Fibre Optical Parametric Amplifiers for Communications

Vladimir Gordienko, Chandra Gaur*, Florent Bessin, Filipe M. Ferreira*** and Nick Doran**
Aston Institute of Photonic Technologies, Aston University, B4 7ET, Birmingham, UK
** Now with SubCom LLC, 250 Industrial Way W, Eatontown, NJ 07724, USA*
*** Now with the University of Angers, LPHIA, SFR MATRIX, F-49000 Angers, France*
**** Now with the University College London, London WC1E 6BT, UK*
e-mail: v.gordienko1@aston.ac.uk

ABSTRACT
We present our recent achievements with polarisation-insensitive fibre optical parametric amplifiers (PI-FOPAs) for optical communications. We have demonstrated a robust fully automated (black-box) PI-FOPA operation in the C and L bands simultaneously with gain of ~20dB and output power over 23dBm when amplifying polarisation-multiplexed WDM QAM signals and a bursty traffic. Additionally, we have demonstrated a PI-FOPA to amplify WDM signals in the S band and across a continuous bandwidth of 40nm. Finally, we have demonstrated a power budget improvement of a transient-sensitive link by up to 8 dB when employing a PI-FOPA with noise figure of ~6 dB as a drop-in replacement of an EDFA.
Keywords: fibre optic parametric amplifiers, optical communications, polarisation, access networks.

1. INTRODUCTION

Fibre optical parametric amplifiers (FOPA) have a great potential to revolutionise optical communications with their unique features such as flexible theoretically unconstrained operation wavelength range, ability of noiseless amplification and lack of transients. Consequently, FOPAs have a synergy with trending topics such as free space communications, quantum communications, access networks and hollow core fibres for FOPAs'. Experimental demonstrations of the FOPA features include gain tuneable across bandwidth over 400 nm [1], a continuous gain bandwidth up to 270 nm [2],[3], noise figure down to 0 dB [4] and gain up to 70 dB [5].

However, a practical employment of these features in optical communications requires to overcome several challenges. The key challenge is that the FOPAs' underlying process, four wave mixing, is polarisation-sensitive, while a practical amplifier for optical communications has to be polarisation-insensitive, so it is crucial to realise polarisation-insensitive FOPAs (PI-FOPAs). The first PI-FOPAs employed two orthogonally polarised pumps [6] but gain magnitude and bandwidth of such PI-FOPAs are limited due to the factor of three penalty on four-wave mixing efficiency incurred by the pumps orthogonality and the difficulty of producing widely spaced pumps. Then, a polarisation-diversity looped architecture employing two gain fibres has opened a potential for broadband PI-FOPAs for WDM applications [7]-[9]. Therefore, it has been the focus of our research to realise practical ultra-wideband PI-FOPAs for WDM applications in optical communications.

In this paper we review our work on broadband PI-FOPAs operating in S, C and L bands and with continuous gain bandwidth up to 40 nm. We demonstrate a robust fully-automated PI-FOPA and present an application scenario where our PI-FOPA significantly outperforms a commercial EDFA.

2. Looped PI-FOPA setup

In our experiments we have employed a looped PI-FOPA configuration with reduced nonlinear crosstalk [10], [11] shown at Fig. 1. An input WDM signal is injected in the loop via an optical circulator followed by a polarization beam splitter (PBS). The PBS splits the input signal into two linearly polarised components counter-propagating in the polarization diversity loop. The loop contains two lengths of gain fibre, each pumped unidirectionally. The counter-propagating signal components are equally amplified in those sections of the gain fibre where they co-propagate with one of pumps, because parametric gain is unidirectional. The amplified signal components are recombined with a PBS and passed to the FOPA output via an optical circulator.

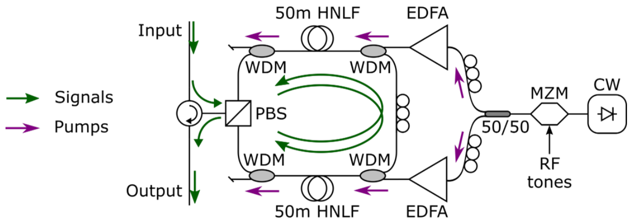

Figure 1. Looped PI-FOPA setup.

The gain fibres were two 50m lengths of highly nonlinear fibre (HNLF) with zero-dispersion wavelength of ~1563 nm, a dispersion slope of ~84 $s\cdot m^{-3}$ and a nonlinearity coefficient of ~8.2 $W^{-1}\cdot km^{-1}$. The pumps for gain fibres were sourced from a single 100 kHz linewidth laser, phase modulated with three RF tones to mitigate SBS and split in two using a 50% coupler. The pumps' wavelength depending on the experiment was in the range

1563.6…1566.2nm. Then, the pumps were independently amplified by respective high power EDFAs to reach the power between 6.5W and 8.2W depending on the experiment. The pumps were coupled and decoupled from the gain fibres via two pairs of wavelength division multiplexers (WDM).

3. PI-FOPA in S, C and L bands

We have done three demonstrations of WDM signals amplification with our PI-FOPA: in the S band, in the L band and in the C and L bands simultaneously. The only difference was a slight adjustment of the pump wavelength and the pump powers.

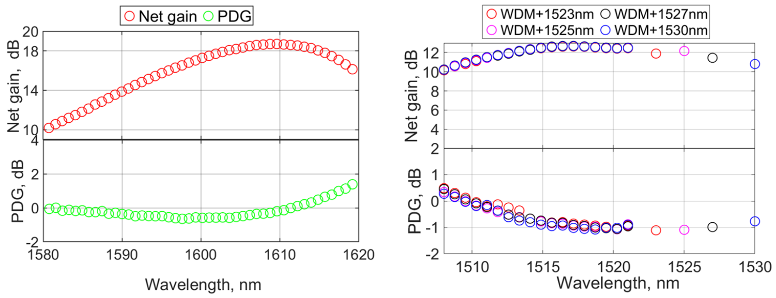

Figure 2. PI-FOPA net gain and polarisation dependent gain (PDG) when configured for WDM operation in the L band (left) and the S band (right).

The left plot at Fig. 2 shows the PI-FOPA net gain and polarisation dependent gain (PDG) when PI-FOPA is configured for operation in the L-band [12]. Net gain >10 dB and PDG <1.5 dB is observed across a 40 nm range. This is the record-wide WDM PI-FOPA operation to date. The right plot at Fig. 2 shows the PI-FOPA net gain and PDG when PI-FOPA is configured for operation in the S-band [13]. Net gain >10 dB and PDG <1 dB are observed across the range of 22 nm. This is the first-ever demonstration of the PI-FOPA operation in the S-band. The gain and bandwidth are less than in the L band because the Raman scattering contribution is positive in the L band (longer wavelength than the pump) and negative in the S band (shorter wavelength than the pump).

Fig. 3 shows operation of PI-FOPA configured for C&L band [14]. The left plot shows that each band contained 10 signal channels (continuous 100G PDM-QAM in the C band and bursty 10G OOK in the L band) which wavelengths were chosen to avoid overlap of signals and idlers produced during signal amplification. The right plot shows that for all channels the net gain was between 17 dB and 22 dB, PDG was <0.5 dB and output power per channel was between 9 dB and 13 dB. The total output power of all channels was >23 dBm.

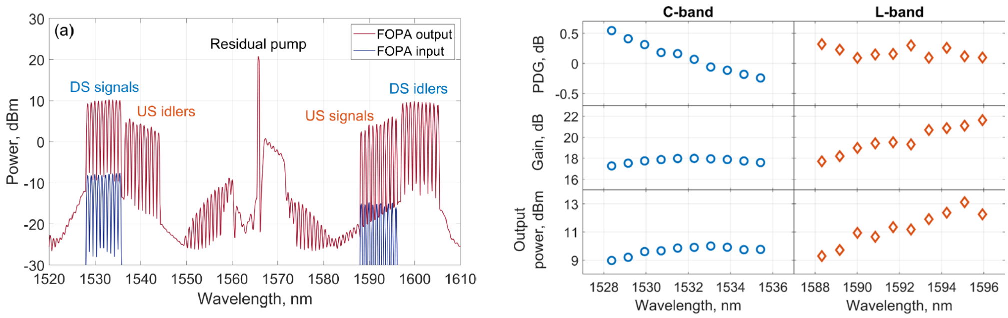

Figure 3. C&L-band PI-FOPA operation: input and output optical power spectra (left), and key PI-FOPA parameters per channel (right).

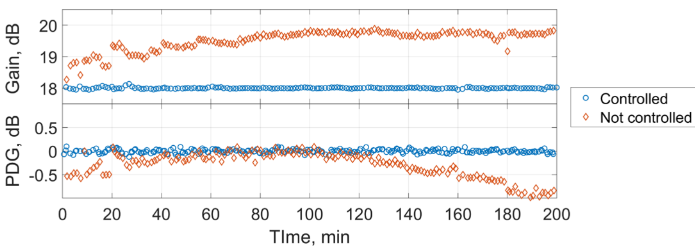

Figure 4. Comparison of net gain and PDG over time in cases they are controlled or not controlled by MATLB algorithm adjusting PI-FOPA parameters in real-time.

Importantly, the PI-FOPA in the last demonstration has been fully automated. High power EDFAs and all polarisation controllers in the setup were connected to a computer and operated by a MATLAB algorithm, which measured net gain and PDG in real-time by capturing optical power spectra through taps in the PI-FOPA. The MATLAB algorithm operated pump powers and polarisations to set and maintain the target PI-FOPA net gain and zero PDG for one of channels thus compensating for polarisation drifts and environmental changes in real-time. Fig. 4 shows comparison of gain and PDG for controlled and not controlled channels over time. The net gain and PDG of uncontrolled channels drifts significantly, while the algorithm is capable to ensure a stable and robust performance as required for practical employment.

4. Comparison of PI-FOPA, EDFA and Raman amplifiers when amplifying burst traffic

One of FOPA features is its ultra-fast response allowing for amplification of bursty traffic without transient effects. One of common applications for bursty traffic is an upstream in access networks, therefore we have employed a looped PI-FOPA in the extended PON architecture and compared its performance with EDFA and a discrete Raman amplifier when amplifying bursty traffic (Fig. 5). Noise figure of this PI-FOPA was 6 dB as measured in [15]. This experiment demonstrated the significant improvements facilitated by employment of PI-FOPA as a drop-in replacement of a commercial EDFA.

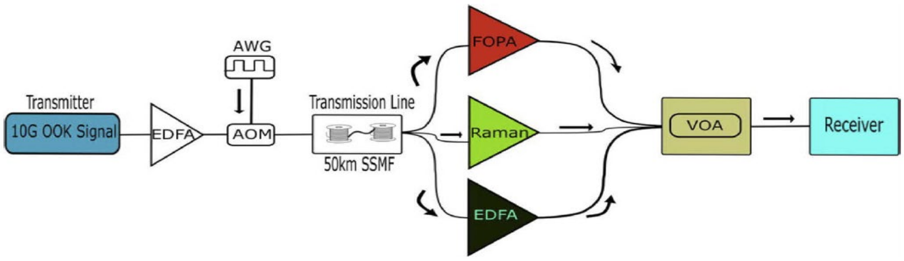

Figure 5. Testbed for comparison of PI-FOPA, EDFA and discrete Raman amplifier in extended PON architecture when amplifying burst traffic.

This experiment explored amplification of 10G OOK signal as is typical for upstream in access networks. A continuous 10G OOK signal sourced at wavelength of 1535nm was amplified by EDFA and shaped into bursts by passing via acousto-optic modulator (AOM) driven by a square wave. The signal was launched into a 50km SSMF transmission line and then passed through one of tested amplifiers. The amplifiers' net gain was set to 13dB. The amplified signal was passed through a VOA (emulating a PON power splitter), filtered, detected by a PIN photodetector and captured with a real-time sampling oscilloscope. The received signal was processed offline to detect bursts, set a decision threshold and to count errors. Eventually, for each tested amplifier we derived a receiver sensitivity defined as the required signal power for BER of 10^{-3}.

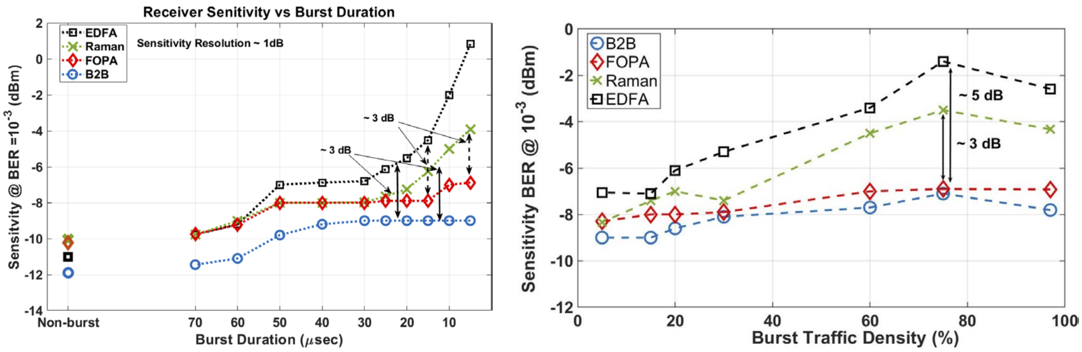

Figure 6. Receiver sensitivity for each tested amplifier for fixed burst period of 100 μs and variable burst duration (left), and for fixed burst duration of 30 μs and variable burst traffic density (right).

Fig. 6 shows receiver sensitivity for each tested amplifier in two cases. In the first case (left figure) the burst period was fixed at 100 μs and the burst duration was varied [16]. It shows that although in the non-burst case (continuous traffic) the EDFA allowed for 1 dB better sensitivity than discrete Raman and PI-FOPA, the EDFA performance as compared to B2B case (no transmission and no amplifier) has dropped significantly as burst duration was changed from 70 μs to 5 μs due to an increased impact of transient effects in EDFA. On the other hand, the difference between the B2B and the transmission plus PI-FOPA cases remained consistently in the range of 1-2 dB for all burst durations and including non-burst case due to lack of transients. Therefore, for the shortest bursts of 5 μs the PI-FOPA has allowed for 8 dB better sensitivity than EDFA. Performance of the discrete Raman amplifier was consistent with PI-FOPA in the non-burst case and burst durations down to 30 μs. Burst duration <30 μs cause transient effect in the Raman amplifier due to significant gain medium length (6.5 km of dispersion shifted fibre), and at burst duration of 5 μs an employment of the discrete Raman amplifier showed 3 dB worse receiver sensitivity than the PI-FOPA.

The right plot at Fig. 6 showed the receiver sensitivity as the burst duration was fixed at 30 μs and the burst period was varied between 1000 μs (traffic density of 3%) and 31 μs (traffic density of 97%) [17]. The PI-FOPA showed a small consistent penalty of ~1 dB as compared to the B2B case, while the EDFA and the discrete Raman amplifier showed the worst sensitivity at traffic density of 75%, which was respectively 5 dB and 3 dB worse than that of the PI-FOPA.

Overall, we have confirmed a lack of transients in PI-FOPA when amplifying bursty traffic and showed that it can allow for up to 8 dB better receiver sensitivity than an EDFA, and 3 dB better sensitivity than a Raman amplifier, whereas the improvement of a receiver sensitivity is a direct contribution to a link budget.

5. CONCLUSIONS

We have demonstrated operation of the same PI-FOPA setup across 3 bands: S, C and L, which demonstrates a unique ability of the same PI-FOPA to operate at different bands across >100 nm range. Moreover, our work includes the first-ever demonstrations of WDM amplification by a PI-FOPA in C&L bands simultaneously and in the S-band, and the record-wide continuous PI-FOPA gain bandwidth of 40 nm. Additionally, we demonstrated that PI-FOPA provided 8 dB and 3 dB better receiver sensitivity than an EDFA and a discrete Raman amplifier respectively when amplifying bursty traffic due to an ultra-fast FOPA response time. Finally, we demonstrated that automation of a PI-FOPA allows to achieve its robust performance for practical employment. Overall, our PI-FOPA technology allows for robust and flexible broadband operation across several bands and significantly outperforms both doper-fibre and Raman amplification technologies when amplifying signal bursts.

ACKNOWLEDGEMENTS

We wish to 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 EPSRC projects EP/R024057/1, EP/M005283/1, EP/S003436/1, EP/S016171/1 and the UKRI Future Leaders Fellowship under Grant MR/T041218/1.

REFERENCES

[1] M. E. Marhic, K. K.-Y. Wong and L. G. Kazovsky: Wide-band tuning of the gain spectra of one-pump fiber optical parametric amplifiers, *J. Sel. Top. Quantum Electron.*, vol. 10, pp. 1133-1141, Sep.-Oct. 2004.

[2] M. Jamshidifar, A. Vedadi and M. E. Marhic: Continuous-wave one-pump fiber optical parametric amplifier with 270 nm gain bandwidth, in *Proc. ECOC*, Vienna, Austria, 2009, paper 1.1.4.

[3] V. Gordienko *et al.*: Ultra-flat wideband single-pump Raman-enhanced parametric amplification, *Opt. Express*, vol. 25, pp. 4810-4818, 2017.

[4] V. Gordienko *et al.*: Phase-sensitive amplification of 11 WDM channels across bandwidth of 8 nm in a fibre optic parametric amplifier, in *Proc. ECOC*, Brussels, Belgium, 2020.

[5] T. Torounidis, P. A. Andrekson and B.-E. Olsson: Fiber-optical parametric amplifier with 70-dB gain, *IEEE Photon. Technol. Lett.*, vol. 18, no. 10, pp. 1194-1196, May 2006.

[6] K. K. Y. Wong *et al.*: Polarization-independent two-pump fiber optical parametric amplifier, IEEE Photon. Technol. Lett., vol. 14, no. 7, pp. 911-913, July 2002.

[7] S. Takasaka and R. Sugizaki: Polarization insensitive fiber optical parametric amplifier using a SBS suppressed diversity loop, in *Proc. OFC*, Anaheim, CA, USA, 2016.

[8] M. F. C. Stephens, V. Gordienko, and N. J. Doran: 20 dB net-gain polarization-insensitive fiber optical parametric amplifier with >2 THz bandwidth, *Opt. Express*, vol. 25, pp. 10597-10609, 2017.

[9] M. F. C. Stephens *et al.*: In-line and cascaded DWDM transmission using a 15dB net-gain polarization-insensitive fiber optical parametric amplifier, *Opt. Express*, vol. 25, pp. 24312-24325, 2017.

[10] M. F. C. Stephens, V. Gordienko, and N. J. Doran: Reduced Crosstalk, Polarization Insensitive Fiber Optical Parametric Amplifier (PI FOPA) for WDM Applications, in *Proc. OFC*, 2018, paper W3D.4.

[11] V. Gordienko *et al.*: Looped Polarization-Insensitive Fiber Optical Parametric Amplifiers for Broadband High Gain Applications, *J. Lightwave Technol.*, vol. 39, pp. 6045-6053, 2021.

[12] C. B. Gaur et al.: Polarization- insensitive fibre optic parametric amplifier with gain bandwidth of 35 nm in L-band, in *Proc. ECOC*, Bordeaux, France, 2021.

[13] C. B. Gaur *et al.*: Polarization Insensitive Fiber Optic Parametric Amplifier with a Gain Bandwidth of 22 nm in S-Band, in *Proc. OFC*, 2022, paper W4J.1.

[14] V. Gordienko *et al.*: Robust polarization-insensitive C & L band FOPA with >17dB gain for both WDM and bursty traffic, in Proc. *OFC*, 2021, paper M5B.3.

[15] V. Gordienko et al.: Noise Figure Evaluation of Polarization-insensitive Single-pump Fiber Optical Parametric Amplifiers, in *Proc. OFC*, San Diego, CA, 2020.

[16] C. B. Gaur *et al.*: Experimental comparison of fiber optic parametric, Raman and erbium amplifiers for burst traffic for extended reach PONs, *Opt. Express*, vol. 28, pp. 19362-19373, 2020.

[17] C. B. Gaur *et al.*: Fibre optic parametric amplifier for high capacity burst-mode access networks, *Opt. Express*, vol. 29, pp. 21190-21198, 2021.