Impact of Pump Phase Modulation on Fibre Optical Parametric Amplifier Performance for 16-QAM Signal Amplification

Mariia Bastamova [(1)], Vladimir Gordienko[(1)], Andrew Ellis [(1)]

[(1)]Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET
210114416@aston.ac.uk

Abstract *We examine impact of fibre optical parametric amplifier pump phase modulation on signals complex amplitude via simulations. We find that in most practical scenarios the required SNR penalty for 16-QAM signals can be less than 0.1dB at BER of 0.03. ©2022 The Author(s)*

Introduction

Fibre optical parametric amplifiers (FOPA) present a major research interest for fibre optic communications for their virtually wavelength unrestricted [1] abilities for broadband [2], phase-sensitive [3] and transient-free [4] amplification.

Although a significant progress in terms of realising polarisation-insensitive FOPA gain and mitigation of nonlinear crosstalk in FOPA has been achieved recently [5], the mitigation of stimulated Brillouin scattering (SBS) remains a challenge for FOPAs. The SBS limits the pump power employable by a parametric device and thus restricts its performance [6]. One common way to mitigate SBS relies on pump linewidth increase, most often via pump phase modulation known as dithering [7]. This technique consists in phase modulation of pump to evenly distribute pump power across bandwidth sufficient to mitigate SBS without inducing the pump amplitude modulation.

Several theoretical and experimental papers have showed that dithering caused temporal variations of the FOPA gain. The gain variation occurs due to instantaneous pump frequency modulation induced by pump phase modulation [8-12]. This effect has been studied in detail but only for directly detected on-off keying signals. These studies therefore have not considered signal phase noise introduced by dithering and do not address penalties for quadrature modulated signals. Moreover, coherent detection relies on signal amplitude rather than signal power, which has not been addressed in previous study as well. Overall, results of the existing impact of dithering studies in FOPA are not applicable for coherently detected QAM signals widely used in modern optical communications.

In this paper we numerically simulate the impact of pump phase modulation on FOPA performance when amplifying 16-QAM signals. First, we derive the dependency of the amplitude gain and the amplified signal phase shift on the pump frequency. Then, we use these data to calculate BER as a function of signal SNR for a range of pump linewidths across the FOPA gain bandwidth. We find that although dithering-induced impairments increase quickly with the pump linewidth, the pump linewidth of 5 GHz sufficient for SBS mitigation in most FOPAs allows to keep the required SNR penalty for coherently detected 16QAM signals below 0.1 dB at BER of 0.03 at all signal wavelengths within the 3 dB gain bandwidth of the simulated FOPA.

Simulation

We examine the impact of pump phase modulation on signal performance arising from induced instantaneous pump frequency modulation. The latter causes temporal variation of FOPA gain and phase shift and thus introduces amplitude and phase noise for an amplified signal. Therefore, we first calculate FOPA gain in the complex domain as a function of pump frequency, then use it to calculate complex amplitudes of an amplified 16-QAM signal for a range of instantaneous pump frequencies, and finally derive the signal BER considering temporal fluctuations of the output signal complex amplitude.

We calculate complex amplitude gain h_3 in FOPA defined as the ratio between output and input signal amplitudes (Eq. (1)) to consider both power amplification and phase shifts introduced by FOPA [13]. Eq. (1) assumes no loss, no pump depletion case, where g is the gain coefficient given by Eq. (2), k is the total propagation constant, L = 214 m is the gain fibre length, P = 1 W is the pump power, and γ = 14 W^{-1}km^{-1} is the gain fibre nonlinearity coefficient. The total propagation constant k is the key parameter because it depends on the group velocity dispersion at the pump wavelength β_2 and the frequency offset of signal from the pump $\Delta\omega$ (Eq. (3)), which are the two parameters modified by the instantaneous pump frequency modulation.

$$h_3 = \frac{A_{out}}{A_{in}} = \left[\cosh(gL) + i\frac{k}{2g}\sinh(gL)\right] \times \\ \times \exp\left[i\left(2\gamma P - \frac{k}{2}\right)L\right]; \quad (1)$$

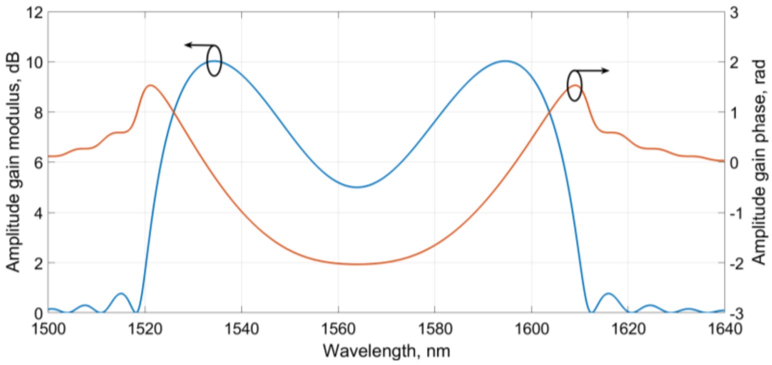

Fig. 1: Gain Amplitude spectra and Gain Phase shift spectra.

$$g = \sqrt{(\gamma P)^2 - k^2/4}; \qquad (2)$$

$$k = 2\gamma P + \beta_2 \cdot \Delta\omega^2. \qquad (3)$$

Fig. 1 shows spectra of the amplitude gain modulus $|h_3|$ and phase calculated for pump wavelength of 1563.7 nm, zero-dispersion wavelength of 1562.9 nm, and dispersion slope of 43 s·m^{-3}. The amplitude gain modulus is the square root of the power gain, so its peak of 10 dB corresponds to the power gain of 20 dB. The amplitude gain phase represents the phase shift introduced to the signal during amplification. Therefore, both values have to be taken into account when calculating impact of pump phase modulation on phase and amplitude modulated signals, e.g. M-QAM.

We simulate the impact of pump dithering on the amplified signal for different pump bandwidths by calculating h_3 at the signal wavelength for 20 pump frequencies distributed across an examined pump bandwidth. Then, the calculated values of h_3 were used to derive a set of output signal complex amplitudes corresponding to different pump frequencies for each point of the 16-QAM constellation diagram. We consequently calculated error probability for every combination of a constellation point and h_3 value. We assumed Gaussian noise distribution for each case, because although temporal fluctuations of h_3 affect overall noise distribution of the output signal, at every instant the output signal has the same noise distribution as the input signal which was assumed Gaussian. Hence, error probability for each point was found as a sum of error functions shown by Eq. (4), where μ is the centre of Gaussian distribution defined by the output signal complex amplitude, x_0 is the decision threshold scaled for all points by the same h_3 corresponding to the central of the simulated pump frequencies, and σ is the standard deviation defined by the input signal SNR [14]. The symbol error rate is found as an average of all error probabilities assuming all constellation points and instantaneous pump frequencies to be equally probable. The BER is found as a ¼ of the symbol error rate due to Gray coding used for 16-QAM signals [15].

$$BER = \frac{1}{2} efrc\left(\frac{x_0 - \mu}{\sigma\sqrt{2}}\right) \qquad (4)$$

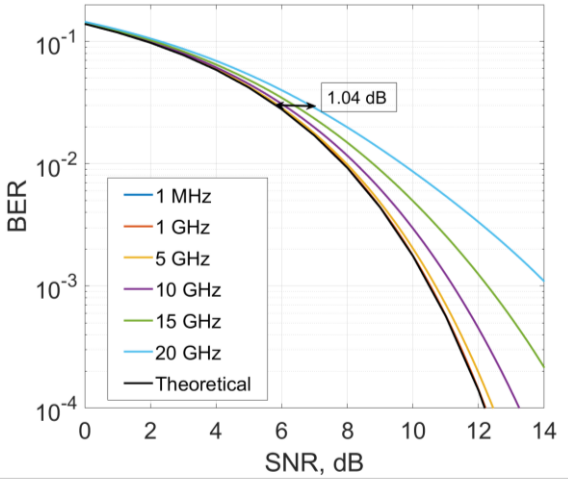

Fig. 2: BER versus SNR for different pump bandwidth for a 16-QAM signal amplified at the FOPA gain peak wavelength.

Results and Discussion

Fig. 2 shows simulated BER of a 16QAM signal at the FOPA gain peak wavelength versus the signal SNR for a set of typical pump linewidths [7, 8]. Fig. 2 additionally shows a theoretical curve (black) for Gaussian-noise limited 16-QAM signals obtained with Eq. (5) [15]. A perfect match between the theoretical curve and our simulated curves for pump linewidths ≤1 GHz implies no performance penalties for such pump linewidths and confirms our model. To characterise the impact of pump phase modulation of higher pump linewidths for a range of signal wavelengths across the FOPA gain spectrum we define the required SNR penalty as the SNR difference between the simulated BER curve and the theoretical (back-to-back) curve at the BER level of 0.03 (close to the forward error correction limit of modern transponders). Thus, the required SNR penalty for the 20 GHz pump linewidth is 1.04 dB (Fig. 2).

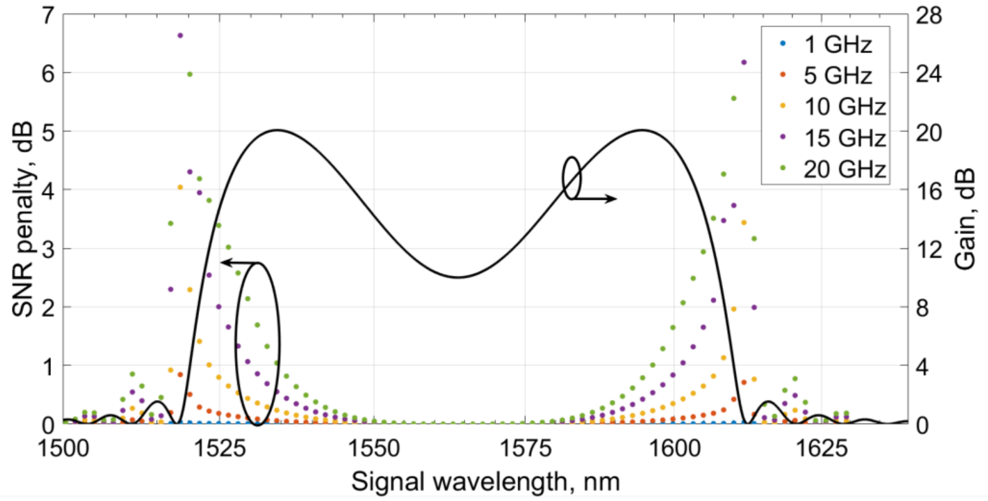

Fig. 3: Gain spectrum and SNR penalty for different pump bandwidths and signal wavelengths.

$$BER = \frac{3}{2} efrc\left(\sqrt{\frac{SNR}{10}}\right) \qquad (5)$$

Figure 3 shows comparison of required SNR penalties for several pump linewidths and a range of signal wavelengths across the FOPA gain bandwidth. Gain spectrum calculated as $|h_3|^2$ is shown for a reference. Expectedly, Fig. 3 shows that the SNR penalties increase with the pump linewidth. The SNR penalty also increases with the signal wavelength offset from the pump wavelength of 1563.7 nm until peaking at the gain spectrum edge. However, essentially only wavelength range within the 3 dB FOPA gain bandwidth presents interest for signal amplification. Then, the biggest SNR penalty occurs at the edge of this band furthermost from the pump (1527 nm) and remains low at the level of 0.1 dB for the pump linewidth of 5 GHz or reaches 2.2 dB for the pump linewidth of 20 GHz. The pump linewidth of 5 GHz allows to increase the SBS threshold by >20 dB if bandwidth-efficient dithering is employed [8] which is sufficient for most FOPA applications [2], although pump linewidth of 20 GHz and more might be required for some ultra-high gain applications [7].

Our results present two spectacular features. First, we observe much less signal performance penalty with 16QAM signal than in previous studies of on-off keying signals (up to 10 dB penalty on Q^2) [9]. Second, we observe a completely different signal penalty distribution across the FOPA gain bandwidth as compared to penalties being minimal at the gain peak and have two maxima at the FOPA gain slopes in [9]. We understand these differences arise due to quadrature-modulation and coherent detection of the signal. Indeed, in case of directly detected on-off keying signals the only source of signal degradation is power gain modulation due to instantaneous pump frequency modulation. Then, the largest degradation occurs where power gain has the largest slopes. However, coherently-detected signals rely on electric field amplitude being square root of power, so the impact of power gain fluctuations on the signal quality is mitigated. On the other hand, quadrature-modulated signals are susceptible to induced signal phase modulation. The correlation between the SNR penalty dependency on the signal wavelength and the complex gain amplitude phase spectrum (Fig. 1) implies that the induced phase noise is the major source of 16QAM signal degradation due to pump phase modulation in FOPA. This explains not only quantitative but also qualitative difference between the SNR penalties of directly-detected on-off keying signals and coherently-detected QAM signals.

Conclusions

For the first time we have numerically studied the required SNR penalty for coherently-detected 16-QAM signals due to pump phase modulation in single pump FOPA. Our results and comparison with previous works indicate that the induced phase noise is the major source of degradation for coherently detected QAM signals, whilst the impact of induced gain fluctuations is mitigated. Consequently, we find that the pump linewidth of 5 GHz sufficient for SBS mitigation in most FOPAs induces the maximum required SNR penalty for 16QAM signal of only 0.1 dB at BER of 0.03 within the 3 dB FOPA gain bandwidth.

Acknowledgements

This paper was funded in part by the EPSRC, grant number EP/S003436/1 (PHOS). Underlying data is available at [16].

References

[1] M. E. Marhic, N. Kagi, T.-K. Chiang, and L. G. Kazovsky, “Broadband fiber optical parametric amplifiers,” *Opt. Lett.*, vol. 21, no. 8, p. 573, 1996,
DOI: 10.1364/OL.21.000573

[2] V. Gordienko, M. F. C. Stephens, A. E. El-Taher, and N. J. Doran, “Ultra-flat wideband single-pump Raman-enhanced parametric amplification,” *Opt. Express*, vol. 25, no. 5, p. 4810, 2017,
DOI: 10.1364/oe.25.004810

[3] M. Vasilyev, “Distributed phase-sensitive amplification,” *Opt. Express*, vol. 13, no. 19, p. 7563, 2005,
DOI: 10.1364/opex.13.007563

[4] C. B. Gaur, V. Gordienko, F. Ferreira, V. Ribeiro, and N. J. Doran, “Fibre optic parametric amplifier for high capacity burst-mode access networks,” Opt. Express, vol. 29, no. 14, p. 21190, 2021,,
DOI: 10.1364/OE.422990

[5] 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., vol. 39, no. 19, pp. 6045–6053, 2021,
DOI: 10.1109/JLT.2021.3099441

[6] 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.*, vol. 66, no. January, pp. 2–6, 2021,
DOI: 10.1016/j.yofte.2021.102646

[7] T. Torounidis, P. A. Andrekson, and B. E. Olsson, “Fiber-optical parametric amplifier with 70-dB gain,” *IEEE Photonics Technol. Lett.*, vol. 18, no. 10, pp. 1194–1196, 2006,
DOI: 10.1109/LPT.2006.874714

[8] J. B. Coles *et al.*, “Bandwidth-efficient phase modulation techniques for Stimulated Brillouin Scattering suppression in fiber optic parametric amplifiers,” *Opt. Express*, vol. 18, no. 17, p. 18138, 2010,
DOI: 10.1364/oe.18.018138

[9] 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.*, vol. 249, no. 4–6, pp. 451–472, 2005,
DOI: 10.1016/j.optcom.2005.01.056

[10]F. Yaman, Q. Lin, S. Radic, and G. E. Agrawal, “Impact of pump-phase modulation on dual-pump fiber-optic parametric amplifiers and wavelength converters,” *IEEE Photonics Technol. Lett.*, vol. 17, no. 10, pp. 2053–2055, 2005,
DOI: 10.1109/LPT.2005.856346

[11]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.*, vol. 267, no. 1, pp. 244–252, 2006,
DOI: 10.1016/j.optcom.2006.05.074

[12] P. Kylemark *et al.*, “Impact of pump phase-modulation on the bit-error rate in fiber-optical parametric-amplifier-based systems,” *IEEE Photonics Technol. Lett.*, vol. 19, no. 2, pp. 79–81, 2007,
DOI: 10.1109/LPT.2006.889014

[13]M. E. Marhic, *Fiber Optical Parametric Amplifiers, Oscillators and Related Devices*, 1st ed. New York: Cambridge university press, 2008,
DOI: 10.1017/CBO9780511600265

[14] J.R. Barry, E. A. Lee, *Digital communication*. Springer Science & Business Media, 2012,
DOI: 10.1007/978-1-4615-0227-2

[15] K. Sankar, “Symbol Error Rate (SER) for 16 QAM”,
http://www.dsplog.com/2007/12/09/symbol-error-rate-for-16-qam/,
accessed on 20 March 2022.

[16] M Bastamova, V. Gordienko, A. Ellis, “Impact of Pump Phase Modulation on Fibre Optical Parametric Amplifier Performance for 16-QAM Signal Amplification,” Aston University (2021)
DOI:10.17036/researchdata.aston.ac.uk.00000547