Phase-sensitive amplification of 11 WDM channels across bandwidth of 8 nm in a fibre optic parametric amplifier

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Abstract We experimentally demonstrate phase-sensitive fibre optic parametric amplification with gain >10dB and optical noise figure below 3dB for 11 channels spaced of 100 GHz. We employ all-fibre dispersion management to achieve a wideband phase-matching between signals and their copies.

Introduction

Phase-sensitive amplifiers (PSA) attract researchers' attention for their potential for noiseless amplification [1]. For instance, a PSA with noise figure of 1.1 dB has been experimentally demonstrated [2]. Low PSA noise figure allows to improve signal SNR and consequently to increase reach of an optical transmission link [3]. Although implementation of a PSA in transmission link requires to additionally transmit signal copies (idlers) thus halving an available bandwidth, the PSA allows to increase overall link capacity when signal SNR is below 3 dB [4]. Thus, PSA has allowed for a world-record sensitivity in free-space communications [5].

Phase-sensitive amplification is achieved in optical parametric amplifiers (OPA) exploiting $X^{(2)}$ or $X^{(3)}$ nonlinearity by "coherent superposition" [4] of an amplified signal and its copy. This requires a precise phase matching of a signal, its copy and a pump at the PSA gain medium input. Consequently, phase-sensitive amplification of WDM signals requires a simultaneous phase-matching over a wide signal bandwidth. This has been proved to be a difficult problem as signals and their copies experience wavelength dependent phase-shift, primarily due to dispersion, between amplification stages [6]. Phase-sensitive amplification in $X^{(2)}$ OPA of 16 channels over ~13 nm has been demonstrated using an optical processor [7]. However, phase-sensitive amplification in $X^{(3)}$ OPA known as fibre optic parametric amplifiers (FOPA) has been limited to amplification at any one wavelength over bandwidth up to 170 nm by using variable delay lines [8], or at three specifically chosen wavelengths within a range of 4 nm [9].

We propose all-fibre dispersion management to achieve phase-matching between signals, its copies and a pump over wide bandwidth, because optical processors introduce large loss and variable delay lines are not practical for a large number of WDM channels.

In this paper we employ a combination of inverse dispersion fibre (IDF) and standard single mode fibre (SSMF) to accurately compensate for phase-mismatch over bandwidth of ~10 nm. Consequently, we demonstrate a phase-sensitive FOPA with the record continuous bandwidth of 8 nm, optical noise figure below 3 dB and gain >10 dB employed to amplify 11 WDM channels simultaneously.

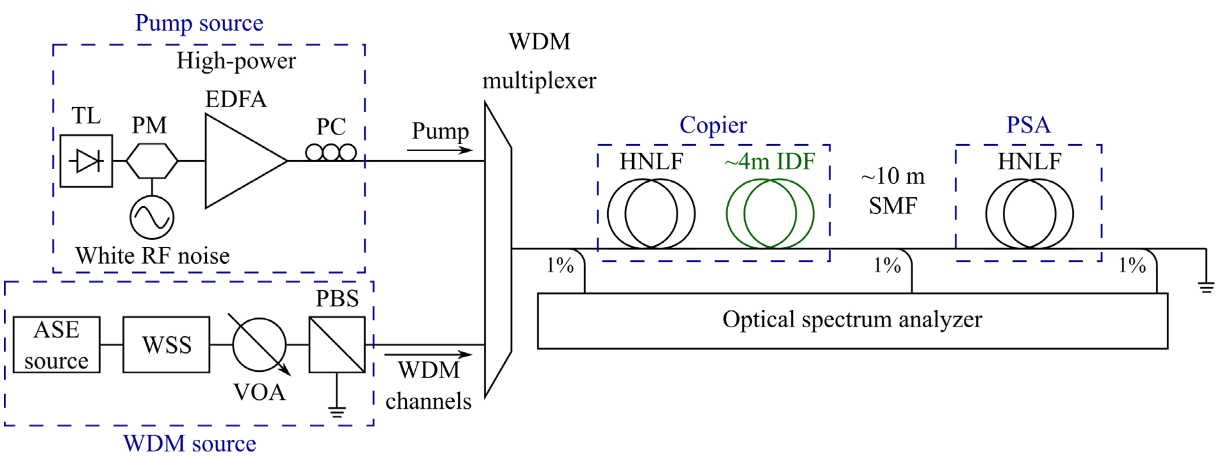

Fig. 1: Experimental setup to demonstrate broadband phase-sensitive amplification

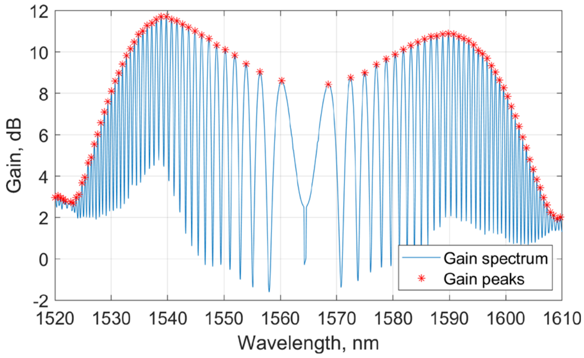

Fig. 2: PSA gain spectrum without dispersion management. Wavelengths of gain peaks are identified for calculation of residual dispersion.

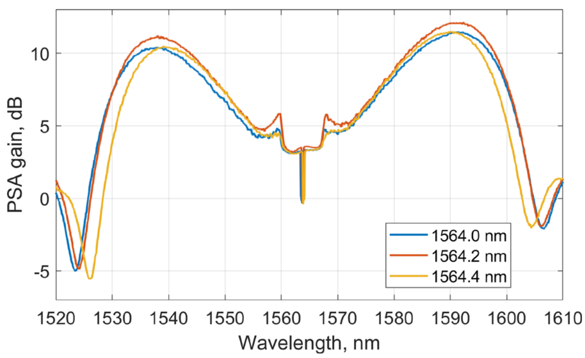

Fig. 3: PSA gain spectrum after dispersion management optimization. Pump wavelength is adjusted to match a parametric gain peak with a wavelength range of phase-matching.

Experimental setup

Fig. 1 shows experimental setup to demonstrate broadband phase-sensitive amplification. In this experiment a pump and a set of WDM channels are multiplexed and passed through a copier to produce copies of WDM channels. Then, the pump, the WDM channels and their copies are passed to a PSA. Gain and noise figure for every channel are measured for the copier and the PSA using calibrated 1% tap couplers and an optical spectrum analyser.

The pump was sourced from a tuneable 100 kHz linewidth laser and phase modulated by white RF noise to mitigate stimulated Brillouin scattering of the pump [10] in the copier and the PSA. Then, the pump was amplified by a high power EDFA with output power of 8 W. Pump wavelength was tuned around 1564 nm.

There were 11x 100-GHz spaced channels with central frequencies from 194.3 THz (1542.9 nm) to 195.3 THz (1535 nm). The channels were produced by shaping amplified spontaneous emission using a wavelength selective switch. The channels' spectral shape mimicked commercial 35 GBaud PDM-QPSK (100G) signals. Power of the channels was set to -40 dBm per channel by a variable optical attenuator (VOA). The channels were passed through a polarisation beam splitter (PBS) to polarise them as both the copier and the PSA were single-polarisation amplifiers.

Both the copier and the PSA were FOPAs which gain mediums were 50 m highly nonlinear fibres (HNLF) with ZDW of ~1562.4 nm, and a nonlinear coefficient of ~13.8 $W^{-1}km^{-1}$. The pump powers at the HNLF inputs were 36.4 dBm (4.4 W) and 33.3 dBm (2.1 W) respectively. The copier has additionally employed ~4 m of inversed dispersion fibre (IDF) with dispersion around -44 ps/nm/km to pre-compensate for dispersion occurring between the copier and the PSA in pigtails and patch cords (next section estimates this length to be ~10 m).

Results and discussion

The PSA gain spectrum was first assessed by amplifying a broadband noise and without any dispersion management. An ASE noise source was connected directly to the multiplexer instead of the WDM channels.

Fig. 2 shows the PSA gain spectrum measured in absence of dispersion management using a broadband gain spectrum measurement technique [11]. At this stage the gain spectrum consists of a large number of peaks due to dispersion occurring between the copier and the PSA [6]. Such a gain spectrum is not practical, but its envelope provides an estimate of a potential PSA gain spectrum. Thus, gain >10 dB over >10 nm could be obtained if phase matching between amplified probes, their copies and the pump is restored in range between 1535 nm and 1550 nm.

$$D = \frac{f_{pump}^2}{c \times \left(\Delta f_{n+1}^2 - \Delta f_n^2\right)} \qquad (1)$$

Frequencies of the gain peaks at Fig. 2 allow to estimate the residual dispersion to be compensated. The residual dispersion D can be calculated using Eq. (1), where f_{pump} is the pump frequency and Δf_n is the frequency detuning between the n-th peak and the pump. Eq. (1) is derived considering that the phase shift between neighbouring peaks is 2π [6]. Wavelengths of 52 peaks are identified on Fig. 2 and shown by red crosses. The average residual dispersion calculated for 51 pairs of peaks was 0.175 ps/nm with standard error of 0.001 ps/nm. This allows to estimate that the total length of SSMF between the copier and the PSA is ~10.3 m (assuming SSMF dispersion of 17 ps/nm/km) and that ~4 m of IDF (dispersion -44 ps/nm/km) is required for dispersion compensation.

IDF was added to the copier to pre-compensate for dispersion occurring between

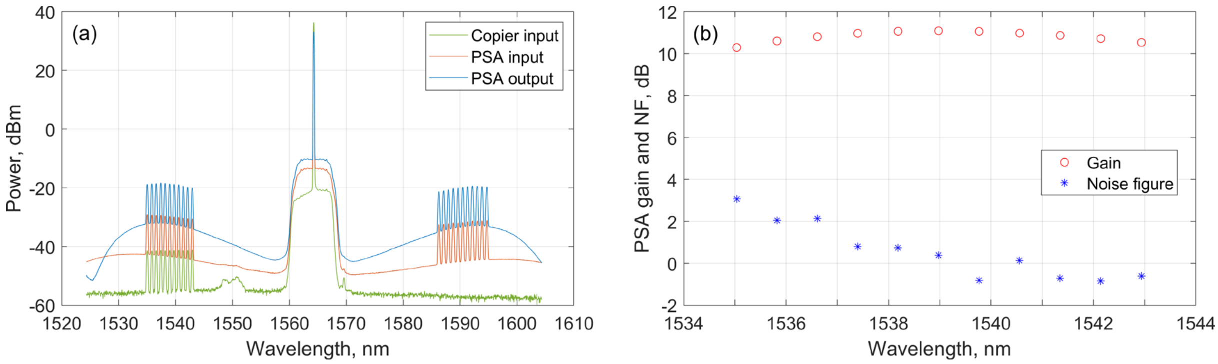

Fig. 4: (a) Optical spectra at the input and output of the copier and the PSA when amplifying WDM channels. (b) Gain and noise figure of each channel in the PSA.

the copier and the PSA. A few iterations have been performed to adjust length of the IDF and its SSMF pigtails. At every iteration the PSA gain spectrum was measured to evaluate the residual dispersion using Eq. (1). Eventually a continuous wideband gain was achieved near the parametric gain peak at ~1540 nm, when the residual dispersion was ~0.008 ps/nm.

The pump wavelength was adjusted to match the parametric gain peak with the wavelength range of the best phase-matching between the channels and their copies. A PSA 10 dB gain bandwidth in excess of 10 nm is achieved for the pump wavelength of 1564.2 nm (Fig. 3). The gain bandwidth was restricted by a negative gain dip at ~1528 nm caused by residual dispersion and by gain reduction within a ~15 nm range around the pump. The gain dip could be eliminated by more accurate compensation of the residual dispersion. The gain reduction around the pump is caused by phase-mismatch inherited from the copier and could be compensated by a more sophisticated dispersion management, for instance, employing a few fibre types with different dispersion profiles.

Fig. 4 shows results obtained with WDM channels amplified in this PSA. Fig. 4(a) shows optical power spectra measured with resolution bandwidth of 0.2 nm at the copier input, the PSA input and the PSA output. Power per channel was -40 dBm at the copier input and -28±1 dBm at the PSA input. Power per channel at the PSA output reached -18±1 dBm, so the total PSA output power was around -8 dBm (not counting for the copies).

Fig. 4(b) shows results of the PSA gain and optical noise figure (NF) measurement. The gain and the noise figure were calculated for every channel frequency using Eq. (2) [12], where S_{in} (S_{out}) and N_{in} (N_{out}) are the signal and noise powers at the input (output) of the PSA measured for every channel using an optical spectrum analyser with resolution bandwidth of 1 nm. Eq. (2) contains factor of 2 because the PSA is single polarisation. Noise power was measured by omitting corresponding channel and thus measuring its background noise.

$$G = \frac{S_{out} - N_{out}}{S_{in} - N_{in}};\ NF = \frac{2\times\left(N_{out} - GN_{in}\right)}{Gh\nu B} - \frac{1}{G} \qquad (2)$$

Fig. 4(b) demonstrates gain >10 dB and noise figure below 3 dB for each of 11 channels across bandwidth of 8 nm. Noise figure for some channels is measured to be <0 dB supposedly due to noise figure measurement error estimated to be ~1 dB. On the other hand, the noise figure approaches 3 dB for short wavelength channels supposedly due to an increase of phase-mismatch between channels and their copies, which reduces an advantage of phase-sensitive amplification.

Conclusion

In this work we demonstrate for the first time to the best of our knowledge a phase-sensitive FOPA to simultaneously amplify 11 WDM channels across bandwidth of 8 nm with optical noise figure below 3 dB. This was enabled by all-fibre dispersion management employing an inversed dispersion fibre to compensate for phase-mismatch between channels and their copies over bandwidth >10 nm. We believe the described techniques will be useful for further development of broadband multichannel phase-sensitive amplifiers.

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