Polarization-interleaved WDM signals in a fiber optical parametric amplifier with orthogonal pumps

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Abstract: We have demonstrated a polarization-interleaved wavelength-division multiplexed system with a two-orthogonal-pump optical parametric amplifier. The sensitivity has been improved by about 2dB compared to its counterpart with all channels co-polarized, with the same signal gain, which itself dramatically improved over the conventional two-parallel-pump OPA.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.2330) Fiber optics communications; (190.4370) Nonlinear optics, fibers

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1. Introduction

Fiber optical parametric amplifiers (OPAs) have recently been demonstrated to be practical amplifiers with high gain [1], large bandwidth [2] and polarization independence [3,4,5]. The quality of signals emerging from OPAs used as signal processors has been investigated by several groups recently, especially with regard to the pump-to-signal RIN transfer [6], cross-phase modulation (XPM) amongst wavelength-division multiplexed (WDM) channels [7], etc. However, four-wave mixing (FWM) and cross-gain modulation (XGM) seem to be the fundamental limits for using OPA as WDM amplifier. Previous work has shown that this kind of degradation is already severe with only three WDM channels in a one-pump OPA (1P-OPA) system [8]. It was also shown that unequal channel spacing slightly improves the FWM degradation [9]. However, the XGM effect still provides a basic detrimental effect when using OPA in WDM systems, mediated through the depletion of the pump(s). Compared to a 1P-OPA, a two-pump OPA (2P-OPA) provides an extra degree of freedom; it can achieve a flattened gain spectrum with a large gain bandwidth [10,11,12]. Previous efforts included the investigation of the relationship between the spurious FWM and signal power and length of nonlinear medium for a 2P-OPA [13]. It has also been shown that with low gain and output power, the crosstalk level and power penalty are acceptable [14,15,16], though the conditions may not be necessarily fulfilled for practical applications, especially when using a fiber OPA as a power booster amplifier. Previously, Jopson et al. have exploited 2OP-OPA to achieve mid-span spectral inversion (MSSI) in a 320-km transmission link [17,18], and we have explored the possibility of using two-orthogonal-pump OPA (2OP-OPA) to suppress WDM crosstalk and showed promising preliminary results [19].

In this paper, we further demonstrate that with the aid of polarization interleaving (POIN) [20], the WDM signal degradation can be improved significantly. That is because FWM is strongly dependent on the states of polarization (SOPs) of neighboring channels and is essentially suppressed if two channels are orthogonal to each other [21]. We will focus on the large-signal behavior in 2P-OPA, particularly 2OP-OPA.

2. Theory

The signal quality degradation of WDM channels due to XGM and FWM in a 2P-OPA system is illustrated in Fig. 1. Only channel #1 (λ_1) is shown with intensity-modulation (IM) for clarity. Also note that the corresponding idlers for all four channels (λ_1 – λ_4) have not been shown here for simplicity. The signal (λ_1) is amplified by the parametric gain (with pump wavelengths at λ_{p1} and λ_{p2}). As it grows, it draws power away from the pump(s), because the total optical power remains constant. As a result, the pump power itself now has IM and all channels #2 – #4 will exhibit slightly different gains at different times, depending on whether they travel with a depleted part of the pump, or an undepleted one. As a result, the amplified channels #2 – #4 will themselves exhibit IM, which constitutes crosstalk. If we now consider that channels #2 – #4 are replaced by independent modulation signals, it is clear that their amplitudes will experience fluctuations due to XGM crosstalk induced by the first channel and vice versa, which will lead to deterioration of their qualities. Furthermore, the spurious FWM also lead to extra signal quality degradation [11].

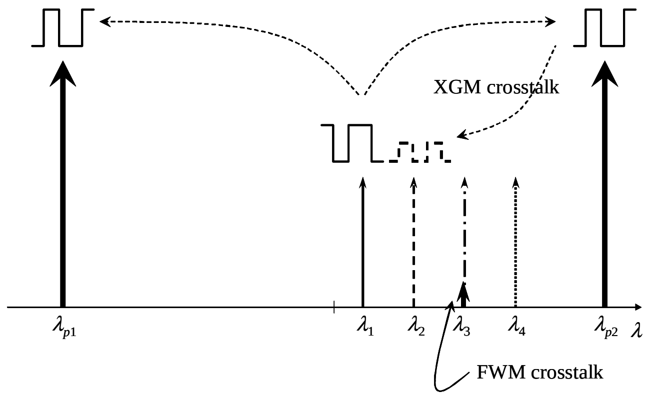

Fig. 1. Illustration of the signal quality degradation of WDM system due to XGM and FWM effects in a 2P-OPA configuration. Refer to the text for details.

Previously, we have demonstrated with co-polarized (COPO) WDM channels in a 2OP-OPA [as shown in Fig. 2(a)], that the WDM signal degradation improved by at least 1.7 dB in the Q-factor measurement, and by more than 2 dB in the power penalty, compared to the 2PP-OPA counterpart. Now, we propose that by using POIN WDM channels [as shown in Fig. 2 (b)], the signal quality can further be improved.

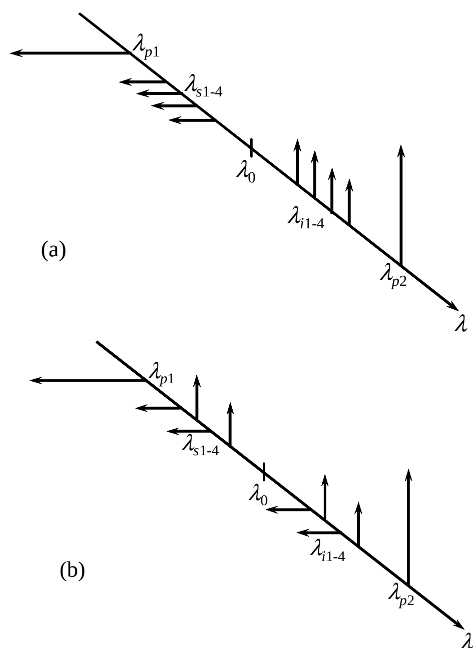

Fig. 2. 2OP-OPA system with WDM channels that are: (a) Co-polarized (COPO); (b) Polarization-interleaved (POIN).

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3. Experiments

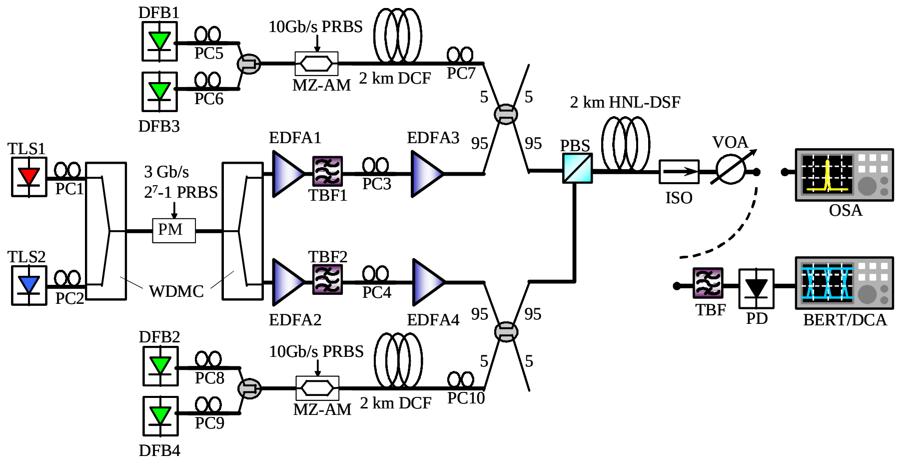

Fig. 3. 2OP-OPA with POIN configuration. TLS: Tunable laser source. PC: Polarization controller. PM: Phase modulator. VOA: variable optical attenuator. MZ-IM: Mach-Zehner intensity modulator. ISO: Isolator.

We performed experiments to verify the predictions of the preceding section. The experimental configuration is shown in Fig. 3. The parametric gain medium consists of 2 km of HNL-DSF (OFS Ltd.) with a nominal zero-dispersion wavelength λ_0 of 1543.4 nm, and a dispersion slope of 0.019 ps/nm^{2}km. The fiber nonlinear coefficient γ is 10.4 W^{-1}km^{-1}. Two tunable laser sources, TLS1 and TLS2, set at 1529.45 nm and 1556.8 nm, respectively, serve as the pump sources. The pump wavelengths, with average wavelength approximately equal to λ_0, are selected to flatten the ASE gain spectrum. The CW pumps are phase-modulated (PM) by a 3 Gb/s 2^7-1 pseudo-random bit sequence (PRBS) to suppress stimulated Brillouin scattering (SBS). The polarization controllers, PC1 and PC2, align the pump SOP's with PM, which helps to reduce the insertion loss. The two pumps are then separated by a WDM coupler (WDMC), amplified by two C-band EDFA's (EDFA1 & 2), and followed by tunable bandpass filters (TBF) with 0.84 nm (TBF1) and 1.96 nm (TBF2) bandwidth, respectively. Pumps #1 and #2 are then amplified by two separate EDFAs, with maximum output power of 21 dBm each, and they are combined with odd (#1, #3) and even (#2, #4) channels by 95/5 couplers, respectively. The two branches are then combined with a polarization beam-splitter (PBS). Furthermore, polarization controllers (PC3 and PC4) are used to ensure that the two pumps incident on the HNL-DSF are orthogonal. Similarly, PC7 and PC10 are used to maintain orthogonal SOPs between odd and even channels. We used 4 WDM channels (DFB1-4, with odd and even channels orthogonal to each other) with spacing of 100 GHz, as signals to determine the signal quality degradation. Each signal is intensity-modulated by a 10 Gb/s PRBS. The signal wavelengths of the WDM channels used are: λ_1 = 1551.1 nm, λ_2 = 1551.9 nm, λ_3 = 1552.7 nm, and λ_4 = 1553.5 nm, respectively. They are decorrelated by 2 km of dispersion-compensating fiber (DCF). The input signal power of each channel is –6 dBm, and the signal gain of each WDM channel is about 13 dB, so that the signal output power of each channel is about 7 dBm. The output spectrum of HNL-DSF, followed by an isolator which prevents any reflection from the variable optical attenuator (VOA), is observed at the OSA. We define the FWM crosstalk term as the newly generated power right next to channel #1 (i.e. 1551.9 nm). After measuring the optical crosstalk, we also measure the eye diagrams and bit-error-rate (BER) using the digital communication analyzer (DCA) and BER tester. In order to quantify the improvement due to POIN, we also measure the eye diagrams and BER of the 2OP-OPA without POIN, with a setup similar to that used in Ref. [19]: essentially the PBS is removed and all WDM channels are co-polarized (COPO).

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4. Results and discussion

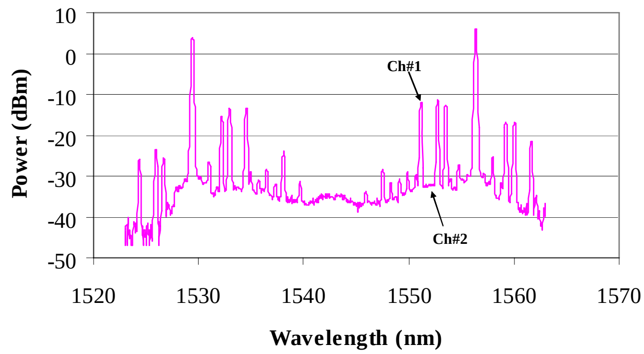

Fig. 4. Optical spectra for 2OP-OPA with three POIN WDM channels.

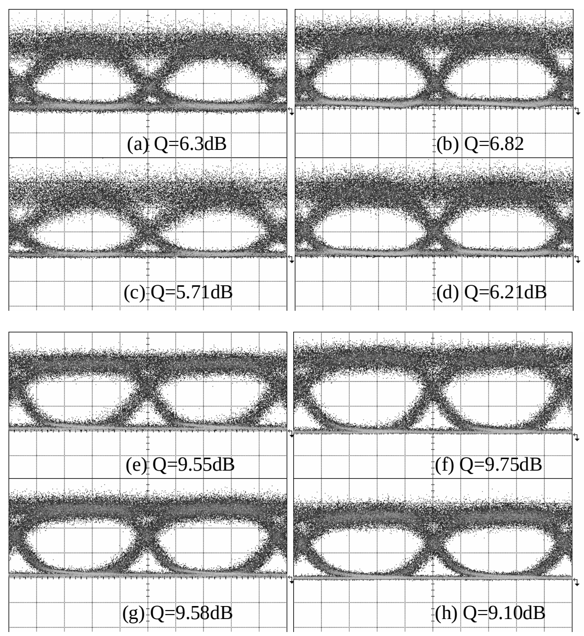

Fig. 5. Eye diagrams (with Q factors) for 2OP-OPA with COPO signals at different λ_s (nm): (a) 1551.1; (b) 1551.9; (c) 1552.7; (d) 1553.5. The corresponding eye diagrams with POIN signals (e) – (h).

The results are shown in Fig. 4, Fig. 5, and Fig. 6. Firstly, Fig. 4 shows the output optical spectrum with channels #1, #3 and #4 turned ON, while channel #2 was OFF. Since the noise floor at channel #2 (1551.9 nm) is about –20dB below channel #1 (1551.1 nm), the FWM crosstalk is at least –20dB, which is marginally better than that measured in a 2OP-OPA with COPO signals (i.e. –19.4dB) [19]. It cannot provide conclusive evidence of the improvement of 2OP-OPA with POIN over COPO signals.

Therefore, we measured the eye diagrams and Q-factors for all four channels (including channel #2, which was OFF in Fig. 4) and the results are shown in Fig. 5(a) – (h). The eye diagrams for 2OP-OPA with POIN signals have wider eye openings than those with COPO signals, as shown in Fig. 5(a) – (h). Also the Q factor is improved by at least 3dB. Note that the increase of the crosspoint is due to the OPA gain saturation. We take advantage of it to suppress the noise in the mark level.

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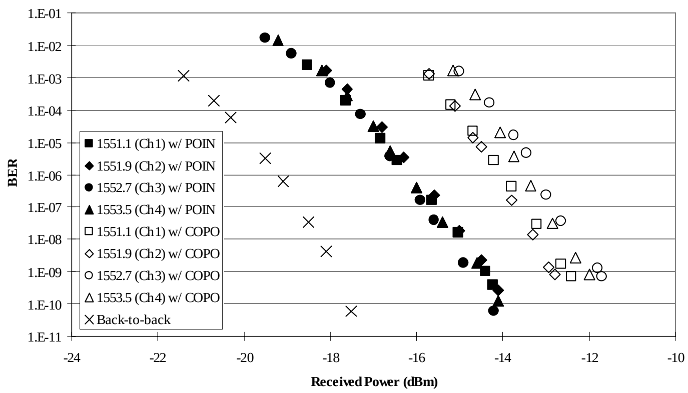

Fig. 6 BER curves for all four channels with POIN and COPO signals.

In order to quantify the power penalty due to the OPA, we also measured the BER of the amplified signal for 2OP-OPA with POIN and COPO signals. The results are shown in Fig. 6. Note that there is about a 2dB improvement in sensitivity of POIN over COPO signals, which is consistent with what we inferred from Fig. 5. The power penalty over the back-to-back curve is due to the imperfect SBS suppression and the ASE noise inherited from the high power EDFA.

We have performed simulations with a commercially available package [22] to quantify these considerations. Sections II-IV in Ref. [22] describe in detail the equations used for modeling propagation in transmission fibers. The model includes dispersion, nonlinearity, and random birefringence, which are also required for studying propagation in fiber OPAs. In previous work, we have found that this package provides numerical results for OPAs that are generally in good agreement with experimental results.

The common parameters used here were the same as in our experiments, namely: Fiber: HNL-DSF; L = 2 km; γ = 10.4 W^{-1} km^{-1}; λ_0 = 1543.4 nm; dispersion slope of 0.019 ps/nm^{2}km. When four WDM channels were present at the same set of wavelengths as in our experiments, the simulation results showed a FWM crosstalk reduction by at least 7dB as the channel separation was increased from 100GHz to 400GHz. This helps to justify limiting our experiments to only four WDM wavelengths, 100GHz apart.

We also extended the system to 32 WDM channels, and similar simulation results were obtained. POIN performed better than COPO by at least 1.5 dB in term of Q-factor for most of the WDM channels, especially those channels with poorer Q-factors.

The rationale for the experiments is based on the FWM reduction due to POIN signals. However, there is no similar expectation for XGM. In fact, since in a polarization-independent OPA the gain is the same regardless of SOP, so should be the pump depletion, and the XGM. Therefore, we conclude that the improvement is due to the suppressed spurious FWM in the POIN over COPO configurations.

5. Conclusion

We have demonstrated, for the first time to our knowledge, a polarization-interleaved WDM system with a two-orthogonal-pump OPA. The sensitivity has been improved by about 2dB compared to its counterpart with all co-polarized WDM channels with the same signal gain. These results should help design high-performance OPAs for use in WDM communication systems.

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