Experimental Validation of Closed-form EGN Model at Zero-dispersion Wavelength for O-band Coherent Transmission

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Abstract *O-band coherent wavelength-division multiplexed transmission is performed, experimentally verifying the previously reported numerical model. Single channel digital backpropagation is evaluated up to 200 transmitted channels, where four-wave mixing and cross-phase modulation are shown to be the largest source of nonlinear interference.*

Introduction

The ongoing growth in data traffic driven by applications such as artificial intelligence, cloud computing, and data centre interconnects (DCI) is driving the need for high capacity transmission systems tailored to short-reach optical links[1]. The O-band has attracted interest for these applications[2] since an ultrawideband bismuth-doped fibre amplifier (BDFA) has been developed, supporting across the O-band[3],[4]. In[5], a total achievable information rate of over 100 Tb/s in O-band coherent dense wavelength-division multiplexed (DWDM) transmission over an 80-km single-mode fibre (SMF) has been already reported. However, O-band WDM transmission near the zero dispersion wavelength (ZDW) of SMFs introduces degradation of signal quality by enhanced accumulation of nonlinear interference[6] from self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). To further improve the throughput of O-band DWDM transmission systems, accurate and fast numerical models of NLI are needed. Although the closed-form Gaussian noise (GN) model[7] for NLI estimation in fibre links was proposed, the estimation error becomes significant when it is applied to O-band since mathematical approximations in the GN model assume significant chromatic dispersion, as is the case around C-band. Recently, a closed-form extended GN (EGN) model tailored to zero-dispersion regime in O-band has been proposed[8],[9] and validated through simulation results. However, the closed-form EGN model in O-band has not been verified experimentally.

In this work, we describe a coherent O-band transmission experiment and compare the measurements to the closed-form EGN model. The separate contributions of SPM, FWM and XPM are estimated by the model and experimentally evaluated the contribution of SPM via nonlinear compensation (NLC) performance from single-channel digital backpropagation (SC-DBP). In addition, the performance change from NLC is evaluated for different number of transmitted WDM channels. The model and experiment agree and show that as the number of transmission channels increases, the contribution from SPM diminishes due to increasing XPM and FWM contributions in the nonlinear regime.

Experimental O-band Transmission Setup

A single-span coherent O-band DWDM transmission system setup is shown in Fig.1. The first three channels are external cavity lasers (ECLs) spaced at 42 GHz, modulated at 40 GBd, 16-QAM from a 120 GSa/s arbitrary waveform generator (AWG). Each set of modulated signals was split with a 3-dB coupler, delayed relative to the other, and then recombined to generate polarisation-multiplexed signals. The centre and adjacent channels were combined with a 3-dB coupler and then combined with ASE for bandwidth loading, emulating Nyquist-spaced WDM signals, up to the desired bandwidth[5]. The channels were spaced at 42 GHz, and the combined signals were amplified by BDFAs up to their maximum output power of 25 dBm, enabling a maximum launch power of 2 dBm/channel for the 8.4 THz loading case, and 8 dBm for all other cases.

After transmission over 80 km of ultra low loss fibre (ULL), the signals and the local oscillator (LO) were combined to be coherently detected with balanced photodiodes connected to a digital storage oscilloscope (DSO) running at 80 GSa/s. The digital signals were then resampled to 2 Sa/s followed by either DBP or electronic dispersion compensation (EDC). EDC was performed such that the received signals had the same amount of residual chromatic dispersion to reduce any impact on the received SNR. The SC-DBP for SPM compensation was performed at 6 steps per span, with an assumed $\gamma = 2$ (W·km)$^{-1}$ and the launch power

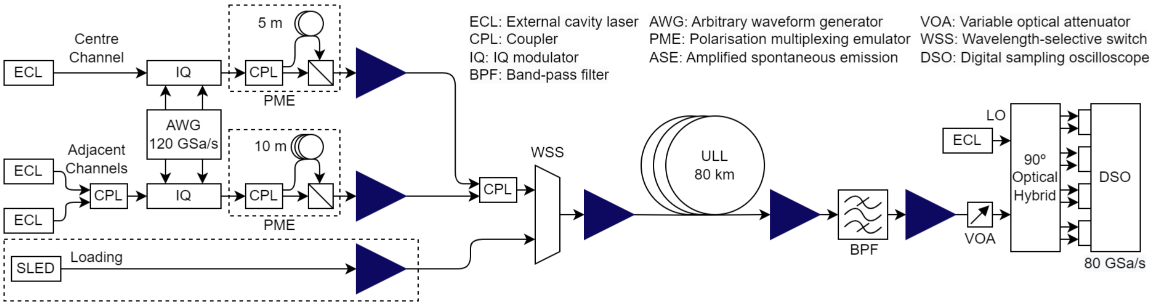

Fig. 1: Experimental setup with variable bandwidth loading.

swept for the highest SNR. The processed signals had the frequency offset removed and then blind adaptive equalization based on a radially directed algorithm was used to demultiplex the polarisations. The filter length was set as 11 taps, considering compensation for any residual chromatic dispersion[5]. After the frame synchronization, the received SNR was then calculated as the ratio of the variance of the transmitted symbols $\mathbb{E}[|X|^2]$ and the variance of the noise $\sigma^2 = \mathbb{E}[|X - Y|^2]$ where $\mathbb{E}[\cdot]$ is the expectation of a random variable, X and Y are the transmitted and received symbols, respectively.

Modelling in O-band

The received SNR is composed of many different sources of impairments and is considered as $\text{SNR}^{-1} = \text{SNR}_{\text{TRX}}^{-1} + \text{SNR}_{\text{ASE}}^{-1} + \text{SNR}_{\text{NLI}}^{-1}$, where SNR_{TRX}, SNR_{ASE}, and SNR_{NLI} are the SNRs due to the transceiver noise, the ASE noise from BDFAs, and the NLI, respectively. The total NLI power σ^2_{NLI} can be expressed as the sum of three types of contributions $\sigma^2_{\text{NLI}} = \sigma^2_{\text{SPM}} + \sigma^2_{\text{XPM}} + \sigma^2_{\text{FWM}}$ where σ^2_{SPM}, σ^2_{XPM}, and σ^2_{FWM} are the noise variances from SPM, XPM, and FWM, respectively.

We used the equations from the recently published closed-form EGN model[8] to calculate the expected NLI contributions. The ASE noise power per polarisation generated from the BDFAs, P_{ASE}, was calculated as $\sigma^2_{\text{ASE}} = n_{\text{sp}} h\nu(G-1)\Delta\nu$, where n_{sp} is the spontaneous emission factor, h is Planck's constant, ν is the carrier frequency, G is the amplifier gain, and $\Delta\nu$ is the optical bandwidth under consideration. n_{sp} was calculated as $n_{\text{sp}} = \text{N}_\text{F}/2$ where N_F is the noise figure of the amplifier previously measured as 6 dB[5]. Gain was assumed to be equal to the link loss which was 27.2 dB measured at 1310 nm. The transceiver SNR (SNR_{TRX}) was measured to be 16.5 dB at 1310 nm and peaked at 17.4 dB at 1286 nm. SNR from ASE and measured transceiver noise are plotted in Fig. 2.

Results and discussion

For the 8.4 THz loaded O-band DWDM transmission, noise variances of SPM, XPM and FWM were calculated from the closed form EGN model for a launch power of -1 dB/channel, and the corresponding SNR values are shown in Fig. 2. The integral model from[6] was also implemented for comparison. It can be seen that the SNR from SPM is always 22 dB higher than XPM or FWM. The FWM is strongest at the ZDW wavelength of 1310 nm, dominating the total NLI generation. This means that the potential of SC-DBP for NLI compensation is quite low for a fully loaded O-band DWDM transmission, unlike in C-band WDM transmission[10]. However, it may be that in deployed O-band transmission systems, more sparsely spaced channels or higher symbol rates will be used which can counteract the impact of XPM and FWM[11].

Experimental measurements of SNR as a function of wavelength are shown in Fig.3. Here the back-to-back performance of the transceiver can

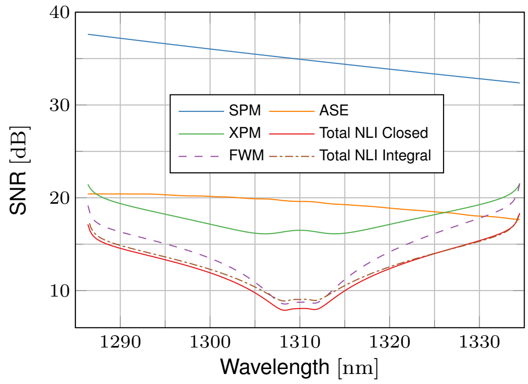

Fig. 2: Calculated contributions of SPM, XPM and FWM towards SNR as a function of wavelength for launch power of -1 dBm per channel.

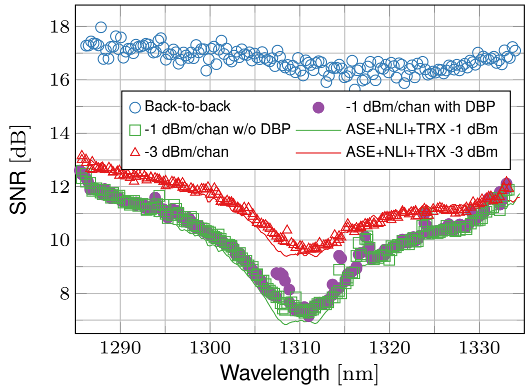

Fig. 3: Experimental measurements of back-to-back SNR and after transmission with and without SC-DBP. The solid lines shows the predicted SNR calculated from the EGN model.

be seen. The SNR smoothly decreases with longer wavelengths by 1.5 dB at 1315 nm from a maximum of 18 dB at 1290 nm before returning to 17.5 dB at 1333 nm. The launch power was fixed to either -3 or -1 dBm per channel and the received SNR was measured, shown as markers. The highest received SNR was 13.0 dB at the shorted transmitted wavelength of 1285.7 nm. As every received SNR was >5 dB lower than the back to back case, it is clear that the transmission performance is not transceiver-noise limited, but is limited mainly by transmission impairments.

The solid lines are for the EGN model which combine the NLI prediction with the measured transceiver noise and ASE noise from BDFAs. The model shows good agreement with the experimental results for both launch powers at the highest and lowest wavelengths, although at the ZDW the model over-estimated the amount of NLI by approximately 0.25 and 0.4 dB for launch powers of -3 and -1 dBm, respectively. The over estimation of NLI at high launch powers was previously noted in[8],[9] with comparison to split step simulations.

As each contribution of NLI is estimated separately within the model, the SPM contribution can be extracted. Experimentally, this is achieved by performing SC-DBP. The received SNRs with and without DBP are compared with the expected results from the model combined with ASE and transceiver noise.

To further understand the contribution of SPM in O-band, the function of the launch power and the number of DWDM channels, the launch power per channel was swept from -6 to 8 dBm per channel, the number of transmitted channels was varied between 1, 2, 3, 5 and 200 and the received SNR of the central was measured. The results are shown in Fig.4. The wavelength of the central channel was 1310 nm; the same as the ZDW of the 80-km ULL fibre, where the largest amount of NLI generation is expected to occur.

For the case of single channel transmission, the highest received SNR was measured to be 15.8 dB. This reduced to 14.3, 13.3, 13.1, 12.5 dB for 2, 3, 5 and 200 channels, respectively. The addition of each set of interfering channels increased the amount of XPM and FWM generation, resulting in the decreasing SNR. After SC-DBP, the highest received SNR for single channel was 16.7 dB. This reduced to 13.3, 12.3, 12.1, 11.5 dB for 2, 3, 5 and 200 channels, respectively. The DBP gain for each transmission bandwidth was 0.67, 0.31, 0.32, 0.11 and 0.05 dB, respectively. The impact of adding more transmission channels reduces the gain from SC-DBP, as the NLI from XPM and FWM start to dominate over the mitigable SPM.

Figure 5 shows the potential gain in SNR from complete compensation of SPM at a fixed launch power. For 3 channels the gain is 1 dB. This decreases rapidly as more channels are added. This agrees with the experimental results shown as markers. It can be seen that for more than 5 transmission channels, the gain from DBP is less than 0.1 dB. As the number of transmission channels is increased even further the DBP gain tends towards zero, as we observed in the transmission experiment and model. This is because, within the captured bandwidth, the SPM is significantly smaller than FWM and XPM. If the captured bandwidth is larger, multi-channel DBP for XPM and FWM compensation is available and would be able to mitigate the NLI to a greater extent.

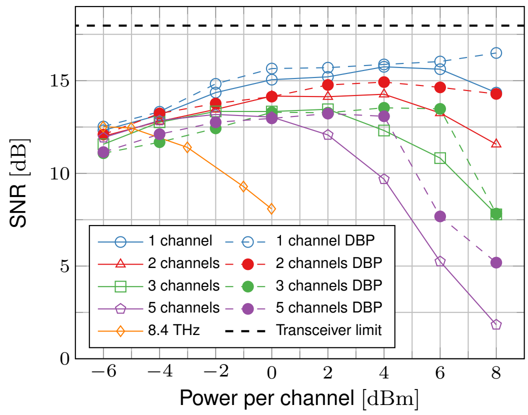

Fig. 4: Measured SNR with and without SC-DBP vs. launch power per channel at 1310 nm.

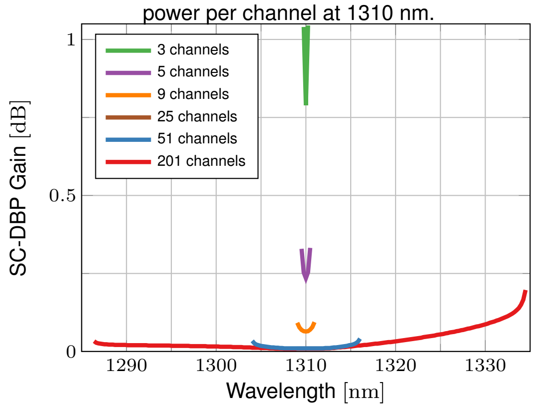

Fig. 5: Theoretical gain in SNR for complete SPM compensation at 1 dBm launch power per channel for multiple transmission bandwidths.

Conclusions

Coherent transmission in O-band is affected by multi-channel nonlinear interference including FWM and XPM. We have shown that performance impact due to NLI can be accurately predicted by our closed-form EGN model. We have verified this model for the first time, demonstrating single-channel DBP gains predicted by the model. For wider transmission bandwidths, the model and experiments show that, single-channel DBP is less effective in compensating for XPM and FWM, but may be mitigated by coarser WDM spacing in the O-band.

Acknowledgements

We would like to thank Furukawa Electric Co., Ltd. and Lightera Labs, Somerset, NJ 08873, USA. for providing the low-loss optical fibre used in this work. This work is supported by EPSRC Programme Grant TRANSNET (EP/R035342/1), EP/W015714/1 Extremely Wideband Optical Fibre Communication Systems (EWOC), UCL Research Excellence Scholarship for R.Aparecido) and a Royal Society Research Professorship (P. Bayvel).

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