\omega) \) introduced in [BEL98]. The concept of transfer functions allows to include the physical properties of the fibre link into \( H_{sp}(\omega) \). Whilst \( H_{sp}(\omega) \) describes the XPM process in the frequency domain a detailed analytical model is presented in the time domain [BEL98b, BON98, SCH99]. The impulse response \( h_{sp}(t) \) derived is linked with \( H_{sp}(\omega) \) by a Fourier transform.
For small pump distortion due to SPM, e.g. short distance or low dispersion, the intensity waveform of the detected channel after transmission exhibits distortion \( \Delta P_s(\omega) / P_s \) due to XPM. Equation (2.40) describes the filtering of the pump input intensity spectrum \( P_p(\omega) \) by \( H_{sp}(\omega) \)

\[
\frac{\Delta P_s(\omega)}{P_s} = P_p(0, \omega) H_{sp}(\omega)
\]  

(2.40)

where \( \langle P_s \rangle \) is the time-averaged output probe power. \( H_{sp}(\omega) \) for a dispersion-compensated link is given as [BEL98]

\[
H_{sp}(\omega) = 2\gamma i \left\{ \exp \left( \frac{i}{2} \beta_{2}^{res} \omega^2 \right) \left( \frac{1 - \exp \left( -\alpha + i \left[ d_{sp} \omega - \beta_{2}^{res} / 2 \right] \right)}{\alpha - i \left[ d_{sp} \omega + \beta_{2}^{res} / 2 \right]} \right) \right. \\
- \exp \left( -\frac{i}{2} \beta_{2}^{res} \omega^2 \right) \left. \left( \frac{1 - \exp \left( -\alpha + i \left[ d_{sp} \omega + \beta_{2}^{res} / 2 \right] \right)}{\alpha - i \left[ d_{sp} \omega - \beta_{2}^{res} / 2 \right]} \right) \right\}
\]  

(2.41)

where \( \beta_{2}^{res} \) is the residual dispersion from the start of the fibre to the end of the system, \( \gamma \), \( \beta_{2} = -\lambda^2 / (2\pi) D \), \( \alpha \) and \( L \) are the nonlinear coefficient, dispersion, loss and length of the nonlinear fibre respectively, and \( d_{sp} = \beta_{2} D \) is the walk-off rate of the channels in the fibre. The function \( |H_{sp}(\omega)| \), calculated using (2.41) for a 60 km span of SSMF (\( \beta_{2} = -21.7 \text{ ps}^2/\text{km} \), \( \alpha = 0.21 \text{ dB/km} \)) with post-compensation resulting in \( \beta_{2}^{res} = -217 \text{ ps}^2 \), is shown in Fig. 2.23, showing good agreement with the values calculated by simulations using the split-step Fourier
algorithm. In section 4.2, the transfer function \( H_{sp}(\omega) \) is calculated for the BT-LEANET link and found to predict accurately the variation of XPM distortion with bit-rate between 1-10Gbit/s.

![Plot of fibre transfer function, \(|H_{sp}(\omega)|\), for 60 km of SSMF, 90% post-compensated](image)

**Fig. 2.23**

**2.3.9 Analytical expression for \( m_s \)**

For most pulse sequences \( \Delta P_c(t) \) cannot be analytically determined, due to the complex form of the inverse Fourier transform to be applied to the expressions of \( \Delta P_c(\omega) \) given in (2.37) and (2.39). Therefore, analytical calculations can be experimentally verified by measurements in the frequency domain [HUI99]. However, the investigation of XPM in the time domain is preferred in most cases since the waveform distortion can be linked to eye closure and the impact of system parameters on XPM is evident. The inverse Fourier transform of equation (2.37) is known for only a few special cases such as sinusoidal modulation in the pump channel. An expression for \( m_s \) was derived based [SCH99] based on expression (2.37). The sinusoidal pump is assumed to be undistorted by SPM and GVD, e.g. in the case of a single span. For \( \omega^2 D\lambda^2 L/(4\pi) \ll 1 \) and \( \alpha L \gg 1 \) equation (2.37) can be simplified by \( \sin(bL) \approx \omega^2 D\lambda^2 L/(4\pi) \) and \( \cos(bL) \approx 1 \). In the time frame moving with \( V_g \) it reduces to

\[
\Delta P_s(\omega) = 4\gamma \langle P_s(0) \rangle \cdot P_p(0,\omega) \cdot e^{-\alpha L} \left( \frac{b}{a} L \right)
\]  

(2.42)

An analytical solution of (2.42) can be obtained for a pump channel given by

\[
P_p(0,t) = \frac{1}{2} P_{p,max} \left[ 1 + \sin(\omega_0 t) \right]
\]  

(2.43)

The sinusoidal waveform approximates the 1010-bit pattern well in case of, for example, a bandwidth limitation due to the optical modulator and receiver. \( \Delta P_c(L,t) \) is obtained by substituting the Fourier transform of equation (2.43), \( P_p(0,\omega) \), into (2.42) and taking the
inverse Fourier transform. The expression for $m_x$ is then given by the peak-to-peak amplitude of $\Delta P_s(L,t)$ normalised to the time-averaged power $<P_s>$$\,$

$$m_x = \gamma P_{p0} \cdot \frac{\omega^2 \lambda^2 DL}{\pi c \sqrt{\alpha^2 + \omega^2 D^2 \cdot \Delta \lambda^2}} \quad (2.44)$$

In Fig. 2.24 the analytical expression (2.44) for $m_x$ is compared with the results of a split-step Fourier simulation for $L=60$km SSMF, $10$dBm/channel, $\alpha=0.21$dB/km, $\lambda=1555$nm, $D=16.5$ps/(km·nm), $\gamma=1.18/(W·km)$ and 1010...-modulation at 10Gbit/s. A good agreement with less than 15% error is achieved between $\Delta \lambda=0.4$nm and $\Delta \lambda=1.6$nm demonstrating the accuracy of equation (2.44). The small under-estimation of the calculated distortion is due to the smoother transitions of the sinusoidal pump approximation in comparison to the Bessel-filtered pulses used in the simulation.

In summary, several techniques have been proposed to enable fast and accurate estimation of XPM-induced distortion. The XPM effect can be adequately described by the transfer function $H_{sp}(\omega)$. Although the different analytical approaches provide simple expressions for the intensity spectrum $P_s(\omega)$, this parameter is difficult to relate to waveform distortion and eye closure measured in the experiments. The inverse Fourier transform required for obtaining $P_s(t)$ of the probe channel has analytical solutions only for a limited number of waveforms such as sinusoidal pump approximation but it determines $m_x$ accurately for single span links. For longer distances the accuracy of these techniques can be improved taking into account pump distortion due to SPM and GVD.
2.4 Summary

In this chapter, linear and nonlinear effects affecting WDM transmission systems were discussed. Fibre attenuation and dispersion require periodic signal amplification and dispersion compensation to increase transmission distance. The Kerr-effect is a result of the intensity dependence of the refractive index at high channel powers and leads to the combination of SPM and XPM, under study in this thesis. SPM and XPM result in a phase variation due to power fluctuation in the same and the neighbouring channels, respectively. The nonlinear phase modulation due to SPM and XPM is converted into signal distortion by the fibre dispersion leading to eye closure and increase of the bit error-rate.

The channel walk-off is important in characterising XPM. For low walk-off, maximum XPM phase modulation is generated. Increasing fibre dispersion increases the PM-IM conversion efficiency but also reduces the initial XPM phase modulation. It was also shown that residual dispersion is important for the understanding of XPM and dispersion. This relatively complex nature of the XPM effect is the main motivation for a detailed study of XPM as a function of typical system parameters in the following chapters of this thesis. XPM intensity distortion can be calculated using analytical techniques which provide insight into the physical nature of XPM. In chapter 4 the XPM intensity distortion is measured as a function of bit-rate in a 2-span link and compared with the analytically calculated transfer function \( H(\omega) \). In chapter 5 the cross-phase modulation index \( m_x \) is calculated as a function of distance and channel spacing and the results are used to predict the impact of XPM on the Q-factor in a 2-channel transmission experiment.
Chapter 3

Cross-phase modulation – literature review

In this chapter, existing literature describing XPM in optical communications systems is reviewed and the state-of-the-art in this field is presented. After a general overview of work studying the physical properties of XPM, reported transmission experiments investigating the impact of XPM on BER and power penalty in WDM systems are reviewed in sections 3.2 and 3.3. In addition, papers investigating XPM distortion in pump-probe experiments are discussed. This is followed by a survey of experimental work investigating XPM distortion as a function of system parameters, as this forms the basis for the experimental work carried out in this thesis. The structure of this chapter is summarised in Fig. 3.1.

3.1 XPM in fibres

First investigation of XPM: The work on XPM followed the discovery of SPM in optical fibres [STO78]. As early as 1980 it was predicted that Raman spectra of ultra-short pulses would be broadened by XPM [GER80]. The investigation of the physical nature of XPM involved the use of free-space optics, and a fibre of a few metres length represented the nonlinear medium. The first experimental confirmation of the XPM effect in the \textit{time domain} is reported in [CHR84] using 2 lasers at $\lambda=1.54\mu$m and $1.3\mu$m with 1mW coupled into 15m of standard fibre. The wide wavelength spacing resulted in a significant walk-off of the 50ps-pulses of over the short fibre. The phase shift $\Delta\phi(t)$ was only qualitatively analysed using an interferometer. In [ISL87] this work was extended investigating the phase change as a function of pulse walk-off. The nonlinear phase shift was also investigated in the \textit{spectral domain} [ALF87]. This experiment used a single laser emitting modelocked pulses (25ps) at 532nm. In the 10m of SSMF both Raman (appendix E) and XPM effects occurred. The Stokes pulse at longer wavelength broadened due to a combination of Raman amplification
and additional XPM phase modulation induced by the fundamental pulse. This broadening was found to be larger than for the Raman effect alone. The total spectral broadening due to SPM and XPM was later measured with a high resolution diffraction grating and the results were compared with theory in [WAN94]. However, the peak power of the pulses was 2W and the fibre length of 1m extremely short. Further experimental work on XPM is presented in [ALF86, WAN90, LOU91], using picosecond laser sources providing single pulses of high peak power in the order of watts. These measurements, even though at 1064nm outside the telecommunication windows, showed intensity variation of the spectrum due to XPM. In summary, at this early stage of investigation XPM experiments were limited to short fibre length and high pulse powers of the available lasers.

Theoretical work investigating the XPM effect started in 1984 with a paper of Chraplyvy et al. [CHR84b]. The magnitude of phase noise $\sigma_\phi$ due to SPM and XPM was calculated as a function of power variation $\sigma_p$. The RMS phase fluctuation for SPM and XPM was shown to
increase by a factor of 2 for XPM. In this work the first investigation of XPM as a function of channel number was reported. An \( N \)-channel WDM system was considered and it was concluded that \( \sigma_\phi \) increases with \( \sqrt{N} \). However, the results for XPM phase noise were not related to intensity noise. The XPM phase noise was also analysed in [BLO94] and the perturbation of a coherent CW signal due to a co-propagating intensity modulated pump was calculated. It was concluded that XPM phase noise increases the overall quantum noise in the system. However, these results were not experimentally verified.

**XPM and GVD:** The temporal and spectral phenomena based on XPM were systematically investigated in a fundamental paper by Agrawal [AGR89]. It was studied in simulations how GVD and nonlinearity affect single pulses both in the time and frequency domains. This work gave a significant contribution to the understanding of the physical nature of XPM providing analytical expressions and description of phenomena resulting from the interaction of XPM and dispersion. The paper is divided into 2 main parts: in the first part, the case of low GVD was considered and the phase shift \( \phi_{\text{XPM}} \) and \( \phi_{\text{SPM}} \), shown in equation (2.18), was derived. XPM resulted in spectral broadening due to nonlinear chirp while the magnitude of the broadening was shown to depend on the relative time delay between the 2 interacting pulses [ISL87]. In the second part, the interaction of XPM and GVD was considered. GVD influences the XPM process via the walk-off and PM-IM conversion. As a result, the shape of the probe pulse becomes asymmetric, broadens and develops internal structure. These features were discussed in separate papers in more detail and are discussed in the following paragraph. A pulse compression mechanism for low intensity probe pulses was also proposed. As there is negligible SPM affecting the probe the nonlinear chirp must be introduced by XPM. It is reported that by using pump pulses wider than the probe and by careful adjustment of the relative delay linear chirp could be introduced on the probe necessary for GVD assisted pulse compression. Unlike the case of solitons discussed in section 2.2.6 pulse compression could be extended into the normal dispersion regime.

**XPM and pulse shape:** Many effects originating from SPM and GVD were also observed for multi-channel operation where XPM and GVD interact, such as modulation instability (MI, section 2.2.5), solitary waves [TRI88], self-focusing [ALF89] and ultrashort pulse generation [KOR98]. The required nonlinear chirp for these effects was introduced by a second channel. Therefore, MI could be observed in the normal dispersion regime where no MI is observed in presence of SPM alone [AGR89c]. Additional experiments investigated MI between 2 modes in a normally dispersive bimodal fibre [MIL97]. The relative walk-off between the lowest two modes is determined by the signal wavelength relative to \( \lambda_0 \) of the fibre. A limitation of this
work was that in order to enable multimode operation the operating wavelength had to be in the visible region below the cut-off wavelength of 790nm requiring several watts launch power. A more general description of XPM between modes in an optical fibre is given in [BOA95]. The optical wave breaking due to GVD and XPM was investigated in [AGR89b]. It results in an oscillation of the pulse intensity near the pulse edges due to interference of chirp components. Unlike SPM-induced wave-breaking, it is only observed at one side due to asymmetry introduced by the channel walk-off. The nonlinear pulse compression discussed above was investigated in [SCH87], [JAS88] and subsequently in [SOU96] where a technique is described using XPM compression and Raman amplification. XPM-induced pulse compression was also observed between different pulse components of a birefringent fibre [ROT90, DRU90].

**XPM switching:** Optical switching taking advantage of the XPM-induced phase shift has been shown for wavelength conversion, regeneration and demultiplexing. This area is potentially one of the most important applications of the XPM effect. The switching process can be achieved by wavelength shifting which is a result of XPM chirp as investigated in several experiments and simulations [ALF89, FEL98]. It is possible to compensate Raman induced frequency shift by XPM chirp [SCH88] although this might not be practical for a large channel number. For short fibre with negligible SRS the wavelength shift of the probe channel was investigated as a function of delay between femto-second pulses in the pump and probe to demonstrate femto-second switching [BOY94]. XPM chirp between orthogonally polarised waves was used to generate a frequency modulated laser beam where XPM was induced by a copropagating intensity-modulated component in polarisation maintaining fibre [MAT97]. The advantage of this all-optical modulation technique over EAM modulators is the high achievable pulse power of a few kW and short duration which is only determined by the pump pulses. The XPM induced wavelength shift can also be used for wavelength routing where the intensity dependent transmission coefficient is a result of XPM between the different pulse components in a birefringent fibre [KIV93, RAM97]. Recently, XPM-induced wavelength shift was used to demonstrate the error-free operation of an OTDM-WDM converter based on a demultiplexer with multiple output channels (MOXIC) [UCH98]. A 100Gbit/s OTDM stream was demultiplexed using a train of chirped clock pulses with each pulse linearly down-shifted in frequency. The clock pulse temporally overlaps with all data pulses of a given OTDM bit-slot during propagation over 3km of DSF. Therefore, each data channel introduces XPM at a given time compensating in this particular time slot the copropagating pre-chirped clock pulse. Due to the pre-chirp of clock pulses this time slot corresponds to a unique wavelength.
Another important application of XPM-induced switching is the nonlinear optical loop mirror (NOLM) [DOR88] which can be used for demultiplexing and pulse format conversion [BLO90, LEE96]. In addition to optical fibres, the XPM effect was also studied in waveguides [FON97] and in semiconductor optical amplifiers (SOA). The phase shift due to XPM in SOAs is utilised in all-optical wavelength converters operating in a Mach-Zehnder interferometric configuration [MAR95, LAC96]. The advantage over optical fibre are the high nonlinearity and small dimensions of SOAs. Although slower than Kerr nonlinearities on optical fibre, operation up to 40Gbit/s has been demonstrated [MIK97]. All-optical regenerators based on XPM switching in SOAs are described separately in chapter 6.

In summary, the early experiments only investigated the physical nature of XPM. This has led to the development of key techniques using the XPM-induced nonlinearity, such as XPM-based optical switching. Theoretical work included the investigation of pulses affected by XPM and dispersion and led to the study of many XPM-related phenomena. However, the expected impairment to multiwavelength optical transmission had not been analysed.

### 3.2 XPM in coherent detection systems

Much of the earliest systems-related work was carried out in the context of coherent optical systems [AGR92]. In coherent systems, the detected signal at the fibre output is optically mixed with the signal of a local laser source. The mixing product can be translated either to the base band (homodyne detection) or to an intermediate frequency (heterodyne detection) [BET95] with subsequent electrical conversion and processing. Many of the earlier transmission experiments used coherent techniques because of the improved receiver sensitivity of typically 20dB over direct detection systems. However, the concept of coherent transmission was later abandoned due to the complex techniques used for modulation and detection in comparison with direct-detection systems. In multi-channel coherent transmission $\Delta\lambda<1\text{nm}$ was used and only low dispersion links of DSF were considered to avoid PM-IM conversion of the phase-modulated signals during transmission. Therefore, XPM is expected to lead to impairments in coherent systems due to the low channel walk-off.

In binary phase shift keying (PSK) formats, the data is encoded by phase-shifting the optical carrier between two distinct states. Therefore, this phase-dependent transmission format is sensitive to additional phase fluctuation due to XPM and SPM. In [TAJ86] the effects of SPM and dispersion on the detected PSK signal are discussed and detrimental intensity distortion was observed due to PM-IM conversion. The amplitude distortion leads to a power penalty at
the detector, and the maximum transmission distance depends quadratically on pulse width and inversely on fibre dispersion [TAJ88]. This distance is typically shorter than the dispersion limited distance in a similar direct detection system due to residual intensity modulation following PM-IM conversion. A simple analytical expression for PM-IM conversion for low dispersion was derived in [DES90].

One of the proposed solutions for reducing amplitude distortion was to operate in a low dispersion regime such as close to $\lambda_0$ in DSF. However, the low walk-off increases the impact of XPM on multi-channel transmission. XPM due to residual IM in a PSK transmission homodyne detection system was experimentally investigated for the first time by direct BER measurements [NOR91]. Both channels were phase-modulated at 10Gbit/s, $\Delta\lambda=1$nm and transmitted over 100km DSF launching 11.7dBm/channel. XPM was introduced by 28% residual amplitude modulation in the pump channel following PM-IM conversion. The power penalty was only due to the additional phase error of the detected PSK signal introduced by XPM. The investigation of XPM was generalised in a theoretical paper taking into account multi-channel transmission [NOR93]. The maximum permitted power change due to residual IM and the maximum phase distortion for BER$<10^{-10}$ were calculated as a function of channel number for PSK and QPSK modulation. It was concluded that the XPM-induced penalty increases sharply with phase distortion and QPSK has a higher penalty than binary PSK for a given amount of distortion. However, this is the only paper investigating XPM for different PSK formats and no experimental confirmation is reported.

XPM has also been investigated in coherent ASK systems [WAN97] calculating power penalties as a function of launch power and channel number. XPM was expected to have more impact on transmission than in PSK because of the larger amplitude fluctuation of the interfering channels. In contrast to the worst-case XPM phase shift considered in [CHR84b], accurate binomial statistics of the data modulation predicted less degradation. Unlike previous papers, dispersion managed links were considered but walk-off was neglected for narrow channel spacing. It was shown that the launch power per channel must not exceed 0dBm for 10 channel systems and the power penalty increases drastically for higher launch power, a restriction due to phase-sensitive detection. In direct-detection systems using SSMF or dispersion-compensated links this limitation no longer exists.

To conclude, experimental and theoretical investigations have shown that coherent transmission systems using PSK and ASK formats are degraded by phase distortion due to SPM and XPM. The impact of XPM on transmission is expected to be worse in coherent systems than in IM/DD systems. Firstly, this is due to the direct detection of the optical phase and, secondly, the low required fibre dispersion results in low channel walk-off. Increasing
the fibre dispersion results in PM-IM conversion and additional intensity fluctuation of the phase-modulated signals. Although no coherent systems are used in the experiments described in this thesis, the work presented in this section is relevant as it highlighted the importance of dispersion and nonlinearities for transmission experiments.

3.3 XPM in direct-detection systems

In direct-detection systems, the optical carrier is intensity modulated and is converted at the receiver into a current proportional to the signal power. Typical parameters to analyse the impact of XPM on transmission are signal-to-noise ratio (SNR), bit-error rate (BER), power penalty, eye-opening penalty (EOP) and Q-factor [MAR90, BER93]. Most papers investigating the impact of XPM on WDM transmission were published during the last 3-4 years in parallel to the work presented in this thesis.

3.3.1 Numerical investigation

**Increasing the number of channels:** One of the first papers on XPM in IM/DD systems investigated the impact of channel number on transmission [MAR94] for different fibre types. The considered link consisted of 3 amplified SSMF spans of 120km with 15mW/channel launch power at 2.5Gbit/s. In contrast to many coherent systems, the walk-off between neighbouring channels, spaced by $\Delta \lambda = 0.8$nm, was taken into account using split-step simulations. ASE effects were not considered to isolate the nonlinear distortion of the bit-pattern. No degradation of the SNR in the 2 centre channels was observed when doubling the channel number from 4 to 8 due to the walk-off between distant channels in SSMF, however, the investigation was limited to only 360km link length. In the subsequent links the fibre dispersion $D$ was varied and the detrimental influence of low walk-off on XPM was confirmed for $\Delta \lambda = 1$nm channel spacing. In this case, enhanced distortion with SNR$<10$dB was obtained for $D<2$ps/(nm-km), typical for DSF.

The impact of the number of channels on XPM was investigated in simulations of a 4-channel system at 10Gbit/s with 1nm channel spacing [ZOU96]. However, only 0dBm/channel launch power were used and ASE was not considered. Therefore, the results were only valid for an idealised system. The amplifier spacing was 50km and the following dispersion maps were investigated: DSF, DSF and SSMF, SSMF and DCF. Cross-phase modulation was isolated comparing 4-channel with single channel transmission. In both cases, the EOP was calculated as a function of transmission distance. For the DSF link 1.5dB penalty due to XPM
were obtained after 3000km reducing to 0.5dB for the DSF-SSMF link. In contrast, no XPM penalty was measured for the SSMF-DSF link.

**Long-distance transmission:** The numerical investigation of power penalties incurred by SPM in IM/DD was for the first time extended to transoceanic links of 6000km in [HAM90]. 100km span length and noiseless amplifiers were assumed using NRZ modulated signals at 2.5Gbit/s. Only SPM and GVD were considered when calculating the eye-opening penalty as a function of the launch power. In another paper combined penalties due to XPM and SPM were investigated for dispersion-compensated fibre spans in pre- and post-compensation. In contrast to experimental work [KIK96, OGA96], much longer distances of up to 3000km were considered in simulations. The modelled system described in [HAY96] uses 50km spans of DSF with alternating dispersion. Up to 16 channels with $\Delta\lambda=0.8$nm were modelled operating between 5Gbit/s and 20Gbit/s. The eye closure penalty was calculated for 8 different channels over up to 3200km. The low launch power of less than 1mW/channel resulted in a penalty variation of 2dB among the channels at different wavelength. The 3dB-transmission distance (length with $E_0P=3$dB) was found to be independent of the channel number at 20Gbit/s and did also not change which the launch power. These results suggested dispersion-limited transmission. However, at 5Gbit/s transmission was limited by nonlinearities, in particular channel dependent penalties were found to be a result of XPM, in agreement with [MAR94]. In [HAY97] the impact of pre-compensation on nonlinearities and in [HAY97b] links using combinations of pre- and post-compensation were analysed using combinations of DSF, SSMF and DCF. It was concluded that combinations of pre-and post-compensation result in the lowest transmission penalty where under-compensation could even further reduce penalties on a per channel basis. However, the channel power was typically less than 1mW and therefore the system was almost linear. Moreover, the XPM-induced penalty was not investigated separately but only in combination with SPM and GVD.

**High power, short distance:** XPM was investigated for a dispersion compensated link at higher launch powers between 5-15mW in [YU98]. This potentially allows for longer span length due to increased SNR, and the transmission performance degradation due to XPM as a function of system parameters can be easily investigated. Transmission of 4x10Gbit/s over exactly post-compensated SSMF spans was analysed and the total transmission distance was 3000km, similar to the distance reported in [HAY96]. The Q-factor for each channel was calculated as a function of distance and channel spacing, and reduction in $Q$ due to XPM for narrow $\Delta\lambda$ and high launch power was obtained. Despite this detailed analysis of the reduction of $Q$ with distance no new results were reported.
Comparison of penalties: In [TEN99], the reduction of the Q-factor due to XPM was compared with SPM and FWM penalties by calculating the Q-factors in a 40-channel 10Gbit/s transmission system over different dispersion maps. It was concluded from the calculated variances that XPM is generally more significant than FWM at $\Delta \lambda = 0.8$nm which is agreement with the FWM/XPM efficiency shown in Fig. 2.16, section 2.3.3.

In summary, the impact of XPM on BER, SNR and Q-factor was investigated in simulations of transmission systems. However, the most comprehensive theoretical analysis of penalties due to SPM and XPM was restricted to systems with low channel powers to achieve transmission over thousands of kilometres. It was found that XPM induced penalties increase with the number of channels, for low dispersion and narrow channel spacing. In this thesis, the work described in chapter 5 is focused on the systematic investigation of the Q-factor in transmission experiments as a function of channel number, $\Delta \lambda$, distance and launch power. The Q-factor was chosen since it can be easily related to both the BER and the standard deviation $\sigma_{XPM}$ resulting from XPM intensity distortion.

3.3.2 Transmission experiments

XPM in DSF: First experiments investigating the power penalty due to XPM are reported for a DSF link in [KIK96, KIK96b] using the set-up shown in Fig. 3.2. Two lasers with $\Delta \lambda = 1$nm were modulated at 10Gbit/s using modulators in Mach-Zehnder (MZ) configuration with variable relative delay of the PRBS pattern and the combined signal was amplified to 7dBm/channel power. Unlike previous systems this experiment was optimised for studying the XPM effect by separating nonlinearity and dispersion. In the DSF fibre, XPM chirp was generated (section 2.3.1) and subsequent PM-IM conversion in the SSMF distorted the received eye-diagram. In chapter 4.1 of this thesis pump-probe experiments are presented based on the configuration in Fig.3.2.

![Fig.3.2](image-url) Key experiment to study penalties due to XPM: 2 channels at 10Gbit/s over single span of DSF followed by a variable length of SSMF for PM-IM conversion
In the experiments described in [KIK96] the XPM power penalty was measured by comparing the BER while all interfering channels were modulated to the case when those channels carried a CW signal. This approach allowed a constant channel spacing in contrast to a technique where $\Delta \lambda$ is varied to study the impact of XPM on the BER. The amount of XPM was found to depend strongly on the initial pattern alignment and a 3dB power penalty was measured for when varying the channel delay. The authors also investigated XPM penalties for 3 spans of DSF using 4 WDM channels. The channel spacing remained constant and only the bit-delay was varied. Dispersion compensation at the receiver using different length of SSMF minimised the residual dispersion of the link and reduced the XPM related penalty from 4.7dB to 0.7dB. This investigation was continued in another paper [KIK97]: the power penalty for variable launch power into the DSF increased exponentially to 4dB at 10dB/channel despite the linear increase of the XPM phase shift with power. The impact of XPM on the penalty was found to be negligible when increasing the walk-off to more than 1bit over $L_{\text{eff}}$, in agreement with a prediction from equation (2.30), [MAR94]. The power penalty due to SPM and XPM was measured separately as a function of residual dispersion in the 3-span post-compensated link in the case of per-span compensation and lumped dispersion at the receiver. In the case of SPM, the BER could be minimised in both schemes due to under-compensation by positive residual dispersion in accordance with Fig. 2.20. Similar results for XPM were reported although the degradation was not as clearly dependent on residual dispersion.

Recent experimental work focuses on the penalty due to XPM in long-haul 10Gbit/s transmission over more than 5000km [PIL99]. 8 channels with $\Delta \lambda=0.8$nm separation were transmitted with only $-1.5$dBm launch power into 50km spans of DSF. In Q-factor measurements the variation $\Delta Q$ as a function of channel number was investigated, similar to the study of SNR in [MAR94], and no significant variation was obtained due to distant channels with $\Delta \lambda>1.6$nm.

In conclusion, most experiments investigating XPM penalties in DSF were limited to 2-3 spans with no distance-dependent measurements. This is due to the low walk-off in DSF resulting in efficient generation of XPM phase modulation. Only recently, long-distance transmission over up to 5000km was reported but this investigation was limited to low launch power $<0$dBm/channel.

**XPM in SSMF:** Since transmission over DSF is degraded by significant XPM and FWM due to low channel walk-off and the possibility of phase matching, respectively, SSMF links were investigated in most of the transmission experiments: 4-channel 2.5Gbit/s transmission over 300km of SSMF and up to 18dBm/channel launch power was reported in [OGA96]. The high
launch power was required for unrepeated transmission and resulted in detrimental XPM. In comparison, a similar system with 3 spans of 100km was investigated in [BRA96]. The XPM and SPM penalties were measured for $\Delta \lambda = 1$nm as a function of EDFA output power and it was concluded that XPM-induced penalties grow slower than SPM penalties due to the channel walk-off. The XPM related penalty could be further reduced in a post-compensated 16-channel link of the same length by using DCF compensation after each span and positive residual dispersion [MIY95], however, no dependence of XPM on other parameters was investigated. In another experiment using 624km of SSMF fibre, the variation of BER as a function of $\Delta \lambda$ was investigated in detail [NEL98, NEL99]. Since the channel walk-off is proportional to $\Delta \lambda$ the relative delay between two channels after one fibre span can result in the realignment of the two bit-pattern as described in chapter 4.2. In this case, the XPM contribution of the following spans will add up in phase. Changing $\Delta \lambda$ therefore results in constructive and destructive interference between XPM from different spans and is observed as a periodic variation of BER with $\Delta \lambda$. SSMF links were also used in this thesis to investigate the variation of the Q-factor with $\Delta \lambda$. However, for longer transmission distances dispersion compensation was required.

**XPM in dispersion-compensated links:** XPM-induced penalties were measured as a function of distance in both post- and pre-compensated links using 40km of SSMF [MIK99], complementing the theoretical work of [HAY96] which was limited to low channel power. Using a fibre recirculating loop 4 channels at 10Gbit/s with $\Delta \lambda = 0.4$nm spacing were transmitted over up to 28 spans. For post-compensated links a reduced transmission distance was measured since XPM and SPM chirp, acquired in the SSMF, broaden the pulses in the following DCF section. Only the total system penalty was analysed, however increased penalty for the inner channels was attributed to XPM. For the first time, the optical spectrum was also measured as a function of transmission distance with 1pm spectral resolution. Penalties due to XPM, SPM and combination of SPM and XPM were measured in [BIG99], using only two channels to eliminate cross-talk due to FWM. A wide range of fibres was investigated as a function of launch power and channel spacing: DSF, NZ-DSF and combinations of SSMF+DCF using two spans of 100km. For the measurement of the XPM penalty the power of the detected signal remained constant, ensuring constant receiver power, and only the launch power of the interfering channel was varied. In different approaches, the interfering channels (constant power and $\Delta \lambda$) were PRBS-modulated and compared with the CW operation [KIK96] or, in chapter 5 of this thesis, $\Delta \lambda$ was varied for PRBS-modulated channels of constant power. For $\Delta \lambda = 1.6$nm, only the SSMF+DCF scheme showed negligible XPM penalties in [BIG99]. NZ-DSF fibre was the worst choice because of low walk-off and
PM-IM conversion, however, DSF was also affected by FWM. In all fibre links SPM was the dominating nonlinearity. For moderate power levels of 8dBm/channel XPM was also negligible in SSMF+DCF links between 0.4nm and 2nm. Unlike in [NEL98] no periodic variation of the XPM penalty with $\Delta \lambda$ was obtained.

In summary, XPM was investigated to date for dispersion-compensated fibre links as a function of wavelength spacing, fibre dispersion and transmission distance. The research work described in this thesis uses dispersion-compensated links to measure the Q-factor as a function of number of channels, distance and wavelength spacing. Among these measurements the main contribution is the investigation of the relation between XPM-induced transmission penalty and XPM-induced intensity distortion for the same link.

**XPM compensation:** Minimising the residual dispersion of a link reduces XPM-induced distortion as it reduces the PM-IM conversion. This was confirmed in transmission experiments [BIG99] where dispersion compensation reduced the penalty due to XPM. As shown in an analytical expression for Gaussian pulses [RAP98] pulse distortion can be reduced by increasing the channel walk-off. Another approach minimising nonlinear distortion was demonstrated for SPM [JEO98] and used pre-chirping by adjusting the modulator bias in the transmitter. The nonlinear chirp due to SPM had the same sign as the negative chirp of the transmitter. Therefore, transmission could be optimised balancing dispersion and SPM with additional linear modulator chirp as shown in BER measurements at 10Gbit/s using 100km of NZ-DSF. The interaction of linear and nonlinear chirp was used to control the chirp of a gain-switched DFB laser with additional XPM chirp [MOR89]. This XPM based chirp-compensation allowed to manipulate the chirp-characteristics of ultrashort laser pulses. The opposite mechanism was reported to compensate XPM [SAU98] by linear pre-chirping the source. 2 channels in pump-probe configuration were transmitted over a single fibre span. The detected CW channel, normally subject to distortion due to XPM chirp, was phase-modulated before transmission with the signal used for intensity modulation of the interfering pump-channel. Therefore, red-shifted components of the probe signal cancelled out the influence of blue-shifted components due to XPM. This relatively complicated approach is no longer practical when more than two channels are transmitted.

A passive compensating technique for XPM using spectrally periodic dispersion was investigated in theory [EIS99] and in experiments [BEL99b]. Considering an exactly compensated link, XPM distortion can be reduced by minimising residual dispersion [BIG99]. However, the temporal channel realignment in this case undoes the walk-off. In this case XPM is enhanced due to constructive interference between different fibre spans [NEL98] and chirp will build up quadratically with the number of spans. Therefore, the XPM suppression mechanism proposed [BEL99b, EIS99] introduces an additional timing offset $\Delta \tau$ between two
consecutive spans as shown in Fig. 3.3. The advantage with respect to under-compensation is that compensation of linear distortion is still obtained but the additional channel delay avoids the accumulation of XPM chirp due to destructive interference. However, the delay $\Delta \tau$ must be specifically optimised for a given combination of $\Delta \lambda$, dispersion and bit-rate. The timing delay between two channels was also varied in pump-probe experiments described in section 4.1. Since only a single fibre span was used the variation of the total distortion was only due to the interaction of XPM and SPM, however, an extension to multiple links would allow to implement this XPM suppression technique.

![Fig.3.3 Principle of XPM suppression for 2-channel system, a) initial bit-pattern alignment, b) alignment after transmission over exactly compensated DCF-SSMF span: $\Delta \tau_{SSMF} + \Delta \tau_{DCF}$ is the relative channel delay after a single span of SSMF+DCF, c) exact compensation but additional time delay $\Delta \tau$ between channels.]

**Bit-pattern:** The impact of bit pattern on the XPM transmission penalty was studied experimentally in [PIL99] and numerically in [LUC99]. It was found that for the RZ format the Q-factor reduces by up to 2dB when increasing the pattern length from $2^7$-1 to $2^{31}$-1 [PIL99] although no physical explanation was provided. The XPM penalty for 16 different channels was calculated using a set of 10 decorrelated NRZ patterns of 128bit length. A variation up to 0.9dB for a given channel was obtained showing the statistical nature of XPM in the case of short bit-pattern. As shown in chapter 2, XPM distortion originates from pulse transitions in the interfering channel and, thus, longer RZ sequences with more transitions are expected to increase the penalty due to XPM. The bit-pattern dependence is subject to experiments described in chapter 4 of this thesis.

In conclusion, XPM-induced transmission penalties were investigated in both experiment and simulation as a function of distance, channel spacing, fibre dispersion, channel launch power, bit-rate and modulation bit-pattern as summarised in table 3.1. Despite the results reported in this section, the impact of $\Delta \lambda$, channel number and power per channel on the Q-factor was not fully investigated yet and the relation between XPM induced-penalties and distortion due to XPM remained unclear. This thesis contributes to these areas by direct BER and Q-factor measurements described in chapter 5.
## XPM in IM/DD transmission systems

<table>
<thead>
<tr>
<th>Reference</th>
<th>Fibre link</th>
<th>Bit-rate</th>
<th>Channel power, $\Delta\lambda$, N</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>[MAR94]</td>
<td>SSMF, up to 6 spans of 120km</td>
<td>2.5Gbit/s, PRBS</td>
<td>5-15mW/ch, N=3-8, $\Delta\lambda=0.2-1.8$nm</td>
<td>SNR calculated, saturation of XPM when adding channels, centre channels only detected</td>
</tr>
<tr>
<td>[HAY96, HAY97]</td>
<td>50km spans, pre- and post-compensation, alternating sign for NZDSF, up to 3200km</td>
<td>5-20Gbit/s, PRBS</td>
<td>0.2-1mW/ch, N=1-16, $\Delta\lambda=0.4-1$nm</td>
<td>parameter dependence of XPM+SPM eye closure, penalty</td>
</tr>
<tr>
<td>[YU98]</td>
<td>SSMF(50km)+DCF, up to 60 spans</td>
<td>10Gbit/s, PRBS</td>
<td>5-15mW/ch, N=4, $\Delta\lambda=0.4-1$nm</td>
<td>Q-factor simulations, optimising transmission distance</td>
</tr>
<tr>
<td>[TEN99]</td>
<td>5x80km, SSMF/NZDSF</td>
<td>10Gbit/s, PRBS</td>
<td>4dBm/ch, N=40, $\Delta\lambda=0.8$nm,</td>
<td>Q-factor for XPM, FWM, single channel</td>
</tr>
</tbody>
</table>

### Table 3.1 Overview of experimental and theoretical work investigating XPM penalties in optical transmission systems
Chapter 3: Cross-phase modulation - literature review

3.4 Pump-probe experiments

In section 3.3 an overview was given of work investigating the system penalty due to XPM. However, these isolated systems experiments gave no significant contribution to the understanding of XPM as the results were specific to the given fibre link. This section focuses on the investigation of XPM-induced intensity distortion as a function of systems parameters which provide insight into the physical process of XPM.

The earliest pump-probe experiments investigated only the XPM-induced phase shift $\Delta \phi_{XPM}(\omega)$ of the probe [KAG94, MAR96]. These were limited to short links of DSF and SSMF and the phase shift was measured as a function of distance, channel spacing and modulation frequency. In 1996, the analysis of XPM was extended to dispersion-compensated spans [MAR96, CHI96] and an analytical expression for $\Delta \phi_{XPM}(\omega)$ was derived as shown in section 2.3.1. The investigation of the XPM phase shift is important for coherent detection systems but not sufficient for the understanding of XPM in IM/DD since residual dispersion and PM-IM conversion were not considered in this work.

In 1996 the first pump-probe experiments were reported on the investigation of XPM intensity distortion in direct-detection systems [SAU96]. The broadening of a CW probe, expressed by the normalised standard deviation $\sigma_{XPM}$, was investigated for a PRBS-modulated pump at 10Gbit/s. Launching 9dBm/channel the channels propagated over up to 5 spans of NZDSF with $D=2ps/(km\cdot nm)$ and $D'= -1ps/(km\cdot nm)$. A linear increase of $\sigma_{XPM}$ with distance was measured for negative $D$ but exponential increase was obtained for positive $D$ due to XPM seeding MI in the probe [SAU97]. Both orthogonal channel polarisation and lumped dispersion compensation were shown to minimise XPM induced distortion. A similar experiment for SPM was reported in [SAU97b]. It was also shown in [SAU96], that XPM distortion can be reduced by dispersion compensation but no explanation for the reduction of $\sigma_{XPM}$ was given. Although the increase of $\sigma_{XPM}$ with distance was investigated for the first time, the shape of XPM-distorted waveform was not investigated and no confirmation of the results by simulations was presented. In 1997, XPM distortion of the probe channel was investigated for a more simplified set-up using only a single span of 80km SSMF [RAP97]. A pump channel modulated with a 7Gbit/s PRBS sequence co-propagated with a CW probe where the pattern generator limited the bit-rate. The distorted probe waveform for 12dBm/channel was measured for the first time and the XPM effect was quantified by $m_i$. The experimental results were in good agreement with simulations using the split-step Fourier algorithm. Although XPM was only measured as a function of channel spacing, this paper is
important for this thesis since a similar set-up was implemented at approximately the same
time for the initial experiments described in chapter 4, section 4.1. However, the dispersion
map for the single span experiments in chapter 4 was modified according to [KIK96]: a span
of test-fibre was followed by a converting fibre for additional PM-IM conversion.

XPM distortion was investigated in pump-probe experiments as a function of different
systems parameters. One important parameter is the bit-rate or, in the case of uniform bit-
pattern, the modulation frequency. In [HUI98] XPM distortion was investigated between 0.1
and 10GHz using 2 spans of NZDSF with $L_{sp} = 100km$ and 11.5dBm/channel launch power. A
network analyser was used to measure the impact of XPM on the RF spectrum of the probe.
The advantage of this approach was a high dynamic range of 60dB. However, since no
analysis of the distorted pulse shape in the time domain was possible this method was not
used in the subsequent experiments of chapter 4. The authors showed that the XPM response
of the link, $H_{sp}(\omega)$, varied with the modulation frequency resulting in distinct notches and
peaks. The number of ripples in a given frequency interval was increased for wide channel
spacing. Similar to [CHI96] where only the phase shift was considered, this oscillation could
be explained as a result of interference between XPM components of different amplified fibre
spans where the frequency difference $\Delta f$ between adjacent maxima or minima is determined
by the walk-off over the span $L_{sp}$

$$\Delta f = \frac{1}{d_{sp} \cdot L}$$

The experiments were extended in [HUI99]: the frequency response for XPM in SSMF and
NZDSF were compared where $d_{sp}$ was increased for SSMF. It was also shown that the
amplitude of the XPM-induced RF components increased with dispersion due to increased
PM-IM conversion. Dispersion compensation of NZDSF links was shown to reduce XPM but
contrary to [CHI96] it was suggested that exact compensation of each span minimised XPM.
However, this conclusion did not take into account the constructive interference of XPM
components of different spans resulting in build-up of XPM distortion with distance. Similar
measurements investigating the variation of BER with $\Delta \lambda$ in a 5-channel transmission at
2.5Gbit/s were reported in [NEL99]. Resonances of the BER were found in the case of
constructive interference between XPM contributions of adjacent spans. However, only spans
of SSMF without dispersion compensation were investigated. Recently, the bit-rate
dependence of XPM distortion was investigated for the first time over installed fibre in the
BT LEANET network [THI99, THI00] in pump-probe configuration. This is an important
contribution to verify laboratory experiments and to estimate the variation of XPM with
different values of attenuation and polarisation in installed fibres. The distortion of the
uncompensated and DCF compensated 2-span link was characterised by $m$, and $\sigma_{XPM}$,
therefore giving a more practical parameter for the waveform than [HUI99]. Symmetrical
dispersion compensation was chosen, shown to minimise distortion due to SPM and GVD
[SCH97]. The results of the field experiments were compared with laboratory experiments
using a replica of the link. The results for both cases were in agreement with the analytical
calculations described in [HUI99] and are described in chapter 4, section 4.2.

A detailed study of XPM distortion using a 2-channel pump-probe configuration is described
in [THI98]. The distortion $m_r$ is measured as a function of $\Delta \lambda$ over a single span of DSF,
SSMF and SSMF+DCF thus extending the work of [RAP97]. With respect to bit-rate
dependent measurements reported in [HUI99, NEL99] it was shown for the first time in
[THI98] that increased distortion at high bit-rates up to 10Gbit/s is due to both increased
number of pump channel transitions per unit time and the decreased pulse rise time. The
increased walk-off for large $\Delta \lambda$ due to high link dispersion reduced the XPM efficiency and
hence the resulting distortion. The results of this investigation are described in chapter 4,
section 4.1.

In [EIS99d, SHT00] the investigation of XPM intensity distortion was restricted to different
channel spacing only. The probe distortion $\sigma_{XPM}$ was measured as a function of $\Delta \lambda$ for 80km
of SSMF or NZDSF. The distortion was inversely proportional to $\Delta \lambda$ in the walk-off limited
regime ($L_{wo} < L_{eff}$) as previously suggested in analytical calculations [SHT98]. For low walk-off
($L_{wo} > L_{eff}$) a saturation of the XPM distortion was shown as described in section 2.3.2 and
no oscillation of XPM with $\Delta \lambda$ was observed due to PRBS modulation of the pump. However,
results were only obtained for 2 different distances and no dispersion management was
considered. The authors also measured XPM originating in EDFAs due to the small effective
area of the Erbium fibre (EDF) [SHT98d]. It was found that XPM caused by the EDFA
becomes comparable to $\sigma_{XPM}$ measured in 80km of SSMF for $\Delta \lambda > 3$nm, causing a background
level of XPM distortion. Recently, this investigation was also extended to L-band amplifiers
[EIS99c]. The measured standard deviation due to XPM of the EDFA was constant over
$\Delta \lambda = 5$nm channel spacing with $\sigma_{XPM} = 10\%$, an order of magnitude higher than in [SHT98d].
This was mainly due to the longer EDF in the L-band EDFA. Similarly increased XPM
distortion is also expected for tellurite-based EDFAs [MAH99]. Due to the narrow channel
spacing and high launch power into the transmission fibre, XPM distortion originating from
EDFAs was not relevant in the experiments described in this thesis.

In early experiments and simulations the impact of dispersion compensation on nonlinear
distortion was only investigated for SPM. In simulations of 10Gbit/s transmission, pre-
compensation was found to be the optimum choice for exactly compensated 50km SSMF spans [ROT96]. In the following, this work was generalised for imperfect compensation. Using 2 spans of 100km and a variable length of DCF corresponding to $0 > D \cdot L > -1600 \text{ps/nm}$, post-compensation with positive residual dispersion minimised the transmission penalties [BEL98c]. This work was of importance for the following experiments described in this thesis although only a single channel was considered. XPM distortion was investigated for post- and pre-compensated links as a function of transmission distance [THI99b] extending the work of [SAU96]. In these first distance-dependent recirculating loop measurements of XPM-induced intensity distortion, also described in chapter 4.3, it was shown that $m_2$ increases linearly with distance for exact span-compensation. This experimental work focuses on the concept of residual dispersion and its impact on XPM-induced intensity distortion. Lumped receiver dispersion was shown to reduce XPM distortion as it minimised the residual dispersion. The results of this work are described in more detail in section 4.4 of this thesis confirming that positive residual dispersion reduces XPM and SPM distortion in a link with post-compensated spans.

Finally, it was experimentally verified that a pump-probe measurement of XPM could be used to predict the XPM-induced Q-factor reduction through comparison with direct BER measurements [THI00b]. The experiments were performed for multi-span 10Gbit/s WDM transmission over dispersion-compensated SSMF for a range of link lengths using a recirculating loop. Good agreement between calculated/measured and actual penalties due to XPM was obtained. This experiment is one of the main contributions of this thesis and is described in chapter 5.

Significant published results of the investigation of XPM-induced distortion are summarised in table 3.2. The highlighted section lists original contributions described in this thesis. The reported experiments investigated XPM as a function of systems parameters such as fibre dispersion, channel spacing, bit-rate, channel number and power. However, the results reported in this previously published work are not complete and important measurements are still missing: the bit-rate dependent measurements were only carried out in the spectral domain and the impact of different pulse shapes on XPM was not investigated yet. There is also no work reported investigating XPM in pump-probe experiments for $\Delta \lambda < 0.4 \text{nm}$ and the increase of XPM with distance was only investigated for a small number of spans.

In general, the reported investigations and results concentrated on specific experimental configurations making it difficult to generalise the results. Therefore, the work in this thesis was aimed towards a systematic investigation of XPM distortion as a function on system parameters to develop a detailed understanding of the physical nature of the XPM process.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Fibre link</th>
<th>Bit-rate</th>
<th>Channels: power, $\Delta \lambda$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Phase distortion</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>[CHI94, KAG94]</td>
<td>50km SSMF or multi-span: up to 3x25km SSMF DSF</td>
<td>0.1-1GHz sinusoidal</td>
<td>7-9 dBm/ch, $\Delta \lambda=3.7-8.1$nm</td>
<td>heterodyne XPM phase measurement,</td>
</tr>
<tr>
<td>[MAR96, CHI96]</td>
<td>13km DSF, multi-span: SSMF (25km) up to $n=3$, n=30 spans simulated, dispersion compensation of DSF with SSMF</td>
<td>0.01-1GHz sinusoidal, 1Gbit/s PRBS</td>
<td>11dBm pump, $\Delta \lambda=3.7-8$nm, DSF: up to 20nm</td>
<td>detailed study of multi-span dispersion compensated links: lumped compensation vs. span-based compensation</td>
</tr>
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<td>[EVA99]</td>
<td>5-8 spans of 80km SSMF / 6000km NZDSF+SSMF</td>
<td>2.5Gbit/s PRBS</td>
<td>13dBm pump, $\Delta \lambda=0.2$-2nm</td>
<td>RZ modulation, only simulation</td>
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<tr>
<td></td>
<td><strong>Intensity distortion</strong></td>
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<td></td>
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</tr>
<tr>
<td>[RAP97]</td>
<td>single span 80km SSMF</td>
<td>7Gbit/s PRBS</td>
<td>12dBm/ch, $\Delta \lambda=0.5$-6nm</td>
<td>first experiment investigating XPM intensity distortion of the probe waveform</td>
</tr>
<tr>
<td>[HU199, HUI98]</td>
<td>NZDSF: up to 3 spans of 114km, 3rd span SSMF</td>
<td>10GHz sinusoidal, 2.5-40GHz simulation</td>
<td>11.5dBm/ch, $\Delta \lambda=0.8$-1.6nm</td>
<td>measuring XPM response of multi-span links using network analyser, comparison with simulation and analytical calculations</td>
</tr>
<tr>
<td>[SAU97, SAU96]</td>
<td>6 spans of 75km NZDSF</td>
<td>10Gbit/s PRBS</td>
<td>9dBm/ch, $\Delta \lambda=2.4$nm</td>
<td>MI caused by XPM, dependent on dispersion sign and suppressed with compensation using DCF</td>
</tr>
<tr>
<td>[SHT98, EIS99d]</td>
<td>80km spans of SSMF, NZDSF, 4 spans compensated with fibre gratings (FBG)</td>
<td>10Gbit/s PRBS, pump: 10dBm, probe: 0dBm $\Delta \lambda=0.5$-5nm</td>
<td>variation XPM with $\Delta \lambda$, $D$ and distance confirming results of [SHT98]</td>
<td></td>
</tr>
<tr>
<td>[THI98, THI99b]</td>
<td>single span DSF, SSMF, DCF+SSMF, recirculating loop with SSMF, DCF and converter</td>
<td>2.5Gbit/s, 1-10Gbit/s, PRBS and 1010... mod.</td>
<td>10-13dBm/ch, $\Delta \lambda=0.4$-2nm, DSF up to 5nm</td>
<td>detailed study of XPM as a function of walk-off: bit-rate, $\Delta \lambda$, pulse shape, role of residual dispersion, length dependence</td>
</tr>
<tr>
<td>[THI00b]</td>
<td>SSMF(65km)+DCF, 7 spans</td>
<td>10Gbit/s PRBS, 1010-modulation</td>
<td>10dBm/ch, $\Delta \lambda=0.4$, 1.6nm</td>
<td>linking distortion $\alpha_{XPM}$ to Q-factor penalties, comparison with analytical results</td>
</tr>
<tr>
<td>[THI00]</td>
<td>2x92km SSMF, DCF-compensated</td>
<td>1-10Gbit/s, 10Gbit/s PRBS, 1010-modulation</td>
<td>13dBm/ch, $\Delta \lambda=0.4$-1.6nm</td>
<td>first field experiment investigating XPM distortion in LEANET, comparison with laboratory experiment and analytical results</td>
</tr>
</tbody>
</table>

Table 3.2 Overview of experimental work investigating XPM distortion in optical transmission systems, the experiments use N=2 channels unless otherwise noted
3.6 Summary

In this chapter published work on the investigation of XPM was reviewed. It can be divided into systems experiments measuring penalties due to XPM and pump-probe experiments investigating XPM distortion. Several authors have investigated XPM in WDM transmission experiments and simulations. Low dispersion in spans of DSF or high launch power resulted in strong penalties increasing with transmission distance. DCF-compensated spans of SSMF showed the smallest penalties where minimising the residual dispersion reduced XPM. Suppression techniques were also investigated based on the deliberate misalignment of the channel delay avoiding build-up and resonant effects of XPM.

Although experiments have begun to investigate the impact of systems parameters on XPM induced penalties and intensity distortion, this analysis is still incomplete. At first, XPM intensity distortion must be further investigated, showing the direct interaction between nonlinearity and dispersion, and isolating XPM from other nonlinearities. This more fundamental approach reduces the complexity of transmission experiments and thus allows the use of analytical techniques to estimate the amount of XPM distortion. The review of published work revealed that important aspects of XPM distortion have not been investigated in detail such as the impact of transmission distance, residual dispersion, bit-pattern, pulse width and shapes. In addition, a validation of the pump-probe results in experiments over installed fibre was not carried out. This thesis addresses these issues in chapter 4.

More research is also needed on the impact of channel spacing on the Q-factor as this approach allows to determine the contribution of XPM to the overall transmission penalty. Also, the ratio of channel number and power per channel must be investigated from the nonlinearity point of view to achieve minimum penalty for a given fibre link. The key contribution required is a link between the transmission experiments and the fundamental pump-probe experiments. In chapter 5 it is shown that XPM penalties can be accurately estimated using results of distance- and Δλ-dependent pump-probe experiments.
Chapter 4

XPM pump-probe experiments

As described in previous chapters, to enable a systematic investigation of XPM in optical transmission, XPM must be separated from other nonlinearities such as SPM and FWM. This can be achieved using a pump-probe configuration as described in this chapter. In the first pump-probe experiments XPM-induced distortion was investigated using a single fibre span comprising combinations of DSF, SSMF and DCF. In these experiments (section 4.1), the dependence of XPM on key system parameters was investigated. In section 4.2, the field experiment using 2 amplified spans of installed fibre in the BT LEANET network is described. New results focusing on the interaction of XPM of different spans were obtained and compared to laboratory experiments. As described in section 4.3 and 4.4, XPM distortion was measured in dispersion-compensated spans as a function of distance using a recirculating fibre loop set-up. Finally, different concepts for reducing XPM distortion are explored, based on minimising the residual dispersion from the point at which XPM occurs to the end of the fibre link.

4.1 Single-span links

4.1.1 Pump-probe technique

As already mentioned in chapter 2, in the presence of a high launch power into a fibre link, SPM, FWM and XPM occur simultaneously. FWM (appendix F) can be suppressed, firstly by avoiding phase matching using dispersive fibre and, secondly, by unequal channel spacing in combination with optical filtering removing FWM induced cross-talk between WDM channels [FOR95]. SPM and XPM are a result of a variation of the optical phase due to power fluctuations and thus the total distortion detected in a multichannel system is a result of both effects. The pump-probe technique is, therefore, a key technique to isolate the effect of XPM.
In its simplest configuration, two channels are launched into the fibre. As already described in section 2.3.6, one channel at $\lambda_p$, called the pump, is modulated with a PRBS or an alternating (1010...) bit-pattern. The other channel at $\lambda_{cw}$, termed the probe, carries a CW signal. Fig. 4.1 illustrates the concept of a pump-probe measurement for a single span of fibre. The pump is 1010...-modulated at 2.5Gbit/s and the channel spacing is $\Delta\lambda = \lambda_p - \lambda_{cw} = 0.4$nm. In this example the power per channel was, launched into 65km of SSMF.

![Diagram of pump-probe configuration](image)

The modulated pump shows SPM distortion after transmission, similar to Fig. 2.10. Since the waveform in the probe channel is constant, no phase modulation $\phi_{XPM}(t)$ due to XPM is induced in the pump. The probe channel itself shows no SPM distortion as it carries a time-independent CW signal. However, transitions in the modulated pump channel result in XPM phase modulation converted into IM at $\lambda_{cw}$. The amount of induced phase modulation and its subsequent conversion to amplitude variation is used to investigate the nature of XPM in detail. The technique described here gives more insight into the total XPM distortion than a similar configuration using a modulated probe channel, or indeed a multi-channel system. Fig. 4.2 shows the detected distortion for 2-channel transmission at 10Gbit/s, $\Delta\lambda=0.4$nm and 65km of SSMF. In one case, the probe is CW and only XPM distortion is detected. In the other case, the probe is modulated with a PRBS and exhibits simultaneous SPM and XPM distortion. A direct comparison between the 2 traces reveals that the detected probe differs near the pulse edges due to localised SPM distortion. However, for a longer duration of the ‘1’-level, the resultant distortion agrees well with the results in the CW case.
Chapter 4: XPM pump-probe experiments

![Image of XPM distortion for both traces](image)

Distortion in probe channel. 65km SSMF, 13dBm/channel, \( \Delta\lambda=0.4\text{nm} \), 10Gbit/s PRBS modulation in pump, **dashed line**: CW signal in probe measuring XPM only, **solid line**: PRBS-modulated probe detecting interference of SPM and XPM distortion.

Using the pump-probe technique, XPM distortion can also be analysed where the '0'-level in a modulated channel normally provides no information. The peaks of the XPM distorted waveform are closely related to the bit-sequence in the pump channel. Fig. 4.3 shows the relation between probe and pump waveform at 2.5Gbit/s transmitted over 65km of SSMF. The XPM distorted probe is calculated for \( \Delta\lambda=\pm0.4\text{nm} \) corresponding to \( \pm0.3\text{bits} \) walk-off over \( L_{\text{eff}} \). Although the amount of distortion in the probe channel at \( \lambda_{\text{CW}} \) is identical in both cases, the relation between a particular peak and pump transition depends on the sign of walk-off \( D(\lambda_{\text{CW}}-\lambda_p) \). For \( \lambda_p>\lambda_{\text{CW}} \), the pump propagates slower than the probe and the relative position of pump and probe are shown in Fig. 4.3(a). In the case \( \lambda_p<\lambda_{\text{CW}} \) the relative walk-off between the channels is reversed and a given transition in the pump results in the opposite sign of XPM induced chirp.

![Image of XPM distortion in probe due to transitions in 1010...-modulated pump at 2.5Gbit/s, 65km SSMF, 10dBm/ch average power](image)

**Fig. 4.3** XPM distortion of probe due to transitions in 1010...-modulated pump at 2.5Gbit/s, 65km SSMF, 10dBm/ch average power, (a) \( \lambda_p>\lambda_{\text{CW}} \), (b) mirrored distortion of same magnitude for \( \lambda_{\text{CW}}>\lambda_p \), note: pump and probe waveforms are on different intensity scales.
Therefore, interchanging the channels results in a mirrored image of the XPM distortion which can also be observed substituting SSMF with fibre with an opposite sign of dispersion. In general, the pump channel is PRBS-modulated and the XPM-induced distortion depends on the pulse width of the interfering pulses. As shown in Fig. 4.4, the XPM distortion is no longer uniform when the 1010...-modulation is substituted by a PRBS. It is evident from the transfer function $H_{sp}(\omega)$ shown in Fig. 2.23 that the shortest pulses create the largest amount of distortion on the probe. The effect of pulse width and bit-rate on XPM distortion was also investigated and described in section 4.1.6.

![Fig. 4.4](image)

**Fig. 4.4**  XPM distortion of probe and relation to PRBS pattern in pump channel, 10Gbit/s, $\Delta\lambda=0.4$nm, 10mW/channel, 65km SSMF, the XPM distortion due to a PRBS is quantified by $\sigma_{XPM}$ defined in section 2.3.6.

### 4.1.2 Measurements of XPM distortion for a single span

At first, XPM-induced distortion was investigated for a straight-line transmission system up to 10 Gbit/s. Figure 4.5 shows the pump-probe experimental set-up used to investigate the contribution of XPM within one amplified span, typically a section of a longer, multi-span system. The test-span comprised dispersion-shifted fibre (DSF) or standard single-mode fibre (SSMF) and dispersion compensating fibre (DCF). The test-fibre was followed by 22km of SSMF, termed conversion fibre, to ensure sufficient PM-IM conversion for direct detection, and equivalent to an additional system dispersion of $D_{\text{conv}}=+370$ps/nm. The fibre parameters for the experiments are shown in table 4.1. The dispersion values listed for DSF and DCF denote the mean values for the combination of fibres used. The zero dispersion wavelength of the DSF was within the range of $\lambda=1547$-1561nm.
Chapter 4: XPM pump-probe experiments

<table>
<thead>
<tr>
<th></th>
<th>$D$ [ps/(nm·km)]</th>
<th>$\gamma$ [1/(W·km)]</th>
<th>$\alpha$ [dB/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSF</td>
<td>$&lt;0.5$</td>
<td>2.43</td>
<td>0.23</td>
</tr>
<tr>
<td>SSMF</td>
<td>+17</td>
<td>1.22</td>
<td>0.21</td>
</tr>
<tr>
<td>DCF</td>
<td>-85</td>
<td>4.86</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 4.1 Parameters for fibre used in the pump-probe experiments

Fig. 4.5 Experimental set-up measuring XPM in pump-probe configuration, EA-modulator in probe is optional, Rx: Receiver (PIN), PC: polarisation controller and/or polarisation scrambler, the EAM in the probe channel was used in the experiments described in section 4.1.4

The SSMF/DCF link was tested in both post- and pre-compensation configurations. Pre-compensation decreases FWM and modulation instability and has been shown to result in pulse compression due to SPM rather than the more detrimental pulse broadening effect with post-compensation [ROT98]. A tuneable external cavity laser (Anritsu MG9638A) and electro-absorption modulator (EAM) were used for the pump at $\lambda_p$, and the probe channel transmitter was a DFB laser in CW mode. The tuneable laser allowed the channel spacing $\Delta\lambda$ to be varied. The modulator was driven with a pattern generator (PPG, Anritsu MP1763B) to give optical pulses with 10-90% rise- and fall-time of 56ps, typical for a 10Gbit/s NRZ system. Since the XPM effect is polarisation dependent the relative polarisation of both channels required constant monitoring. In this experiment, the pump was polarisation-scrambled at 600kHz with respect to the probe using a fibre-coil driven by a signal generator to reduce the variability due to polarisation. This technique compensated for statistical fluctuations of the relative channel polarisation and ensured long-term stability required for reproducible results. The two channels were combined and boosted with an EDFA (Corning FGM-P-027) to +13dBm per channel. After propagation, the probe was selected using a free-
space grating demultiplexer [TIM96], detected with a fast photodiode (BW=20GHz) and analysed on a sampling oscilloscope (Tektronix CSA803A) to determine \( m_x \). The XPM modulation index \( m_x \) was defined in equation (2.34), section 2.3.6, and is used to quantify the probe distortion due to a 1010...- modulated pump channel. XPM distortion was investigated as a function of the following parameters:

- Fibre dispersion including different dispersion maps and converting fibre
- Channel spacing
- Pulse form: bit-rate, pulse rise time and pattern
- Channel power

4.1.3 Combination of XPM and dispersion

A key factor determining the amount of XPM generated in a fibre link is the walk-off which was shown in Fig. 2.15 as a function of \( \Delta \lambda \) for different fibre types. In this section, XPM distortion is compared for the limit of low and high walk-off. In the experiments, DSF and SSMF were used. For a given fibre dispersion, the channel spacing was additionally varied. Initially, the DSF was followed by dispersive fibre to carry out PM-IM conversion. This is a particularly suitable configuration to study fundamental properties of XPM as the nonlinear section (DSF) is clearly separated from the linear phase to amplitude conversion (SSMF). Figure 4.6 shows the measured time-averaged distorted probe waveform after transmission obtained by averaging the traces on the sampling oscilloscope.

**SSMF versus DSF**: The distortion measured for DSF fibre with low walk-off was compared to the case when SSMF fibre was used as the test-fibre. For \( \Delta \lambda = 1 \text{nm} \), XPM induced distortion is reduced from \( m_x = 0.44 \) for DSF to 0.11 for SSMF due to the increased walk-off of both channels over the first fibre from \(< 0.1\) bit in DSF to \( \approx 2\) bits in SSMF. The sharp peak structure for DSF indicates localised build-up of nonlinear chirp converted into IM by the following converting fibre. Therefore, the higher dispersion of SSMF within \( L<L_{\text{eff}} \) is advantageous as it reduces XPM distortion.
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![Graph showing probe distortion in pump-probe configuration.](image)

**Fig. 4.6** Probe distortion in pump-probe configuration. $\Delta \lambda = 1$ nm, 13 dBm/channel. (a) XPM after 45 km DSF with 22 km SSMF converter, $D_{\text{crosstalk}} = 370$ ps/nm, 2.5 Gbit/s 1010...-modulation in pump, solid line: experiment, dashed line: split-step Fourier simulation, (b) (45+22) km SSMF, (c) qualitative explanation of distortion for low and high channel walk-off

**Bit pattern:** Next, the length of the 1010... sequence of the pump was varied by adding ‘1’- and ‘0’- to form longer clusters causing the temporal spacing between pulse transitions to increase from 100 ps to 800 ps. For the initial 1010...-sequence, the walk-off over the DSF fibre was less than 0.1 bits. As a result, the peaks due to XPM distortion in the probe are clearly isolated similar to Fig. 4.6(a). From Fig. 4.7(a) to (d) the magnitude of the XPM modulation index, expressed by $m_a$, remains constant, however, the standard deviation $\sigma_{\text{XPM}}$ of the probe waveform increases for shorter pulse periods since more transitions occur within a given time interval. Therefore, $\sigma_{\text{XPM}}$ is more appropriate to quantify the total distortion of the probe. In the limit of low walk-off where neighbouring transitions are clearly isolated $m_a$ remains constant and is only determined by the magnitude of individual, separate transitions.
As a result, $m_x$ is expected to be independent on the modulation pattern under these circumstances and 1010…-modulation can be used instead of a PRBS pattern.

Channel spacing: To investigate the influence of channel spacing on XPM, $m_x$ was measured as a function of $\Delta \lambda$ and this variation is shown in Fig. 4.8. The channel walk-off increases with $\Delta \lambda$, filtering the pump channel as described by the transfer function $H(\omega)$, and thus reducing the phase modulation of the probe by the increased averaging over the waveform. XPM distortion of $m_x > 0.1$ was detected for DSF over an interval of more than $\pm 10\text{nm}$, whilst $m_x > 0.05$ was confined to $\Delta \lambda < 1.2\text{nm}$ for SSMF. The alternative use of DCF as the converting fibre following DSF generated the same magnitude of XPM distortion because of the identical absolute dispersion. These measurements extend the results of Fig. 4.6 and indicate that $\Delta \lambda$ can be reduced in SSMF due to less XPM. The close channel spacing allows to increase the WDM transmission capacity. An interesting feature of the DSF measurement was a local maximum, at approximately 6nm from $\Delta \lambda = 0$ yielding an asymmetric plot with respect to $\Delta \lambda = 0\text{nm}$. The increase of $m_x$ away from $\Delta \lambda = 0$ is a result of the walk-off in DSF reaching a minimum when the zero dispersion wavelength $\lambda_0$ is situated exactly between pump and probe channel. This was also in good agreement with the simulations of this experiment shown in Fig. 4.8. To avoid XPM even for wide channel spacing, careful consideration of $\lambda_0$ was necessary during the system design. The graph in figure 4.8 became symmetrical either
by placing the channels far away from $\lambda_0$ or by placing the probe channel directly at $\lambda_0\approx1555\text{nm}$.

![Graph](image)

Fig. 4.8  
XPM distortion of the probe as a function of $\Delta\lambda$, (○): SSMF, (●): DSF, (—): DSF simulation, 1010...-modulation, 2.5Gbit/s, 13dBm/channel, parallel polarisation

4.1.4 Interaction of XPM with SPM and FWM

XPM and SPM: Although the pump-probe configuration provides detailed analysis of XPM alone, measurements involving modulated channels are still necessary to obtain the total system penalty. In the previous section, the probe allowed to isolate XPM-induced distortion since the CW-probe signal suppressed SPM distortion. In this section, pump and probe channels were modulated to study the combined effects of SPM and XPM on transmission over the DSF+SSMF link. The pulse transitions of the 1010...-modulated pump induced XPM distortion in the PRBS-modulated probe channel similar to the configuration discussed in Fig. 4.2. The interference between the bit patterns was investigated using the internal delay function of the PPG. The relative delay $\Delta\tau$ between the two waveforms could be adjusted with 1ps accuracy. As shown in Fig. 4.9 the probe channel exhibits isolated peaks due to XPM distortion, typical for DSF fibre. Unlike the previous CW-mode measurements, the pulse edges show distortion due to the overlap of chirp components originating from SPM and XPM, interfering constructively or destructively depending on $\Delta\tau$. In the previous section XPM alone was investigated. This experiment reveals that for the given channel spacing the magnitude of the SPM-induced intensity distortion is comparable to XPM and, therefore, must be taken into account in the full analysis of the system nonlinearities.
Distortion could only be minimised for a section of the probe waveform cancelling positive with negative chirp. Since the pump waveform exhibits an equal number of rising and falling edges, the total distortion due to SPM and XPM measured over the entire probe waveform remained constant. For a long bit-sequence of '1'-bits in the PRBS, only the position of the XPM peaks varied in the interval $\Delta \tau = 0$-800ps but not the total amount of distortion. Due to the finite EAM extinction ratio of approximately 10dB, residual distortion of the '0'-level of the probe amounted to nearly 15% of the typical '1'-level distortion due to the remaining probe power. These measurements showed excellent agreement with the results obtained in simulations.

The combination of SPM and XPM was also experimentally studied in the case of large channel walk-off. The channels were modulated with the same bit-pattern at 10Gbit/s and the DSF was replaced with SSMF to create a fibre span of $L=65km$ with $D=16ps/(nm^2km)$ and $\Delta \lambda=0.4nm$. As in the earlier experiments, the total walk-off in SSMF remained at 20-times the amount in DSF for the same $\Delta \lambda$. In Fig. 4.10 similar observations were made as already before in Fig. 4.9. The eye opening of the probe channel was strongly dependent on $\Delta \tau$. The high sensitivity of the EOP to channel delay was caused by the short pulses of the PRBS.
sequence, shown on the left hand side, resulting in significant overlap of XPM and SPM at the pulse edges.

**XPM and FWM:** In the experiments using DSF, the channel spacing had to be increased to $\Delta \lambda = 2\text{nm}$ to avoid pump depletion due to FWM. High local dispersion or wide channel spacing $\Delta \lambda > 2\text{nm}$ could be used to reduce the impact of FWM on the transmission over DSF. The cross-talk due to FWM sidebands coinciding with optical channels can be avoided in a two channel system using optical filtering. However, pump depletion still reduces the power of the '1'-level of the probe due to the presence of a '1' in the pump channel. Fig. 4.11 shows the optical spectrum measured after 45km DSF and 22km SSMF. Unlike in the previous measurements using DSF, $\lambda_p$ and $\lambda_{CW}$ were close to $\lambda_0 \approx 1555\text{nm}$ for efficient generation of FWM ($\eta_{\text{FWM}} \approx 0.9$). Fig. 4.12 shows the combined effects of FWM and XPM on the probe waveform measured as a function of channel spacing in the range $\Delta \lambda = 1\text{nm}$ to $3\text{nm}$ with $13\text{dBm}$ per channel launch power. As before, the influence of SPM on the waveform remained constant for all $\Delta \lambda$ and was not considered. However, distortion due to FWM depletion dominates over XPM distortion for narrow channel spacing $\Delta \lambda < 2\text{nm}$. At $\Delta \lambda = 1\text{nm}$ the probe trace was completely depleted due to the periodic modulation of the pump channel. For $\Delta \lambda > 2\text{nm}$, the distortion due to XPM corresponds to the results shown in Fig. 4.9.
In conclusion, typical channel spacing of 0.4nm or 0.8nm used in WDM transmission results in detrimental waveform distortion when close to $\lambda_0$. For these reasons DSF is not suitable for high-power WDM transmission but was used in the single channel OTDM experiments described in chapter 6.

![Measured optical spectrum after DSF+SSMF link used in XPM pump-probe experiments](image)

**Fig. 4.11** Measured optical spectrum after DSF+SSMF link used in XPM pump-probe experiments, $\Delta\lambda=0.8$nm, 13dBm/channel, parallel polarisation (worst case FWM), FWM2, FWM3: higher order FWM, $\lambda_0=1555$nm

![Combined distortion of probe waveform due to XPM, SPM and FWM pump depletion](image)

**Fig. 4.12** Combined distortion of probe waveform due to XPM, SPM and FWM pump depletion. 45km DSF + 22km SSMF, 13dBm/channel launched into link, parallel polarisation, $\Delta\lambda=1$, 1.5, 2, 2.5 and 3nm, 2.5Gbit/s, probe: PRBS, pump: 1010- sequence, SPM remains constant for all $\Delta\lambda$
4.1.5 XPM in dispersion-compensated links

Reducing residual dispersion: In the previous sections, XPM was studied in links with uniform dispersion maps, either DSF or SSMF fibre followed by a constant length of SSMF conversion fibre. In the following experiments, a single span of 40km SSMF fibre was combined with approximately 8km of DCF fibre for exact dispersion compensation, followed by 22km of SSMF conversion fibre, resulting in a similar span length as before. XPM-induced distortion was investigated for pre- and post-compensated links with 13dBm/channel launch power and the results for $m_x$ versus $\Delta \lambda$ are compared with DSF in Fig. 4.13. The values of $m_x$ were a factor of >4 lower than for the DSF experiments due to higher walk-off between channels in the SSMF and DCF, approximately by a factor of 10 as determined by the difference in fibre dispersion. For the 2.5Gbits/s experiment and 45km span length, the walk-off increases by 1.8 bits for every $\Delta \lambda=1$nm increase in channel spacing. The residual dispersion for both dispersion maps is shown in Fig 4.14. The higher distortion in the pre-compensated (DCF+SSMF) span, shown in Fig. 4.14(b), was due to the larger positive residual dispersion averaged, $L_{\text{eff}}$, because SSMF following the DCF+SSMF link increased PM-IM conversion. In Fig. 4.14(a), the residual dispersion over $L_{\text{eff}}$ is minimised reducing the subsequent PM-IM conversion of XPM phase modulation. In summary, these measurements highlight that the combination of increased walk-off over $L<L_{\text{eff}}$ and low residual dispersion effectively reduce XPM intensity distortion.

![Fig. 4.13 2.5Gbit/s pump-probe experiments, $m_x$ versus $\Delta \lambda$, lines: split-step Fourier algorithm, test-fibre followed by SSMF converter: (●): SSMF+DCF, (▲): DCF+SSMF link, (■): DSF](image)
Fig. 4.14 Residual dispersion $D'_{\text{ref}}(z)$, given by equation (2.33), for (a) post-compensation, (b) pre-compensation, followed by 22km of SSMF ($D_{\text{cen}}=+370\text{ps/nm}$). In (a) the distance-averaged residual dispersion over $L_{\text{eff}}$ is minimised reducing PM-IM conversion and XPM intensity distortion, in (b) pre-compensation increases the total residual dispersion.

**XPM interference**: The interference between the XPM from the DCF and SSMF fibre in pre-compensation was investigated in more detail for different periodic bit-sequences. Fig. 4.15 compares $m_\tau$ versus $\Delta \lambda$ for 1010...- and 1100...-modulation. The XPM modulation index is plotted on a logarithmic scale to highlight its oscillation over the full range of measured $\Delta \lambda$. For increased channel spacing the channel walk-off along the full DCF section increases by 2bit per nm resulting in re-alignment of the periodic pattern after the DCF and, since the power is attenuated by only 4dB, additional XPM is generated in the subsequent SSMF. The additional PM from the nonlinearity of the SSMF fibre can interfere constructively with the XPM components created in the DCF resulting in increased distortion. In contrast, the minima of $m_\tau$ indicate destructive interference between XPM generated in both fibres. In experiments reported in [HUIJ99], XPM distortion was shown to oscillate dependent on the bit-rate of the pump. The oscillation period reduced with increased bit-rate and $\Delta \lambda$. However, bit-rate and $\Delta \lambda$ both affect the walk-off and, therefore, the measurements shown in Fig. 4.15 are described by the same interference mechanism. In the case of the 1010...-pattern maximum XPM distortion was measured for $\Delta \lambda=0.8\text{nm}$, 1.2nm and 1.7nm. The pulse width of the bit-pattern was increased by a factor of 2 reducing the bit-rate of the pump channel. The 11001100... bit-sequence decreased the walk-off by 50% for the same $\Delta \lambda$ resulting in higher XPM distortion and reduced oscillation of $m_\tau$. 
In conclusion, this experiment shows for the first time the variation of distortion due to intra-span interference between XPM generated in two different fibre types. This mechanism is similar to the interference between XPM from different spans in a multi-span link. The extended analysis of the interaction between XPM contributions from different fibre spans will be presented in section 4.2 describing the BT-LEANET network.

An important parameter for XPM is the pulse width increasing the channel walk-off at higher bit-rates. The pulse transition time decreases for high bit-rates and, therefore, the nonlinear chirp generated by each of these pulse edges in the pump also increases. Unlike other investigations [HUI99] this section describes a new approach separating the effect of pulse width and transition time on XPM-induced distortion. First, XPM was investigated for 65km of SSMF and \( \Delta \lambda = 0.4 \)nm channel spacing. The PPG allowed to vary the bit-rate whilst maintaining a constant 10-90\% pulse rise time of \( \Delta t = 56 \)ps. Fig. 4.16 shows a comparison of the experimental waveform at the EAM output for 2.5Gbit/s and 10Gbit/s pump modulation indicating constant rise time at all bit-rates.
Chapter 4: XPM pump-probe experiments

Bit-rate: Initially, the bit duration was varied from $T_B=1000\text{ps}$ (1Gbit/s) to $T_B=100\text{ps}$ (10Gbit/s) whilst maintaining a constant amount of XPM chirp induced by each pulse edge. The short pulses at high bit-rates resulted in high distortion as shown in Fig 4.17. Close spacing of the pulse transitions at high bit-rates and the fibre dispersion cause interference between neighbouring peaks affecting the shape of the XPM distortion and increasing its magnitude by approximately a factor of 2. This overlapping of individual components occurred for $>5\text{Gbit/s}$ whilst the distortion $m_x$ remained relatively constant at lower bit-rates. The shape of XPM distortion is characteristic only for the amount of walk-off experienced during the nonlinear interaction. For low bit-rates (1Gbit/s) and walk-off (<1 bit), the shape of the XPM intensity distortion in SSMF fibre is very similar to the DSF results shown in Fig. 4.7. The variation expected for $m_x$ would be even greater in practical systems because at bit-rates lower than 10Gbit/s the bandwidth is normally reduced and, therefore, the pulse rise time would typically be longer than 56ps used throughout the experiments.

Pulse shape: The influence of the pulse rise time $\Delta t$ on XPM distortion was calculated numerically by a variation of the pulse shape for the SSMF link, and the results are shown Fig. 4.18. The pump pulses were modelled by filtering square pulses with a sixth order Bessel filter. For a given bit rate, the distortion increases for sharper pulse edges due to increased chirp introduced by each transition. At low bit-rates, the pulse shape has the strongest influence on $m_x$, increasing the distortion from $m_x=0.1$ at $\Delta t=100\text{ps}$ to $m_x>0.2$ for $\Delta t=20\text{ps}$. A comparison with Fig. 4.17 reveals that at bit rates below 5Gbit/s the peaks due to XPM distortion are still isolated and, therefore, $m_x$ is only determined by the amount of distortion due to the isolated transitions. At $\Delta t=56\text{ps}$, $m_x$ versus bit-rate for the experimental waveform distortion can be obtained as shown in Fig. 4.18.
Fig. 4.17 Dependence of XPM distortion in probe channel on bit-rate, pump: 1-10Gbit/s, 1010...-sequence, single SSMF span (L=65km), 13dBm/channel, Δλ=0.4nm, simulation: split-step Fourier algorithm, pulse rise time: Δt=56ps

This measurement highlights the interaction of nonlinearity and dispersion at bit-rates up to 10Gbit/s. The XPM efficiency in equation (2.31), an indicator for the amount of PM generated, decreases at high bit-rates due to increasing channel walk-off. However, this effect is reduced by fibre dispersion leading to constructive interference between adjacent distortions. The effect of distortion is enhanced by shorter pulse transitions at 10Gbit/s increasing the amount of chirp generated by each transition. These results [THI98] were
confirmed by the work of [HUI99] which reported increased XPM distortion with bit-rate. In this section the worst case of XPM distortion in a single span of a longer system is described, since for multiple spans $m$, would no longer experience a continuous increase with bit-rate, but would be more complex due to interference of XPM generated in different spans. This multi-span interference is described in section 4.2 for the BT-LEANET link.

![Graph showing distortion $m_t$ of probe calculated for $L=65$km of SSMF in dependence of pulse rise time $\Delta t$ and bit-rate, pump: 1010... bit-sequence, $\Delta \lambda=0.4$nm channel spacing, (■): 1.25Gbit/s, (●): 2.5Gbit/s, (▲): 5Gbit/s, (▼): 10Gbit/s]

**Fig. 4.18** Distortion $m_t$ of probe calculated for $L=65$km of SSMF in dependence of pulse rise time $\Delta t$ and bit-rate, pump: 1010... bit-sequence, $\Delta \lambda=0.4$nm channel spacing, (■): 1.25Gbit/s, (●): 2.5Gbit/s, (▲): 5Gbit/s, (▼): 10Gbit/s

### 4.1.7 Dependence of XPM on channel power

In the last section a shorter pulse transition time was shown to increase distortion due to higher chirp while maintaining constant walk-off. Another parameter increasing the magnitude of XPM-induced chirp is the channel power. The launch power into a fibre span must be increased for long inter-amplifier distance to maintain a constant optical signal to noise ratio (SNR) after transmission. Fig. 4.19 shows the variation of XPM distortion for the previously discussed link using DSF and SSMF fibre. Two channels were used in pump-probe configuration with $\Delta \lambda=1.4$nm and the pump was modulated with a 1010...- sequence at 2.5Gbit/s. The power of the probe channel $P_s$ was constant measuring the different amount of XPM induced by the pump channel. The distortion due to XPM increases linearly with the pump power $P_p$, a result of increased nonlinear chirp in the DSF. The PM-IM process of the subsequent SSMF is power independent resulting in intensity distortion proportional to the chirp.
The dependence of \(m_x\) on channel power was also compared at 2.5Gbit/s and 10Gbit/s. Using the DSF+SSMF link with \(\Delta \lambda = 1\)nm (FWM minimised by adjusting the pump polarisation) the results were compared in Fig. 4.20 with XPM distortion for 65km of SSMF. A variable attenuator at the EDFA output was used to adjust the power of both channels launched into the fibre link. For a given bit-rate, \(\Delta \lambda\) and dispersion map, the variation \(\Delta m_x / (\Delta P_p + \Delta P_t)\) is similar to \(\Delta m_x / \Delta P_p\). In both cases, the slope \('m_x\ per mW'\) is approximately 0.035/mW for the DSF+SSMF link at 2.5Gbit/s. This important result indicates that only the variation \(\Delta P_p / \Delta t\) gives rise to the nonlinear chirp, already shown in section 4.1.6 investigating XPM for different pulse shapes. The results shown in Fig. 4.20 were in agreement with the analytical expression for \(m_x\) in equation (2.44) predicting a linear increase of \(m_x\) with pump power where the slope was determined by the fibre dispersion \(D\) and modulation frequency \(\omega\). It was confirmed in simulations, that the amount of XPM distortion was almost independent on the modulation depth in the pump channel when the averaged power and the pulse rise time of the pump remained constant. The typical modulation depth in the pump channel was more than 10dB in all experiments and determined by the EAM.

As shown in Fig. 4.20 the XPM-induced distortion decreased with dispersion for constant launch power. This is governed by the XPM efficiency for the particular configuration increasing at higher bit-rates and for low dispersion (DSF). In DSF for example, \(m_x > 0.6\) was obtained for 20mW channel power, whereas \(m_x\) was smaller than 0.1 for SSMF in this configuration. In summary, XPM distortion is linearly proportional to the optical launch power as predicted by the equations (2.40) and (2.41) and this can be applied to all previous results of section 4.1. It was confirmed that the measured distortion is independent of the probe channel power and only depends on the rise time \(\Delta P_p / \Delta t\).
4.1.8 Additional sources of pulse distortion

In the previous investigation of XPM the PM-IM conversion of nonlinear chirp took place in the transmission fibre. However, additional optical elements can affect the amount of detected distortion. The free-space grating was used in the experiments as the demultiplexer (demux). Fig. 4.21 shows the demultiplexer transmittance passband obtained for an ASE input spectrum. The measured insertion loss of the demux was approximately 10dB at the central wavelength $\lambda_D$, and the 3dB bandwidth was 15GHz. The XPM-induced distortion was measured for a DCF+SSMF link in pump-probe configuration with $\Delta \lambda = 0.5\text{nm}$, and 2.5Gbit/s 1010...-modulation and the demux was detuned by $\Delta \lambda_D = \lambda_{\text{CW}} - \lambda_D$. 

Fig. 4.21 Transmission spectrum of free-space demux used for extracting the probe channel at $\lambda_{\text{CW}}$, input source: EDFA-ASE at 0dBm, gain flattened (<0.5dB over 10nm)
Fig. 4.22 shows a significant change of the detected probe waveform when detuning the demux by $\Delta \lambda_D = \pm 0.05\text{nm}$. This small change results in negligible linear cross-talk from the neighbouring pump spaced 0.5nm apart. A dispersion-compensated fibre link with 8km DCF and 40km SSMF was used to obtain low residual dispersion and high sensitivity with respect to the demultiplexer alignment. Due to the alternating positive and negative XPM chirp in the probe, caused by the 1010...-pattern of the pump, the demux misalignment suppressed either of the red-shifted or blue-shifted components. As a result, only every other peak of the distorted probe was attenuated creating an asymmetric trace. The traces obtained for $\Delta \lambda_D = +0.05\text{nm}$ and $-0.05\text{nm}$ were combined and compared with the measurement for the exactly aligned demux in Fig. 4.23.

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**Fig. 4.22**

XPM after link with 8km DCF+45km SSMF, pump: 2.5Gbit/s, 1010...-modulated, $\Delta \lambda = 0.5\text{nm}$, $\lambda_{cw} < \lambda_p$, probe detected with demux tuned by $\Delta \lambda_D = \pm 0.05\text{nm}$, 13dBm/channel, parallel polarisation, investigation of XPM induced chirp: blue-shifted components (solid line, $\Delta \lambda_D = -0.05\text{nm}$), red-shifted ($\Delta \lambda_D = +0.05\text{nm}$, dashed line)

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**Fig. 4.23**

Same set-up as Fig. 4.22, comparison of added waveforms from red- and blue-shifted measurements (solid line) with XPM distortion detected directly using exactly aligned demux $\Delta \lambda_D = 0$ (dashed line)
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The close agreement between the probe waveforms in Fig. 4.23 indicates that the red-shifted and blue-shifted components of the nonlinear phase modulation add up independently to the total XPM distortion in the probe channel. Moreover, the distortion $m_x$ detected for the misaligned demux was approximately twice as high as for the exact alignment. This mechanism enhancing the detected XPM distortion is important for all transmission systems since additional PM-IM conversion can occur due to accidental misalignment of the demultiplexer or other wavelength selective components, demonstrated in this work for the first time. This effect is expected to be particularly important for links with optimised residual dispersion. A simple technique to monitor the optical power after the demux, maximised for $\Delta \lambda_D=0$, can be used to ensure exact demux alignment.
4.2 LEANET field experiment

The impact of cross-phase modulation (XPM) distortion on WDM transmission was investigated for different bit-rates up to 10Gbit/s in a field experiment over the installed LEANET/UK fibre network. Effects of interference between XPM components generated in multiple spans were observed. The field experiment was conducted using a section of the LEANET fibre network connecting BT Laboratories / Ipswich and Norwich. The measured XPM distortion was compared with laboratory experiments at UCL using a replica of this link to analyse the variation of XPM between similar links. The main motivation for this comparison is that installed fibre provides more accurate statistics in particular for the evolution of signal polarisation during the XPM process. For both experiments, the results were confirmed in analytical calculations and simulations using the split-step algorithm. The nonlinear distortion was investigated as a function of channel power and bit-rate for $\Delta \lambda=0.4\text{nm}$ using different dispersion maps. Finally, the impact of channel spacing on XPM was studied at 10Gbit/s. This also included the investigation of the sensitivity of XPM distortion to wavelength fluctuations in an optical channel. The studies suggest a high sensitivity of XPM distortion to bit-rate, in particular if the contribution of several amplified fibre spans is taken into account.

4.2.1 Experimental set-up

Two amplified fibre spans of the LEANET network were used, each with 92km of standard single mode fibre (SSMF). The link was symmetrically dispersion-compensated using DCF with 6dBm per channel launched into each DCF spool. Transmitter and receiver were located in Ipswich, with an EDFA in Norwich connecting the two spans. The pump-probe configuration shown in Fig. 4.24 allowed the separation of XPM from other nonlinearities. A tuneable laser and a modulator in Mach-Zehnder configuration (MZM) driven by a pattern generator (1-10Gbit/s NRZ signal) were used as the pump at $\lambda_p$. The pump caused XPM distortion in the CW probe from a second DFB laser operating at $\lambda_{CW}$. Pump and probe channels were combined and amplified using a Corning EDFA (FGM-P-027), launching 13dBm/channel into the link. The transmission SSMF in the field experiment had a mean dispersion of $D=16.5\text{ps/(km*nm)}$ and $\alpha=0.27\text{dB/km}$ loss ($\alpha=0.20\text{dB/km}$ for the laboratory link replica). The mean PMD of the link was 4ps and, therefore, negligible in this case. The signals were re-amplified to 9dBm/channel in Norwich and returned over the second span. The DCF section consisted of several fibres with dispersion values between $-70$ and
After transmission, the probe channel was selected using a free-space grating demultiplexer, detected with a high-speed photodiode and displayed on a sampling oscilloscope. The magnitude of XPM in the probe was again quantified by the index \( m_x \) in the case of 1010...-modulation. For PRBS modulation, the standard deviation \( \sigma_{XPM} \) was chosen to characterise the XPM distortion of the probe waveform.

First, the impact of channel power on XPM-induced distortion was measured in the field experiment for \( \Delta \lambda = 0.4 \text{nm} \) channel spacing at 10Gbit/s using 1010...-modulation. The link was dispersion-compensated to reduce the total distortion and the launch power \( P \) into the Ipswich–Norwich link was adjusted using a variable attenuator at the EDFA output. Fig. 4.25 shows linearly increasing distortion up to \( m_x = 0.2 \) for 16dBm total launch power. The total distortion in the compensated link was sufficiently small to provide linear PM-IM conversion by the fibre dispersion. In this linear regime, the slope was \( \Delta m_x / \Delta P \approx 0.008/\text{mW} \). Increasing the walk-off by a factor of two at \( \Delta \lambda = 0.8 \text{nm} \) reduced XPM to \( m_x = 0.11 \) for +16dBm. The variation of \( \Delta P \) at \( \Delta \lambda = 0.8 \text{nm} \) therefore results in a reduced slope of 0.0044 per milliwatt. The linear dependence of distortion on \( P \) allows the estimation of \( m_x \) at a given bit-rate and channel spacing where the conversion factor \( \Delta m_x / \Delta P \) increases for small \( \Delta \lambda \) and high bit-rates. In the single span pump-probe experiments shown in Fig. 4.20 the slope related to XPM distortion using 65km SSMF and 10Gbit/s pump modulation was \( \Delta m_x / \Delta P = 0.007/\text{mW} \) for \( \Delta \lambda = 1 \text{nm} \) and was therefore higher than in the installed fibre with DCF compensation.
Fig. 4.25 Measured power dependence of XPM distortion in BT-LEANET, symmetrically compensated with DCF, \( \Delta \lambda = 0.4 \text{nm} \) (50GHz), pump: 1010...-pattern at 10Gbit/s, only launch power into first SSMF span is varied.

### 4.2.3 Effect of dispersion compensation on modulated channel

The impact of SPM and dispersion on a modulated channel are described in this section. Since FWM was found to be negligible due to high local dispersion in the LEANET link, SPM is the other important nonlinearity determining the total nonlinear distortion. This measurement shows the effective reduction of SPM-induced distortion by minimising the residual dispersion of the link. The pump distortion as a function of bit-rate was compared for back-to-back operation, uncompensated SSMF link and symmetrically compensated link in Fig. 4.26.

Fig. 4.26 left: single channel transmission in laboratory experiment for different types of fibre, modulated with 1-10Gbit/s, (■): back-to-back, (●): SSMF only, (▲): SSMF with dispersion compensation

right: PRBS modulation in pump channel at 10Gbit/s, detected after BT-LEANET with DCF-compensated spans

(a) eye diagram at transmitter

(b) eye after transmission showing distortion and ASE noise
On the left hand side of Fig. 4.26, the modulation index measuring $P_{\text{max}} - P_{\text{min}}$ in the $1010...$-modulated pump channel is normalised to the modulation index obtained at the low bit-rate of 1 Gbit/s where the bit-sequence was least affected by SPM and dispersion. The modulation index remained almost constant at all bit-rates in the back-to-back measurement since the combined optical bandwidth of the receiver and the demux was high enough to avoid pulse distortion during detection (>10GHz for laboratory experiments). Without dispersion compensation, the detected pulses were slightly compressed at lower bit-rates due to SPM in the SSMF fibre. Short pulses at 10Gbit/s, however, were significantly affected by dispersion and the modulation index decreases to 20% of its initial value. In transmission experiments this is equivalent to detrimental eye closure caused by the short pulses of a PRBS.

In the case of exact dispersion compensation the modulation index of the pump was similar to the previous back-to-back measurement. This is also reflected in eye diagrams measured for the DCF-compensated LEANET link shown in Fig. 4.26. The open eye after transmission in the field experiment confirmed the effective use of symmetric DCF-compensation for reducing distortion due to SPM and dispersion [ROT98]. In addition, the diagram also indicates noise accumulation due to the EDFAs and the long SSMF spans reducing the SNR. These measurements have shown that 10Gbit/s transmission in the LEANET network requires the use of dispersion compensation to reduce the distortion due to SPM and dispersion. Bit-rate dependent results also indicate that short pulses above 6Gbit/s are most distorted.

### 4.2.4 Impact of bit-rate on XPM in LEANET

The intensity distortion due to XPM was investigated in pump-probe configuration launching +13dBm/channel into the Ipswich - Norwich link [THI00]. Initially, XPM distortion was investigated for the uncompensated link using two spans of SSMF only. The XPM modulation index $m_x$ was measured for a $1010...$-bit-pattern in the pump varying the bit-rate between 1 and 10Gbit/s. The probe waveforms shown in Fig. 4.27 are clearly distorted by XPM due to the high launch power and narrow channel spacing $\Delta \lambda=0.4\text{nm}$. At low bit-rates <2.5Gbits, the pulse transitions in the pump channel lead to isolated peaks of XPM distortion in the probe channel. At higher bit-rates and shorter pulse widths, more pulse transitions occur in a given time interval and consequently neighbouring peaks in the probe begin to overlap resulting in increased XPM distortion. It has been shown for single amplified spans [HUI98, THI98] that XPM distortion continuously increases with bit-rate due to a high pass characteristic of the fibre transfer function as shown in Fig. 2.21. In Fig. 4.27, however, the XPM contribution of the second fibre span must be taken into account reducing the total XPM distortion above 6Gbit/s due to destructive interference. The channel walk-off over the first SSMF span is 3 bit periods ($3\cdot T_o$) for $\Delta \lambda=0.4\text{nm}$ and 10Gbit/s resulting in destructive
interference. Realignment of the bit-pattern after an even number $2n \cdot T_0$ for the pulse walk-off over the same fibre span will lead to the constructive interference between XPM components from both spans. The walk-off in the single span experiments described in section 4.1.6 was comparable to the LEANET measurements and typically less than one bit over $L_{eff}$.

![Probes waveform distorted by XPM in uncompensated LEANET experiment](image)

**Fig. 4.27** Normalised probe waveform distorted by XPM in uncompensated LEANET experiment, $\Delta \lambda = 0.4\text{nm}$, probe: CW, pump: 1010-...-modulation, parallel polarisation, 13dBm/channel

![Pump-probe experiment investigating $m_x$ as a function of bit-rate for uncompensated link](image)

**Fig. 4.28** Pump-probe experiment investigating $m_x$ as a function of bit-rate for uncompensated link, $\Delta \lambda = 0.4\text{nm}$, 1-10Gbit/s, 1010-...-pattern, (■): measured data, (—): simulation

(a) Laboratory link at UCL: single span compared to 2-span link

(b) Analytically calculated XPM intensity transfer function $H(o)$ for parallel polarisation, according to [HUI99]

**Laboratory experiment:** In Fig. 4.28(a) the results for the laboratory experiment are presented where the LEANET link was replaced by 2 spools of SSMF. In the first SSMF section the pulse walk-off was $2 \cdot T_0$ at 3Gbit/s and the channels were therefore realigned at the beginning of the second span. Higher order interference maxima with 4 and 6 bit-period walk-off occur for 6 and 9Gbit/s, respectively. This interference is a result of the uniform 1010-...
pattern in the pump because of the periodic realignment of the pulses and, hence, constructive interference, for multiples of twice the bit-period. For this link, the contribution to XPM of the first span alone was calculated showing a constant increase of $n_x$ with bit-rate. Although the total launch power into the second SSMF link was only +12dBm, it increased the total XPM distortion at particular bit-rates by as much as a factor of two compared to a single span due to constructive interference. The experimental results for two spans agree well with the split-step Fourier simulation, assuming parallel polarisation of the channels. The frequencies of the maxima and minima of $n_x$ correspond to those of the XPM intensity transfer function with sinusoidal pump intensity, analytically calculated according to [BEL98, HUI99] and shown in Fig. 4.28(b). Larger XPM distortion was measured at low modulation frequencies than shown by the transfer function since the modulator rise time was constant for all bit-rates in the experiment, and hence the pulses consisted of higher modulation frequency components in addition to the waveform’s fundamental component.

Values of $n_x$ measured for the dispersion-compensated link are plotted in Fig. 4.29 and compared to the uncompensated link, showing a reduction in the distortion with the DCF. This is due to the reduced PM-IM conversion, resulting from the lower residual dispersion between the start of each span and the photodetector.

![Image](image_url)

**Fig. 4.29** $n_x$ measured as a function of bit-rate for laboratory link, $\Delta \lambda=0.4$nm: comparison for uncompensated link ($\bullet$), symmetrical compensation with DCF ($\circ$), simulations: (——)

**Field experiment:** The measurements were repeated over installed fibre in the BT-LEANET network. Fig. 4.30(a) shows the values of $n_x$ for the uncompensated and compensated SSMF link. The XPM distortion is a factor of two lower despite the same link length as in the previous laboratory experiments. This is due to the increased attenuation ($\alpha=0.27$dB/km) of the older LEANET fibre, longer pump pulse rise-times and, most importantly, the relative polarisation of the two channels. Calculations show that the difference in the fibre attenuation
accounts for approximately a 15% reduction in XPM. The Mach-Zehnder modulator used in the laboratory experiment has a 10-90% pulse rise time $\Delta t$ of approximately 40ps. The faster pulse rise time in comparison to the modulator in the LEANET experiment ($\Delta t=56\text{ps}$) also increases XPM. The remaining difference between values of $m_x$ measured in laboratory and field experiments can be explained by the polarisation of the channels. In the case of the laboratory experiments they were carefully aligned to achieve maximum XPM distortion, whereas no access to the polarisation controller at Norwich was possible in the field experiment. Fig. 4.30(b) shows the analytically calculated intensity transfer function $H(\omega)$ of the LEANET link, with a polarisation angle between the channels in both spans of $3\pi/8$ radians.

![Graph](image)

**Fig. 4.30**

(a) $m_x$ measured as a function of bit-rate for installed fibre link, $\Delta\lambda=0.4\text{nm}$: comparison for uncompensated link ($\bullet$), symmetrical compensation with DCF ($\circ$), simulations (dashed lines)

(b) Analytically calculated XPM intensity transfer function with $3\pi/8$ radians polarisation angle between channels at link input, maintained over both spans (solid line) and increased to $\pi/2$ radians in second span (dashed line)
Reduction in the amplitude of the transfer function oscillations was observed when the angle was further increased in the second span to $\pi/2$ radians, providing a possible explanation of the lower oscillations of $m_x$ with bit-rate measured in the field experiment. The difference between laboratory and field experiments in the frequency at which maximum $m_x$ was measured was due to slight differences in link length, fibre dispersion and channel spacing and was taken into account in the simulations and the calculation of the LEANET transfer function. The decreasing distortion at higher bit-rate in the field measurements was a result of the narrower demultiplexer bandwidth attenuating high frequency components.

The LEANET link was then dispersion-compensated, using the same DCF positioning as for the laboratory experiment. From Fig. 4.30(a) it can be seen that a reduction in the measured XPM-induced intensity distortion by a factor similar to the laboratory experiment was observed.

### 4.2.5 Sensitivity of XPM distortion to wavelength fluctuations

In the previous section, a high sensitivity of the XPM intensity transfer function to $\Delta \lambda$, bit-rate and span length was observed and, therefore, the exact knowledge of all system parameters was essential to predict the XPM distortion for a particular bit-rate. In the following, the effects of a small variation $\Delta \lambda$ on $m_x$ were also investigated. In real systems this can take place due to a temperature-induced wavelength drift of the pump laser at $\lambda_p$. XPM-induced distortion was analysed for the DCF-compensated LEANET link in increments of 0.01nm over the interval $\Delta \lambda=0.37\text{nm}...0.45\text{nm}$. $\lambda_p$ was varied and the bit-rate dependence of $m_x$ between 1Gbit/s and 10Gbit/s was calculated for a given $\Delta \lambda$ using the split-step algorithm.

The wide distribution of the values for $m_x$ in Fig. 4.31 highlights the sensitivity of $m_x$ to $\Delta \lambda$.

![Graph showing variation of XPM modulation index $m_x$ for $\Delta \lambda=0.37...0.45\text{nm}$ at a given bit-rate between 1-10Gbit/s, pump: 1010...-modulation, DCF-compensated LEANET link](image)
since the channel walk-off is dependent on bit-rate and channel spacing. The range of \( m_x \) was between 0.05 and 0.3, almost independent of the bit-rate when varying \( \Delta \lambda \). Therefore, the maximum for \( m_x \) obtained in this calculation must be taken into account when estimating XPM distortion during the link design. The value of \( m_x = 0.3 \) agrees well with the upper threshold of the XPM distortion obtained in previous bit-rate dependent BT-LEANET measurements at \( \Delta \lambda = 0.4 \text{nm} \) shown in Fig. 4.30(a).

### 4.2.6 Impact of \( \Delta \lambda \) on XPM for PRBS

In the previous measurements and calculations, the pump was modulated with a periodic 1010...-pattern. This has lead to a strong oscillation due to walk-off dependent constructive and destructive interference between both SSMF spans in the LEANET link. In the following experiment, the pump was modulated with a PRBS and XPM was measured as a function of \( \Delta \lambda \) between 0.4 and 2nm. Fig. 4.32 shows the measured XPM distortion at 10Gbit/s for a \( 2^{15}-1 \) pattern in the pump. A longer pattern length had no effect on the XPM distortion. Due to the different pulse lengths in the PRBS-modulated pump, equivalent to different bit-rates in the experiments with 1010...-modulation, the XPM distortion is non-uniform as shown in the inset to Fig. 4.32. Therefore, \( \sigma_{\text{XPM}} \) is used to quantify the distortion rather than \( m_x \) relevant for periodic waveforms. The parameter \( \sigma_{\text{XPM}} \) was earlier defined in Fig. 2.21.

![Image of Fig. 4.32](image-url)
For all configurations, compensated and uncompensated, $\sigma_{XPM}$ was inversely proportional to $\Delta \lambda$ as predicted by equation (2.41), and XPM distortion was reduced for wide channel spacing due to the increased walk-off between the channels. No significant oscillation of $\sigma_{XPM}$ with $\Delta \lambda$ was observed for the PRBS modulated pump pattern since the standard deviation takes into account all frequencies contributing to the total distortion and the non-periodic pump channel waveform prevents the pattern from being realigned after propagation through the first SSMF span. Similar to the bit-rate-dependent measurements at $\Delta \lambda = 0.4 \text{nm}$, the distortion measured in the laboratory experiments was approximately a factor of two higher than in the field experiments.

In summary, XPM distortion was investigated for the first time in an installed fibre network (LEANET) and the results were compared with a laboratory replica of the link. For these nominally similar links, there was a large difference in the variation of $m_x$ with bit-rate between 1-10Gbit/s. The distortion shows a high sensitivity to system parameters such as bit-rate and channel spacing as, for a periodic 1010...-pattern, the channel walk-off leads to a strong interference between XPM components generated in different fibre spans. 1010...-patterns, with parallel channel polarisation, therefore allow to estimate the worst case distortion. Dispersion compensation using DCF was shown to be effective in reducing pulse distortion. In the case of modulation with a PRBS, XPM-induced intensity distortion was characterised by the standard deviation $\sigma_{XPM}$ and was shown to be inversely proportional to the channel spacing. The amount of XPM distortion in the installed fibre was lower by a factor of two, accounted for by channel polarisation, fibre properties and the slower rise time of the transmitter modulator.
4.3 Multi-span links

The dependence of XPM distortion on system length was investigated using multi-span dispersion-compensated links. To date most experiments were based on linear links [SHT00, SAU97] and hence were limited to relatively few spans. Fig. 4.33 shows the schematic experimental set-up: a recirculating optical fibre loop was used consisting of a single span of SSMF ($L=40$km) exactly compensated with DCF, which allowed to carry out distance-dependent measurements of $m_x$ by varying the number of recirculations.

![Diagram of recirculating loop set-up for length-dependent XPM measurements](image)

The set-up is an extension of the configuration shown in Fig. 4.5 replacing the single span of test-fibre with a recirculating loop. The transmitter consists of a tuneable pump laser and a DFB laser operating as the probe. A tuneable external cavity laser (ECL) was used followed by an electro-absorption modulator (EAM) with 10dB insertion loss and modulation bandwidth of 15GHz. When operating over a tuning range of approximately 2nm this combination could be replaced by an integrated transmitter combining a temperature-tuned DFB with the EAM. The pump was modulated either at 2.5Gbit/s or 10Gbit/s with a 1010... or PRBS sequence. A low frequency bias signal of 30kHz was applied to the probe laser during CW operation to broaden the linewidth avoiding backscattering due to SBS (appendix E). The relative polarisation between the two channels was adjusted using a polarisation controller (PC) and a polarisation scrambler (PS). The fibre-coil based polarisation scrambler was used in two different locations of the set-up. Firstly, in the transmitter averaging over the relative polarisation of the two lasers and, secondly, inside the loop for altering the polarisation during the recirculations of the signal. Unlike a linear transmission link, the fibre recirculating loop affects the polarisation since the PDL for all spans is identical and...
polarisation hole burning (PHB) occurs in the EDFAs [BER95]. The recirculating loop includes a 3-stage EDFA (Corning FGM-P-027) with +16.5dBm saturated output power and a low noise figure of 4.5dB. The pump lasers of this EDFA were gated to avoid transient processes during the loop operation. The fibre link following the EDFA was tested in pre- and post-compensation configuration schemes. Fibre spans with DSF were not investigated because of the severe transmission degradation due to FWM and XPM shown in section 4.1.4. The variable attenuator inside the loop was used for balancing the power at the output of AOM1 and AOM2 whilst the signal at the EDFA output was monitored using a photodiode (PD). The loop operation is controlled by the NEOS acousto-optical switches (AOM). Distance-dependent measurements were controlled by a high precision delay generator (Stanford Research DG535) and performed as follows. Fig. 4.34 shows the timing diagram used for the loop measurements.

1) **Initial settings**: AOM1 open, AOM2 closed, EDFA off

In this configuration, the signal is applied to the input of the loop EDFA, the EDFA is switched off and AOM2 is closed.

2) **Stabilisation of loop EDFA**: AOM1 open, AOM2 closed, EDFA on

The loop EDFA is switched on with the signal at the input and AOM2 is still off. In this time period, the transient processes ($\approx 1$ms) in the loop EDFA are minimised and the signal propagates into the loop fibre. The typical duration of this process is a few ms.

3) **Loop transmission**: AOM1 closed, AOM2 open, EDFA on

The input signal is recirculating inside the fibre loop. The loop propagation time for a given distance $L$ is determined by $\Delta T = n \cdot \Delta t_{rec}$ where $\Delta t_{rec}$ defines the time for each recirculation and $n$ represents the total number of recirculations. For the configuration used in the experiments, each recirculation takes approximately $\Delta t_{rec} = 240\mu s$.

4) **Loop measurement**: AOM1 closed, AOM2 open, EDFA on, detection at receiver

During the loop recirculation the signal for each span is detected at the receiver in intervals of $\Delta t_{rec}$. After the appropriate time $\Delta T' = (n-1) \cdot \Delta t_{rec}$ the receiver is gated for the duration of a single recirculation $\Delta t_{rec}$. In this way the signal corresponding to $n$ times the loop length is detected. The number of bits measured depends on the loop length and the bit-rate. At 10Gbit/s, $2.5 \cdot 10^8$ bits can be detected each time. This has important implications on BER measurements. To obtain a reliable measurement for error-free transmission, commonly defined as BER $< 10^{-9}$, the total data acquisition for such as measurement must extend over several cycles.

5) **Completing measurement**: AOM1 closed, AOM2 closed, EDFA off
After the data acquisition, the loop transmission is terminated by shutting down the EDFA and closing AOM2.

![Timing diagram for the loop operation](image)

Fig. 4.34 Timing diagram for the loop operation, the intervals 1) – 5) are described in the text.

Additional lumped compensation of the residual dispersion could be added at the receiver. In this case, 22km of SSMF or the equivalent length of DCF was added at the loop output. After transmission the probe channel was analysed by a fast sampling scope. The trigger signal was provided by an optical receiver extracting the clock signal from the pump, modulated at 10Gbit/s or 2.5Gbit/s. A gated Fabry-Perot filter was also used for distance-dependent high-resolution measurements of the optical spectrum. This device could be wavelength-tuned and was time-distance synchronised to the loop allowing measurement of the total spectrum over several measuring cycles. This technique is described in reference [MIK99] and section 4.3.2.
4.3.1 Evolution of the optical spectrum with distance

XPM pump-probe measurements were carried out for different transmission distances. Fig. 4.35(a) shows a typical optical spectrum as a function of system length for DCF+SSMF links up to 12 recirculations. The pump was modulated at 2.5Gbit/s and the CW probe was spaced by $\Delta \lambda = 0.5\text{nm}$ towards longer wavelengths. The launch power per channel was 0dBm and, therefore, the influence of nonlinearities was negligible. For longer distances, ASE reduced the optical SNR to 10dB after $n=12$. The SNR and thus the achievable transmission distance could be improved with a tuneable optical filter following the EDFA. However, this solution was restricted to narrow channel spacing, limited by the FWHM-bandwidth of the filter of approximately 2nm. In the measurements shown in Fig. 4.35(b) the launch power was increased to $+13\text{dBm}$ per channel. The optical SNR after $n=12$ was improved to approximately 20dB for the pump, however, nonlinear effects had to be taken into account. The probe in CW mode was attenuated due to SBS-induced backscattering, a result of narrow linewidth and high launch power into the fibre. No channel was dithered in this experiment to demonstrate the effect of SBS on transmission. In the following loop experiments, however, the probe was dithered using a low frequency sinusoidal modulation as described earlier.

![Fig. 4.35 Optical spectrum after $n=1,2,4,6,8,10,12$ recirculations in loop, $n'(\text{DCF+SSMF})$ link, $\Delta \lambda = 0.5\text{nm}$, pump-probe for (a) 0dBm/channel, (b) 13dBm/channel, no dithering of channels, bold lines: $n=12$, dashed lines: $n=1$ recirculation](image)

Fig. 4.36 demonstrates the effect of SBS suppression in more detail after 5 spans of SSMF+DCF for the experiment described before. A distinct attenuation of approximately 5dB in the channel power of the probe was observed, decreasing the SNR due to SBS-induced backscattering.
4.3.2 Impact of XPM on the optical spectrum

The XPM-induced nonlinear chirp can be measured directly in the frequency domain as it results in nonlinear spectral broadening of the transmitted channels. The combined effects of SPM and XPM on spectral broadening were investigated in [MIK99] as a function of transmission distance. In this thesis, a pump-probe configuration is chosen to analyse the broadening due SPM and XPM separately. The advantage of this technique is that XPM can be investigated for close channel spacing $\Delta \lambda < 0.4\text{nm}$ since no demultiplexer is needed for this measurement. A gated Fabry-Perot spectrometer (~1pm resolution) was used at the recirculating loop output to investigate SPM and XPM spectral broadening for a dense WDM system at 10Gbit/s down to $\Delta \lambda = 0.2\text{nm}$ channel spacing. The set-up of the spectral measurement is shown in Fig. 4.37.

![Diagram of Fabry-Perot spectrometer set-up](image)

**Fig. 4.37** Set-up for gated Fabry-Perot measurement at recirculating loop output, ADC: analogue-digital converter, PC: polarisation controller

The distortion of the CW probe spectrum was quantified by the sideband-to-carrier ratio (SCR). The distortion was measured for up to 15 amplified spans in 100% compensated links.
of SSMF+DCF and DCF+SSMF. The optical spectra for 1010...- modulation of the pump channel and both compensation schemes are shown in Fig. 4.38(a) for back-to-back and in 4.38(b)-(c) after transmission over 5 spans. In the absence of distortion and nonlinearities spectral sidebands were detected only for the modulated pump. Therefore, the presence of distinct sidebands around the carrier-frequency of the probe after transmission indicates XPM distortion introduced by the 1010...-modulation of the pump. In the case of a PRBS-modulated pump continuous spectral broadening of pump and probe was observed. The initial SCR for the modulated pump channel increased with distance, in particular for the DCF+SSMF scheme because of the strong influence of SPM on the waveform. The XPM-induced broadening of the probe spectrum was similar for pre- and post-compensation, approximately the same order of magnitude as the SPM-induced broadening due to the close channel spacing reducing the channel walk-off. The sidebands of both channels with closest spacing to each other were increased as expected by the low walk-off between these components resulting in a slightly asymmetric shape of the spectra.

Fig. 4.38 Increase of the sideband-to-carrier ratio (SCR) in the optical domain as a result of XPM in 10Gbit/s pump-probe transmission, $\Delta \lambda=0.2\text{nm}$, 1pm optical resolution, 13dBm/channel
(a) FP spectrum, back-to-back, of probe (left) and pump (right),
(b) after $n=5$ recirculations for DCF+SSMF spans, (c) $n=5$ for SSMF+DCF spans
Finally, the increase of XPM-induced spectral components was measured as a function of transmission distance. Fig. 4.39 shows the distance-dependent SCR of the probe channel for both dispersion maps at 10Gbit/s. The SCR increases with distance due to XPM-induced distortion. The higher spectral broadening observed for the pre-compensated configuration is surprising as the filtering effect of the increased channel walk-off in the DCF should lead to reduced phase modulation predicted by equation (2.29). However, this equation does not take into account the effect of SPM on the pump shape. In the exactly pre-compensated configuration, the pulses are increasingly compressed with transmission distance, compared to the broadening they experience in the post-compensated case. Hence, the increased chirp due to the fast pump transitions counteracts the filtering effect of the walk-off, leading to the larger XPM spectral broadening. The effect of increased SPM can also be observed by the larger pump carrier depletion in the pre-compensated plot. These results demonstrate the effectiveness of using the gated high-resolution Fabry-Perot spectrometer together with the recirculating loop to investigate SPM and XPM directly.

Fig. 4.39 FP measurements investigating XPM distortion in pump-probe configuration, sideband-to-carrier ratio of probe for \( \Delta \lambda = 0.2 \text{nm} \), 13dBm/channel, PRBS-modulated pump: pre-compensation (■) and post-compensation (○)

4.3.3. Length-dependent measurement of XPM distortion

The impact of XPM on the probe waveform was also analysed in the time-domain since the results can be easily used to predict the impact of XPM on the eye-opening penalty (described in chapter 5). Pump-probe experiments were carried out investigating XPM-induced distortion as a function of transmission distance for spans of DCF+SSMF (pre-compensated) and SSMF+DCF (post-compensated). The exact compensation brought the channels back into
alignment after each recirculation resulting in zero walk-off over each span, hence, maximizing the increase of XPM phase modulation with distance. The results for up to 10 spans, with 0.6nm channel separation and 2.5Gbit/s 1010...- modulation are shown in Fig. 4.40. The inset illustrates the typical XPM distortion in the probe channel obtained for the post-compensated scheme after \(n=6\) recirculations with excellent agreement between the experimental and simulated waveforms. Extending the results of the single span experiments shown in Fig. 4.13, \(m_x\) increases linearly with distance, as also predicted by the analytical expression (2.44) for XPM distortion. For post-compensation, \(m_x=0.42\) was reached after 10 spans corresponding to approximately \(\Delta m_x/\Delta L=4\%\) contribution from each span.

![Graph showing variation of \(m_x\) vs. number of spans]

\[m_x = 0.42 \text{ for } n=10\]

For distances greater than 8 recirculations \(m_x\) varied by less than 0.05 because of the SPM-induced distortion of the pump pulses. For \(n=1\), the results obtained from measurements using a linear transmission link are included into Fig. 4.40 resulting in \(m_x=0.11\) and \(m_x=0.07\) for exact pre-compensation and post-compensation, respectively. These values are in agreement with the distortion expected from the measurements using the loop and, therefore, show the suitability of the recirculating loop for length-dependent XPM measurements. As a result, the value of \(\Delta m_x/\Delta L\) can be determined in single span experiments described in section 4.1. It was confirmed that in the case of negligible SPM-induced pump distortion the values for a single span, expressed by \(\Delta m_x/\Delta L\), increased linearly with the transmission distance \(L\).
4.3.4 Influence of wavelength spacing for multiple spans

The effect of channel spacing on XPM was investigated for a single span in section 4.1.3. The channel walk-off was found to determine the minimum required channel spacing to limit XPM-induced distortion. In this section, the measurements of $m_x$ versus $\Delta \lambda$ are generalised for longer transmission distances and the results are shown in Fig. 4.41. The XPM-induced distortion for $n=3$ and $n=10$ spans are compared and found to be inversely proportional to $\Delta \lambda$ in both cases. For a given number of spans, $m_x$ increased for both dispersion compensation schemes and narrow channel spacing because of reduced channel walk-off between the bit streams, allowing localised build-up of the phase distortion. Although the XPM distortion for a typical channel spacing, e.g. 0.8nm, was small for short link lengths, this was no longer the case for longer distances and $\Delta \lambda$ had to be increased accordingly. For the SSMF-DCF link and $n=3$, the minimum channel separation required to maintain $m_x< 0.1$ was $\Delta \lambda_{\text{min}} \approx 0.8$nm. However, after 10 recirculations, $\Delta \lambda_{\text{min}}$ increased to approximately 1.8nm. As already observed in Fig. 4.40, the exactly compensated link showed slightly higher distortion for pre-compensation. This result reveals the critical role of XPM in WDM transmission over long distances limiting the total capacity due to increased channel spacing.

In a similar experiment, the effect of $\Delta \lambda$ on $m_x$ was investigated for higher bit-rate at 10Gbit/s. Fig. 4.42 shows the increase of XPM with distance measured for pre-compensated spans of SSMF. The optical launch power had to be lowered to +10dBm per channel to reduce pump pulse distortion preventing clock recovery of the received signal for more than 5
recirculations. Although the measured distortion was lower than in the case of 13dBm/channel launch power, enhanced XPM distortion was observed when lowering the channel spacing from $\Delta \lambda = 1 \text{nm}$ to $0.5 \text{nm}$. The slope was increased to $\Delta m_c / \Delta L = 3.7\%$ per span for $\Delta \lambda = 0.5 \text{nm}$. This is a result of a reduction of the walk-off by a factor of 2 leading to an increased amount of phase modulation acquired by the probe within the nonlinear effective length of each span.

![Figure 4.42](image)

**Fig. 4.42** Length dependence of XPM distortion at 10Gbit/s, pump-probe experiment, 10dBm/channel, exactly compensated DCF + SSMF spans, (O): $\Delta \lambda = 0.5 \text{nm}$, (●): $\Delta \lambda = 1 \text{nm}$, lines: simulations

### 4.3.5 Effect of bit-pattern alignment on XPM

In the single span experiments of section 4.1.4 the interaction of XPM and SPM was investigated for two modulated channels using DSF. It was concluded that the total distortion depends on the initial alignment of the two interacting channels. A similar experiment for XPM-induced penalties was described in [KIK96]. The effect of channel alignment was studied in exactly compensated links using the recirculating loop. The walk-off over each span is zero and, therefore, the delay between both channels is varied for all spans by the same amount. In this experiment, the detected probe channel was PRBS-modulated and the interfering pump channel modulated by a 1010...-sequence which could be time-shifted using an electrical delay at the pattern generator. XPM distortion was investigated for $\Delta \lambda = 0.5 \text{nm}$ and transmission over 10 exactly compensated spans of DCF+SSMF. Single '1'-bits of the probe channel were significantly distorted by SPM and XPM, resulting in a strong dependence of the eye-opening on the initial channel delay. The probe distortion increased when a pump transition coincided with the centre of the probe pulse as shown in Fig. 4.43(a). The distortion was decreased when XPM- and SPM-induced chirp compensated each other at the pulse edges as indicated by the improved eye-opening in Fig. 4.43(b). Between these two
cases the eye-opening showed a continuous variation with the initial channel delay. The difference $\Delta \tau$ in delay between maximum and minimum eye opening was 200ps, corresponding to half the bit-duration.

![Eye diagram showing XPM and SPM distortion after 10 amplified spans of DCF+SSMF, probe: PRBS at 2.5 Gbit/s, pump: 1010...modulated from clock output, $\Delta \lambda=0.5$nm, variable electrical channel delay $\Delta \tau$ at pattern generator, parallel polarisation of pump and probe, (a) worst case setting for $\Delta \tau$, (b) best case, $\Delta \tau=200$ps](Image)

In summary, the XPM-induced distortion was investigated as a function of transmission distance using amplified dispersion-compensated spans of SSMF. It was shown for pre- and post-compensation that XPM-induced distortion increases almost linearly with distance reaching 60% after 10 spans of DCF+SSMF due to high launch power and $\Delta \lambda=0.4$nm. For SSMF+DCF the amount of XPM is lower due to less residual dispersion following XPM in the system. Narrow channel spacing with $\Delta \lambda<0.8$nm increases XPM due to low walk-off of the channels, approximately less than 0.5bits at 2.5Gbit/s within the effective length of SSMF. XPM was measured as a function of $\Delta \lambda$ to evaluate the XPM-imposed limitation of channel spacing for multiple amplified spans ultimately limiting long-haul transmission of dense WDM signals. After 10 spans, XPM with $m_x>0.2$ was found to occur over $\Delta \lambda>1.2$nm dictating the minimum channel spacing in the presence of XPM distortion. The effects of XPM were also investigated in the spectral domain using a Fabry-Perot at the recirculating loop output. For the first time, XPM and SPM distortion could be separately detected at $\Delta \lambda=0.2$nm in a pump-probe experiment extending the work of [MIK99]. The results showed a linear increase of nonlinear broadening with distance similar to the time domain measurements. The recirculating loop introduces unparalleled flexibility in measurements of XPM. To date most experiments were based on linear links [SHT00, SAU97] and hence were limited to relatively few spans. The technique used here allows to vary the transmission distance and, therefore, the total link length over a large range.
4.4 Impact of residual dispersion on XPM

The concept of residual dispersion was introduced in section 2.3.5 and mentioned previously. In this section it is shown how the total PM-IM conversion can be reduced by minimising the residual dispersion following the generation of XPM phase modulation. The concept of under- and over-compensation on XPM was studied and different compensation schemes were compared.

4.4.1 XPM in a single-span dispersion-compensated link

In the previous distance-dependent measurements XPM distortion was present even in the case of exact dispersion compensation. Only the linear pulse distortion due to dispersion was completely compensated. In this section, the impact of residual dispersion on XPM is investigated for a single span and the results are generalised in the following sections. As already shown in Fig. 4.13, the difference in \( m_x \) between the pre-compensated and the post-compensated link is due to the additional PM-IM conversion in the SSMF fibre following the exactly compensated SSMF-DCF combination. The influence of the additional lumped dispersion \( D_{\text{conv}} \) on XPM distortion was further investigated in simulations and the results are shown in Fig. 4.44.

![Graph showing \( m_x \) calculated as a function of converter dispersion following a single dispersion-compensated span of SSMF: pre-compensation (solid line) and post-compensation (dashed line), \( \Delta \lambda=0.4\text{nm} \), pump: 2.5Gbit/s, 1010...-modulation, +13dBm/channel, parallel polarisation of pump and probe](image)

The distortion grows linearly for both compensation schemes with the absolute values of \( |D_{\text{conv}}-D_{\text{min}}| \) where \( D_{\text{min}} \) is the lumped dispersion corresponding to minimum \( m_x \). This indicates the linearity of the PM-IM process for the case of low pump pulse distortion. In pre- and post-compensation, the XPM distortion increases continuously with for large values of \( D_{\text{conv}} \). The
total distortion can be reduced using under-compensation, minimising the distance-averaged residual dispersion $D_{\text{res}}(z)$ in the case of post-compensated links and over-compensation for pre-compensated links. This technique was demonstrated for SPM in single-span links plotted in Fig. 2.20. The results are similar for XPM. The XPM-induced distortion reached a minimum for positive $D_{\text{conv}}$ in the post-compensated system, whilst negative $D_{\text{conv}}$ minimised $m_x$ for pre-compensation. The value of $D_{\text{min}}$ for the minimum distortion was dependent on the nonlinearity of the system and, therefore, the optical launch power into the link. It is evident from equation (2.33) that in the case of $D_{\text{conv}}$ following the exactly compensated span of SSMF and DCF, $D_{\text{conv}}=D_{\text{res}}(0)$. The nonlinear distortion due to XPM remained between $m_x = 0.05 ... 0.1$ for no additional conversion fibre ($D_{\text{conv}}=0$). The minimum distortion for pre-compensation was slightly higher in this case because of the small effective area of the DCF in agreement with the results in Fig. 4.40.

### 4.4.2 Optimising the dispersion map using lumped receiver dispersion

The impact of residual dispersion on nonlinear distortion was investigated for different transmission distances using the recirculating loop. A complete study of the nonlinear effects must also include the contributions of SPM to the total distortion. This aspect is particularly important since SPM is always present for modulated channels whilst the impact of XPM can be reduced via the channel walk-off for wide channel spacing. The interaction of GVD and SPM was investigated for 3 exactly post-compensated spans and is shown in Fig. 4.45.

![Graph showing normalised peak power of single channel at 10Gbit/s as a function of $D_{\text{conv}}$, 10dBm/channel, measured at loop output after 3 recirculations, spans with SSMF+DCF.](image)

*Fig. 4.45* Normalised peak power of single channel at 10Gbit/s as a function of $D_{\text{conv}}$, 10dBm/channel, measured at loop output after 3 recirculations, spans with SSMF+DCF, (○): experiment, (—): simulation.
The peak power of a 1010...-modulated channel at 10Gbit/s is normalised to the input signal and deviations to higher and lower values indicate pulse compression and broadening, respectively. After the exact compensation and no lumped receiver dispersion the pulses are broadened due to SPM and dispersion, qualitatively shown in Fig. 2.10(d), reducing the peak power by 20%. Additional DCF with $D_{\text{conv}} = -340 \text{ps/nm}$ dispersion after the link would further reduce the eye opening to 50% due to further broadening of the SPM chirped pulses, a result of the large amount of residual dispersion following the generation of SPM. It was experimentally verified that SSMF at the receiver restored the pulse shapes to those of the input pulses due to pulse recompression. The measured eye diagrams for exact compensation and under-compensation are shown for post-compensated spans in Fig. 4.46 and agree well with the simulation for this system.

![Eye diagrams](image)

**Fig. 4.46** Effect of SPM on eye-opening after 3 spans of SSMF+DCF using a recirculating loop, single channel at 10Gbit/s with a PRBS modulation, 10dBm launch power, parallel polarisation, **top**: exact compensation, **bottom**: 22km SSMF after transmission **left**: experiment, **right**: simulations

SPM distortion depends - similar to the case of XPM - on the amount of additional lumped dispersion $D_{\text{conv}}$ at the output of the exactly compensated transmission link. The nonlinear distortion could be minimised using lumped dispersion to under-compensate the post-compensated fibre link. However, the question is whether the choice of the optimum dispersion, $D_{\text{conv}} = D_{\text{min}}$, at the receiver depends on the total link length. The single channel distortion was investigated for a range of transmission distances and for each distance the optimum amount of lumped dispersion minimising SPM was calculated as shown in Fig. 4.47. The required dispersion varied from approximately $D_{\text{min}} = +250 \text{ps/nm}$ for a single span to $+450 \text{ps/nm}$ after 10 recirculations. The increase was almost linear with distance and the slope of $+20 \text{ps/nm}$ per span corresponds to just 1km of additional SSMF. These small changes in the required lumped dispersion are a result of identical spans with exact dispersion
compensation in each span. According to Fig. 4.40 each span contributes the same amount to the signal distortion and, therefore, the amount of lumped dispersion for minimising SPM/XPM distortion is expected to be the same. Therefore, the lumped dispersion remained constant at +340ps/nm during the following experiments. In Fig. 4.48 the improvement of transmission by lumped receiver dispersion is demonstrated. With exactly post-compensated spans and 13dBm launch power the eye-opening penalty (EOP) increases by 0.44dB per span reaching 4dB after 9 spans. Adding $D_{\text{conv}} = +340\text{ps/nm}$, equivalent to 20km of SSMF, lumped dispersion reduces SPM distortion and increases the eye-opening. As a result, a value of EOP= 1dB was obtained after 15 spans instead of just 3 spans without additional SSMF.

Fig. 4.47 Calculated optimum lumped dispersion $D_{\text{min}}$ at receiver as a function of transmission distance for minimising SPM distortion, calculated for single channel at 10Gbit/s with PRBS-modulation, link consisting of SSMF+DCF spans, 13dBm launch power, according to [KIL99]

Fig. 4.48  EOP as a function of distance calculated for single channel at 10Gbit/s, PRBS modulation, 13dBm, exact span compensation of SSMF+DCF spans, (O): no lumped receiver dispersion, (■): additional dispersion $D_{\text{conv}} = +340\text{ps/nm}$ at receiver, according to [KIL99]
4.4.3 Optimising the dispersion map to minimise XPM distortion in a multi-span link

Following the analysis in the previous section of SPM distortion, the role of residual dispersion on XPM distortion was studied for the SSMF-DCF scheme using the recirculating loop. Fig. 4.49 shows the distorted probe waveforms after 6 recirculations for different receiver dispersion. DCF fibre at the loop output increased the residual dispersion for the probe signal resulting in higher intensity distortion compared with the results for the exactly compensated link. The opposite effect was observed when SSMF fibre (L=22km) was added at the receiver.

![Image](image_url)

Fig. 4.49  Effect of residual dispersion on XPM distortion in pump-probe experiment after 6 recirculations using SSMF+DCF spans, Δλ=0.6nm, 13dBm/channel, probe: CW, pump: 1010…-modulation at 2.5Gbit/s, lumped dispersion D_con at receiver: A: +340ps/nm, B: ±0ps/nm, C: -340ps/nm, left: experiment, right: simulation

This is in agreement with the results for SPM in the previous section and the simulations for XPM in single-span links shown in Fig. 4.44. Next, the impact of over- and under-compensation on m_x was investigated as a function of transmission distance. The results for Δλ=0.6nm channel spacing are shown in Fig. 4.50 for the case of additional positive and negative dispersion at the loop output. DCF at the loop output increased the residual dispersion for the phase-modulated probe signal resulting in higher intensity distortion m_x > 0.6 at the receiver after 8 spans. The opposite effect was observed when SSMF fibre (L=22km) was added at the receiver, partially compensating the residual dispersion of the post-compensated links as previously shown in Fig. 4.14. In this case, the XPM intensity distortion was reduced to m_x ≈ 0.2 at n=8, a 30% reduction in comparison to the exactly compensated case of Fig. 4.40. Without SSMF converter at the receiver, the same amount of
$m_r = 0.2$ was reached after only 3 spans due to the higher residual dispersion. Therefore, the additional SSMF spool allowed to increase the transmission distance by almost a factor of 3 for a given XPM distortion indicating the effectiveness of this method. In a WDM system, the lumped compensation $D_{conv}$ can be tailored individually after demultiplexing the channels and, therefore, SPM and XPM can be minimised on a "per-channel" basis.

![Graph](image)

**Fig. 4.50**  
XPM distortion for multiple spans of SSMF+DCF, $m_r$ vs. transmission distance, $\Delta \lambda = 0.6$nm, $13$dBm/channel, probe: CW, pump: 1010...-pattern at $2.5$Gbit/s, 10-90% rise time: 56ps, corresponding to $10$Gbit/s modulation with $4x1,4x0$ sequence, $D'_{ref}(0) = -340$ps/nm (DCF, $\bigcirc$) and $+340$ps/nm (SSMF, $\bullet$), lines: simulation using split-step algorithm.

**4.4.4 Lumped compensation vs. in-line compensation**

It was shown that XPM- and SPM-induced distortion was effectively reduced by under-compensation of SSMF-DCF spans using additional dispersion at the receiver. Another scheme under-compensates every span of the transmission link without using additional dispersion at the receiver. Both schemes are compared in Fig. 4.51.

The reduction of XPM distortion in post-compensated links was investigated in pump-probe simulations at $10$Gbit/s and the results were compared for in-span and lumped under-compensation. Firstly, the optimum length of the DCF fibre in each span was calculated for a single transmitted channel since XPM cannot be considered without minimising SPM. 10% under-compensation per span, corresponding to the $D'_{ref}(0) = +107$ps/nm, was found to minimise the residual dispersion following the generation of SPM for the launch power of $10$dBm/channel. Secondly, XPM distortion for $\Delta \lambda = 0.4$nm was calculated for this amount of in-line under-compensation and for optimised lumped under-compensation, $D'_{ref}(0) = +425$ps/nm, with exact in-span compensation.
Chapter 4: XPM pump-probe experiments

(a) Minimising residual dispersion of SSMF+DCF link by under-compensation at receiver, highlighted: additional SSMF fibre

(b) Minimising residual dispersion of SSMF+DCF link by under-compensation of each span with a reduced length of DCF (highlighted), no fibre at receiver

Fig. 4.51

The results in Fig. 4.52 indicate a relatively small difference in the XPM distortion for both dispersion maps. Under-compensation of each span results in reduced XPM distortion in comparison to the lumped scheme, and after 6 spans the XPM distortion is reduced by approximately 30% with respect to the exactly compensated link. Since the channel walk-off over each span was non-zero in the case of in-line under-compensation the exact realignment of both channels at the beginning of each span was avoided. However, the residual dispersion following XPM is larger, especially for the earlier spans, and so PM-IM conversion is greater. This explains the relatively small difference in XPM distortion. Avoiding realignment of the channels without increasing PM-IM conversion can be realised, for example, by using a XPM suppressor [BEL99, EIS99]. For the practical system designer, a combination of in-line...

Fig. 4.52

Calculated XPM distortion $\sigma_{XPM}$ of probe channel after multiple spans of 63km SSMF and DCF, pump: 10Gbit/s PRBS-modulation, $\Delta\lambda=0.4\text{nm}$, (●): lumped compensation, $D'_{\text{ref}}(0)=+425\text{ps/nm}$, (○): under-compensation for each span, $+107\text{ps/nm}$
undercompensation and additional dispersion at the receiver may be used, with the values varying from channel to channel due to the slope of the dispersion.

4.5 Summary

In this work, the impact of XPM on WDM transmission was evaluated systematically using the pump-probe technique which allowed to isolate XPM from other nonlinearities, and study the influence of system parameters on XPM. Initially, XPM distortion was investigated for a single fibre span. This system was suitable for fundamental studies of XPM due to its simplicity. These single-span results were completed by a field experiment over 2 spans of installed fibre using the LEANET network. Finally, XPM intensity distortion was investigated in recirculating loop experiments as a function of transmission distance and residual dispersion.

Critical parameters for XPM

The main results of this chapter are summarised in a list providing guidelines for the reduction of XPM-induced distortion and the design of multi-channel transmission systems.

Optical power: The XPM-induced intensity distortion by each span, $\Delta m_i/\Delta L$, increased linearly with the optical power. For a single span and $\Delta \lambda=0.4$nm, $\Delta m_i/\Delta P < 0.01$/mW was measured for SSMF increasing to $\approx 0.03$/mW for DSF+SSMF. For more than 10dBm/channel launch power XPM intensity distortion could be detected for $\Delta \lambda < 1$nm.

The fibre attenuation $\alpha$ determines the nonlinear length $L_{\text{eff}}$ and the amount of XPM distortion. In dispersion-compensated systems, a reduction of XPM intensity distortion by 20% was estimated for an increase in the attenuation by 0.1dB/km.

Walk-off: The walk-off, defined as $d_{\text{sp}} = D \cdot \Delta \lambda_{\text{sp}}$, is one of the key parameters for XPM indicating the relative shift of the channel bit-patterns during propagation. For the description of the impact of walk-off on XPM, dispersion, $\Delta \lambda$ and the bit-rate must be considered simultaneously. The walk-off increased with dispersion and channel spacing minimising the build-up of XPM phase modulation due to averaging over the bit pattern of the interfering channels. In the case of SSMF, the XPM intensity distortion was inversely proportional to $\Delta \lambda$ and negligible for $\Delta \lambda > 1$nm over a single span. However, for low dispersion and narrow $\Delta \lambda$ the walk-off length became comparable to $L_{\text{eff}}$ resulting in isolated distortion due to nonlinear chirp and little variation of $m_i$ with $\Delta \lambda$ was observed.

The following conclusions were made:
- DSF is not suitable for WDM transmission due to low walk-off and phase matching resulting in XPM distortion and FWM, respectively.

- In addition to the walk-off, the initial channel delays have to be considered determining the total distortion due to the combination of SPM and XPM.

- The walk-off for SSMF is higher than for DSF by an order of magnitude reducing XPM phase distortion. However, the increased dispersion of SSMF results in efficient PM-IM conversion dominating the channel walk-off for narrow $\Delta \lambda$.

- The ratio of channel walk-off to pulse length increases for short pulses at high bit rates. However, between 1-10Gbit/s the XPM distortion could increase by a factor of more than two due to interference of neighbouring chirp components.

**Pulse transitions:** The total distortion increased with the number of pulse transitions in the interfering channel creating nonlinear chirp. The pulse transition, characterised by $\Delta P/\Delta t$, determined the magnitude of the chirp. Therefore, fast modulators with a high bandwidth and many short pulse transitions, as found in a 1010...-pattern, increased the impact of XPM on transmission. At a given bit-rate, the chirp due to RZ-modulated pump channels was expected to introduce more chirp than NRZ due to the faster pulse rise time and the large number of pulse transitions. However, the channel walk-off significantly reduced the build up of chirp averaging over the positive and negative chirp induced by each '1'-bit.

**Transmission distance:** XPM increased linearly with distance for links of multiple amplified spans in the case of negligible SPM-induced pump distortion. This was a result of exact dispersion compensation of each span realigning the bit-patterns channels and adding up the contributions to XPM constructively. For dispersion compensated spans, 13dBm/channel launch power and $\Delta \lambda=0.4$nm the slope was approximately $\Delta m_x/\Delta L \approx 0.05...0.07$ depending on the dispersion map. Significant distortion up to $m_x = 0.6$ was measured after $n=8$ spans of DCF+SSMF and $\Delta \lambda=0.4$nm. The parameter $\Delta m_x /\Delta L$ was also linearly proportional to $P$ and inversely proportional to $\Delta \lambda$ and could be measured in single span pump-probe experiments.

**Dispersion management:** Dispersion compensation reduces the residual dispersion in the system following the generation of XPM thus minimising the PM-IM conversion. Since XPM is generated within the entire nonlinear length of the fibre, XPM distortion cannot be fully compensated. However, the XPM distortion in dispersion-compensated links can be minimised, for example, by adding lumped dispersion at the receiver. XPM intensity distortion was reduced by 30% after 8 exactly compensated spans of 40km SSMF and DCF using 22km SSMF at the receiver. However, XPM phase modulation was not
affected lumped dispersion. Under- or overcompensation of each span resulted in a more efficient reduction of XPM distortion since XPM contributions of different spans interfered destructively and also the build-up of phase distortion was reduced. However, this scheme is not practical for a system consisting of a large number of spans, and wide bandwidth, due to the dispersion slope.

The investigation of XPM in WDM transmission links is vital since it can introduce significant intensity distortion with high bit-rate, narrow channel spacing, high launch power and long transmission distance. The most critical parameter with respect to XPM generation is the channel walk-off depending on channel spacing, dispersion and bit-rate. Another important parameter is the residual dispersion of the link. In typical links channel spacing and bit-rate are given defining the channel walk-off. Therefore, the proper choice of the dispersion map is essential to reduce XPM intensity distortion. This is undercompensation of each span in the case of a multi-span post-compensated link, or positive lumped dispersion at the receiver allowing a more convenient modification of the dispersion map.

It was demonstrated that additional filtering in the receiver, caused by a misaligned demultiplexer, could increase the total distortion by a factor of two due to additional PM-IM conversion. In the frequency domain, new spectral sidebands were generated around the optical carrier of the probe channel as shown in high-resolution distance-dependent Fabry-Perot measurements. In the time domain, XPM distortion results in a vertical eye closure of the detected signal increasing the BER at the receiver. The results presented in this chapter are important for understanding the impact of XPM on the bit-error rate in transmission experiments discussed in chapter 5.
Chapter 5

Q-factor measurements

In chapter 4 the impact of transmission system parameters on XPM was investigated using the pump-probe technique. It was shown that XPM-induced distortion leads to signal distortion and eye closure, however, no relation between XPM and transmission parameters such as power penalty, BER and Q-factor was considered. Having established a relationship between XPM distortion and parameters including channel spacing, bit-rate and dispersion, the next step is to investigate the impact of XPM on WDM transmission penalties.

The transmission penalties are affected by the combination of nonlinearities, dispersion and ASE noise whilst in the earlier pump-probe measurements XPM was only considered alone. The Q-factor is used to characterise the system performance as it can easily be related to eye diagrams and the previously measured XPM distortion. In addition, the Q-factor can be determined by direct BER measurements. The work presented in this chapter is aimed at estimating these XPM-induced transmission penalties by comparison with XPM-induced distortion measured in pump-probe experiments.

In section 5.1, the measurement of the Q-factor and its relation to the BER are described. The first experiments in section 5.2 were carried out to investigate the impact of XPM on the Q-factor in transmission over a single span as a function of system parameters such as dispersion, launch power and span length. The Q-factor is also studied as a function of distance in transmission over multiple dispersion-compensated spans using a recirculating loop. The results of these measurements were related to distance-dependent measurements of XPM distortion and are described in section 5.3. This chapter concludes with the analysis of the channel power and number of channels to optimise transmission in a given fibre link from the viewpoint of nonlinearities.
5.1 Q-factor degradation due to XPM distortion

In a WDM transmission system, the BER increases due to fibre dispersion, nonlinearities and ASE noise. The presence of timing jitter narrows the horizontal eye opening and is caused by the GVD-induced arrival time variations due to nonlinear chirp caused by XPM and pulse compression due to SPM and XPM [ESS99, EIS99b]. In contrast, ASE noise and amplitude distortion due to PM-IM conversion of SPM and XPM chirp result in vertical eye closure and the decrease in SNR or Q-factor. As previously shown in Fig. 2.12, single pulses are broader for NRZ than for RZ. At 10Gbit/s, the duration of a single ‘1’ bit for NRZ is 100ps and less than 50ps for RZ. Therefore, timing jitter due to XPM is expected to be significant for RZ pulses due to the shorter pulse width whilst NRZ pulses are mainly degraded by intensity distortion. In chapter 4 where the pump channel was modulated with a NRZ pattern at 2.5 and 10Gbit/s the vertical eye closure due to XPM dominated, in agreement with the experimental results reported in [EIS99b]. The eye diagram depicted in Fig. 5.1 was obtained in a back-to-back measurement using a single channel modulated at 10Gbit/s in a NRZ format. It is evident that both the ‘1’-level (marks) and the ‘0’-level (spaces) broaden due to noise and distortion. \( \mu_1 \) and \( \mu_0 \) are defined as the mean voltage value of the ‘1’- and ‘0’-levels, respectively, whilst \( \sigma_1 \) and \( \sigma_0 \) describe the standard deviation of the voltage values at these respective levels. \( Q \) is defined as a function of these parameters in equation (5.1).

![Typical eye diagram for a 10Gbit/s NRZ signal using a LiNbO3 modulator and a DFB laser](image)

\[
Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}
\] (5.1)

The pump-probe measurements of XPM distortion in chapter 4 revealed that XPM distortion increases with the optical power in all channels and, hence, the ‘1’-level is expected to be most affected by nonlinearities. The increase of \( m \) and \( \sigma_{XPM} \) reduces the Q-factor and leads to an increased BER. The relation between BER and Q-factor is described by an analytical expression in the case of a Gaussian distribution of the distortion characterised by \( \sigma_1 \) and \( \sigma_0 \) [MAR91c]. This approximation, valid for Q-factors limited by ASE noise, can also be applied to uncorrelated XPM distortion acquired over several fibre spans or in the case of multi-
channel experiments where all interfering channels carry independent bit sequences. In this case, the relation between BER and Q-factor is given by equation (5.2) where $erf(.)$ represents the error-function.

$$BER = \frac{1}{2} erf \left( \frac{Q}{\sqrt{2}} \right)$$

In Fig. 5.2 the contribution of XPM-induced distortion is calculated for transmission over a single span of SSMF with $\Delta \lambda = 0.4 \text{nm}$, 13dBm/channel and 10Gbit/s PRBS-modulation in both channels. The total distortion due to SPM and XPM can be compared to the case of single channel transmission demonstrating the effect of XPM distortion on the signal and, hence, the Q-factor. The distortion of the ‘1’-level was increased due to additional XPM-distortion broadening $\sigma_i$. This led to 10% vertical eye closure whilst the horizontal eye closure due to timing jitter was negligible. Since this configuration is similar to the single-span and multi-span experiments described in this chapter the results justify the analysis of the vertical eye-closure alone.

![Fig. 5.2](image)

Fig. 5.2 65km SSMF, 13dBm/channel launch power, $\Delta \lambda = 0.4 \text{nm}$, 10Gbit/s PRBS modulation in both channels, solid line: XPM and SPM from both channels, dotted line: SPM from single channel.

### 5.1.1 Direct measurement of Q

It is not practical to obtain the Q-factor directly via a BER measurement using equation (5.2) for low BER $< 10^{-15}$ due to the long acquisition time. A technique was proposed in [BER93] using an indirect measurement of the Q-factor by varying the decision threshold of the BER test set. This is the technique used in this work for Q-factor measurements. The decision level $D$ is set and a received voltage $V > D$ represents a ‘1’ whilst $V < D$ is regarded as ‘0’. As a consequence, when the threshold $D$ is continuously varied across the eye diagram shown in Fig. 5.1 the BER varies as a function of $D$ and reaches a maximum for $D \geq \mu_1$ and $D \leq \mu_0$. The contributions of the ‘1’- and ‘0’-level to the total BER can be treated independently and are derived from equation (5.2) as:
Chapter 5: Q-factor measurements

\[
BER(D) = \frac{1}{2} \left\{ \text{erf} \left( \frac{\mu_1 - D}{\sigma_1} \right) + \text{erf} \left( \frac{\mu_0 - D}{\sigma_0} \right) \right\}
\]  

(5.3)

The aim of the technique described in [BER93] was to determine the optimum decision voltage \( D = D_{opt} \) within the interval \( \mu_0 < D < \mu_1 \) which results in the lowest BER and the true Q-factor for the given signal. The Q-factor can be determined in the following straightforward way:

- The BER is measured as a function of the decision voltage \( D \)
- The data is divided into two sets at the point of lowest BER. Each data set is governed by either the errors of the '1'-level or '0'-level alone and can be analysed separately
- The BER of each set is a simple expression given by a single \( \text{erf}(\cdot) \) function in equation (5.3). The parameters \( \mu \) and \( \sigma \) in the expression for the error-function define the Q-factor of the system and are to be determined.
- A particular data set from the BER measurement is passed through an inverse error-function which is approximated by a polynomial expression with \( x = \log(BER) \)

\[
\left( \log \left( \frac{1}{2} \text{erf} \left( \cdot \right) \right) \right)^{-1} \approx 1.192 - 0.6681 x - 0.0162 x^2
\]  

(5.4)

This approximation was used in [BER93] and shown to have an accuracy of ±0.2% over the range of \( BER = 10^{-5} \) to \( 10^{-10} \)
- Finally, a linear interpolation is performed for both data sets. The values for \( \sigma \) and \( \mu \) are given by the slope and intercept of the interpolated graphs.
- The Q-factor itself is determined by the intersection of the two lines. This intersection also defines the optimum decision voltage \( D_{opt} \) and the corresponding BER can be obtained using equation (5.3)

A typical example for Q-factor measurements is illustrated in Fig. 5.3. On the left hand side, the BER measurements are shown as a function of \( D \) and the increase of the BER close to the '1'-level (\( \mu_1 \)) and the '0'-level (\( \mu_0 \)) can be seen. The second graph shows the linear interpolation based on equation (5.4). For small values of \( \sigma \) in the case of nearly noise-free transmission, these lines become almost parallel moving the intersection point and, hence, the Q-factor towards larger values. The error-free window for the transmission system, characterising the system margin, is defined by the intersection of the two BER curves with the constant line at \( BER = 10^{-9} \).
This method of measuring the Q-factor has the following advantages:

- Firstly, the interpolation allows to measure the Q-factor for systems with a high margin, e.g. with BER<10^-15, where a direct measurement is not practical due to the long acquisition time.
- Secondly, the accuracy is improved when calculating the Q-factor using a large data set of BER measurements. This approach eliminates the statistical impact of each data point in the case of polarisation or power fluctuations.

### 5.1.2 Impact of XPM distortion on Q-factor

It was proposed in this work and described in [KIL00b] that the broadening of the ‘1’-level, described by $\sigma_1$, is found by the convolution of the detected ASE noise distribution and SPM distortion, $\sigma_{\text{SPM}}$, with the XPM-induced distribution, $\sigma_{\text{XPM}}$. With the Gaussian approximation of these distributions the total standard deviation of the ‘1’-level is given by

$$\sigma_1 = \sqrt{\sigma_N^2 + \sum_{i=1}^{N} \sigma_{\text{XPM}(i)}^2} \quad (5.5)$$

where $N$ is the number of interfering channels and $\sigma_{\text{XPM}(i)}$ is the standard deviation of the distortion due to the $i$th channel. $\sigma_N$ can be measured separately in single channel experiments and $\sigma_{\text{XPM}}$ is obtained in pump-probe experiments measuring the distortion due to XPM alone. Similar to equation (5.2) statistically independent modulation patterns in all channels are
assumed when the variances $\sigma^2$ are added in equation (5.5). To achieve this in the following experiments, the bit-pattern in the PRBS-modulated channels was either optically decorrelated, using a length of optical fibre at the transmitter, or electrically, using a variable delay for the modulator signal. Equation (5.5) predicts increasing distortion of the '1'-level with the number of channels of the WDM system since more contributions are added. The absolute value of $\sigma_{XPM}(i)$ increases with distance and in the case of low channel walk-off as shown before. The aim of the experiments was to validate this dependence as this would allow the use of simple pump-probe measurements for the prediction of transmission penalties due to XPM.

5.2 Single-span transmission

In this section transmission experiments are described, carried out to investigate the impact of XPM on the Q-factor for a single dispersion-compensated fibre span. The Q-factor was measured as a function of channel spacing, launch power and fibre dispersion. This section aims to investigate XPM using transmission over a single fibre span and to compare the results with Q-factor simulations. The simplicity of the considered link also allows the comparison with results of previous pump-probe measurements investigating XPM-induced distortion.

5.2.1 Experimental set-up

The set-up shown in Fig. 5.4 is similar to the pump-probe experiment used for measuring XPM distortion in chapter 4. The channels were PRBS-modulated at 10Gbit/s using a LiNbO$_3$ modulator in Mach-Zehnder configuration (10-90% rise time: 40ps), driven by a PPG (Anritsu MP1763B). The electrical delay between the two modulators could be varied with an electrical delay line to study the impact of the relative channel delay on XPM. The modulated probe channel was combined with one or more modulated pump channels using a fibre coupler. The total power into the single span of 63km SSMF fibre was +16.5dBm using a high-power EDFA (Corning FGM-P-027). An additional spool of DCF fibre (-1000ps/nm) was used before the EDFA to decorrelate the channels by 4bits ($\Delta\lambda=0.4$nm) before the nonlinear section of the SSMF fibre.
This fibre arrangement provided dispersion compensation for the link and minimised linear pulse distortion. After transmission the probe channel was selected with the free-space grating demultiplexer (demux) and detected using a 10Gbit/s receiver unit. The signal was subsequently analysed using a 10Gbit/s Anritsu BERT (MP1764A) and a Tektronix sampling oscilloscope (CSA 803A). For the Q-factor measurement, described in section 5.1, the BERT operation was computer controlled via a GPIB interface allowing to automate the BER data acquisition. A computer program was used to change the decision voltage in small increments (0.001V-0.01V) and the BER was recorded as a function of the decision voltage. For comparison between Q-factor and corresponding XPM-distortion, the probe channel was operated in CW mode and $\sigma_{XPM}$ was measured in pump-probe configuration.

5.2.2 Q-factor for different channel spacing

The BER was measured as a function of the decision threshold for different channel spacing $\Delta\lambda$, and the Q-factor was obtained by the interpolation described in section 5.1.1. Both channels were modulated with independent 10Gbit/s PRBS sequences with $2^{15}$-1 length and the receiver input power was set to -35dBm. An increase of the pattern length from $2^7$-1 to $2^{21}$-1 caused a power penalty of approximately 1dB in the transmission experiments. This was due to the pattern dependence of the receiver confirmed in back-to-back measurements.

Measuring BER versus $\Delta\lambda$: The BER was measured as a function of $\Delta\lambda$ over the range 0.4nm to 2nm using 13dBm/channel launch power and a $2^{15}$-1 PRBS pattern at 10Gbit/s. Since the 2 channels in this experiment had independent bit-patterns from 2 different outputs of the pattern generator, the decorrelating fibre was omitted and only the SSMF span was used. The system was optimised for single channel transmission by increasing the channel spacing to $\Delta\lambda$=2nm where XPM distortion was negligible. The timing and voltage level of the
decision threshold were adjusted to the lowest BER determined by SPM distortion, ASE noise and dispersion. In the following, \( \Delta \lambda \) was varied resulting in additional XPM distortion for narrow \( \Delta \lambda \). The Q-factor was determined for a given \( \Delta \lambda \) using the decision threshold method. The BER measurements are shown as a function of the decision threshold in Fig. 5.5.

**'1'-level:** The slope of the '1'-level BER measurement indicates \( \sigma_1 > \sigma_0 \) because there is additional signal-ASE beating noise for the '1'-level and not for the '0'-level. The '1'-level is also more affected by XPM than the '0'-level as it is clearly shifted towards the '0'-level with decreasing \( \Delta \lambda \). For narrow channel spacing, \( \Delta \lambda = 0.4\text{nm} \), the BER changed by one order when the decision voltage was varied by approximately 12mV whilst this interval was reduced to \( \approx 8\text{mV} \) for \( \Delta \lambda = 2\text{nm} \). However, for all values of \( \Delta \lambda \) error-free transmission was obtained. For \( \Delta \lambda = 2\text{nm} \), when only SPM distortion and ASE noise were present, the error-free interval extended over approximately 0.5V but decreased to about 0.1V for \( \Delta \lambda = 0.4\text{nm} \).

**'0'-level:** The BER varied by about one order of magnitude when the decision voltage was changed by only 1mV for all \( \Delta \lambda \), indicating a stationary '0'-level with little broadening. The data set representing the '0'-level was shifted by up to 0.2V for values with BER\( < 10^{-8} \) when the \( \Delta \lambda \) was increased from 0.4nm to 2nm. The slight broadening of the '0'-level may be due to XPM-induced pulse broadening leading to ISI from adjacent '1' bits. This broadening is less significant than the broadening of the '1'-level which is also affected by nonlinear distortion.

![Fig. 5.5 BER vs. decision threshold D measured for different \( \Delta \lambda \), 63km SSMF, 13dBm/channel, 10Gbit/s PRBS, 2^{31} - 1 bit sequence, for (□): 2nm, (X): 0.6nm, (O): 0.4nm](image-url)
Calculating Q-factor: The results of Fig. 5.5 were used to calculate the Q-factor and the results are shown in Fig. 5.6(a). For $\Delta \lambda = 0.4\,\text{nm}$ the Q-factor decreased to $Q \approx 6$, corresponding to $\text{BER}=10^{-9}$. For wide channel spacing, $\Delta \lambda > 1\,\text{nm}$, the total variation was $\Delta Q < 0.5$, in agreement with previous pump-probe measurements in chapter 4 investigating XPM distortion versus $\Delta \lambda$ for the same SSMF link. In Fig. 4.8 it was shown that XPM-induced distortion was negligible for $\Delta \lambda > 1\,\text{nm}$ and, therefore, the Q-factor was only determined by SPM, dispersion and ASE noise. In Fig. 5.6(b) the results are shown as a function of $1/\Delta \lambda$ and the Q-factor was found to depend linearly on the inverse channel spacing over the entire wavelength range.

![Fig. 5.6](image)

**Fig. 5.6** Q-factor obtained from BER measurements for SSMF link, (♦) experimental data, line: interpolation, 10Gbit/s PRBS modulation, $2^{15}-1$ sequence, 13dBm/channel, (a) as a function of $\Delta \lambda$, (b) for $1/\Delta \lambda$, receiver power: $R_p = -34\,\text{dBm}$

In addition the contribution of XPM distortion, $\sigma_{XPM}$, was investigated in pump-probe experiments using the same fibre link. In this case, the pump was PRBS-modulated and the probe was in CW mode. In Fig. 5.7(a) the measured distribution of $\sigma_{XPM}$ is shown as a function of $\Delta \lambda$ and was found to be proportional to $1/\Delta \lambda$. The histograms in the inset of Fig. 5.7(a) for $\Delta \lambda = 0.4\,\text{nm}$ and $2\,\text{nm}$ indicate that the '1'-level is broadened for narrow channel spacing due to XPM-induced distortion of the probe. In addition, $\sigma_{XPM}$ was determined in simulations for orthogonal and parallel polarisation of pump and probe.

For a single span of SSMF, the results obtained for $\sigma_{XPM}$ were compared to the wavelength-dependent Q-factor measurements shown in Fig. 5.6. Initially, the Q-factor was calculated for $\Delta \lambda = 2\,\text{nm}$ using the BER data presented in Fig. 5.5. The parameters $\mu_1$, $\mu_0$, $\sigma_0$ and $\sigma_1$ were determined according to section (5.1.1) assuming negligible XPM with $\sigma_i(\Delta \lambda = 2\,\text{nm}) \approx \sigma_N$. In the following, the experimental results for $\sigma_{XPM}$ shown in Fig. 5.7(a) were used to calculate $\sigma_i(\Delta \lambda)$ in the interval $\Delta \lambda = 0.4 \ldots 2\,\text{nm}$ and it was assumed that only $\sigma_1$ was affected by XPM-
induced distortion. Therefore, the decrease of the Q-factor with $1/\Delta \lambda$ was calculated using $\sigma(\Delta \lambda)$ and the parameters $\mu$, $\mu'$ and $\sigma_0$ determined for $\Delta \lambda=2\text{nm}$. In Fig. 5.7(b) the calculated Q-factor is compared with the Q-factor determined in direct BER measurements. For $\Delta \lambda>0.8\text{nm}$, these two graphs agree well, however, for small $\Delta \lambda$ the pump-probe experiment underestimates the reduction of the Q-factor by up to 13%. This is due to the variation of the polarisation between pump and probe as shown by the calculation of $\Delta Q$ for orthogonal and parallel polarisation. The values for the Q-factor given by the measurement of $\sigma_{XPM}$ are within the interval determined by the calculated Q-factor for both states of polarisation.

![Fig. 5.7(a)](image)

Experimental normalised XPM distortion measured for link used in Q-factor measurements of Fig. 5.6, 13dBm/channel: $\sigma_{XPM}$ vs. $\Delta \lambda$ at 10Gbit/s, (O): pump-probe experiment, dashed line: parallel polarisation, dotted line: orthogonal polarisation, inset: histograms showing broadening of ‘1’-level of the CW probe due to XPM for small $\Delta \lambda$, same bin size.

![Fig. 5.7(b)](image)

Comparison of Q-factors vs. $1/\Delta \lambda$, 10Gbit/s with $2^{15}-1$ PRBS modulation, single span of 63km SSMF, 13dBm/channel, (O): calculated using $\sigma_{XPM}$ from pump-probe experiment, (■): directly measured Q-factor, dashed line: parallel polarisation, dotted line: orthogonal polarisation.
In section 5.3.3 the Q-factor reduction due to XPM as a function of distance and Δλ is estimated using the results of pump-probe experiments and analytically calculated XPM distortion for up to 12 post-compensated spans.

5.2.3 Dependence of Q-factor on systems parameters

In this section, the results of the Q-factor measurements versus Δλ are described, extended to different dispersion maps, launch powers and system lengths to determine the impact of these parameters on the absolute value of $Q$ and the slope $\Delta Q/\Delta \lambda$. As before, 2 channels at 10Gbit/s were transmitted over a single span of 63km SSMF.

**Dispersion:** Both channels were modulated with PRBS and additional DCF was added to the link. Unlike with the dispersion-managed schemes discussed in chapter 4, the DCF fibre was placed before the EDFA and, hence, only compensates for the linear pulse distortion of the link. Therefore, the residual dispersion following the generation of XPM was not affected. As shown in Fig. 5.8, the Q-factor improved by $\Delta Q \approx +1.5$ with respect to the uncompensated SSMF span, independent of $\Delta \lambda$. In summary, the compensation for linear pulse distortion in the pre-compensated link increases the absolute values of $Q$ but does not change the variation of XPM with $\Delta \lambda$ expressed by the slope $\Delta Q/\Delta \lambda$.

![Fig. 5.8 Q-factor vs. 1/Δλ measured at 10Gbit/s, 2^{15}-1 PRBS, 13dBm/channel, receiver power: $R_s = -34dBm$, (O): SSMF fibre only, (■): DCF+SSMF, DCF before EDFA compensated only for linear distortion](image)
**Optical power:** To confirm that the variation of $Q$ with $\Delta \lambda$ is caused by XPM alone, the launched power into the SSMF fibre was decreased to 3dBm/channel and the resulting Q-factor was re-measured as a function of $\Delta \lambda$. The results in Fig. 5.9 show very little variation from the constant value of $Q \approx 7$. This is consistent with the linear regime where the transmission is only limited by fibre dispersion and ASE noise.

![Fig. 5.9](image)

*Fig. 5.9* Experimental values of $Q$ vs. $\Delta \lambda$ for 3dBm/channel launched into 63km SSMF fibre, PRBS modulation at 10Gbit/s

The Q-factor was calculated using the split-step algorithm for a range of launch powers between 3dBm/channel and 13dBm/channel as shown in Fig. 5.10(a). As expected from the XPM-induced chirp, which increases with optical power, the variation of the Q-factor increased for higher launch power and can be expressed by the factor $|\Delta Q/\Delta(1/\Delta \lambda)|$. The initial value of the Q-factor for wide channel spacing was dependent on SPM and Gaussian noise. In the power-dependent calculations, the Q-factor was normalised to $Q(\Delta \lambda=1.6\text{nm})$ in all cases to highlight only the variation of the slope $\Delta Q/\Delta(1/\Delta \lambda)$ with launch power. For example, 10dBm/channel resulted in $\Delta Q \approx -0.3 \cdot \Delta(1/\Delta \lambda)$ whilst this figure was increased to $-0.7 \cdot \Delta(1/\Delta \lambda)$ for 13dBm/channel. This was due to the increased distortion of the '1'-level of the detected channel with launch power resulting in a decrease of the eye-opening and Q-factor. For a given channel spacing, the penalty due to XPM was investigated as a function of the launch power. At $\Delta \lambda=0.4\text{nm}$ the impact of XPM on the Q-factor was negligible. However, $\Delta Q= -0.5$ was measured for 10dBm/channel launch power and was reduced to approximately $\Delta Q= -1.3$ for 13dBm/channel. In Fig. 5.10(b) a linear decrease of the Q-factor with launch power is shown, resulting in $\Delta Q/\Delta P \approx -0.06/\text{mW}$. This reduction is a result of the linear increase of the XPM-induced distortion $\sigma_{\text{XPM}}$ with launch power.
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Distance: The length of the SSMF span was varied between \( L = 20\text{km} \) and \( 80\text{km} \) maintaining a constant launch power of \( 13\text{dBm/channel} \), using \( 10\text{Gbit/s} \) PRBS modulation in both channels. As a result, the XPM distortion increased with the span length due to increased PM-IM conversion in the fibre following the generation of XPM. The calculated Q-factor decreased with increasing span length \( L \), independently of the channel spacing, at a rate \( \Delta Q/\Delta L \approx -0.046/\text{km} \) as shown in Fig. 5.11. Since the additional fibre only affects the linear PM-IM conversion, the total amount of nonlinear phase distortion remains constant, as confirmed by the identical slope \( \Delta Q/\Delta (1/\Delta \lambda) \) in all cases. However, \( \Delta Q/\Delta (1/\Delta \lambda) \) was only changed for \( L = 20\text{km} \) where \( L \approx L_{\text{eff}} \), and for \( L < L_{\text{eff}} \), the negative slope was reduced since less XPM chirp occurred in the span. In the following section, the length-dependent Q-factor measurements are extended to multiple amplified spans where each span contributes to XPM distortion.
In summary, wavelength-dependent Q-factor measurements at 10Gbit/s over a single fibre span have shown that the Q-factor is reduced for narrow channel spacing due to increased XPM distortion. It was confirmed that $Q$ decreases linearly with $1/\Delta \lambda$. This is consistent with pump-probe measurements of chapter 4 using the same fibre span which have shown that XPM distortion $\sigma_{\text{XPM}}$ is proportional to $1/\Delta \lambda$.

The negative factor $\Delta Q/\Delta (1/\Delta \lambda)$, indicating the transmission system tolerance to XPM distortion, was investigated as a function of systems parameters in both experiments and simulations. The absolute value of this parameter increased with launch power, however, it remained constant when varying span length and linear dispersion compensation.

Fig. 5.11 Calculated variation of Q-factor vs. $\Delta \lambda$ due to PM-IM conversion, 2 channels, 10Gbit/s PRBS, 13dBm/channel into SSMF link, length: $L=20\text{km}$, 40km, 65km and 80km, increased PM-IM conversion decreases Q-factor
5.3 Measurement of Q-factor in a recirculating fibre loop

The investigation of the Q-factor was extended to longer transmission distances using a recirculating fibre loop. The impact of XPM on the Q-factor was previously studied in simulations for different link lengths [YU98, TEN99]. The length-dependent experiments described in this section were carried out to analyse the effect of channel spacing, transmission distance and number of channels on the Q-factor, which imposes a limit on the achievable transmission distance due to XPM. Also, 2-channel transmission experiments were carried out and the Q-factor was compared with results obtained from the combination of single channel Q-factor measurements with distance-dependent pump-probe experiments. This technique allows to link the transmission experiments and the more fundamental measurements of XPM distortion described in chapter 4.

5.3.1 Experimental set-up

The experimental set-up shown in Fig. 5.12 is similar to the system used for the length-dependent pump-probe experiments in section 4.3. However, the span length was increased to 75km, combining DCF and SSMF, for a more realistic amplifier spacing and to reduce the effect of high lumped loss from loop components (3dB coupler and AOM). The output of a DFB and a tunable laser, modulated by LiNbO$_3$ Mach-Zehnder modulators, were combined with the same polarisation states and powers.

![Fig. 5.12 Recirculating loop set-up investigating the impact of XPM on the Q-factor, 10dBm/channel, 10Gbit/s PRBS bit-sequence, exactly post-compensated SSMF span, power at Rx: -33dBm](image-url)
The loop consisted of an EDFA (+10dBm/channel output power), 63km of SSMF \((D = 17\text{ps/(nm-km)}, \alpha = 0.21\text{dB/km})\), exactly compensated at the end of the span by 12km of DCF \((D = -89\text{ps/(nm-km)})\). Total loop loss, including acousto-optic modulator (AOM) was 28dB. As before, the probe channel was demultiplexed at the loop output, using a free-space grating demultiplexer, and amplified with a low noise EDFA before detection with a receiver and BERT. Lumped under-compensation using 20km of SSMF \((D_{\text{comp}} = +340\text{ps/nm})\) at the output of the loop minimised SPM-induced eye closure at the receiver, as described in section 4.4.2.

### 5.3.2 XPM-induced penalty as a function of system length

Similar to section 5.2.2, the Q-factor was investigated as a function of \(\Delta\lambda\) for variable transmission distances. In Fig. 5.13 the results of the BER measurements are shown as a function of decision threshold \(D\) for a single span and 6 recirculations. In each case, the BER measurements were compared for different \(\Delta\lambda\). It is evident from these results that the XPM effect reduces the error-free interval \((\text{BER}<10^{-9})\) with increasing system length \(L\) and decreasing values of \(\Delta\lambda\). For a single recirculation, corresponding to the span length used in the previous single-span experiments, the BER curves show only a small variation over the total range of \(\Delta\lambda\) indicating a negligible impact of XPM distortion on transmission. The influence of XPM is expected to be lower than in section 5.2, even for the same span length, since the DCF followed the nonlinear SSMF section. Therefore, the total amount of residual dispersion following the generation of XPM chirp was minimised reducing the total PM-IM conversion of the span. Another reason for reduced XPM distortion was the reduction of the launch power by 3dB with respect to the single span experiments shown in Fig. 5.5.

![Fig. 5.13 Experiments measuring BER vs. decision voltage in recirculating loop, investigation of Q as a function of distance L and Δλ. 2 channels, 10Gbit/s PRBS, SSMF+DCF spans, (■): Δλ=0.4nm, (○): Δλ=0.8nm, (●): Δλ=1.2nm, (×): Δλ=2nm, power at R\(\text{X}\)=34dBm](image-url)
The launch power was reduced to maximise the error-free transmission distance limited to 6 recirculations for a single channel due to SPM. After 6 recirculations, the BER increased due to the accumulated XPM distortion with distance and error-free multi-channel transmission was no longer possible. The detected BER at the optimum decision point showed a strong variation with $\Delta \lambda$ increasing to $10^{-7}$ for $\Delta \lambda = 0.4 \text{nm}$.

The Q-factor for transmission over multiple spans was increased for large $\Delta \lambda$ reducing the BER near the '1'-level as shown in Fig. 5.13. The strong variation of the '1'-level of the BER-curve indicates transmission limitations due to nonlinearities. XPM-induced distortion also slightly affects the broadening of the '0'-level after $n=6$ recirculations with $\Delta \lambda = 0.4 \text{nm}$ shifting the optimum decision voltage by -0.1V. At $n=1$ and $n=6$, only a small variation of the BER curves with $\Delta \lambda$ was observed when increasing the channel spacing to $\Delta \lambda > 1.2 \text{nm}$, equivalent to a low value of $m_z$ in the corresponding pump-probe measurements of chapter 4.2. The Q-factor, calculated from the BER measurements in the previous graph, is shown in Fig. 5.14 as a function of $1/\Delta \lambda$ for a different number of recirculations.

![Fig. 5.14](image)

**Fig. 5.14** Q-factor vs. $1/\Delta \lambda$ measured for $n=1...7$ recirculations, SSMF+DCF spans, dotted line: BER=$10^{-9}$ threshold, 10dBm/channel, 10Gbit/s PRBS, 2 channels, parallel polarisation, (●): 1, (▲): 2, (▼): 3, (♦): 4, (♦): 5, (◆): 6, (★): 7 recirculations

- $n=1...3$: Error-free transmission was achieved for all $\Delta \lambda = 0.4 ... 2.5 \text{nm}$ and the variation of $\Delta Q < 0.5$ over the measured interval indicates negligible impact of XPM. The overall decrease of the Q-factor with the number of recirculations was mainly due to the additional ASE noise and SPM introduced by each span.
- $n=4...6$: The transmission is increasingly affected by XPM resulting in $Q \leq 5$ at $\Delta \lambda = 0.4 \text{nm}$ and $\Delta Q = 1$ for $n=4$. This is due to the zero walk-off from one span to the next resulting in a continuous build-up of XPM distortion with distance.
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- \( n > 7 \): Error-free transmission was impossible at \( n = 7 \) indicating the detrimental effect of XPM, SPM and ASE on transmission over long distances even for dispersion compensated spans.

5.3.3 XPM-induced penalty as a function of number of channels and distance

In all previous experiments investigating XPM-induced distortion and Q-factors a 2-channel system was used. This simplification allowed the convenient study of XPM as a function of various systems parameters and all the measured XPM distortion could be related to a single interfering channel. However, in more realistic systems XPM is caused by many WDM channels, which carry arbitrary bit-patterns and, consequently, the impact on the probe channel is less deterministic. In this section, previous results investigating \( Q \) and \( \sigma_{xpm} \) as a function of \( \Delta \lambda \) are extended by varying the number of channels between 2 and 16, transmitted over 7 exactly post-compensated spans. The channel spacing between adjacent channels was \( \Delta \lambda = 0.4 \text{nm} \). When increasing the number of channels, the optical power per channel must be considered. Two separate cases were investigated:

A. The power per channel was maintained constant and, therefore, the total launch power into the fibre varied with the number of channels \( N \).

B. The total launch power was kept constant and thus the power per channel varied with the number of channels \( N \).

A. Constant power per channel

Additional CW channels were introduced to keep the power per channel constant and to maintain constant power into the loop EDFA so that it operated to give the same saturated output power \( P_{\text{total}} \). These channels were located greater than 5nm away from the transmitted channels ensuring negligible influence of the CW channels on the measured XPM distortion.

To increase the number of active WDM channels in the XPM experiment, a number of CW channels was removed and the same number of modulated pump channels was added spectrally close to the detected probe channel as shown in Fig. 5.15. The advantage of this method is a low noise figure of the saturated EDFA and no necessary adjustment of the channel power as the total channel number was maintained constant.
Initially, the impact of multiple pump channels on XPM distortion was investigated in a pump-probe experiment carried out to compare $\sigma_{XPM}$ for one or two modulated pump channels spaced by $\pm 0.4\text{nm}$ with respect to the probe. Fig. 5.16 shows the normalised values of $\sigma_{XPM}$ versus $\Delta \lambda$ at 10Gbit/s after a single span launching 11.2dBm/channel. For constant channel power, the contributions of $\sigma_{XPM}(i)$ to $\sigma_t$ add up according to equation (5.5). In the case of negligible noise and SPM distortion, $\sigma_n < \sigma_{XPM}$, the additional pump channel increases $\sigma_t$ by a factor $\sqrt{2}$. The ratio $\sigma_{XPM}(2\text{pump})/\sigma_{XPM}(1\text{pump})$ is shown in the inset to Fig 5.16. The factor $\sqrt{2}$ obtained for all $\Delta \lambda$ confirms that, firstly, both pump channels introduce the same amount of distortion $\sigma_{XPM}$ due to identical channel power and walk-off and, secondly, both pump channels can be considered to have statistically independent bit-patterns. Therefore, the total XPM distortion variance of a multi-channel system can be obtained as the sum of the variances $\sigma_{XPM}^2$ caused by the interfering channels, with the resultant Gaussian distribution due to the Central Limit Theorem.

In Fig. 5.17 the Q-factor is shown for distance-dependent measurements for up to 7 post-compensated spans of 75km length using a modulated probe channel with 0, 2, 4 and 6 pump channels at 7.5dBm/channel. For a given transmission length, the Q-factor decreased with the
number of channels due to XPM penalty alone. After $n=2$ recirculations, the Q-factor was reduced on average by -0.25dB/channel when adding up to 6 pump channels. For a constant number of channels the variation of $Q$ with distance was $-0.66$dB/span due to SPM, XPM and ASE noise. The impact of XPM on $Q$ is twofold: firstly, XPM distortion increases with transmission distance since contributions from each span add up constructively for exactly dispersion-compensated spans. Secondly, XPM distortion increases with the number of channels $N$ since the contributions of these channels are combined as the sum of their variances $\sigma_{\text{XPM}}^2(i)$ with $i=1...N$. However, the impact of spectrally distant channels was reduced due to the increased channel walk-off. Using more than one pump channel, a statistical fluctuation of $Q$ with distance was observed. Since this variation was enhanced for multi-channel experiments it is assumed to reflect the polarisation dependence of XPM inside the loop. The relative polarisation of the increasing number of WDM channels was difficult to control as was the PDL of the loop components so that polarisation-scrambling was used to reduce the fluctuations of the Q-factor.

![Q-factor measured as a function of number of channels and transmission distance, spans: 63km SSMF+DCF, 10Gbit/s PRBS, 7.5dBm/channel, receiver power: -33dBm, $Q(\text{dB})=2\log(Q)$, (□): single channel (SPM and ASE only), (○): 2, (▲): 4, (◆): 6 pump channels, dotted line: BER=$10^{-9}$, all pump channels are decorrelated and polarisation-scrambled](image)

**Accuracy of measurements:** Both the Q-factor and $\sigma_{\text{XPM}}$ were found to vary statistically with $\Delta \lambda$ due to experimental limitations. The polarisation varied randomly with time, and since the free-space demultiplexer had a PDL of approximately 2-3dB, the detected optical power at the receiver also fluctuated by this amount. Fig. 5.18 highlights the variation of $Q$ with receiver power measured in a back-to-back measurement. For $\Delta P=2$dB the total variation in the Q-factor was $\Delta Q=2$dB which can be explained by the power fluctuation due to PDL alone. In the transmission experiments the signal polarisation into the demux was adjusted using a
polarisation controller and an additional EDFA following the demux operated in saturation to reduce the power fluctuation at the receiver to approximately 0.5dB.

![Graph showing Q variation in addition to XPM-induced variation](image)

Fig 5.18 (■): Back-to-back measurement of Q-factor versus receiver power at 10Gbit/s, $2^{31}-1$ PRBS sequence, $Q(\text{dB}) = 20 \cdot \log(Q)$

**B Total power constant**

The Q-factor was also investigated as a function of channel number with constant optical launch power into the fibre. In contrast to the previous section, the power in each channel is dependent on the total number of WDM channels in the system. Whilst the previous experiments have shown a constant increase of XPM distortion with the number of channels, the results of this investigation are expected to be different. The total XPM distortion increases with the number of interfering channels. However, the contribution of each channel to XPM decreases since the channel power is reduced with increasing number of channels. In addition, the contribution of SPM in the detected channel also varies with the capacity of the WDM transmission system. For the post-compensated spans, the optimum combination of channel power and number of channels was investigated to maximise the Q-factor. A recirculating loop was used to investigate the Q-factor as a function of transmission distance and channel power for constant total launch power of 16dBm into the post-compensated spans.

**Multiple channels, low power/channel:** In Fig. 5.19(a) the Q-factor is compared for 6 pump channels equally spaced by $\Delta \lambda = 0.4\text{nm}$ around the detected channel with 7.5dBm/channel. For reference, the pump channels were operated in CW-mode to determine the Q-factor due to SPM and ASE-noise alone. Therefore, the difference $\Delta Q$ is a measure for the XPM-induced penalty at that distance. The XPM-induced penalty increased with distance, up to 1.2dB after 5 recirculations. By comparison, the single channel penalty increased by 0.9dB/span.
**Few channels, high power/channel:** In Fig. 5.19(b) the results of $Q$ versus distance are shown for two channels with 13dBm/channel. As a result of higher channel power the penalty due to SPM increased to 1.2dB/span. The XPM-induced penalty was increased to approximately 1.5dB after 5 spans, comparable to the previous measurement with many pump channels at lower power.

The Q-factor was investigated after 5 recirculations varying the channel number between 2 and 16 with adjacent channels spaced by $\Delta\lambda=0.4$nm. Therefore, the launch power per channel varied between 13dBm and 4dBm. Fig. 5.20 summarises the Q-factor for different channel configurations taking into account SPM, XPM and ASE noise. In the limit of linear transmission with 16 channels, the Q-factor was reduced to $Q=13.5$dB after 5 recirculations. No significant XPM penalty was measured launching 4dBm/channel into the span. In comparison to the initial value of $Q\approx 18.5$dB, measured in back-to-back mode, the Q-factor was reduced on average by 1dB per span. This is due to the low channel power in combination with a lumped loss of 28dB inside the loop resulting in a low EDFA input power of $-24$dBm/channel. In the nonlinear case, $Q=13.8$dB was obtained for 2 channels after 5 recirculations, limited by nonlinear distortion due to SPM and XPM. In this case, the EDFA input power increased to $-12$dBm/channel and the EDFA output power could be saturated by a single channel alone resulting in improved SNR. For all configurations, the transmission penalty varied over a range of 2dB and the optimum performance with $Q>15.5$dB was obtained for a 5-channel system launching 9dBm/channel. Since the XPM penalty was comparable for 2 and 7 transmitted channels, shown in Fig. 5.19, the decreased Q-factor for
the 2-channel configuration could be explained by the increased signal distortion due to SPM for 13dBm/channel.

![Diagram showing Q-factor versus channel number after n=5 recirculations, all channels PRBS-modulated at 10Gbit/s, power per channel (40/N)mW](Image)

In summary, the impact of XPM on intensity distortion and Q-factor was investigated as a function of the number of channels. In this section two different approaches were used to investigate XPM penalties as a function of channel number:

In the first experiments the power per channel was constant. In this case, additional pump-probe experiments confirmed that the variances $\sigma_{XPM}^2$ could be added to obtain the total distortion simplifying the prediction of XPM after upgrading the number of WDM channels. It was previously shown in simulations [MAR94] and experiment [PIL99] that the penalty due to XPM saturates with increasing number of channels due to the increasing walk-off between distant interfering channels and the centre channel. In this work, the measurements of XPM were extended to a range of transmission distances using a recirculating loop. However, statistical fluctuations of the polarisation in the loop in combination with polarisation dependent components made it difficult to verify the saturation effect of XPM quantitatively.

In the second approach the total launch power was constant decreasing the power for each channel with increasing channel number. This configuration was used to determine the channel-power combination for maximised $Q$. It was shown that transmission was limited by noise for 16 channels with 4dBm/channel whilst it was limited by SPM and XPM for only 2 transmitted channels with 13dBm/channel.
5.3.4 Estimation of penalties in pump-probe and transmission experiments

In this section it is proposed and experimentally verified that a pump-probe measurement of XPM can be used to predict the XPM-induced Q-factor reduction through comparison with direct BER measurements. The experimental set-up shown in Fig. 5.12 was used for single and 2-channel transmission over up to 12 post-compensated spans of SSMF. Q-factor measurements were performed at 10Gbit/s using $2^{15}$-1 PRBS sequences and pump-probe experiments were carried out to measure $\sigma_{XPM}$ as a function of transmission distance [THI00b]. The experimental verification was performed in three steps:

A Measuring XPM distortion

- The CW probe channel was tuned to $\Delta \lambda = 0.4$nm from the modulated pump channel. Fig. 5.21(a) shows a typical averaged trace of the XPM-distorted CW probe after 6 spans.
- The XPM index $\sigma_{XPM}$, normalised to the average probe power, was calculated as shown in Fig. 5.21(b). To increase the accuracy, 256bits of the PRBS sequence were used to calculate $\sigma_{XPM}$. As a result, the statistical error of the estimated $\sigma_{XPM}$ caused by considering a short sequence length was avoided.

$\sigma_{XPM}$ reached 0.09 after 5 spans, in good agreement with the results of split-step simulations using an adaptive step-size to reduce the calculation time for multi-span links. In the simulation of the pump-probe measurements the EDFAs were assumed to be simple gain elements since the effect of ASE noise was eliminated in the time-averaged traces of the experiment. After a single span the distortion was lower than in the previous single span measurements in Fig. 5.7 due to the reduced launch power of 10dBm/channel. For comparison, the analytical expression $\Delta P_s(\omega) = P_p(\omega)H_{sp}(\omega)$ described in section 2.3.8 was used to estimate $\sigma_{XPM}$ for the probe channels $s$ [KIL00b]. The calculated and experimentally obtained values agreed closely for 1 span (8% accuracy). However, for longer distances the build-up of distortion was overestimated (81% error for 7 spans) due to the assumption of an undistorted pump waveform, which is inaccurate due to SPM-induced pulse broadening. For an undistorted pump and exactly compensated spans a linear increase is expected indicated by the dotted line in Fig. 5.21(b). The calculation was repeated, using the distorted pump channel waveforms at the input of each span obtained in single channel simulations and more accurate results were obtained.
Fig. 5.21 (a) Measured trace of XPM-distorted CW probe channel after 6 spans.
(b) Standard deviation of measured distortion (●), split-step Fourier simulation (solid line),
analytical results assuming undistorted pump (dotted line) and SPM distorted pump (dashed line).

B Using $\sigma_{XPM}$ to predict Q-factor reduction due to XPM

The experimentally measured values of $\sigma_{XPM}$ in Fig. 5.21(b) were used to predict the Q-factor reduction due to XPM caused by an interfering channel at $\Delta\lambda=0.4$nm, with both channels modulated at 10Gbit/s.

- At first, wide channel spacing was used, so that the XPM distortion was negligible due to the large walk-off $d_p = D\Delta\lambda$. In this case, the standard deviation of the '1'-level was dominated by ASE noise and SPM. The values of $\sigma_N$ were found from measurements of the BER as a function of the decision voltage.
- Using equation (5.5), the values for $\sigma_{XPM}$ and $\sigma_N$ were used to calculate $\sigma_1$ with $\Delta\lambda=0.4$nm channel spacing. The resulting BER values used for this analysis are plotted as solid lines in Fig. 5.22(a)-(b) after 3 and 5 recirculations.

To confirm the results of the calculations, the BER measurements were repeated, now with 0.4nm channel spacing. Good agreement between predicted and actual BER values can be seen in Fig. 5.22. The signal was degraded by XPM at $\Delta\lambda=0.4$nm, and this is reflected in the significant variation of the '1'-level with $\Delta\lambda$. On the contrary, the '0'-level remained almost unchanged for both $\Delta\lambda$ since $\sigma_0$ was least affected by nonlinearities. This indicates that, for NRZ signal formats, XPM penalties can be accurately estimated from the distortion of the '1'-level alone. The error-free interval, the range of decision voltage with BER< $10^{-9}$, narrows down to zero for $\Delta\lambda=1.6$nm when the link length increased to 5 spans in Fig. 5.22(b), and for $\Delta\lambda=0.4$nm the minimum BER increased to $10^{-7}$ due to XPM-induced distortion.
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Fig. 5.22 BER curves for 2 channels, 10Gbit/s recirculating loop experiment, SSMF+DCF spans, 10dBm/channel, receiver power: -33dBm (O): \( \Delta \lambda = 1.6 \text{nm} \), (■): \( \Delta \lambda = 0.4 \text{nm} \), (—): calculated using experimental results for \( \sigma_{XPM} \), (a) after 3 recirculations, (b) after 5 recirculations.

C Comparison with direct measurement of Q

Fig. 5.23 shows the Q-factors predicted from the measurements of \( \sigma_{XPM} \), together with the values obtained from the measured BER curves. The data points represent the direct Q-factor measurements for wide and narrow channel spacing. A continuous decrease of \( Q \) with transmission distance was observed due to ASE noise, SPM and XPM distortion. After transmission over 5 spans the Q-factor was reduced by 1.5dB when the channels were tuned from wide spacing to 0.4nm. Excellent agreement between calculated and measured values for \( \Delta \lambda = 0.4 \text{nm} \), with only +0.2dB overestimation of the Q-factor reduction for 5 spans, demonstrates the validity of using pump-probe characterisation to estimate XPM-induced penalties.

Fig. 5.23 Q-factor as a function of distance for multiple spans of SSMF+DCF, 10Gbit/s PRBS 2\(^{15}-1\), (O): \( \Delta \lambda = 1.6 \text{nm} \), (■): \( \Delta \lambda = 0.4 \text{nm} \), (—): Q calculated using measured \( \sigma_{XPM} \), Q(dB)=20\cdot\log(Q)
Finally, the error-free transmission distance was extended by placing an additional EDFA before the DCF. This configuration, shown in Fig. 5.24(a), increased the optical SNR, reducing the build-up of ASE noise with distance due to the loop loss of 28dB. As a result, the error-free transmission distance could be increased to 12 recirculations.

As shown in Fig. 5.24(b) the XPM-induced penalty $\Delta Q$ increased from 1.5dB at $n=6$ to approximately 2.2dB at $n=12$. Due to the lower launch power into the SSMF in this modified span the transmission remained error-free for all $\Delta \lambda$ at $n=6$. However, the Q-factor was reduced to $Q<15.5$dB for $\Delta \lambda<0.6$ after 12 recirculations, corresponding to BER$>10^{-9}$. The direct measurements of the Q-factor for 2-channel transmission agree well with the combined results obtained from a single channel measurement and the analytically calculated contribution $Q_{XPM}$.

In summary, a pump-probe characterisation of a WDM link was used for the first time to make accurate predictions of the impact of XPM on BER. This is one of the main contributions of this thesis linking transmission experiments and the more fundamental pump-probe experiments. Results of analytical calculations of XPM-induced distortion were found
to be in good agreement with experimental results, although the effects of SPM and dispersion on the pump channel waveform must be taken into account to ensure accuracy for longer distances.

5.4 Summary

In this chapter, the impact of XPM on multi-channel WDM transmission was systematically investigated. The Q-factor was determined as a function of these key transmission parameters: channel spacing, number of channels, power per channel and distance. Initially, the Q-factor was measured for a single fibre span and found to be inversely proportional to $A/l$. The variation of $Q$ with $\Delta\lambda$, resulting from XPM occurring in the transmission link, increased with launch power and number of channels. In contrast, the span length and linear dispersion compensation were found to change $Q$ independent of the particular wavelength spacing.

Using the recirculating loop, the Q-factor was studied as a function of distance in post-compensated links. The error-free distance was limited by ASE due to the 28dB loop loss but could be increased adding a second loop amplifier. The impact of channel number on XPM was investigated for WDM transmission. In this thesis the analysis was divided into two separate cases: firstly, keeping the power per channel constant the Q-factor decreased with the number of channels since more XPM distortion was introduced. The variances of separate channels could be used to obtain the total distortion. Secondly, assuming a constant launch power into the link the optical SNR of each channel depends on the total channel number. For large channel numbers transmission is limited by ASE noise. In the case of fewer channels, the measured effects of XPM and SPM were found to degrade $Q$ significantly.

For the first time, Q-factor measurements were quantitatively related to pump-probe experiments. XPM distortion was shown to accurately estimate the Q-factor for multi-channel transmission. This technique was successfully demonstrated in two cases:

- The penalty due to XPM was investigated as a function of distance. Measurements and analytical calculation of XPM distortion for the same link allowed to estimate the Q-factor for 2-channel transmission. A comparison with directly measured Q-factors showed that this technique was accurate within 0.2dB after 5 recirculations.

- For a constant number of spans, the Q-factor was initially measured for a single channel. The Q-factor for 2-channel transmission for a range of $\Delta\lambda$ was calculated by combining the single channel Q-factors and $\sigma_{XPM}$ obtained in pump-probe experiments, and shown to give good agreement with the direct Q-factor measurements.
Chapter 6

OTDM experiments

In chapter 4 and 5 the effects of XPM distortion were investigated in detail for WDM systems for NRZ-modulated channels. In this chapter the impact of the multi-channel nonlinear effects XPM and FWM on transmission is eliminated by single-channel high-speed RZ transmission where. In this case, information would no longer be carried in parallel by distinct optical channels but combined in a serial transmission over a single channel using optical time-division multiplexing (OTDM). Hence, for a WDM system with a bit-rate of 10Gbit/s and 8 channels the equivalent OTDM transmission would require a channel modulated at 80Gbit/s. Multiplexing the channels in the time domain requires RZ modulation with an appropriate duty cycle to ensure channel separation. As already explained in section 2.2.6, RZ is a digital format where the pulse shape is independent of the bit pattern. Therefore, nonlinearities and fibre dispersion affect all pulses in the same way. It is the uniformity of the RZ pulse distortion that allows to compensate for transmission degradation using all-optical regeneration techniques.

In this chapter, nonlinearities are shown to be beneficial for OTDM transmission. This is due to constructive interaction of SPM and fibre dispersion in the anomalous dispersion region of the fibre. In the first part, transmission limitations at 40Gbit/s due to SPM and dispersion are investigated. The OTDM transmitter and receiver used for the transmission experiments are described in section 6.1. This is followed by direct BER measurements and the analysis of optical spectrum and pulse form as a function of fibre dispersion, signal wavelength and transmission distance using a recirculating loop. Although the transmitted pulses exhibited soliton-like properties no active soliton control was applied. Since soliton propagation theory is outside the scope of this thesis, the reader is referred to the extensive literature for a more detailed description of solitons [AGR95, TAY90]. The second part of this chapter focuses on all-optical 3R-regeneration as an application of nonlinearity-assisted optical switching used for signal restoration by RE-amplification, RE-shaping and RE-timing. In section 6.2 an all-optical regenerator based on the XPM effect in a semiconductor optical amplifier (SOA) was characterised in back-to-back measurements and was used in transmission experiments where the error-free transmission distance could be increased.
6.1 OTDM transmission experiments

6.1.1 Principle of OTDM transmitters

In Fig. 6.1 the principle of optical time division multiplexing is illustrated for 4 independent channels combined into a single data stream. To enable demultiplexing of the OTDM signal with low cross-talk and avoid interaction between neighbouring pulses during transmission the width of the optical pulses must be significantly less than the duration of the allocated timeslot $T_0$, e.g. $\ll 25\text{ps}$ for 40Gbit/s. For a system operating at an aggregate bit-rate greater than 40Gbit/s the source must produce very short pulses, typically less than 10ps duration. Therefore, when multiplexing the different data streams each data stream illustrated in Fig. 6.1 needs to run at the base rate with a low duty cycle, and a high extinction ratio of the RZ pulses (typically $>20\text{dB}$) to minimise coherent cross-talk between signal and the background.

To date, channel line rates of 40Gbit/s were used over 900km SSMF and DCF spans [HAR99] and more recently 320Gbit/s over 200km NZ-DSF [RAY00] were reported or even 640Gbit/s over 92km using a combination of SSMF and reverse dispersion fibre [YAM00]. Using active soliton control at 40Gbit/s the transmission distance could be extended to 70,000km over DSF [SUZ98].

![Schematic of OTDM combining N=4 data channels for serial transmission.](image)

The data encoding is carried out at the base rate, i.e. 4 independent RZ-coded data streams of 10GHz drive the respective amplitude modulators (e.g. LiNbO$_3$) as shown in Fig. 6.2. Another approach is the direct modulation of the RZ source with a 40GHz data modulator. In this case, the 10GHz output of the RZ pulse generator can either be optically interleaved first
to provide a 40GHz output or a direct 40GHz pulse source can be used. In the following experiments, however, a third configuration was used with a single 10Gbit/s LiNbO₃ modulator placed before the 1x4 splitter modulating the 10GHz RZ pulses directly with a PRBS sequence from the PPG (HP 71612A). The modulator was driven with a wide-band amplifier (15KHz-10GHz) with an output signal of 15V peak-to-peak. In the subsequent passive interleaver the 10Gbit/s signal was split into 4 different channels which were delayed relative to each other and recombined. The length of the fibre delay lines was sufficient to decorrelate a $2^7$-1 pattern prior to the multiplexing to 40Gbit/s. For the interleaving of $N=4$ optical streams with $\tau=100$ps bit repetition rate at 10GHz, the time difference in the absolute delay $\Delta t$ between any two channels must be $\tau/N + \tau n = (25+100\cdot n)$ps where the integer $n$ depends on the length difference of the delay lines for neighbouring channels. In the following experiments, the length of the path could be fine-tuned with free-space delay lines over a variable range of approximately 3cm corresponding to 100ps. Polarisation maintaining (PM) fibre, polarisation controllers and a polarising beamsplitter were used to ensure all bits of the 40Gbit/s signal had the same state of polarisation.

![Fig. 6.2 Conceptual diagram of OTDM transmitter comprising RZ pulse source, data encoding and optical interleaving, PC: polarisation controller: (a) used in experiments, (b) parallel encoding of 4 OTDM channels, (c) direct modulation of multiplexed channel at 40Gbit/s](image-url)
6.1.2 RZ pulse sources

The RZ sources used in the experiments described in this chapter are based on mode-locked external cavity lasers (ML-ECL) and electro-absorption modulators (EAM) and were operated with a pulse repetition rate of 10GHz. In addition to these pulse sources, a variety of other sources is described in the literature and the most important ones are listed in Table 6.1. The main criteria for the pulse source are pulse width and extinction ratio, followed by stability issues such as timing jitter.

<table>
<thead>
<tr>
<th>Source type</th>
<th>Comments / typical data</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>mode-locked ECL</td>
<td>high nonlinear chirp, pulse width 4.2ps, SNR (&gt;40dB)</td>
<td>[WIE90]</td>
</tr>
<tr>
<td>electro-absorption modulator (EAM)</td>
<td>low extinction ratio, optical SNR=25dB, pulse width 14ps, simplicity, robustness</td>
<td>[M0095]</td>
</tr>
<tr>
<td>gain-switched DFB</td>
<td>high RMS jitter, 7ps, simplicity</td>
<td>[LIU81]</td>
</tr>
<tr>
<td>supercontinuum</td>
<td>ideal source, 2ps pulse width, 9.95GHz repetition, 400Gbit/s after MUX</td>
<td>[BOI00]</td>
</tr>
<tr>
<td>colliding-pulse mode-locked semiconductor laser</td>
<td>192GHz repetition rate, RMS jitter 0.6ps, 1.3ps pulse width</td>
<td>[HAS98]</td>
</tr>
<tr>
<td>mode-locked laser with integrated EAM</td>
<td>pulse repetition 102GHz, 2.4ps pulse width, 0.33ps RMS timing jitter</td>
<td>[SAT98]</td>
</tr>
<tr>
<td>monolithic mode-locked laser diode</td>
<td>pulse width 790fs, 20GHz repetition rate, jitter: not measured</td>
<td>[ARA00]</td>
</tr>
<tr>
<td>mode-locked erbium fibre ring laser</td>
<td>40GHz repetition, 1.9ps pulse width, timing jitter &lt;0.1ps</td>
<td>[BAK00]</td>
</tr>
<tr>
<td>active fibre ring laser</td>
<td>1.6ps pulse width, RMS jitter 0.46ps</td>
<td>[ELL99]</td>
</tr>
</tbody>
</table>

Table 6.1 Overview of RZ pulse sources, the highlighted sources were evaluated in experiments, pulses: FWHM width listed with RMS timing jitter

A Mode-locked ECL

The schematic diagram for a mode-locked semiconductor external cavity laser (EC-MLL) is shown in Fig. 6.3. The laser cavity is formed between the front facet of a semiconductor device (e.g. FP laser) and an external diffraction grating coupled to the rear facet. The semiconductor section was driven by sine wave modulating the population inversion of the gain medium. The bulk grating allowed wavelength tuneability and the appropriate bandwidth for the desired pulse width. A larger spot size and smaller grating pitch increased the bandwidth inside the cavity, and the coupling of a large number of spectral modes reduced the temporal pulse width. The pulses were chirped due to the change of carrier density when the laser was driven by the RF signal. The pulses originating in the semiconductor device were
blue-shifted at their leading edge with a frequency variation across the pulse. By choosing fibre with negative dispersion ($D<0$) the red-shifted components propagated faster and, therefore, the pulses could be linearly compressed. Optimising the fibre length, the pulses at the laser output were transform limited, i.e. their temporal width was solely determined by the input spectral width. For the EC-MLL used in the experiments, approximately 0.5km of DCF with $D\approx-50$ps/(km-nm) were used to minimise the linear chirp and produce pulses with 6ps FWHM and 10GHz repetition rate. The main advantages of using the ML-ECL are tuneability of wavelength, short pulse width and the high extinction ratio (>40dB) between pulses and ASE background.

![Schematic of external cavity mode-locked semiconductor laser, driven by external 10GHz sinusoidal signal, subsequent linear pulse compression and data modulation using MZM](image)

**Fig. 6.3**

10Gbit/s, PRBS, MZM data modulator

10GHz RZ eye-diagram measured at output

In addition to the EC-MLL source a RZ transmitter based on EAMs was evaluated in the experiments. The set-up of this transmitter is shown in Fig. 6.4. A combination of two EA modulators was used to shape the pulse from the CW input signal. These MQW devices had a typical insertion loss of 10dB and an extinction ratio of approximately 30dB. The main advantage of the cascaded EAMs is the reduction of the duty cycle in comparison to a single EAM to less than 10% at 10GHz, which allowed multiplexing of the signal up to 40Gbit/s.
When shaping the low duty-cycle RZ pulses at 10GHz, two approaches were combined to reduce the resulting pulse width: firstly, the modulators were driven with a 10GHz sinusoidal signal combined with its second harmonic at 20GHz leading to a faster pulse rise time (by a factor of 1.8) as shown in Fig. 6.5(a). Due to the high reverse bias of $-8V$ and 30dBm RF output power into the EAM only the narrow pulses with 10GHz repetition rate resulted in transmission of the signal through the EAM reducing the pulse width and duty cycle of the RZ pulse train. Secondly, the transmission window of the cascaded EAMs was brought to a temporal overlap reducing the pulse width, e.g. by a factor $\sqrt{2}$ for two identical Gaussian pulse shapes as illustrated in Fig. 6.5(b).

---

**Fig. 6.4** RZ transmitter for 10GHz low duty cycle pulses, data modulation and pulse compression

**Fig. 6.5**

(a) Enhancement of the EAM drive signal by combining 10GHz and 20GHz component resulting in faster rise time and lower duty cycle (--), 10GHz signal alone ( ), (b) further pulse narrowing at transmitter output due to 2 cascaded EAMs where the associated transmission windows coincide in time for minimum pulse width
Increasing the temporal mismatch between the two EAM transmission windows resulted in a decrease of the signal-to-background contrast compromising the optical SNR of the output pulse and increasing cross-talk when multiplexing the pulses into an OTDM signal. The DCF was used to counteract the linear chirp inevitably accompanying the amplitude modulation imposed by the EAM and allowed to compress the pulses to a FWHM width of 6-8ps. Fig. 6.6 shows the eye diagram of the 10GHz RZ signal in back-to-back mode measured for the PRBS-modulated EAM source and the pulses were compressed using additional DCF at the output. Since the pulse shape displayed on the sampling oscilloscope was limited by the bandwidth of the receiver photodiode (approximately 20GHz), an auto-correlation measurement was used for the accurate measurement of the pulses. After comparison of the oscilloscope traces a sech² profile was assumed for the pulses corresponding to a full width half maximum (FWHM) of approximately 7ps.

**Fig. 6.6 left:** eye diagram measured at output of EAM-based RZ transmitter, 10GHz repetition rate, 2¹¹⁻¹ PRBS modulation, $\lambda$=1557nm, **right:** auto-correlation trace for 10GHz RZ signal, pulse width determined as $T_{\text{FWHM}}$≈ 7ps

### 6.1.3 Recirculating loop for OTDM transmission

Both the EAM and the EC-MLL source were used to transmit a 40Gbit/s OTDM signal over a multi-span link investigating transmission limitations due to SPM and dispersion. The total length of the loop was 98.9km with 3 equal spans using DSF fibre to keep the total accumulated dispersion during the propagation low, e.g. 5.9ps/nm at $\lambda$=1550nm. The mean value $\lambda_0$=1548.6nm, obtained by averaging over the fibre data shown in table 6.2, was also confirmed by propagating a tuneable laser through the link. Close to $\lambda_0$, spectral broadening due to FWM between the CW line and the ASE background could be observed on the OSA. The full experimental set-up of the recirculating loop used for investigation of transmission limitations is shown in Fig. 6.7.
Table 6.2 Fibre data for DSF used in OTDM transmission experiment, $dD/d\lambda = 0.06\text{ps/(km-nm)}^2$

<table>
<thead>
<tr>
<th>span no.</th>
<th>length [km]</th>
<th>$\lambda_0$ [nm]</th>
<th>loss [dB/km]</th>
<th>$D$ [ps/(km-nm)] @1550nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.65</td>
<td>1548</td>
<td>0.214</td>
<td>+0.12</td>
</tr>
<tr>
<td>1</td>
<td>15.44</td>
<td>1549</td>
<td>+0.06</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>18.31</td>
<td>1549</td>
<td>0.223</td>
<td>+0.06</td>
</tr>
<tr>
<td>2</td>
<td>12.73</td>
<td>1549</td>
<td>+0.06</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1548</td>
<td>+0.12</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>8.84</td>
<td>1545</td>
<td>0.217</td>
<td>+0.03</td>
</tr>
<tr>
<td>3</td>
<td>11.03</td>
<td>1550</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>8.84</td>
<td>1550</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1548</td>
<td>+0.12</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6.7 Experimental set-up of OTDM recirculating loop experiment, the tuneable filters were adjusted for maximum SNR.

The loop operation and timing was controlled by NEOS AOMs with 3dB insertion loss and at least 45dB of contrast between the ‘on’ and ‘off’ state. The EDFA's used were single pump (1480nm) units with up to 12dBm output power and 6dB noise figure. At the EDFA output, tuneable filters TB1570 with 3nm bandwidth were used to reduce accumulation of amplifier ASE. The power into each DSF span was about 5-10dBm and could be adjusted to optimise
the transmission distance. A high-precision time synthesiser controlled the loop timing as a master oscillator. The timing of the individual AOMs and loop EDFAs was performed by four different delay generators: signal injection into the loop, controlling the total loop transmission time, the gating window for distance-dependent measurements and switching the pump lasers of the loop EDFAs. A simplified timing diagram for this loop is shown in Fig. 6.8. Unlike the loop timing for XPM measurements in chapter 4 the total time frame for the loop operation was constant and given by the time synthesiser. The duration was fixed in the interval 5-10ms accounting for signal injection, signal propagation inside the loop and clearing the loop. The duration for a single recirculation over 3 spans was $\Delta t_{rec} = 485\mu s$. The total delay $\Delta t=n\cdot 485\mu s$ determined the propagation distance for a particular measurement. As can be seen in Fig. 6.8, AOM-1 operates inversely to AOM-3 resulting in a constant back-to-back signal at the loop output whenever the loop is inactive. This feature allowed convenient back-to-back measurements as well as a reduction of transient processes in the EDFAs due to the switching of the pump lasers at the output of AOM-2 at the beginning and end of the loop operation.

Fig. 6.8 Loop timing diagram showing electrical driving signal from delay generators, and typical values for timing, circled number indicates corresponding AOM in Fig. 6.7

Fig. 6.9 shows an example of the loop timings displayed on an oscilloscope where the lower trace displays the loop output signal detected with a photodiode (PD). Of interest is the relative position of the PD trace with respect to the other traces shown previously in Fig. 6.8. During the time when the back-to-back signal was connected to the loop output a constant waveform was detected. However, the detected signal fluctuated during transmission and could be used to distinguish particular loop recirculations. In this example, $\Delta t$ was chosen to measure the signal after 10 recirculations corresponding to 1000km.
6.1.4 Optical demultiplexer and receiver

OTDM receivers must recover one of the base rate electrical signals from the serial OTDM data stream. A receiver unit, therefore, consists of three logical blocks: a clock recovery circuit, a demultiplexer and a decision circuit as shown in Fig. 6.10.

The electrical clock recovery could be directly operated at the line rate using a PLL circuit. In these experiments, it contained a voltage-controlled oscillator (VCO) at 10GHz and a 40GHz mixer shown in Fig. 6.10(a). The VCO signal was up-converted in two stages to provide a local 40GHz signal (LF) mixed with the detected OTDM signal (RF). The beat signal (IF) in the mixer was analysed by the PLL electronic control circuit adjusting the VCO voltage in order to lock onto the incoming signal. As a result, the VCO provided a stable clock signal at 10GHz base rate, which could be distributed among the receiver components. The RMS jitter of the clock was measured to be less than 0.3ps [ELL97]. The sensitivity of the clock recovery is defined as the minimum input power to allow synchronisation between signal and local oscillator. In the experiments the receiver sensitivity was measured to be better than -15dBm.

An active demultiplexer is required to separate out the channels at the base rate. In the receiver an electro-optical technique was employed where a single electroabsorption modulator (EAM) was used as discussed in [MOO95] with possible line rates up to 80Gbit/s. The EAM was driven by the recovered clock signal where a variable phase delay was used to select a channel from the OTDM stream as shown in Fig. 6.10(b). The EAM switching window of ≈13ps, synchronised to the incoming data stream, allowed to isolate a single channel at 10GHz from the 40Gbit/s RZ signal whilst the other 3 neighbouring channels were
suppressed. The EAM insertion loss was 7dB and the extinction ratio was approximately 20dB effectively suppressing the cross-talk from the neighbouring channels in the receiver.

![Diagram of electronic clock recovery circuit](image)

**Fig. 6.10** (a) diagram of electronic clock recovery circuit, VCO: voltage controlled oscillator, LF: local oscillator frequency, IF: mixing signal (b) schematic block diagram of 40Gbit/s OTDM receiver including clock recovery, demultiplexer (channel 1 selected) and BER analysis

### 6.1.5 Transmission experiments at 40Gbit/s

The signal from the EC-MLL pulse source was multiplexed to 40Gbit/s by optical interleaving and injected into the recirculating loop. Fig. 6.11(a) shows the laser output spectrum. The separate modes of the mode-locked laser, spaced in intervals of 10GHz, are clearly visible. The optical signal to noise ratio was approximately 20dB and the FWHM width was about 0.44nm. The auto-correlation measurement in Fig. 6.11(b) shows distinct peaks for the PRBS-modulated OTDM signal. The smaller peaks correspond to cross-correlation between different OTDM channels. Due to the fibre delay lines in the interleaver the channels are independent and result in half the peak amplitude of the maximum due to the
equal statistical distributions of ‘1’ and ‘0’. Without a modulation signal all channels are correlated resulting in the same height of all peaks. The main peak of the auto-correlation trace is the due to the correlation of the detected channel with itself. It is used to calculate the FWHM pulse width as 6.5ps with a time-bandwidth product of 0.35. Therefore, the transmitter provided, after pulse compression in the DCF, almost transform limited hyperbolic \( \text{sech} \) pulses characteristic for solitons (ideal: 0.31 according to [DUL95]).

![Graph](image)

**Fig. 6.11** (a) measured spectrum of EC-MLL at input of recirculating loop, (b) autocorrelation trace of 40Gbit/s PRBS in back-to-back mode with linear pulse compression giving time-bandwidth product of 0.35, side peaks are additionally broadened due to timing jitter between the multiplexed channels

**Optical spectrum:** During transmission, the signal was subject to pulse broadening due to dispersion and noise was accumulated with every EDFA. Dispersive broadening could be reduced by increasing the launch power into the link resulting in SPM recompressing the pulses or optimisation of the signal wavelength to keep the accumulated dispersion low. The error-free transmission distance was found to depend strongly on the signal wavelength with respect to the mean \( \lambda_0 \) of the link:

- For \( \lambda=1551.5\text{nm} \) and accumulated dispersion of \( D \cdot L=17.2\text{ps/nm} \) per recirculation, the error-free distance for stable operation (\( T>20\text{min} \)) was 3 recirculations. After more than 5 recirculations the transmission was believed to be limited by polarisation mode dispersion and a low BER could only be maintained by a continuous adjustment of the signal polarisation inside the loop.
- For \( \lambda=1549.5\text{nm} \) and accumulated dispersion \( D \cdot L=5.2\text{ps/nm} \) per recirculation, up to 10 recirculations of error-free transmission were achieved with stability for several minutes. After 20 recirculations BER= \( 10^{-9} \) was measured and the transmission distance showed a high sensitivity to the polarisation inside the loop suggesting an increasing influence of PMD which breaks up the pulses. The minimum BER after 30 recirculations increased to BER=\( 10^{-7} \).
Fig. 6.12 shows the spectral shape measured for the pulse centred at $\lambda = 1551.5$nm as a function of transmission distance up to 15 recirculations. The optical spectrum was measured at the loop output and the time-dependent output signal could be directly translated into the propagation distance by the time $\Delta t_{rec} = 485\mu s$ required for each recirculation. The pulse shape shows a periodic change with time: the constant pulse shape corresponds to the time when the back-to-back is signal directly connected to the output via AOM-1. It separates the cycles of loop recirculation where the spectrum broadens with distance due to dispersion and nonlinearity. The signal broadening is evident in Fig. 6.14 where the three-dimensional graph is projected into the time-wavelength plane and the time-dependent signal for a given wavelength is shown as a contour plot. In addition to linear broadening due to dispersion, additional spectral broadening was observed increasing towards shorter wavelength. The spectral components of the signal close to $\lambda_0$ of the transmission fibre experiences FWM between the signal and the background ASE as a result of the near phase-matching condition.

As discussed before, the error-free transmission distance was increased to over 1000km by tuning the signal to $1549.5$nm illustrated in Fig. 6.13 and Fig. 6.15. The shape of the spectrum remained constant over almost the entire transmission distance of 3000km. Since the dispersive broadening close to $\lambda_0$ was expected to be small the launch power into the link had to be lowered to reduce the amount of SPM counteracting dispersion. In case of soliton-like pulses the dispersion constant $\beta_2$ and peak power are coupled via the nonlinearity of the fibre for a given pulse width. According to [AGR95], the following relation must be satisfied for time-independent pulses:

$$P \approx \frac{3.11|\beta_2|}{\gamma T_{FWHM}^2}$$

(6.1)

For 6.5ps FWHM pulse width and the given values of $\lambda$ and $\lambda_0$, the peak power in the experiments had to be reduced to approximately $5$dBm to maximise transmission distance. This is in agreement with equation (6.1) using $\gamma = 2.43/(W$km) and $\beta_2 = -1.15$ps$^2$/km for $\lambda = 1549.5$nm.
Chapter 6: OTDM experiments

Fig. 6.12 Optical spectrum vs. distance up to 1500km measured in recirculating loop experiment. 40Gbit/s OTDM signal at $\lambda=1551.5\text{nm}$, launch power 10dBm.

Fig. 6.13 Optical spectrum vs. distance up to 3000km measured in recirculating loop experiment. 40Gbit/s OTDM signal at $\lambda=1549.5\text{nm}$, launch power 5dBm.
Fig 6.14 Contour plot of spectral broadening versus distance for signal at $\lambda=1551.5$nm, broadening increases for signal components close to $\lambda_0$.

Fig 6.15 Contour plot of spectral broadening versus distance for signal at $\lambda=1549.5$nm.
RF spectrum: The RF spectrum of the PRBS-modulated channel was used for a qualitative analysis of the pulse evolution with transmission distance. During the loop transmission, the amplifier ASE was shaped by the cascaded in-line filters similar to the optical signal passing through these filters. Therefore, the optical spectrum of the transmitted signal containing noise cannot be clearly distinguished from a noise-free signal. The RF spectrum analyser, however, could monitor characteristic frequency components of the signal at the loop output to estimate the signal degradation with distance. The frequency sweep of the RF analyser was set to zero and the RF signal power at the given frequency \( \Omega \) was detected as a function of loop propagation time. For a pattern length of \( 2^7 \cdot 1 \) at 10GHz, the lowest frequency component of \( \Omega_1=(10\text{GHz}/127)=78.74\text{MHz} \) corresponds to the repetition rate of the complete data sequence. The evolution of the \( \Omega_1 \) frequency component of the PRBS signal with distance is shown in Fig. 6.16. It is compared with the 10GHz clock signal of the demultiplexed base-rate channel and a background noise measurement at \( \Omega_1/2=39\text{MHz} \). An important observation is the constant level of RF power of the data signal during all 30 recirculations at \( \lambda=1549.5\text{nm} \) maintaining an electrical SNR of 20dB. These results confirm that the 40Gbit/s signal propagated in a temporally pulses during the loop transmission, in agreement with the time-independent spectral pulse width shown in Fig. 6.15.

![Eye diagram](image)

**Fig 6.16**  RF spectrum of demultiplexed 40Gbit/s signal with \( 2^7 \cdot 1 \) PRBS modulation, measured as a function of transmission distance over 1-30 recirculations, \( \lambda=1549.5\text{nm} \), monitoring of 10GHz clock, \( \Omega_1=78.74\text{MHz} \) data signal component and background noise

Eye diagram: The sensitivity of the transmission results towards fibre dispersion was also analysed in the time domain. Fig. 6.17 shows the measured eye diagram after 1000km transmission for \( \lambda=1549.5\text{nm} \) and \( \lambda=1557\text{nm} \). The low dispersion of approximately...
+0.1ps/(\text{nm-km}) close to $\lambda_0$ results in low pulse distortion and the clear traces in the eye-diagram indicate a low error-rate. However, when the dispersion increases to 0.7ps/(\text{nm-km})
the eye diagram is totally distorted after 10 recirculations with considerable noise and jitter.

Fig. 6.17  Eye diagram of 40Gbit/s signal after 1000km loop transmission over DSF fibre, 7dBm launch power into spans, (a) for $\lambda=1549.5$nm, (b) for $\lambda=1557$nm

6.1.6 Analysis of transmission results

The maximum achievable transmission distance for $\text{BER}=10^{-9}$ was calculated as a function of the signal wavelength and compared with the experimental results of section 6.1.5. For the following calculation, soliton-like pulses were assumed in agreement with autocorrelation measurements. As observed before in the experiments, the pulses were mainly degraded by the decreased signal-to-noise ratio and increased timing jitter. The BER was calculated using analytical expressions for the Gordon-Haus jitter [GOR86, ELL97]. The timing jitter was found to increase with the dispersion limiting the transmission distance when $\lambda$ was tuned away from $\lambda_0$. The transmission results shown in Fig. 6.18 were calculated using DSF with $L_{sp}=33\text{km}$ span length, $A_{eff}=50\mu \text{m}^2$, $\alpha=0.2\text{dB/km}$ fibre loss, jitter-free pulses with $T_{\text{FWHM}}=6.5\text{ps}$, $P=7\text{dBm}$ launch power and 400GHz optical and 7GHz electrical filter at the receiver. These results show the maximum error-free distance as a function of signal wavelength, and hence, dispersion.

In the transmission fibre the Gordon-Haus jitter was dominant limiting the error-free transmission distance with increased fibre dispersion. In this regime, the effect of PMD (<0.06ps/\text{V-km}) and SNR was negligible on the pulses. Close to $\lambda_0$ the power necessary for soliton-like pulses decreases according to equation (6.1) and, therefore, the BER increases with reduced SNR. Optimum transmission reaching up to a few thousand kilometres was confined to an interval $\Delta \lambda \approx 1\text{nm}$, shifted by $+1.5\text{nm}$ into the anomalous dispersion region. In this wavelength range, the longest experimental transmission distance was achieved.
The experimental results of this thesis qualitatively follow the calculated traces for the jitter-limited error-free distance but are limited to shorter distances. One important factor for this additional degradation was the pulse quality of the RZ source which was assumed to be ideal in the calculations. However, the accuracy of the delay lines in the fibre interleaver determined the variation in the relative spacing between neighbouring pulses and peak power fluctuation and the pulse position jitter all contribute to the total transmission penalty observed in the experiments. For comparison, the transmission distance could be improved by almost a factor of 2 when using a fibre ring laser as the pulse source [ELL96]. Enhanced performance is also expected when employing alternating polarisation to suppress soliton-soliton interactions and guiding filters to reduce timing jitter [ELL97].

In summary, a recirculating loop test-bed was used to investigate high-speed OTDM transmission at 40Gbit/s. A mode-locked external cavity laser (ML-ECL) provided a tuneable RZ pulse source with 10GHz repetition rate passively interleaved to form a 40Gbit/s data stream. The error-free transmission distance was investigated as a function of accumulated fibre dispersion and it was found that timing jitter limited the maximum distance to approximately 1200km. Although longer error-free distances at 40Gbit/s were shown experimentally the primary aim of this work was to design and test a transmission link for subsequent all-optical regenerator experiments.
6.2 All-optical regeneration

Propagation of soliton-like pulses allows transmission of the OTDM data stream over ultralong distances. However, as shown in section 6.1 the accumulation of timing jitter and amplitude noise imposes a limit on the achievable bit-rate distance product. It is therefore desirable to re-time, re-shape, and re-amplify the transmitted data. In an all-optical network using optical cross-connects and add-drop multiplexer, signals routed over different distances result in variation of signal quality. Regeneration, however, results in digital transmission, including cascadability of links and modularity, as the signal quality no longer depends on its routed path.

In the previous section it was shown that unrepeatered 40Gbit/s transmission is severely limited by timing jitter due to the residual link dispersion, spectral broadening and decreased SNR. As result, long-distance transmission over more than 1000km was found to be restricted to a small wavelength interval <1nm only. In this section, the concept of 3R regeneration is described using a semiconductor optical amplifier (SOA) for optical switching to overcome these limitations. Unlike in chapter 4 and 5, the XPM effect is used to increase transmission distances utilising all-optical switching techniques.

6.2.1 Introduction and overview

The concept of optical regeneration is illustrated in Fig. 6.19 showing the 2 key elements essential for optical regeneration:
(a) The local clock source operating at the line rate with low-jitter pulses at the output
(b) The regenerative stage using the degraded transmission signal to encode the data on the local clock signal

Optical regenerators can be divided into 2R and 3R regenerators. The main difference is the local clock source present in the 3R regenerator allowing to re-time the pulses in addition to amplification and reshaping, thus removing timing jitter. 2R- and 3R regeneration have been studied in detail for both fibre-based regenerative gates and for semiconductor-based gates. In this work, the focus is on SOA-based gates using an ultrafast non-linear interferometer (UNI) which was first described by [PAT96]. Recently, it has been shown by Hall et al. that this configuration is capable of operating at 100Gbit/s [HAL98] however no regeneration has been demonstrated at these repetition rates. Fig. 6.20 provides an overview of the different concepts for regenerative stages. For the clock recovery used in 3R units, different techniques can be utilised which were already described in section 6.1.4.
Chapter 6: OTDM experiments

Nonlinear Element / Regenerative gate

Regenerative gates

Semiconductor-based gates
[PIN99, MIK97]

Fibre-based gates
[PE95]

Cross-phase modulation (XPM)

SOA-based gates

Cross-gain modulation (XGM)
[DUR96]

Ultrafast nonlinear interferometer (UNI)
[PAT96, TH98]

Small, integrable

Fast, ASE-free

Fig. 6.19  Principle of 3R regeneration using a nonlinear switching device to encode the local clock signal at $\lambda_1$ on the incoming data stream at $\lambda_2$, the input shows fluctuation in power and timing

Fig. 6.20  Overview of different techniques used in regenerative stages

Among the SOA-based gates, the XGM stages (these are not in an interferometric configuration) have the advantages of robustness against signal power variations and polarisation insensitivity, and have been demonstrated at up to 40Gbit/s operation [DAN96]. However, the chirp generated in the XGM process and the inverted data signal of the XGM-regenerated signal are drawbacks of this solution. Since XPM primarily generates a power-dependent phase shift, the regenerative stages based on XPM must be used in an interferometric configuration where the phase shift is converted into an amplitude variation sufficient for switching. Durhuus developed in 1995 [DUR95] a hybrid SOA–fibre Mach-Zehnder Interferometer (MZI), illustrated in Fig. 6.21. In this configuration the variation of the refractive index in a SOA due to gain saturation was used as the basis for optical switching. The operation of the interferometer is as follows: a data signal at $\lambda_1$ unbalances the MZI inducing additional phase shift and gain variation in the SOAs resulting in a variation of the output intensity at $\lambda_2$. The principle of the UNI operation is similar to the MZI. In this specific case, the two different optical paths used in MZI configuration are substituted by two orthogonally polarised signal components, which are separated by $\Delta \tau$ and recombined after passing through a single SOA as shown in Fig. 6.23. For optical switching, the refractive index of the SOA is varied by the switching signal for only one pulse component. The
resulting variation of the relative delay between the two pulses leads to an intensity variation at the UNI output. The main advantages of optical gates in MZI configuration is the noise reduction as a result of the flat top of the sinusoidal transmission curve obtained for the maximum signal power. Therefore, small power fluctuations of the '1'-level as induced by ASE noise of the incoming signal leave the output unaffected and the extinction ratio of the signal at the MZI output increases. Co-propagating configurations require 2 different wavelengths for the input and output, i.e. the regenerated signal is shifted by $\Delta \lambda$ and must be separated by the original input signal using optical filters. Counter-propagation on the contrary has the advantage of signal regeneration without wavelength shift eliminating additional wavelength conversion following the optical gate.

![Diagram of Mach-Zehnder interferometer using 2 SOAs for optical switching](image)

For the UNI configuration discussed in this thesis, the signal was split into 2 orthogonally polarised components mimicking the MZ configuration. In general, polarisation-based devices often suffer from long-term polarisation instability of the interferometer and polarisation control is therefore an important issue. 2R regeneration [DUP98] was not considered in this thesis because it does not allow to correct the timing jitter. A schematic comparison between both the 2R and 3R concept is made in Fig. 6.22.

An overview listing recent work in this active field of 3R optical regeneration is given in table 6.3 which provides information on the type of optical gate, optical or electrical clock recovery, bit-rate, span length before regeneration and, in the case of cascaded operation, the total distance. The optical gates are either fibre- or semiconductor-based. In the latter case, 2
stage configurations are used to improve the pulse reshaping. The importance of XPM for optical regeneration is evident throughout Table 6.3.

![Diagram](image)

**Fig. 6.22** left: 2R regenerator using SOA-based optical gate, right: 3R regenerator for additional correction of timing jitter, in both cases $\Delta \lambda = \lambda_1 - \lambda_2 = 0$ is possible for counter-propagation

<table>
<thead>
<tr>
<th>Gate</th>
<th>Clock recov.</th>
<th>Bit rate</th>
<th>Regen. Span</th>
<th>Total distance</th>
<th>Comments</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Kerr shutter (XPM)</td>
<td>Fibre ring laser</td>
<td>40Gbit/s</td>
<td></td>
<td></td>
<td>first 40Gbit/s regeneration</td>
<td>BT</td>
</tr>
<tr>
<td>InP based MZ-modulator</td>
<td>O/E</td>
<td>20Gbit/s</td>
<td>90km, DSF</td>
<td>40000km</td>
<td>cascadability, soliton systems</td>
<td>Alcatel</td>
</tr>
<tr>
<td>InP based MZ-modulator</td>
<td>O/E</td>
<td>40Gbit/s</td>
<td>90km DSF</td>
<td>20000km</td>
<td>cascadability, polarisation indep.</td>
<td>Alcatel</td>
</tr>
<tr>
<td>UNI (XPM)</td>
<td>n/a</td>
<td>40Gbit/s</td>
<td></td>
<td></td>
<td>long pattern, first single $\lambda$ at 40Gbit/s</td>
<td>BT</td>
</tr>
<tr>
<td>UNI (XPM)</td>
<td>O/E</td>
<td>40Gbit/s</td>
<td>100km. DSF</td>
<td>2000km</td>
<td>first cascadability at 40Gbit/s, single $\lambda$</td>
<td>BT</td>
</tr>
<tr>
<td>E/O modulator</td>
<td>O/E</td>
<td>40Gbit/s</td>
<td>135km DSF</td>
<td>20000km</td>
<td>cascadability, theory only</td>
<td>Alcatel</td>
</tr>
<tr>
<td>E/O modulator</td>
<td>none</td>
<td>40Gbit/s</td>
<td></td>
<td></td>
<td>first asynchronous regenerator</td>
<td>BT</td>
</tr>
<tr>
<td>UNI (XPM)</td>
<td>n/a</td>
<td>80Gbit/s</td>
<td></td>
<td></td>
<td>highest bit-rate, wavelength conv.</td>
<td>BT</td>
</tr>
</tbody>
</table>

Table 6.3 Overview of progress in 3R-regeneration, 'n/a' denotes that no clock recovery was used in back-to-back operation, O/E: opto-electronic, own contributions are highlighted

### 6.2.2 UNI in back-to-back operation

In the first part of the experiments, the UNI was investigated alone. The schematic diagram of the UNI is illustrated in Fig. 6.23 and the experimental set-up used to demonstrate 40Gbit/s data regeneration is shown in Fig. 6.24. The UNI was implemented in a counter-propagating configuration allowing regeneration without wavelength shift. The output from a 10GHz
external cavity modelocked laser (EC-MLL) with $T_{\text{FWHM}} = 3.5\text{ps}$ pulses at 1550nm was spilt using a 3dB coupler. 50% of the signal was passively multiplexed up to 40GHz using a fibre interleaver, thus forming an RZ clock signal for the UNI. The remaining 50% of the signal were amplitude modulated by a 10Gbit/s, $2^{31}-1$ PRBS sequence using a lithium niobate modulator. This data signal was passively multiplexed up to 40Gbit/s using a polarisation maintaining fibre interleaver shown in Fig. 6.2, and was used as a switching signal to drive the UNI corresponding to the degraded signal in transmission experiments. The output signal of the UNI was demultiplexed to 10Gbit/s for measurements using an EA modulator, and then fed into a bit-error-rate (BER) test set. Varying the electrical delay at the modulator input allowed the selection of different channels.

Fig. 6.23 Schematic diagram of UNI based on XPM in a SOA device, polarisation controllers are omitted in the set-up, 2nd PM fibre with adjustable PMD using PZT, clock input: 40Gbit RZ, $45^\circ$ with respect to the principal axes of the PM fibre, signal input: 40Gbit/s RZ data for switching the SOA gate

Fig. 6.24 Experimental set-up of 40 Gbit/s data regeneration using a semiconductor nonlinear interferometer (UNI), EC-MLL used for clock signal synthesis and RZ data source.
Chapter 6: OTDM experiments

The operation of the UNI is based on the optical switching in a SOA and can be described as follows: At the input to the UNI, the clock signal was split into two orthogonally polarised pulses by launching it at 45° to the axes of a 7m long PM fibre. After traversing the PM fibre, the two orthogonal pulses were separated by Δt=15ps before they pass through a polarisation-insensitive SOA. The separation in time allowed to influence the pulse components inside the SOA individually by controlling the time delay Δτ of the switching pulses. The SOA was a large bandgap device with a gain recovery time of 80ps, and an alpha-parameter of ~9 [MAN98]. After the SOA the pulse pair is launched at −45° into a second length of PM fibre, where the delay between the two clock pulses is reversed and the two components recombine on passage through a fibre polariser. This second length of PM-fibre is wound onto a piezoelectric transducer (PZT), allowing simple adjustment of the interferometer bias. To set up the UNI properly, the output signal is minimised without switching input by adjusting iteratively the polarisation controller and the piezo-electric drum. The 40Gbit/s switching signal is then launched into the SOA via a 3dB coupler so that it counter-propagates with respect to the clock pulse pairs. As a switching pulse passes through the SOA of the UNI a rapid transition in its refractive index occurs. If it enters the SOA the instant the leading pulse has passed through the SOA - the trailing clock pulse component will be subject to a nonlinear phase shift as a result of the XPM effect.

Therefore, the trailing component of the clock will experience an additional delay T resulting in a total delay Δt+T before entering the second PM fibre. The mismatch of the pulse delays alters the interference after recombination and switching occurs at the UNI output. In order to suppress patterning effects it is necessary to enhance the effective recovery time of the SOA [MAN97]. In practice, this was achieved by optimising the clock signal power allowing the leading clock pulse to influence the carrier density evolution, rather than the following switching pulse. Recently, the operation of the UNI at 80Gbit/s was reported [KEL99]. The PMD of the PM-fibre was reduced to 5ps and a 2mm long polarisation insensitive MQW SOA was used as the optical gate with co-propagating clock and switching signal.

**Regeneration:** Initially, the clock signal was multiplexed to 40Gbit/s as indicated in Fig. 6.24 to allow true 40Gbit/s regeneration. Fig. 6.25 shows the results of 10Gbit/s BER measurements carried out on the 40Gbit/s regenerated output from the UNI. The regenerator operated error-free, with no indication of an error floor, although a penalty of 2.2dB was measured. This was due to the finite switching window of the UNI, approximately 8ps, determined by the separation of the clock pulses of 15ps, the dimensions of the SOA and the pulse width of the interacting pulses. The inset of Fig. 6.25 shows the oscilloscope traces of the 40Gbit/s input switching data stream with slight power variations of the channels, the
40GHz input pulse stream of the local source (clock), and the 40Gbit/s regenerated output, which shows a clear open eye and no indication of patterning.

![Graph](image)

**Fig. 6.25** All-optical 40Gbit/s data regeneration for $2^{31-1}$ RZ pattern, (■): 40 Gbit/s back-to-back, (□): 40Gbit/s regenerated data signal, Inset: (a) 40Gbit/s input data (switching signal); (b) 40GHz input pulses (clock); (c) 40Gbit/s regenerated data stream for counter-propagation

**Regenerative demultiplexing:** Reducing the frequency of the clock signal to 10GHz, all-optical 40-10Gbit/s regenerative demultiplexing was achieved. This is illustrated in the inset of Fig. 6.26, which shows the incoming 40Gbit/s data stream, and the four demultiplexed and regenerated 10Gbit/s channels. BER measurements indicate error-free operation, with a penalty between 1.4dB and 2.6dB, depending on the channel. This small variation of the penalties for demultiplexing was due to tolerances in the temporal channel alignment after the optical interleaving. In this UNI experiment, the switching power was measured (in-fibre) to be +4dBm implying an extremely low switching energy of only 120fJ.
6.2.3 Analysis of the UNI performance

**Bit-pattern:** In this section, the variation of the regenerator penalty under different operating conditions was investigated. At first, the impact of the bit-pattern length on the penalty of the UNI was analysed. The UNI was operated with counter-propagating clock and switching signal of the same wavelength $\lambda=1549\text{nm}$. In the experiment, BER measurements were performed using PRBS modulation with either $2^7$-1 or $2^{31}$-1 word length for the switching signal and the results are shown in Fig. 6.27. In the back-to-back configuration, the effect of different pattern length on the receiver was found to be negligible. However, the regenerated 40Gbit/s signal showed a small power penalty of 1dB for a $2^7$-1 pattern and an additional penalty of approximately 1.8dB when increasing the pattern length to $2^{31}$-1. The total penalty for 40Gbit/s regeneration for $2^{31}$-1 was in agreement with the results shown in Fig. 6.25. In summary, this measurement allowed to estimate the patterning in the UNI, i.e. the dependence of the penalty on the bit-pattern length. The penalty of 1.8dB due to the $2^{31}$-1 pattern was significant, however, in the experiments described in this thesis 3R regeneration at 40Gbit/s was shown for the first time shown at $2^{31}$-1.
Counter vs. co-propagation: The switching signal can be launched into the UNI in two different configurations: either clock and switching signal co-propagate or counter-propagate inside the SOA. In the case of counter-propagation, shown in Fig. 6.23, the same wavelength can be used for the switching and clock signal. Therefore, no additional wavelength conversion is required to maintain the optimum wavelength for retransmission of the regenerated OTDM signal. The UNI was investigated for both launch directions of the switching signal using $2^{31}-1$ pattern length. As shown in Fig. 6.28, the power penalty for regeneration using counter-propagation was about 3.2dB whilst for co-propagation 1.9dB were obtained. The increased penalty for regeneration in counter-propagation with $\Delta \lambda = 0$ is a result of internal reflections of the switching pulse at the two SOA facets which had a reflectivity of $\approx 10^{-4}$. This reflected signal light contributed to the signal at the UNI output increasing the BER and resulting in 1.3dB additional power penalty. Despite the slightly higher penalty, counter-propagation was chosen because of the cascadability of the UNI.

Signal polarisation: The tolerance of the UNI to polarisation fluctuations in the input data signal was also investigated for co-propagation of probe and switching signal, the configuration shown to have the lowest penalty (1.9dB with respect to back-to-back). With no active control of the polarisation during transmission the penalty introduced by the UNI was expected to change due to the polarisation dependence of the XPM process. The UNI was operated at 40Gbit/s with a $2^{31}-1$ PRBS sequence and a polarisation controller was used to vary the polarisation of the switching signal into the UNI. In Fig. 6.28 the results of BER
measurements for optimised polarisation and worst case polarisation are presented. The penalty varied by only 0.8dB for arbitrary input polarisation. More critical, however, was the correct alignment of the clock signal polarisation in the UNI before the measurements since the interferometer was using PM fibre as described in the beginning of this section.

Fig. 6.28  
(a) co-propagation vs. counter-propagation  
(b) polarisation tolerance for co-propagation

In summary, error-free 40Gbit/s all-optical regeneration using a semiconductor nonlinear interferometer was demonstrated with a pattern length of $2^{31}-1$. By changing the locally generated clock signal to the OTDM base-rate of 10GHz, 40Gbit/s to 10Gbit/s regenerative demultiplexing was achieved. For demultiplexing applications it is essential to ensure unwanted channels are completely removed. In this case, inter-channel cross-talk was eliminated simply by the absence of light from the low duty-cycle clock pulses at 10GHz while interacting with the 40GHz data signal. Operation at 40Gbit/s was achieved through the use of an optimised SOA device structure and a quasi-holding beam was formed by the clock pulses increasing the gain recovery time. The factors limiting the operation of the UNI were also investigated and the variation of the input signal polarisation was found to result in a penalty of less than 1dB. In addition, increasing the data pattern length from $2^7-1$ to $2^{31}-1$ increased the penalty by 1.8dB. The operation of the UNI with counter-propagating clock and switching signal resulted in a penalty of 1.3dB due to signal reflections from the SOA facets.
6.2.4 Transmission experiments using the UNI

After characterisation of the UNI in isolation all-optical regeneration was investigated in 40Gbit/s transmission experiments. In this section, multiple 40Gbit/s optical 3R data regeneration in a transmission link using a SOA-based nonlinear interferometer and electronic clock recovery is discussed. The cascadability, jitter tolerance and amplitude noise suppression of the regenerator were investigated and the error-free transmission was increased to distances greater than 2000km. The experimental set-up shown in Fig 6.29 combines the loop described in Fig. 6.7. The UNI-based 40Gbit/s data regeneration was investigated before and after loop transmission and after each recirculation.

The transmitter consisted of a 10GHz external cavity mode-locked laser (EC-MLL #1) operating at 1549.6nm, which produced 7ps pulses after nonlinear compression in 100 meters of dispersion decreasing fibre (DDF), to remove residual chirp. The pulse width was similar to the value used in section 6.1 and optimised for transmission. As before, 10GHz RZ pulses were modulated by a 2\(^{-1}\) PRBS data sequence using a lithium niobate modulator, and passively multiplexed to 40Gbit/s using a fibre interleaver. The output of the last fibre span (DSF 3) was used to drive the regenerator in case the UNI was operated inside the loop.

![Diagram of 40Gbit/s transmission experiment](image)

Fig. 6.29 40Gbit/s recirculating loop experiment investigating of all-optical regenerators. DSF 1-3: \(L_{op}=33\text{km}\) each, EC-MLL #1: external cavity mode-locked laser used as transmitter, (a), (b), (c) indicate the configurations investigated in UNI transmission experiments, EC-MLL #2 (clock for UNI) and the clock recovery unit are included in the UNI symbol.
The degraded 40Gbit/s data signal at \( \lambda_1 \) was split using a 3dB coupler before entering the UNI. One output was used as the switching signal to drive the SOA-based optical gate. The second output of the coupler was fed into an electronic clock recovery unit, which is based on an electronic phase-locked loop discussed in section 6.1.4. The recovered 10GHz clock signal at the output was subsequently used to drive a second RZ source (EC-MLL #2) producing \( T_{\text{FWHM}} = 4 \text{ps} \) pulses at \( \lambda_2 = 1550.5 \text{nm} \). This laser was optimised for short pulse width and operation with the UNI. This 10GHz optical pulse stream of EC-MLL #2 was then passively interleaved to 40GHz, and used as a high-quality clock signal to the UNI. The regenerated signal with \( \lambda_2 = \lambda_1 \) was (re-) launched into the loop or directly detected. For detection, the loop output signal was demultiplexed to 10Gbit/s using an electro-absorption modulator, and then analysed with the BERT.

**Loop transmission without UNI:** The BER of the 40Gbit/s PRBS pattern was measured as a function of transmission distance using the recirculating loop. For loop operation without the regenerator, error-free transmission at 40Gbit/s could be achieved up to 1200km when using the EC-MLL #1 at \( \lambda = 1549.6 \text{nm} \). As described in section 6.1.6 the main limiting factor was timing jitter due to the residual dispersion totalling \(+0.2 \text{ps/(km}\cdot\text{nm})\) at the operating wavelength.

**Configuration (a) - UNI before loop:** Shortening the pulse width of the transmitted pulses from \( T_{\text{FWHM}} = 7 \text{ps} \) to 4.5ps, either by locating the regenerator directly after the transmitter, or exchanging the pulse source with EC-MLL #2, reduced the error-free distance to 200km. A simulation of the transmission link as discussed in section 6.1.6 predicts a jitter-limited transmission distance of approximately 2000km at \( \lambda = 1550.5 \text{nm} \) launching 4ps pulses. This is a reduction of approximately 20% in distance compared to a system using 7ps pulses. However, the significant difference between the calculated transmission distance and the measurements using the EC-MLL #2 confirms the strong dependence of the achievable transmission distance on the light source and show that this distance depends critically on the properties of the probe source such as pulse width and jitter. In the following, the EC-MLL #2 was chosen as the local source supplying the RZ probe pulses for the UNI. In this case, the results of this measurement, approximately 200km, determine the maximum transmission distance between two regenerator stages.

**Configuration (b) - UNI after loop:** When the regenerator was placed at the output of the loop, the error-free transmission distance was reduced from 1100km to 700km. This was due to the finite switching window of approximately \( \Delta r = 8 \text{ps} \) of the UNI estimated by the flight
time difference of 15ps determined by the physical dimensions of the SOA, and the pulse widths of the two interacting pulses. In the case of transmission without UNI the switching window was given by the demultiplexing EAM and corresponds to half the bit-period, 12.5ps for 40Gbit/s transmission. The degree of timing jitter of the incoming data bits tolerable for the interaction of the clock and signal pulse is determined by the width of the switching window $\Delta \tau$ and determines the error-free transmission distance. According to [AGR95] the jitter-limited distance scales as $\Delta \tau^{2/3}$ with the switching window of the UNI. Therefore, with the UNI connected to the loop output, the expected transmission distance was approximately 800km, in good agreement with the BER measurement.

![Graph showing Bit-error-rate (BER) vs. distance measurement for 40Gbit/s signal (2^-1 PRBS).](image)

**Fig. 6.30** Bit-error-rate (BER) vs. distance measurement for 40Gbit/s signal (2^-1 PRBS).

- **No regeneration:** (×): loop transmission without regenerator using EC-MLL #1, (●): loop transmission using EC-MLL #2 as transmitter,
- **Regeneration:** (▲): regeneration after transmission using EC-MLL #1 for loop transmission, (■): transmission of regenerated signal from EC-MLL #2, (O): transmission with 20 cascaded regenerators (BER <10^-5)

**Configuration (c) - UNI inside loop:** The UNI was placed inside the loop giving an effective regenerator spacing of 100 km. Error-free transmission was extended to greater than 2000km, an order of magnitude greater than that achieved with the direct transmission of EC-MLL #2 and almost twice as far as in case of optimised transmission at $\lambda=1549.6$nm using EC-MLL #1. This fact clearly demonstrates the cascadability of the regenerator, and the associated reduction in jitter accumulation since the maximum jitter is only determined by the fibre span between two regenerators. Fig. 6.31 shows the results of 10Gbit/s BER measurements made on the 40Gbit/s input signal, the 40Gbit/s signal after a single regeneration, and the 40Gbit/s regenerated signal after 2000km transmission through 20 regenerators.
The penalty of the 40Gbit/s signal after a single regeneration compared with the 40Gbit/s input back-to-back was only 1.4dB, lower than the value 2.2dB obtained in the experiments described in section 6.2.2. This is due to the shorter pattern length of $2^7-1$ and the different clock source (ECL-MLL #2). By adding 20 regenerative stages the system still operated error-free and the penalty was only increased by a further 1.9dB, corresponding to a penalty of only 0.1dB per stage.
6.3 Summary

In summary, all-optical 3R regeneration was investigated using a semiconductor ultra-fast nonlinear interferometer (UNI). Initially, 40Gbit/s all-optical data switching, without wavelength conversion, was demonstrated using a pattern length of $2^{31} - 1$. By varying the delay of the locally generated clock with respect to the incoming data stream, 40Gbit/s to 10Gbit/s regenerative demultiplexing was also achieved. The penalty of the UNI due to varying polarisation of the switching signal was $< 1$dB and can be further reduced by polarisation insensitive SOA devices. However, the long-term stability of the UNI depends critically on the polarisation fluctuations of the RZ pulses providing the clock pulses for the UNI. The performance of the UNI can be further improved by minimising the spurious reflections from the SOA facets, causing in 1.3dB penalty when operating in counter-propagation. The temporal switching window of the UNI must be decreased to enable operation at bit-rates beyond 40Gbits/s. However, the reduced switching window requires to reduce timing jitter of the incoming signal, e.g. by reduced regenerator spacing.

The UNI was also investigated in 40Gbit/s transmission experiments. Whilst the short optical pulses required for correct operation of the regenerator resulted in a non optimised transmission performance, it was demonstrated that cascading regenerators significantly increased the error-free transmission distance to greater than 2000km. Transmission involving 20 cascaded regenerative units was successfully demonstrated, confirming the jitter suppression anticipated for these devices. Experiments involving regeneration after loop transmission indicate that timing jitter of the transmission system can be a limiting factor for the further increase of the spacing between regenerators.

Comparison WDM – OTDM: In this thesis nonlinearities in WDM and OTDM transmission were investigated. A typical WDM transmission system investigated in chapter 4 and 5 consisted of two or more 10Gbit/s channels using the NRZ format. In contrast, the OTDM system described in chapter 6 used a single channel at 40Gbit/s transmitting a RZ signal. The different transmission formats are compared on the basis of the experiments described in this thesis.

Clearly, in single channel RZ transmission SPM can be used to counteract the linear pulse broadening due to dispersion, increasing the error-free transmission distance. However, the OTDM system required an accurate control of dispersion map, power and wavelength. The wavelength tolerance for transmission over more than 1000km was shown to be less than 1nm. The generation of short pulses also required a more complex transmitter set-up than in a WDM experiment with NRZ pulses. However, due to the digital nature of single channel RZ
transmission, all-optical regeneration could be used to overcome pulse distortion and timing jitter. The concept of regeneration reduced the sensitivity of OTDM to the dispersion map, power and wavelength. Although the regeneration and cascadability of the UNI was demonstrated at 40Gbit/s, the successful operation required a careful and constant control of the signal polarisation. In addition, the short pulses required for the operation of the UNI resulted in non-optimised transmission performance limiting the distance between two subsequent regenerators. Increasing the capacity of the single channel RZ transmission, all-optical regeneration based on the UNI will become more complex, since all channels must be demultiplexed before regeneration. The use of WDM for RZ-based systems must also ensure that dispersion and nonlinearity are balanced for all wavelengths requiring the use of dispersion slope compensation.

Relatively simple NRZ-based WDM transmission used the total transmission bandwidth by adding channels at different wavelengths. However, in this thesis multi-channel nonlinear effects were shown to degrade the transmission performance significantly for narrow channel spacing and high launch power. Unlike RZ pulses in OTDM, the NRZ pulses were distorted by XPM and dispersion in a non-uniform way, and the distortion could not be cancelled but only minimised by reducing the residual dispersion of the link. In particular long sequences of '1'-bits experienced XPM-induced intensity distortion whilst RZ pulses in the single channel experiments were mainly degraded by timing jitter.
Chapter 7

Summary and conclusions

This thesis has investigated the detrimental and beneficial impact of nonlinearities on high-speed transmission. The project primarily focuses on transmission impairments due to nonlinearities in WDM systems, in particular cross-phase modulation (XPM), and interaction between SPM/XPM and fibre chromatic dispersion. In addition, the role of nonlinearities in OTDM systems was investigated to improve the transmission performance.

The investigation of the XPM effect had the following aims: firstly, to undertake a systematic investigation of XPM distortion in IM-DD systems as a function of system parameters to develop a detailed understanding of the physical nature of the XPM process allowing experimental results of laboratory and field experiments to be predicted by analytical calculations and numerical simulations. Secondly, the development of a simplified description of XPM enabling the prediction of penalties in complex transmission systems. Finally, the proposal of techniques to minimise XPM distortion. The additional aim of this thesis was the analysis of nonlinear effects in combination with OTDM. Analysing signal degradation due to SPM and dispersion the transmission was optimised by regeneration based on all-optical switching techniques.

The impact of XPM on optical transmission systems was studied in experiments and theory. Early published results were restricted to the analysis of temporal and spectral effects using single pulses in free-space optics. In IM-DD transmission systems the penalty due to XPM was investigated for different fibre infrastructures and channel configurations and strategies for the reduction of XPM were discussed. Additional insight into the variation of XPM with systems parameters was obtained by measuring XPM-induced distortion in pump-probe configuration. However, a detailed review of existing research in this area revealed that this analysis was incomplete. In particular, the build-up of XPM with distance, the impact of residual dispersion and critical role of channel walk-off was not investigated in detail. Due to the complexity arising from many optical channels and multiple amplified fibre spans, transmission experiments could only be compared with full numerical simulations based on the nonlinear Schrödinger equation. The advantage of the pump-probe technique, used in this
work, was to compare the results directly with rapid (analytical) calculations. However, prior to this research no published work had linked the relatively simple pump-probe technique to transmission experiments in order to quantify XPM transmission penalties in more complex systems. The work in this thesis used a systematic approach to investigate XPM, and to yield guidelines for the design of optical communication systems in the presence of XPM.

**Pump-probe experiments:** Initially, single span pump-probe experiments were carried out to separate XPM from other nonlinearities. The main objective of these measurements was the investigation of XPM distortion and consequently high channel power of 13dBm/channel and low fibre dispersion were chosen to enhance the XPM effect before investigating techniques to minimise XPM. The amount of XPM distortion $m_e$ was found to depend primarily on the channel walk-off determined by the independent parameters of dispersion, channel spacing and pulse width. The increased walk-off over SSMF had the advantage of pulse averaging and negligible distortion was measured for $\Delta \lambda > 1$nm for a single fibre span. In addition, the superposition of the XPM effect with SPM and FWM was considered generalising the idea of 'classical' pump-probe. It was shown that the total distortion by SPM and XPM in a modulated probe critically depends on the relative channel delay. The time-delay between channels was a key parameter also in other research work suppressing the build-up of XPM. All experiments indicated that multichannel transmission over DSF was severely limited and pointed to the advantage of SSMF for WDM transmission. The third parameter determining the walk-off is the pulse width. It was investigated in bit-rate dependent measurements, but unlike other publications the pulse rise time was constant. For low bit-rates or long sequences of '1'-bits in the bit-pattern the XPM distortion resulted in isolated peaks typical for low walk-off. The intensity distortion for an uncompensated link increased monotonically with bit-rate up to 10Gbit/s due to overlapping of adjacent chirp components caused by pulse transitions of the pump. It was concluded that short pulses $\leq 100$ps in a PRBS sequence contribute most to XPM intensity distortion despite the increased walk-off normalised to the pulse width. The complex dependence of the XPM effect on walk-off was found to be due to the combination of these three parameters. Although the XPM intensity distortion due to PM-IM conversion was increased with bit-rate and dispersion, the same parameters decreased the build-up of XPM phase modulation due to increased channel walk-off. At 10Gbit/s and $\Delta \lambda = 0.4$nm the effect of PM-IM conversion dominated the averaging effect of phase modulation. However, for constant dispersion and bit-rate the walk-off always became more significant for increased $\Delta \lambda$ since less XPM phase modulation was generated. Therefore, significant XPM intensity distortion was limited to configurations with narrow $\Delta \lambda$ at bit-rates of 10Gbit/s. XPM distortion is also determined by the amount of nonlinear chirp introduced.
by individual pulse transitions of the interfering channel. One obvious consequence was the linear increase of XPM distortion with the channel power. A second aspect was the numerical investigation of the impact of pulse shapes on XPM. The chirp increased for fast pulse rise times.

Although this thesis focuses on the optical fibre, other components of the transmission system also influence the measured distortion: linear chirp of the sources is converted by the PM-IM process in the fibre and can be used to counteract XPM distortion. Enhanced XPM distortion was observed in experiments due to increased PM-IM conversion by misaligned filters.

**LEANT:** A question remained about the accuracy of the laboratory measurements to predict XPM distortion in installed fibre. Therefore, XPM was investigated for the first time in a field experiment over 192km of SSMF connecting BT-Laboratories (Ipswich) and Norwich. The sensitivity of XPM distortion to bit-rate was investigated in a 2-span link of this network and the results were compared with a laboratory experiment using a replica of this link. Due to a 1010-pattern in the pump the probe distortion showed periodic distortion varying with bit-rate and $\Delta \lambda$, a phenomenon caused by the walk-off over each span and accurately described by the XPM transfer function $H(\omega)$. This periodicity was also anticipated for wavelength-dependent measurements using a periodic pattern. However, when using a PRBS in the pump, a $1/\Delta \lambda$ law for XPM distortion was confirmed. It was further shown that dispersion compensation effectively reduces XPM distortion due to less residual dispersion although the additional DCF results in a complex spectral response of this link to XPM. The amount of XPM distortion measured in the installed fibre was reduced by a factor of approximately 2 compared to the reference laboratory experiment. The installed fibre could be accurately described by simulations and calculations taking into account the higher fibre attenuation and the variation of the relative polarisation between the two channels during propagation. These results provided and improved the physical understanding of the XPM process.

**Distance-dependent measurements:** XPM was investigated as a function of transmission distance in pre- and post-compensated spans using a recirculating fibre loop. The linear increase of the spectral broadening due to XPM and SPM with distance was investigated in a 10Gbit/s pump-probe experiment for channel spacings down to 0.2nm. In the exactly compensated spans the total walk-off was zero, realigning the channels after transmission. As a result, the XPM index $m_x$ increased linearly with the number of spans, saturating after $n=7$ spans due to SPM-induced pump distortion. It was verified that the factor $\Delta m_x/\Delta L$ can be determined by single-span measurements alone in the case of negligible pump distortion thus predicting the increase of XPM distortion with distance. Due to the build-up of XPM
distortion with the number of amplified spans the minimum channel spacing $\Delta \lambda_{\text{min}}$ required not to exceed a given amount $m_r$ had to be increased limiting the capacity of WDM transmission at long distances. For 13dBm/channel and 10 exactly post-compensated spans the minimum was $\Delta \lambda = 1.8 \text{nm}$ for $m_r < 0.1$.

This research had already identified the critical role of residual dispersion for XPM. Initially, the impact of positive and negative lumped dispersion on XPM was studied using a single pre- or post-compensated span. Under-compensation was shown to minimise XPM in post-compensated spans as it reduces the amount of residual dispersion following the generation of XPM and therefore minimises the PM-IM conversion. However, the XPM phase modulation was not reduced by lumped compensation. The concept of under-compensation was studied for different launch power and only linear transmission required exact compensation. The technique for minimising XPM was also applicable to SPM and it was shown experimentally that pulses were recompressed restoring the eye-opening after transmission. The required amount of lumped dispersion for post-compensated spans was 20km SSMF, almost independent of distance as all spans had the same length. After 8 spans, lumped dispersion at the receiver reduces XPM distortion by 30% in comparison to the exactly compensated link. Although under-compensation per span reduced XPM even further due to nonzero walk-off the concept of lumped compensation requires less modification of the link and can be optimised after the demultiplexer on a per channel basis. In links where the capacity dictates the bit-rate and $\Delta \lambda$, dispersion management, channel delay and power map become the most important parameters to influence the amount of XPM.

**Q-factor experiments:** The pump-probe technique simplifies the experiments and isolates the effect of XPM. In WDM systems, however, the BER or Q-factor are commonly used as they directly measure the performance of the system. Therefore, the impact of XPM on the Q-factor and the relation to the previous results had to be investigated. In contrast to earlier pump-probe measurements SPM, dispersion and ASE noise were also considered. The Q-factor was measured for a single post-compensated span and for up to 12 spans using a recirculating loop. $Q$ was found to decrease linearly with $1/\Delta \lambda$ due to XPM and the magnitude of the factor $\Delta Q/\Delta (1/\Delta \lambda)$ quantified the amount of XPM generated. One of the main contributions of this work was the comparison of XPM obtained in pump-probe measurements with direct BER measurements. In this case, pump-probe measurements were carried out to predict the additional penalty due to XPM for 2-channel transmission. The key advantage of this technique is its simplicity since experimental or analytically calculated values $\sigma_{\text{XPM}}$ can be used to determine the XPM-related penalties with high accuracy. To increase accuracy over long distances the SPM-induced pump distortion must be included in
Chapter 7: Summary and conclusions

The analytical calculations. Another objective of the Q-factor experiments was the analysis of XPM for multiple dispersion-compensated spans as a function of number of channels and optical power. The interfering channels were spaced in a 0.4nm grid symmetrically around the detected channel. These experiments showed significant statistical fluctuation of the Q-factor due to the influence of polarisation. In the case of constant EDFA output power, the channel power was dependent on the number of channels. For two channels with 13dBm/channel the transmission was limited by nonlinearities whilst ASE noise dominated for 16-channel transmission with 4dBm/channel. When using constant power per channel instead, the Q-factor at a given distance decreased monotonically with the number of channels as the sum of the variances $\sigma^2_{xpm}$ due to each pump channel increased the total distortion.

In the last part of this thesis, OTDM was investigated as an alternative transmission format. Since only one channel and low dispersion fibre was used, XPM was not relevant. However, other research has shown that for high dispersion such as SSMF intra-channel XPM/FWM have to be considered. Nonlinearities such as self-phase modulation (SPM) resulted in pulse distortion limiting the transmission distance in DSF. However, when balancing SPM against the other limiting factor of fibre dispersion, both effects could be compensated and error-free transmission was achieved. Although OTDM-based transmission is not the main topic of this thesis, this work still demonstrates the relevance of nonlinearities for other areas of optical communications. This investigation had the following aims: firstly, the set-up of a recirculating loop test-bed for 40Gbit/s transmission. Secondly, the investigation of nonlinearities in OTDM transmission at high bit-rates, in particular the sensitivity to system parameters such as the signal wavelength. Finally, the improvement of transmission by all-optical 3R regeneration.

Using a 3-span recirculating loop with 100km DSF the limitation of dispersion due to SPM and dispersion was investigated. A gain switched DFB was chosen as a low cost source providing low-jitter pulses with a FWHM width of 7ps. As shown in simulation and confirmed in 40Gbit/s transmission experiments, compensation of both effects only occurred for a narrow wavelength range but it enabled error-free transmission of soliton-like pulses up to 1200km. The main focus of this work, however, was the optical regeneration of the transmitted 40Gbit/s signals and the experimental study of 3R regenerators. It was shown that a unidirectional nonlinear interferometer (UNI) removed pulse distortion and timing-jitter. The operation with counter-propagating data and clock signal enabled cascadability of the UNI increasing the transmission distance. In back-to-back measurements regeneration of $2^{31}$-1 bit-pattern at 40Gbit/s was demonstrated for the first time with only 2dB penalty. In subsequent transmission experiments a world record with 20-fold regeneration at 40Gbit/s was achieved with only 0.1dB penalty per regenerative stage.
In summary, this thesis has investigated nonlinear effects in optical communications systems. The main contribution is the understanding of the XPM effect achieved through detailed fundamental pump-probe and WDM transmission experiments. The channel walk-off and dispersion map were shown to be the most critical parameters for XPM responsible for the complex nature of this effect. It was confirmed that the walk-off dominates the PM-IM conversion for increased channel spacing reducing the XPM intensity distortion. The walk-off determines the amount of phase modulation whilst the amount of intensity distortion depends on the residual dispersion which could be minimised by under-compensation of post-compensated spans and lumped receiver dispersion. However, the dispersion map could only minimise the PM-IM conversion whilst the XPM efficiency was given by the channel walk-off normalised to the bit-rate. In this thesis work, interference of XPM contributions of different spans turned out to be another significant research area. This aspect was investigated as a function of wavelength spacing and bit-rate in the LEANET and recirculating loop configuration. The LEANET experiment, the first reported pump-probe experiment over installed fibre, gave new insight into the role of fibre loss and polarisation on XPM in direct comparison with a laboratory replica. The superiority of the pump-probe technique for system analysis was highlighted by the first experiments estimating XPM transmission penalties, thus simplifying the investigation of complex systems considerably.

Finally, the role of all-optical regeneration was investigated for single channel RZ transmission at 40Gbit/s. Cascadability of regenerators was successfully demonstrated which is essential for long-distance error-free transmission. Although this technique was still limited by sensitivity to polarisation and long-term stability, the results show an approach to reduce the detrimental impact of dispersion and nonlinearity in optical networks.

In future work, a detailed comparison of XPM in systems using the RZ and the NRZ format is required. With respect to XPM chirp, RZ pulses are expected to generate more nonlinear phase modulation on a CW probe due to faster pulse rise time and more transitions than the same data sequence using the NRZ format. However, when all channels are modulated the intensity distortion is expected to be higher for the NRZ format due to the PM-IM conversion of chirp carried by longer sequences of ‘1’-bits in the detected channel. 40Gbit/s single channel NRZ and RZ transmission experiments will reveal the impact of XPM distortion at high bit-rates and also allow the investigation of new effects such as intra-channel XPM. Finally, the technique used to predict the penalty due to XPM can also be extended to multichannel transmission estimating the decrease of the Q-factor when adding more WDM channels. These studies will contribute to the improved understanding of the role nonlinearities in optical communications systems.
## 8 Appendices

### A Symbols, common values and units

<table>
<thead>
<tr>
<th>symbol</th>
<th>parameter</th>
<th>typical values</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>speed of light</td>
<td>$3 \times 10^8$</td>
<td>m/s</td>
</tr>
<tr>
<td>$v_g$</td>
<td>group velocity</td>
<td>$2 \times 10^8$</td>
<td>m/s</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>attenuation</td>
<td>0.21 (SSMF), 0.5 (DCF)</td>
<td>dB/km</td>
</tr>
<tr>
<td>D</td>
<td>dispersion parameter</td>
<td>-100 (DCF), ±1 (DSF)</td>
<td>ps/(km nm)</td>
</tr>
<tr>
<td>$dD/d\lambda$</td>
<td>dispersion slope</td>
<td>±5 (NZ-DSF), 17 (SSMF)</td>
<td>ps/(nm² km)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>group velocity dispersion</td>
<td>-21.67 (SSMF)</td>
<td>ps²/km</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>zero-dispersion</td>
<td>1300 (SSMF), ±1550 (DSF)</td>
<td>nm</td>
</tr>
<tr>
<td>$L_D$</td>
<td>dispersion length</td>
<td>SSMF: 166 (10Gbit/s), 10.4 (40Gbit/s)</td>
<td>km</td>
</tr>
<tr>
<td>$A_{eff}$</td>
<td>effective area</td>
<td>80 (SSMF, LEAF), 50 (DSF), 25 (DCF)</td>
<td>µm²</td>
</tr>
<tr>
<td>$L_{eff}$</td>
<td>effective length</td>
<td>20 (SSMF, DSF), 8 (DCF)</td>
<td>km</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>nonlinear coefficient</td>
<td>1.18 (SSMF), 2.43 (DSF), 4.86 (DCF)</td>
<td>1/(W km)</td>
</tr>
<tr>
<td>$\Delta\lambda$</td>
<td>channel spacing</td>
<td>±0.2 for WDM</td>
<td>nm</td>
</tr>
<tr>
<td>$B$</td>
<td>bit-rate</td>
<td>2.5-10 (WDM), 40 (OTDM)</td>
<td>Gbit/s</td>
</tr>
<tr>
<td>$P$</td>
<td>launch power</td>
<td>0-13 per channel</td>
<td>dBm</td>
</tr>
<tr>
<td>$M$</td>
<td>number of channels</td>
<td>1-32</td>
<td>-</td>
</tr>
<tr>
<td>$n$</td>
<td>number of recirculations</td>
<td>1-12</td>
<td>-</td>
</tr>
<tr>
<td>$L_{sp}$</td>
<td>span length</td>
<td>50-75 (UCL), 92 (LEANET), 33 (BT)</td>
<td>km</td>
</tr>
<tr>
<td>$\eta_{XPM}$</td>
<td>XPM efficiency</td>
<td>&lt;1</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta\phi$</td>
<td>phase mismatch parameter</td>
<td>±0 (FWM)</td>
<td>m/µm</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>loop recirculation time</td>
<td>240 for loop in chapter 4, 300 (chapter 5), 485 (chapter 6)</td>
<td>µs</td>
</tr>
<tr>
<td>$\Delta t_{10-90%}$</td>
<td>pulse rise time</td>
<td>40-56 for MZM/EAM</td>
<td>ps</td>
</tr>
<tr>
<td>$\Delta t_{RZ}$</td>
<td>pulse width (RZ source)</td>
<td>&gt;4 (EC-MLL), &gt;7 (EAM source)</td>
<td>ps</td>
</tr>
<tr>
<td>$d_p$</td>
<td>walk-off</td>
<td>$D_1 \Delta \lambda = D_2 \Delta \lambda$</td>
<td>ps/km</td>
</tr>
<tr>
<td>$Q$</td>
<td>Q-factor</td>
<td>&gt;15.5 for BER&lt; $10^{-9}$</td>
<td>dB</td>
</tr>
<tr>
<td>$m_{XPM}$</td>
<td>XPM index</td>
<td>$(P_{max} P_{min})/&lt;P&gt;$</td>
<td>-</td>
</tr>
<tr>
<td>$\sigma_{XPM}$</td>
<td>normalised XPM standard</td>
<td>$\sqrt{\frac{1}{n} \sum_{i=1}^{n} (P_i - \langle P \rangle)^2 / \langle P \rangle}$</td>
<td>-</td>
</tr>
</tbody>
</table>
## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADC</td>
<td>Analog-Digital Converter</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>AOM</td>
<td>Acousto-Optical Modulator</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>ASK</td>
<td>Amplitude Shift Keying</td>
</tr>
<tr>
<td>ATT</td>
<td>Attenuator</td>
</tr>
<tr>
<td>B2B</td>
<td>Back-To-Back</td>
</tr>
<tr>
<td>BER</td>
<td>Bit-Error Rate</td>
</tr>
<tr>
<td>BERT</td>
<td>Bit-Error Rate Test-Set</td>
</tr>
<tr>
<td>CNR</td>
<td>Carrier-to-Noise Ratio</td>
</tr>
<tr>
<td>CSA</td>
<td>Communication Signal Analyser</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DCF</td>
<td>Dispersion-Compensating Fibre</td>
</tr>
<tr>
<td>DDF</td>
<td>Dispersion-Decreasing Fibre</td>
</tr>
<tr>
<td>DFB</td>
<td>Distributed Feedback Laser</td>
</tr>
<tr>
<td>DSF</td>
<td>Dispersion-Shifted Fibre</td>
</tr>
<tr>
<td>DXPM</td>
<td>Degenerate Cross-Phase Modulation</td>
</tr>
<tr>
<td>EAM</td>
<td>Electro Absorption Modulator</td>
</tr>
<tr>
<td>ECL</td>
<td>External Cavity Laser</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium-Doped Fibre Amplifier</td>
</tr>
<tr>
<td>EM</td>
<td>Electro-Magnetic</td>
</tr>
<tr>
<td>EOP</td>
<td>Eye-Opening Penalty</td>
</tr>
<tr>
<td>ETDM</td>
<td>Electrical Time-Division Multiplexing</td>
</tr>
<tr>
<td>FBG</td>
<td>Fibre Bragg Grating</td>
</tr>
<tr>
<td>FDM</td>
<td>Frequency-Division Multiplexing</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward Error Correction</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FP</td>
<td>Fabry-Perot</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency Shift Keying</td>
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<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>FWM</td>
<td>Four-Wave Mixing</td>
</tr>
<tr>
<td>GVD</td>
<td>Group-Velocity Dispersion</td>
</tr>
<tr>
<td>IFWM</td>
<td>Intra-Channel Four-Wave Mixing</td>
</tr>
<tr>
<td>IM</td>
<td>Intensity Modulation</td>
</tr>
<tr>
<td>IM/DD</td>
<td>Intensity Modulation /Direct Detection</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter Symbol Interference</td>
</tr>
<tr>
<td>IXP</td>
<td>Inter-Channel Cross-Phase Modulation</td>
</tr>
<tr>
<td>LEANET</td>
<td>London East Anglia Network</td>
</tr>
<tr>
<td>MI</td>
<td>Modulation Instability</td>
</tr>
<tr>
<td>MLL</td>
<td>Mode-Locked Laser</td>
</tr>
<tr>
<td>MQW</td>
<td>Multi Quantum Well</td>
</tr>
<tr>
<td>MSSI</td>
<td>Mid-Span Spectral Inversion</td>
</tr>
<tr>
<td>MUX</td>
<td>Multiplexer</td>
</tr>
<tr>
<td>MZ</td>
<td>Mach-Zehnder</td>
</tr>
<tr>
<td>NF</td>
<td>Noise Figure</td>
</tr>
<tr>
<td>NLOM</td>
<td>Nonlinear Optical Loop Mirror</td>
</tr>
<tr>
<td>NLSE</td>
<td>Nonlinear Schrödinger Equation</td>
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<tr>
<td>NRZ</td>
<td>Non-Return-To-Zero</td>
</tr>
<tr>
<td>NZ-DSF</td>
<td>Nonzero Dispersion-Shifted Fibre</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical Spectrum Analyser</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>-------------</td>
<td>-----------------------------------------------</td>
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<tr>
<td>OTDM</td>
<td>Optical Time-Division Multiplexing</td>
</tr>
<tr>
<td>PBS</td>
<td>Polarising Beam Splitter</td>
</tr>
<tr>
<td>PC</td>
<td>Polarisation Controller</td>
</tr>
<tr>
<td>PD</td>
<td>Photo Diode</td>
</tr>
<tr>
<td>PDL</td>
<td>Polarisation-Dependent Loss</td>
</tr>
<tr>
<td>PHB</td>
<td>Polarisation Hole Burning</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
</tr>
<tr>
<td>PM</td>
<td>Phase Modulation</td>
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<tr>
<td>PMM</td>
<td>Polarisation Maintaining</td>
</tr>
<tr>
<td>PMD</td>
<td>Polarisation Mode Dispersion</td>
</tr>
<tr>
<td>PPG</td>
<td>Pulse Pattern Generator</td>
</tr>
<tr>
<td>PRBS</td>
<td>Pseudo Random Bit Sequence</td>
</tr>
<tr>
<td>PS</td>
<td>Polarisation Scrambler</td>
</tr>
<tr>
<td>PSK</td>
<td>Phase Shift Keying</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RX</td>
<td>Receiver</td>
</tr>
<tr>
<td>RZ</td>
<td>Return-To-Zero</td>
</tr>
<tr>
<td>SBS</td>
<td>Stimulated Brillouin Scattering</td>
</tr>
<tr>
<td>SCM</td>
<td>Subcarrier Multiplexing</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-To-Noise Ratio</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
</tr>
<tr>
<td>SPM</td>
<td>Self-Phase Modulation</td>
</tr>
<tr>
<td>SRS</td>
<td>Stimulated Raman Scattering</td>
</tr>
<tr>
<td>SSMF</td>
<td>Standard Singlemode Fibre</td>
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<tr>
<td>TDM</td>
<td>Time-Division Multiplexing</td>
</tr>
<tr>
<td>TF</td>
<td>Tuneable Filter</td>
</tr>
<tr>
<td>TX</td>
<td>Transmitter</td>
</tr>
<tr>
<td>UNI</td>
<td>Unidirectional Nonlinear Interferometer</td>
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<tr>
<td>VCO</td>
<td>Voltage-Controlled Oscillator</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength-Division Multiplexing</td>
</tr>
<tr>
<td>XGM</td>
<td>Cross-Gain Modulation</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross-Phase Modulation</td>
</tr>
</tbody>
</table>
C  Propagation of light in optical fibres

As with all electromagnetic phenomena the propagation of the optical signal in the fibre is described by the Maxwell equations

\[ \mathbf{\nabla} \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \]

\[ \mathbf{\nabla} \times \mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t} \]

\[ \mathbf{\nabla} \cdot \mathbf{D} = \rho \]

\[ \mathbf{\nabla} \cdot \mathbf{B} = 0 \]

where \( \mathbf{E} \) and \( \mathbf{H} \) are the electric and magnetic field and \( \mathbf{B} \) and \( \mathbf{D} \) are the magnetic and electric flux densities, which are the combined result of the vacuum fields \( \mathbf{E} \) and \( \mathbf{H} \) with the electric and magnetic polarisation \( \mathbf{P} \) and \( \mathbf{M} \).\(^1\) In the absence of free charges the source terms with charge density \( \rho \) and current density \( \mathbf{j} \) disappear, \( \mathbf{M} \) is also zero for fibres. The electric field is one order of magnitude stronger than the magnetic field so that the wave equation is derived for the electric dipole field. The curl \( (\mathbf{\nabla} \times \mathbf{E}) \) is taken of the first equation of (C.1), and \( \mathbf{B} \) is substituted with the second equation where \( \mathbf{B} \) and \( \mathbf{D} \) are expressed in terms of \( \mathbf{H} \), \( \mathbf{E} \) and \( \mathbf{P} \). As a result, the wave equation for the electromagnetic field is obtained. This is a second order differential equation in four independent variables \( t \) and \( r=(x,y,z) \) in which the electric polarisation \( \mathbf{P} \) acts as the source term for the electric field of the signal. \( \mathbf{P} \) generally contains a linear part \( \mathbf{P}_{\text{lin}} \) and an additional part \( \mathbf{P}_{\text{NL}} \) nonlinear in \( \mathbf{E} \):

\[ \mathbf{\nabla} \times \mathbf{\nabla} \times \mathbf{E}(r,t) - \frac{1}{c^2} \frac{\partial^2 \mathbf{E}(r,t)}{\partial t^2} = -\mu_0 \frac{\partial^2}{\partial t^2} \left( \mathbf{P}_{\text{lin}}(r,t) + \mathbf{P}_{\text{NL}}(r,t) \right) \]

(C.2)

and the field terms are:

\[ P_{\text{lin}}(r,t) = \left( \mathbf{P}_{\text{lin}} + \mathbf{P}_{\text{NL}} \right) = \mathcal{E}_0 \left( \chi^{(1)}_{\text{lin}} : E_j E_k + \chi^{(2)}_{\text{nl}} : E_j E_k E_l + \chi^{(3)}_{\text{nl}} : E_j E_k E_l E_m + \ldots \right) \]

(C.3)

\[ E(r,t) = E_0(r,t) \exp \left( -i\omega t \right) \]

(C.4)

The coupling factor \( \chi^{(0)} \) is the \( n \)-th order susceptibility and \( \mathcal{E}_0 \) is the dielectric constant. The first term linear in the electric field exists for all isotropic media and contains the effects of attenuation and dispersion which are both consequences of a complex dielectric constant \( \varepsilon_d(\omega) = 1 + \chi^{(1)} \). The frequency dependence of the real part of \( \varepsilon_d(\omega) \) describes the dispersion by the refractive index \( n^2(\omega) = \varepsilon_d(\omega) \) and imaginary part \( \varepsilon_{\text{MCF}}(\omega) \) accounts for the linear attenuation \( \alpha \). The term quadratic in the electric field vanishes in (C.3) due to the inversion

\(^1\) Vectors are indicated by bold notation.
symmetry of silica and the first nonlinear contribution to the electric polarisation is the term proportional to \( \chi^{(3)} \). These nonlinear effects are discussed in chapter 2.

C.1 **The nonlinear Schrödinger equation**

In solving equation (C.2) the following assumptions are made. Firstly, the polarisation is constant during propagation resulting in a scalar electric field. Secondly, \( P_{\text{NL}} \) is treated as a small perturbation to the linear polarisation, which is the case for transmission with launch powers of the order of mW. Moreover, the electric field is quasi-monochromatic, i.e. the spectral width \( \Delta \omega \) is much smaller than the carrier frequency \( \omega_0 \) as applicable for pulse widths greater than 1ps. In the first step of solving equation (C.2), the slowly varying amplitude approximation is used to separate the rapidly varying part with the carrier frequency \( \omega_0 \) of the electric field \( E(r,t) \) from the time dependence of the field amplitude \( E_0(r,t) \) shown in equation (C.4). The field amplitude is Fourier-transformed as

\[
\tilde{E}(r, \omega) = \int_{-\infty}^{\infty} E_0(r,t) \cdot \exp\left[i(\omega - \omega_0) \cdot t\right] dt
\]

and the polarisation terms are defined accordingly. The solution can be further simplified by separation of \( E(r, \omega - \omega_0) \) into a radial part \( F(x,y) \) and a longitudinal part \( A(z, \omega - \omega_0) \) along the propagation direction \( z \) of the fibre and the parts can be solved independently

\[
E(r, \omega - \omega_0) = F(x,y) \cdot A_0(z, \omega - \omega_0) \cdot \exp\left(i\beta z\right)
\]

where \( \beta_0 \) is a propagation constant. \( F(x,y) \) represents the general solutions for the core region of the fibre described by guided modes which are expressed as a linear combinations of Bessel functions due to the cylindrical symmetry [AGR95]. To investigate transmission along the \( z \)-axis only the component \( A(z, \omega) \) in propagation direction (\( z \)-axis) is solved for the nonlinear regime. Using the slowly varying amplitude approximation, the term \( \partial^2 A(z, \omega)/\partial z^2 \) in (C.2) can be neglected and equation (C.6) is substituted into the Fourier transformed expression of equation (C.2). For the component \( A(z, \omega - \omega_0) \) follows

\[
\frac{\partial A(z, \omega)}{\partial z} = i[\beta(\omega) + \Delta \beta - \beta_0] A(z, \omega)
\]

where \( \beta(\omega) \) is a linear propagation constant describing the effects of dispersion and \( \Delta \beta \) is a correction to \( \beta \) obtained using perturbation theory which takes into account the refractive index change \( \Delta n \) due to the nonlinearity of the medium. In the following, \( \beta(\omega) \) is expanded as a series around \( \omega_0 \) as
\[
\beta(\omega) = n(\omega) \frac{\omega}{c} = \beta_0 + (\omega - \omega_0)\beta_1 + \frac{1}{2} (\omega - \omega_0)^2 \beta_2 + \frac{1}{6} (\omega - \omega_0)^3 \beta_3 + \ldots \quad (C.8)
\]

The terms \( \beta_n \) with \( n \geq 2 \) can normally be neglected for pulse widths greater than 1ps. However, in the case of low dispersion fibre with \( \beta_2 \approx 0 \) the cubic term must also be included, for example with dispersion-shifted fibre (DSF). \( \beta_1 = 1/v_g \) where \( v_g \) is the group velocity of the signal and \( \beta_2 \) is referred to as group velocity dispersion (GVD). Equation (C.8) is substituted into (C.7) and the inverse Fourier transform \( A(z,t) \) of the amplitude \( A(z,\omega-\omega_0) \) is taken. Finally, the nonlinear Schrödinger equation (NLSE)

\[
\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i \gamma |A|^2 A \quad (C.9)
\]

for \( A(z,t) \) is obtained with the nonlinearity coefficient \( \gamma \) defined as

\[
\gamma = \frac{n_2 \omega_0}{c A_{\text{eff}}} \quad (C.10)
\]

where \( n_2 \) is the nonlinear coupling coefficient of the fibre and \( A_{\text{eff}} \) is the effective area of the fibre. Typically \( n_2 \approx 2.2-3.4 \times 10^{-20} \text{ m}^2/\text{V} \) in silica fibre. For standard single mode fibre (SSMF), \( A_{\text{eff}} = 80 \mu\text{m}^2 \) and \( 50 \mu\text{m}^2 \) for dispersion-shifted fibre (DSF), 20-25\( \mu\text{m}^2 \) for dispersion compensated fibre (DCF) and only about \( 10 \mu\text{m}^2 \) for special high nonlinearity fibre [SEN99]. Equation (C.9) describes the propagation of the lightwave along the \( z \)-axis of the fibre and includes the fibre loss represented by \( \alpha \), the dispersion expressed by \( \beta \) and fibre nonlinearity \( \gamma \). The impact of these parameters on fibre transmission is discussed in chapter 2. There are no known analytical solutions of equation (C.9) but numerical methods can be used such as the split-step Fourier algorithm described in appendix D.
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D Split-step Fourier algorithm

In appendix C the non-linear Schrödinger equation was derived describing wave propagation in non-linear media. Unfortunately, the analytical solution for (C.9) is known only for a few cases, such as zero dispersion. Therefore, a general numerical solution has been developed for the solution of the full transmission system with all its parameters. A technique most commonly used is the split-step Fourier algorithm/ method [FIS75].

The split-step Fourier method calculates numerically a solution for the nonlinear Schrödinger equation derived in appendix C

\[
\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i\gamma |A|^2 A
\]  

Equation (D.1) can be written as a first order differential equation for the field amplitude \(A(z,t)\) by introduction of new operators \(\hat{D}\) and \(\hat{N}\)

\[
\frac{\partial A}{\partial z} = (\hat{D} + \hat{N})A
\]  

\(\hat{D}\) describes the linear effects of dispersion and absorption whilst \(\hat{N}\) includes the nonlinearity

\[
\hat{D} = -\frac{i}{2} \beta_2 \frac{\partial^2}{\partial t^2} + \frac{1}{6} \frac{\partial^3}{\partial t^3} - \frac{\alpha}{2}
\]

\[
\hat{N} = i\gamma |A|^2
\]  

The key point of the split-step Fourier method is the separation of nonlinear and linear effects. It is assumed that over a small distance, \(\Delta h\), both effects can be considered independently. In this case the complex field \(A(z+\Delta h)\) is calculated from the values for \(A(z)\). From \(z\) to \(z+\Delta h\) the solution of the NLSE is carried out in two steps

\[
A(z+h,t) = \exp(h\hat{D})\exp(h\hat{N})A(z,t)
\]  

In equation (D.5) the non-linearity operator is first applied and then the dispersion operator. For increased accuracy it is important to reduce the step size \(\Delta h\) in presence of nonlinearity. In particular, a large step-size in the split-step algorithm introduces spurious FWM in the optical spectrum as shown in [BOS00]. The accuracy of the split-step algorithm is described by the Baker-Hausdorff formula for the two operators \(\hat{N}\) and \(\hat{D}\). The error is found to be of the order of \(\Delta h^2\). A modification with higher accuracy of the order \(\Delta h^3\) is illustrated in Fig. D.1 [AGR95].
The evaluation of dispersion and non-linearity is shifted by \( h/2 \) against each other along the fibre. In the following the implementation of the split-step algorithm is described:

- Calculation of the Fourier-transformed field \( \tilde{A}(z, \omega) \) from the initial complex field \( A(z, t) \) at input \( z \)
- Propagation of \( \tilde{A}(z, \omega) \) by \( \Delta h/2 \) considering dispersion only. Calculation of dispersed complex field according to equation (D.3). Inverse FFT of \( \tilde{A}(z, \omega) \) into time domain
- Application of nonlinear term \( \tilde{N} \) in equation (D.4) to the complex field \( A(z+\Delta h/2, t) \)
- Propagation from \( z+\Delta h/2 \) to \( z+\Delta h \) to complete the calculation evaluating fibre dispersion.

In this thesis, a MATLAB program developed by Dr R. Killey and based on the split-step algorithm was used. Additional simulations were performed using the PHOTOSS program, a system simulator developed at the University of Dortmund, Germany.
E Stimulated scattering processes

E.1 Simulated Brillouin scattering (SBS)

Local changes of the refractive index cause scattering of light, either elastic, termed Rayleigh scattering, or inelastic where the energy is exchanged with the transmission medium via phonons. The inelastic scattering process is known as Brillouin scattering [AGR95]. In a classical description, the electric field of the initial pump signal creates vibrations of the fibre medium by electrostriction resulting in a periodic density modulation varying the refractive index. The pump light is scattered by the induced grating structure. In a quantum mechanical description, one pump photon of the original signal at $\omega_1$ creates an acoustic phonon at $\omega_{ph}$ (longitudinal vibrational mode of the host lattice) and a red-shifted Stokes wave at $\omega_2$, the scattered signal, with $\omega_1 = \omega_2 + \omega_{ph}$. The phonon has the largest momentum $\Delta k = k_1 - k_2$ when the light is backscattered corresponding to the maximum frequency shift $\Delta \omega = \omega_{ph}$ of the light wave.

In stimulated Brillouin scattering (SBS) the beating of the two light waves reinforces the phonon providing gain $g_b$ for the backward scattered light at $\omega_2$. The SBS process is a threshold process with a characteristic threshold power. Typical values for a CW signal propagating over SSMF fibre are $P_{th} = 7$ dBm for a Brillouin gain-bandwidth of 50 MHz [CHR90]. In WDM systems, SBS leads to nonlinear attenuation of the channels. The power $P_{th}$ is applicable to each channel since the induced diffraction grating is characteristic for a particular signal. For lasers in CW mode, the spectral linewidth must be broadened to increase $P_{th}$. Using the method of dithering, a low-frequency sinusoidal signal (typically 20-30 kHz) is added to the laser drive current increasing the SBS threshold, see for example [GAU94]. Alternatively, a phase modulator can be used to modulate the output signal [HAD86]. The backwards scattered Stokes light can be suppressed using an optical isolator. The impact of SBS on transmission is investigated in chapter 4, section 4.3.1. To summarise, the critical power levels for different fibre types are listed in table E1.

<table>
<thead>
<tr>
<th>$\lambda$ [(\mu)m]</th>
<th>1.3 (SSMF)</th>
<th>1.55 (SSMF)</th>
<th>1.55 (DSF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_b \times 10^{11}$ mW</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>$P_{th}$ [dBm]</td>
<td>7.6</td>
<td>5.2</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Table E.1 Critical launch power $P_{th}$ for a PRBS-modulated channel propagating over 100km of fibre, according to [HAN95]
The Raman effect is a nonlinear scattering process exciting the vibrational modes of the host molecules. The molecular frequencies are in the order of 10THz in comparison to the vibrational modes of 0.1GHz associated with SBS. The process can be understood as the absorption of a photon at \( \omega_0 \) transforming the molecule from the ground state \( E_0 \) into an intermediate excited state \( E_1 \). The system returns to a final state of lower energy \( E_2 \) emitting a photon at \( \omega_2 \). If \( E_2 = E_0 \), the process is called elastic and Rayleigh scattering occurs. In general, the system relaxes into \( E_2 > E_0 \) and the emitted photon is red-shifted, a phenomenon known as Stokes-shift. During the process of spontaneous Raman scattering, present at any optical power, the scattered light at \( \omega_2 \) is uncorrelated and with arbitrary direction due to the spontaneous emission process. Unlike SBS, stimulated Raman scattering (SRS) occurs above a power threshold \( P_r \) given by the total optical power in the fibre. The presence of light at \( \omega_2 \), for example, due to appropriate WDM channels in the system, results in stimulated emission of photons at \( \omega_2 \) together with an optical phonon. The interaction of the phonons with the input light reinforces the Stokes-shifted light providing Raman gain \( g_R(\Delta \omega) \) at \( \omega_2 \). The gain curve increases linearly with \( \Delta \omega = \omega_1 - \omega_2 \) up to 17THz in a characteristic triangular shape. In contrast, the channel separation relevant for SBS is only about 50MHz. Therefore, all channels of a WDM system are affected by SRS when \( P_{total} > P_R \) with \( P_R \) given by [SM172]

\[
P_R \approx 16 \cdot \frac{A_{eff}}{L_{eff} \cdot G_{R \max}}
\]

with \( L_{eff} = (1 - e^{-\alpha L}) / \alpha \). The critical power levels for different fibre types are listed in table E.2 and are significantly higher than for SBS in the same fibre link. However, increasing number of WDM channels requires higher launch powers into the fibre and SRS degrades transmission. As a result of the triangular shape of \( g_R(\omega) \), the attenuation linearly increases at the shorter wavelengths resulting in a ‘tilted’ channel spectrum after transmission and decreased SNR for the distant wavelengths. Therefore, channel pre-emphasis can compensate for the frequency-dependent nonlinear loss induced by SRS. The beneficial aspect of the Raman effect, the broadband gain, is used in remote amplification, where SSMF fibre is optically pumped providing gain for WDM channels [HAN97].

<table>
<thead>
<tr>
<th>( \lambda ) [( \mu )m]</th>
<th>1.3 (SSMF)</th>
<th>1.55 (SSMF)</th>
<th>1.55 (DSF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_R \cdot 10^{-14} ) [m/W]</td>
<td>3.81</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>( P_R ) [dBm]</td>
<td>34.3</td>
<td>32.5</td>
<td>33.0</td>
</tr>
</tbody>
</table>

Table E.2 Critical launch power \( P_R \) for a PRBS-modulated channel propagating over 100km of fibre, according to [HAN95]
FWM is a result of the Kerr effect where electric fields of different frequencies $\omega$ interact and new frequency components $\omega_{FWM}$ are generated as shown in equation (2.14). In particular, a new photon is created by combination of three photons from the incoming signal in a stimulated process. If any two frequencies are equal, partially degenerate FWM occurs. Unlike SRS and SBS, no energy is exchanged with the medium and both energy and momentum conservation applies for all 4 photons involved. In comparison, momentum conservation is automatically achieved for SRS and SBS due to the presence of a phonon.

The evolution of the FWM components from $N$ optical channels in the fibre is derived starting from the nonlinear wave equation (C.2) using the undepleted pump approximation valid for low FWM amplitudes. The power loss of the input signals due to FWM is negligible and only determined by the fibre attenuation. $P_{NL}$ is substituted by equation (C.3) as linear combination of four interacting electric fields $i,j,k,l = 1...N$. Assuming that the electric fields are time-independent (CW) with $A(z) = A(z,t) = A_0 \exp(-\alpha z / 2)$ the evolution of the $l$-th field $A_l(z)$ is described by a nonlinear coupled wave-equation [HIL78]

$$\frac{dA_l(z)}{dz} + \frac{1}{2} \alpha A_l(z) = \frac{i}{3} \sum_{ijkl} d_i A_i^*(z) A_j(z) A_k(z) \exp(i\Delta \beta z)$$  \hspace{1cm} (F.1)

where $d_i$ denotes the degeneracy factor with $d_l= (1,3,6)$ for three, two or no identical frequencies, respectively, and the sum of all permutations $\Sigma_{ijk}$ is calculated. $\Delta \beta$ is the phase mismatch between the propagation constant $\beta=1/n_g$ of $A_i$ and the combination of the other signals $\Delta \beta= -\beta_i + \beta_j + \beta_k - \beta_l$. The FWM frequency is given as $\omega_l = -\omega_i + \omega_j + \omega_k$ and the number of distinct FWM contributions increases rapidly with $\frac{1}{2}N^2(N^2-1)$ [ROT98]. For two channels exhibiting partially degenerate FWM there are two FWM peaks termed Stokes (longer wavelength) and anti-Stokes (shorter wavelength) but the number increases to 24 when doubling the input channels. The power $P_{F}(L)$ converted into the FWM band can be obtained by integrating equation (F.1) along the fibre length $L$

$$P_{F}(L) = P_{0}P_{0}P_{0} \left( \frac{\gamma d_l}{3} \right)^2 \exp(-\alpha L) \left| \frac{\exp\left[\left(-\alpha + i\Delta \beta\right)L - 1\right]}{i\Delta \beta - \alpha} \right|^2$$  \hspace{1cm} (F.2)

Due to the linear attenuation of the pump channels $P_{0}$, the converted power in equation (F.2) drops exponentially with distance and also depends on the phase mismatch $\Delta \beta$. Fig. F.1 highlights the impact of $\Delta \beta$ on the generation of FWM in an experiment over 60km SSMF with $\Delta \lambda = 0.4$nm, +13dBm/channel and parallel polarisation. At first, DSF fibre with a mean zero dispersion value of $\lambda_D=1555.4$nm was used resulting in $\Delta \beta=6.68 \times 10^{-5}$/m. Significant
FWM was observed, and the FWM peaks were suppressed by -15dB with respect to the pump signal at the fibre output. In addition, second-order FWM was observed due to beating between the first-order FWM contribution and the closest pump channel. In comparison the phase mismatch in the SSMF span increased by two orders of magnitude to $\Delta \beta = 2.93 \times 10^{-3}$/m. As a result, the channels walk off faster and FWM is reduced to -35dB.

![Comparison of FWM spectrum in experiment over different fibre, 60km span, 50GHz channel spacing, 13dBm/channel launch power, left: DSF, right: SSMF](image)

Therefore, FWM can be minimised by high local dispersion increasing $\Delta \beta$. The amount of FWM generated for a given set of physical parameters such as dispersion and channel spacing can be related to the case of $\Delta \beta = 0$ in equation (F.2) where the highest amount of FWM is expected. The FWM efficiency $\eta_{FWM}$ is independent of the channel power and defined as

$$\eta(\Delta \beta) = \frac{\alpha^2}{\alpha^2 + (\Delta \beta)^2} \left( 1 + \frac{4 \exp (-\alpha L) \sin^2 (\Delta \beta L / 2)}{(1 - \exp (-\alpha L))^2} \right)$$

with $\eta_{FWM}(\Delta \beta = 0) = 1$. For a given $\Delta \beta$ determined by the fibre dispersion and channel spacing equation (F.3) predicts an oscillation of $\eta_{FWM}$ with $L$ due to the periodic conversion of power between the pump and the FWM sidebands (parametric process). The period of this oscillation determines the coherence length $L_{coh}$ given by the argument of the sine function as

$$L_{coh} = \frac{\pi}{\Delta \beta}$$

In the experiment using SSMF, $L_{coh}$ was approximately 1km but increased for a DSF span of equal length to 47km resulting in continuous FWM conversion along almost the entire fibre span. Fig. F.2 shows the FWM efficiency as a function of channel spacing for 60km of DSF and SSMF. For DSF fibre $\eta_{FWM} = 1$ for 50GHz channel spacing, but it is reduced by more than two orders of magnitude at 200GHz. The efficiency of FWM in SSMF was 1000 times lower over the considered range of $\Delta f$. 

![Comparison of FWM spectrum in experiment over different fibre, 60km span, 50GHz channel spacing, 13dBm/channel launch power, left: DSF, right: SSMF](image)
FWM efficiency $\eta_{FWM}(\Delta f)$ calculated as a function of pump channel spacing using equation (F.3) for 2 channels, 60km SSMF (solid line) and DSF (dashed line).
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