Employment of polarization diversity architecture to mitigate an impact of pump phase modulation in FOPA

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Abstract: We demonstrate via simulations and experiments that a FOPA polarization-diverse architecture allows to mitigate an impact of pump phase modulation on amplified signals and thus reduce or almost eliminate the signal required-OSNR penalty. ©2023 The Author(s)

1. Introduction

Fiber optical parametric amplification (FOPA) attracts researchers' attention for its ability to provide broadband, phase-sensitive, and transient-free amplification without wavelength restrictions for applications in fiber optic communications and beyond. Recent advancements in FOPAs have addressed issues of polarization sensitivity, low noise, and crosstalk operation [1], but mitigation of Stimulated Brillouin Scattering (SBS) remains a significant challenge in FOPAs [2] and methods to mitigate SBS in FOPAs continue to be actively developed [3]. The most practical approach to significantly increase the SBS threshold and enable a large FOPA net gain is pump phase modulation, known as dithering [4]. It has been demonstrated that pump dithering induces instantaneous pump frequency modulation and causes gain fluctuations in FOPAs, degrading amplified signals [5,6], but impact of pump phase modulation in polarization-insensitive FOPAs (PI-FOPA) has not been studied yet [7].

In this paper, we discuss that a two-path polarization diversity architecture [1] employed by a single-pump PI-FOPA allows for mitigation of the dithering impact if pumps in the arms of the polarization-diverse FOPA appear with delay in time. This mechanism is similar to employment of counter-phase dithering in two-pump FOPAs [5] but can be employed in more practical single-pump FOPAs. We examine via simulations and experiment an improvement of an amplified 16QAM signal required optical signal to noise ratio (rOSNR) penalty as we adjust the pumps' optical path difference and the pump phase modulation frequencies. We experimentally demonstrate that the signal rOSNR penalty can be decreased by at least 32% and that theoretically the signal rOSNR penalty due to pump phase modulation can be decreased by a factor of 10.

2. Concept

Fig. 1 shows the polarization-diversity architecture of PI-FOPA which is explained in detail in [1]. An input signal in PI-FOPAs employing a polarization diversity architecture is split by a polarization beam splitter (PBS) into two orthogonal linearly polarized components counter-propagating in a loop. Each signal component is independently amplified in one of two nominally identical highly nonlinear fibers (HNLF) in the loop by its corresponding co-propagating pump. Then, the amplified signal components are recombined by the same PBS. The pumps are sourced from a single pump laser, phase modulated, and then split by a 3 dB coupler in two to be amplified by high power EDFAs and coupled into their respective lengths of HNLF. The pumps are phase modulated with a combination of 4 sine tones, whereas the lowest tone frequency (base tone) is 25 MHz and higher frequencies are obtained via multiplication by 3.05, 3.05^2 and 3.05^3.

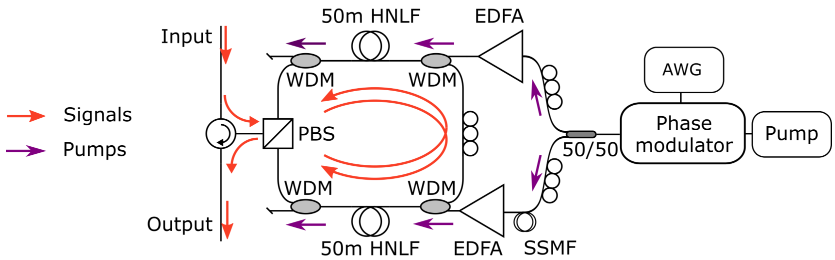

Fig. 1. Scheme of PI-FOPA with different fiber lengths between fiber coupler and EDFAs. PBS – polarization beam splitter, AWG – arbitrary waveform generator.

The impact of pump dithering can be significantly mitigated in a single-pump looped PI-FOPA by ensuring that the impact of dithering on signal phase and amplitude is opposite in the PI-FOPA arms. This opposite impact can be achieved owing to the periodic nature of the tones used for pump phase modulation. Indeed, the pumps follow different optical paths from the phase modulator to gain fibers (HNLFs), hence the pump phase modulation waveforms and the distortions induced to the signal components can be shifted in time. Consequently, if the optical path difference between pumps corresponds to the half period of their phase modulation waveform, the pumps in gain media appear in counter-phase. Then, distortions to signal components induced by the pump phase modulation are opposite and can be at least partially cancelled out upon the signal recombination.

3. Simulations and Experiment

We evaluate the impact of pump dithering in FOPA in terms of rOSNR penalty, defined as the OSNR difference between the simulated/experimental and the back-to-back BER vs OSNR curves at BER level of 0.01. We have followed the algorithm described in [7], deriving the instantaneous pump frequency over time from the pump phase modulation waveform for each arm considering the optical path difference between them. Then we calculate the complex signal gain in each arm across 1000 uniformly spaced points within a 100ns time frame using the instantaneous pump frequency at each point. The total PI-FOPA gain was calculated as a weighted sum of complex gains in each arm, where the weighting factor represents the ratio between signal powers in the arms. We pre-calibrated a commercial transceiver by measuring the rOSNR penalty while modulating phase and amplitude of the received 35GBaud PDM-16QAM (200Gbit/s) signal in back-to-back configuration across the frequency range of 25-2000 MHz and with varied modulation amplitude. We have used the relation between modulation amplitude and rOSNR penalty to derive rOSNR penalty from the simulated instantaneous phase and amplitude shifts.

Fig. 2(a) shows an example simulated power gain versus time for three scenarios. In the first case (blue line) the components of the polarization division multiplexed (PDM) signal are aligned with the PBS axes. This is the worst-case scenario having the most significant gain fluctuation and similar to single-polarization operation. In the second case (purple line), the PDM signal components are aligned at a 45-degree angle to the PBS axes (purple) resulting in an equal split of signal power between FOPA arms. The fluctuation of FOPA gain is noticeably suppressed in this case: peak-to-peak gain amplitude decreases from 0.3 dB to 0.1 dB. In the third case (red dots) the signal polarization varies randomly from point to point. In this case some mitigation occurs depending on signal polarization. Histograms clearly show that the signal gain distribution is much lower in this case than in the ‘single polarization’ case (blue).

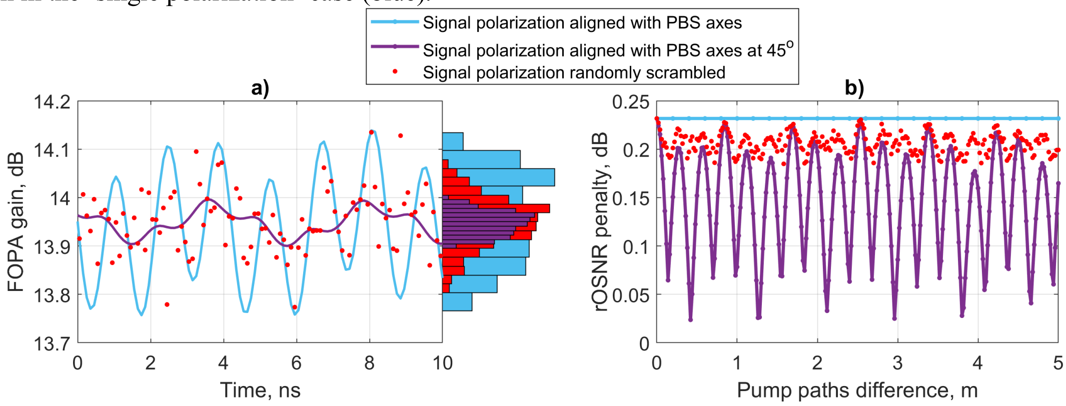

Fig. 2. a) PI-FOPA gain distribution and b) rOSNR penalty versus path difference between pumps for PDM signal polarization aligned with the PBS axes (blue), equally split (purple) or randomly scrambled (red). Histograms depict the distribution of gain.

Figure 2(b) shows the simulated rOSNR penalty as a function of the path difference between pumps for the three scenarios described above. When signal polarization is aligned with the PBS axes the rOSNR penalty is 0.23dB regardless of the pump path difference (blue line). When signal polarization is equally split between the PI-FOPA arms, the rOSNR penalty strongly depends on the pumps’ optical path difference. Thus, there are two series of minima with periods of ~28cm and ~84cm. These minima correspond to the cancellation of distortion caused by the highest (709MHz) and second highest (233MHz) pump phase modulation tones respectively. These tones provide the most significant impact on amplified signals among the four tones, so their mitigation almost eliminates the rOSNR penalty reducing it below 0.03dB. In case of random signal polarization (red), the result is averaged across all polarizations, so the achievable average rOSNR penalty is ~0.18dB if an optimal pump paths difference (or equivalently, base frequency) is chosen.

It might be not practical to carefully measure and adjust the optical path difference to achieve the best performance, instead, the pump phase modulation frequencies can be adjusted to optimize performance with the existing optical path difference between pumps. Fig. 3(a) shows that adjustment of both the pump path difference and the pump phase modulation base tone frequency allows the reduction of the rOSNR penalty by an order of magnitude when compared to the worst-case (i.e. 0.02dB vs 0.22dB) if the signal polarization is equally split between in the PBS. Fig. 3(b) shows that if the signal polarization is random (each point is calculated as an average of many polarizations taken from the same set), adjustments of the optical path difference and/or modulation frequencies can still reduce the rOSNR penalty by approximately 30%, as observed in Fig. 2(b).

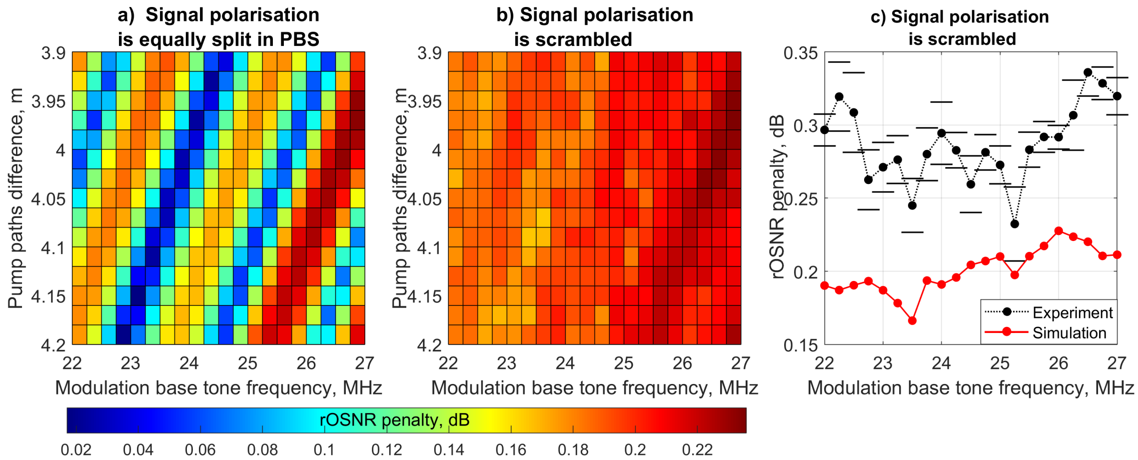

Fig. 3. rOSNR penalty calculated for combinations of pump path difference in meters and pump modulation base tone frequencies for PDM signal polarization (a) equally split or (b) randomly scrambled. (c) rOSNR penalty vs. pump modulation base tone frequency: experimentally measured (black) and simulated for pump path difference of 4.06 m (red).

Fig. 3(c) shows the experimentally measured rOSNR penalty (black dots) versus the variable modulation base tone frequency when the signal polarization was scrambled. We have measured the optical path difference between pumps to be 4.06 m, so we compare the experimental result with the simulation for this pump path difference (a horizontal cross-section of the Fig. 3(b)). The experiment shows a higher rOSNR penalty than the simulation due to the impact of other impairments, such as nonlinear distortion in the FOPA. The two lowest experimentally measured penalties were observed at base tone frequencies of 23.5 MHz and 25.25 MHz as predicted by our simulation. Thus, adjustment of the modulation base tone frequency can reduce the rOSNR penalty from the maximum of 0.34 dB to the minimum if 0.23 dB, i.e. by 32%. We believe this confirms that performance improvement can be achieved by matching the pump phase modulation frequency with the path difference between pumps. It should be noted that the penalty could, in principle, be eliminated if polarization sensitivity were acceptable.

4. Conclusion

The polarization-diverse architecture of looped FOPA offers a solution for mitigation of the pump dithering effects by controlling pump optical path lengths, dithering frequencies and the signal's polarization if possible. We experimentally demonstrate that the rOSNR penalty can be reduced by ~32% via adjustment of the pump dithering frequency. Our simulations show that if an additional signal polarization control is employed, the rOSNR penalty due to pump dithering can be reduced by an order of magnitude. This finding may have implications for other SBS-limited parametric devices, such as wavelength converters and optical phase conjugators, by enabling pump dithering compensation while employing a single pump.

Acknowledgements

We thank Dr Shigehiro Takasaka and Dr Ryuichi Sugizaki of Furukawa Electric for highly nonlinear fibers, and Dr Charles Laperle of Ciena for the transponder. The work was funded by UK EEMC project EP/S016171/1. Data underlying the results presented in this paper are available in Ref. [8].

References

[1] V. Gordienko, F. M. Ferreira, C. B. Gaur, and N. J. Doran, "Looped Polarization-Insensitive Fiber Optical Parametric Amplifiers for Broadband High Gain Applications," J. Light. Technol. 39, 6045–6053 (2021).

[2] V. Gordienko, D. Szabó, M. F. C. Stephens, V. Vassiliev, C. B. Gaur, and N. J. Doran, "Limits of broadband fiber optic parametric devices due to stimulated Brillouin scattering," Opt. Fiber Technol. 66, 2–6 (2021).

[3] C. Guo, M. Vasilyev, Y. Akasaka, P. Palacharla, S. Takasaka and R. Sugizaki, "Temperature-tuned two-segment highly-nonlinear fiber with increased stimulated Brillouin scattering threshold,"Opt. Fiber Commun. (OFC), San Diego, CA, USA, 2023, pp. 1-3

[4] J. B. Coles, B. P.-P. Kuo, N. Alic, S. Moro, C.-S. Bres, J. M. C. Boggio, P. A. Andrekson, M. Karlsson, and S. Radic, "Bandwidth-efficient phase modulation techniques for Stimulated Brillouin Scattering suppression in fiber optic parametric amplifiers," Opt. Express 18, 18138 (2010).

[5] A. Vedadi, A. Mussot, E. Lantz, H. Maillotte, and T. Sylvestre, "Theoretical study of gain distortions in dual-pump fiber optical parametric amplifiers," Opt. Commun. 267, 244-252 (2006).

[6] J. M. C. Boggio, A. Guimarães, F. A. Callegari, J. D. Marconi, and H. L. Fragnito, "Q penalties due to pump phase modulation and pump RIN in fiber optic parametric amplifiers with non-uniform dispersion," Opt. Commun. 249, 451–472 (2005).

[7] M. Bastamova, V. Gordienko, and A. Ellis, "Impact of Pump Phase Modulation on Fibre Optical Parametric Amplifier Performance for 16 -QAM Signal Amplification," Eur. Conf. Opt. Commun. 1–4 (2022).

[8] M. Bastamova, V. Gordienko, N. J. Doran, and A. D. Ellis, "Employment of polarization diversity architecture to mitigate an impact of pump phase modulation in FOPA," Aston University (2023). https://doi.org/10.17036/researchdata.aston.ac.uk.00000615