Dual-Band Amplification of downstream L-band and upstream C-band signals by FOPA in extended reach PON

Chandra B Gaur[(1)], Vladimir Gordienko[(1)], Florent Bessin[(1)], Nick J Doran[(1)]

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

Abstract: We employ a polarisation-insensitive fibre optical parametric amplifier (PI-FOPA) to demonstrate a dual-band bi-directional 50-km reach symmetric 10G-PON link with a splitter power budget of 14dB. The PI-FOPA provides >16dB gain for a bursty upstream and non-burst downstream signals at 1533nm and 1586nnm respectively.

Introduction

Modern optical communication systems are bi-directional with signals in C+L-band employed for optical transmission and multiband optical links are developed [1]-[2]. Bi-directional transmission in Passive Optical Networks (PON) typically involves C-band signal for downstream (DS) and O-Band signal for upstream (US) traffic [3]. US traffic is bursty in nature to support time division multiplexing [4].

Fibre optic parametric amplifiers (FOPA) are capable of ultra-wide gain bandwidth in excess of 200 nm [5]-[6]. Ultra-fast response time of FOPA (<<10 fs) can provide transient free amplification to burst mode signals in reach extended PON [7]. In recent demonstrated work, FOPA can provide >3 dB improvement in receiver sensitivity for burst traffic amplification in comparison to Erbium doped and Raman Fiber amplifiers [8]. FOPA also has superior features like a) gain on arbitrary wavelengths b) ultralow noise figure in phase sensitive configuration and c) very large gain [9]-[11]. However, dual band amplification of signals in burst and non-burst mode by FOPA simultaneously have not been demonstrated previously. Bi-directional amplification by FOPA have been demonstrated [12]-[13] but later work showed that this scheme is not viable due to nonlinear interaction between counter-propagating pumps via Stimulated Brillouin Scattering (SBS) [14].

In this paper, we experimentally demonstrate a simultaneous amplification of a DS signal in L-band and a bursty US signal in C-band counter-propagating in 50 km reach extended PON architecture using a single PI-FOPA with >16 dB net gain. Both signals were 10G on-off keying (OOK). We report a splitter power budget of 14 dB, which could be increased to 16 dB if the US traffic is non-burst. This denotes: 1) the first to the best of our knowledge parametric amplification of signals >50 nm apart, 2) a novel scheme for bi-directional signal amplification, 3) amplification of bursty and non-burst traffic simultaneously. This demonstrates a potential of FOPAs as in-line amplifier for dual-band bi-directional optical communication networks.

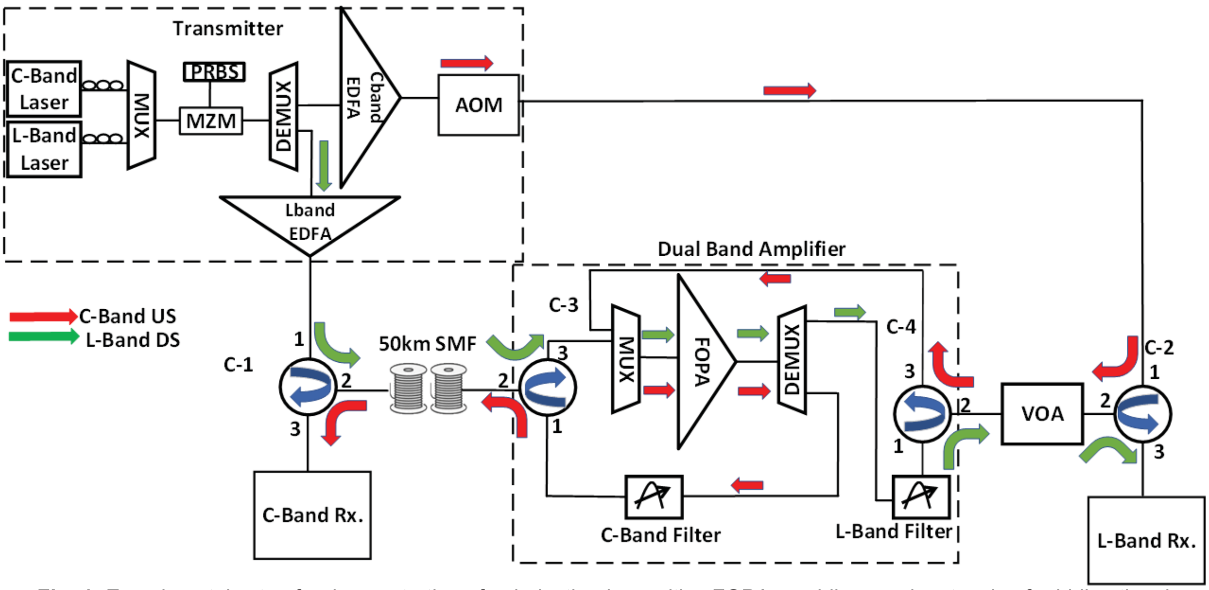

Fig. 1: Experimental setup for demonstration of polarization-insensitive FOPA providing reach extension for bidirectional dual-band PON link

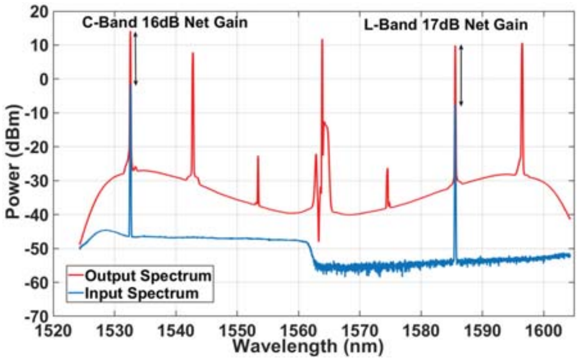

Fig.2: Optical power spectra at the FOPA input and output, when amplifying C-band upstream and L-band downstream signals.

Experimental Setup

Figure 1 shows the experimental setup consisting of a C+L-band transmitter, a bi-directional PON link, and two receivers to detect C- and L-band signals.

The transmitter employed two lasers to source two continuous waves at 1533 nm in C-band and at 1586 nm in L-Band. The continuous waves were multiplexed and modulated by the same Mach Zehnder modulator (MZM) to generate 10 Gbps OOK signals in C and L-bands. Then, the signals were demultiplexed to be used for US and DS and amplified by their respective EDFAs, with output power of 13 dBm and 6 dBm. The US signal in PON is typically bursty, so the US C-band signal was modulated with an acousto optic modulator (AOM) driven by 10 kHz square wave generator to produce signal bursts with duration of 50 µs and period of 100 µs. The average output US signal power was 2.5 dBm. Considering the duty cycle of 50%, the US signal power during burst was 5.5 dBm.

The PON link consisted of a 50 km standard single mode fibre (SSMF) span, a VOA emulating a splitter, and a dual-band bi-directional amplifier module based on a PI-FOPA. The C-band and the L-band signals were injected through opposite ends of the PON link to perform as upstream and downstream respectively. Consequently, the PON link was connected via optical circulators to a C-band transmitter and L-band receiver on one end and to a L-band transmitter and C-band receiver at the other end.

PI-FOPA is used as an in-line amplifier for amplification of counter-propagating C+L-band signals. However, a FOPA is a unidirectional amplifier [15], so a novel experimental setup is demonstrated to amplify bi-directional signals simultaneously. The DS and the US signals are decoupled from the SSMF span and the VOA respectively using optical circulators. Then, they are multiplexed by a C/L band splitter and amplified in a dual-band PI-FOPA employing a half pass loop architecture [16] and described in detail in [17]. The PI-FOPA pump powers were 33.4 dBm and 32.7 dBm and net gain for signals was >16 dB. Amplified signals are demultiplexed with another C/L band splitter. Each signal is additionally filtered using a 1 nm wide tuneable band pass filter to remove broadband noise and an idler of another signal. Amplified and filtered downstream and upstream signals are coupled in the VOA and the SSMF span respectively using optical circulators.

Both receivers employed the same PIN photodetector with 0.3 A/W responsivity. The photodetector was connected to a real time oscilloscope for signal analysis. Off-line digital signal processing (DSP) was used for threshold detection, burst signal processing and bit error ratio (BER) calculation. It is described in detail in [8].

Result and Discussion

Fig. 2 shows calibrated optical power spectra taken with resolution of 0.1 nm at the PI-FOPA input and output, when amplifying C-band US and L-band DS signals. The VOA was set to the minimum attenuation of 0.56 dB for this

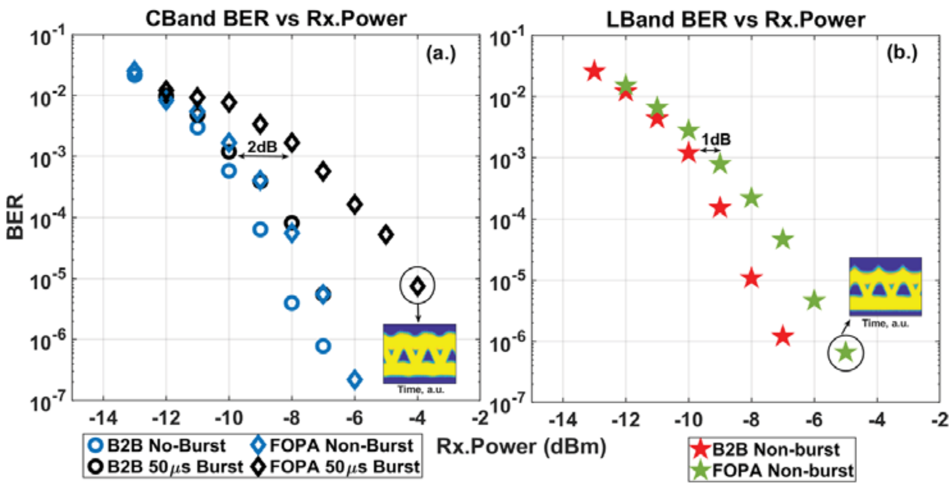

Fig. 3: BER vs Received Power curves for (a) C-band Upstream Signal (b) L-band Downstream Signal

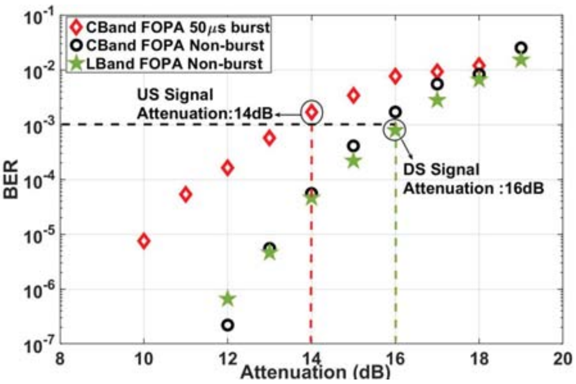

Fig. 4: BER vs splitter attenuation for C-band upstream and L-band downstream signals counter-propagating in 50-km reach PON.

measurement. Input (output) powers of the C and L band signals were -1.6 dBm (14.2 dBm) and -7.4 dBm (9.9 dBm) respectively. Consequently, their corresponding net gains are ~16 dB and ~17 dB respectively. Although the signals had similar power at the transmitter output (5.5 dBm), their power at the PI-FOPA input was different because of their paths: the L-band signal has propagated through the 50 km span, and the C-band signal has propagated through the VOA. Consequently, the L-band signal power at the input VOA was 7.9 dBm and the C-band signal power at the 50 km SMF input was 13.5 dBm. Received signal powers of the C and L band signals were 3.8 dBm and 7.1 dBm respectively.

Fig. 3 shows BER vs. received signal power for C- and L-band signals in 'B2B' and 'FOPA' scenarios. The received signal power was varied from -3 dBm to -14 dBm by adjusting the VOA. The 'B2B' scenario implies that receiver was connected directly to the transmitter. The 'FOPA' scenario implies counter-propagation of the signals in the PON link with their amplification by >16 dB in the PI-FOPA. Open eye diagrams of the C-band and L-band signals are shown inset for received powers of -4 dBm and -5 dBm respectively.

Fig. 3 (a) shows results for the upstream C-band signal for both burst and non-burst traffic scenarios. In the burst traffic scenarios, the received signal power implies signal power during bursts. In the B2B scenario the burst traffic suffers from ~1 dB received power penalty as compared to the non-burst traffic. This penalty occurs in transmitter and/or receiver due to signal bursts. The FOPA scenario introduces a received power penalty of ~1 dB for non-burst traffic and of ~2 dB for burst traffic as compared to the B2B. This implies that the PON link with FOPA introduces ~1 dB signal power penalty for non-burst traffic and an additional ~1 dB signal power penalty for burst traffic.

Fig. 3(b) shows results for the non-burst downstream L-band signal. Only a small received power penalty of <1 dB is observed between B2B and FOPA scenarios at BER of 10^{-3}. This is similar as the upstream C-band signal.

Fig. 4 shows BER as a function of the VOA attenuation for C-band upstream and L-band downstream signals counter-propagating in 50-km reach PON. Measurement for the US signal is performed in burst and non-burst modes. Attenuation achieved at a BER level of 10^{-3} indicates the maximum available splitter power budget. We observe that in the case of non-burst traffic both signals perform very similarly and allow for splitter attenuation up to 16 dB. This demonstrates that the PI-FOPA is able to amplify signals spaced by >50 nm with good performance. However, the requirement to operate the upstream signal in burst mode introduces ~2 dB penalty and decreases the available splitter power budget to 14 dB.

Conclusions

In this work we demonstrate a 50 km reach PON featuring non-burst downstream and bursty upstream 10 Gbps signals in C and L- bands respectively with 14 dB power budget for a splitter. The power budget could have been 16 dB, if both data streams were non-burst. The reach extension of PON is enabled by employment of a polarization insensitive FOPA amplifying signals at 1533 nm and 1586 nm simultaneously and by a novel arrangement allowing for amplification of counter propagating data streams using the same amplifier. Overall, this work confirms great potential for FOPA implementation in extended reach PON as well as in other bi-directional and/or multiband optical transmission links.

Acknowledgements

This work is funded by UK EPSRC for project UPON EP/M005283/1, FPA- ROCS EP/R024057/1 and project MULTIPLY. To see underlying research data https://doi.org/10.17036/researchdata.aston.ac.uk.00000474.

References

[1] A. Napoli et al, "Towards multiband optical systems." 2018, July, Photonic Networks and Devices pp. NeTu3E-1. Optical Society of America.

[2] A. Ghazisaeidi, et al, "Advanced C+L-band transoceanic transmission systems based on probabilistically shaped PDM-64QAM." 2017, Journal of Lightwave Technology, 35(7), pp.1291-1299.

[3] ITU-T Recommendations, "10-Gigabit-Capable Symmetric Passive Optical Network (XGS-PON)" Sector, I.T.S., 2016.

[4] ITU-T, G., 2014. 989.2 40-Gigabit-capable passive

optical networks 2 (NG-PON2): Physical media dependent (PMD) layer specification. International Telecommunication Union.

[5] M. C. Ho, K. Uesaka, M. Marhic, Y. Akasaka, and L. G. Kazovsky, "200-nm-bandwidth fiber optical amplifier combining parametric and Raman gain," J. Light. Technol. 19, 977–981 (2001)

[6] 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 25, 4810-4818 (2017)

[7] R.W. Boyd., 2019., "*Nonlinear Optics".* Chapter. 4, Academic press.)

[8] C.B Gaur, F. Ferreira, V. Gordienko, V. Ribeiro, A.D. Szabó and N.J Doran, "Experimental comparison of fiber optic parametric, Raman and erbium amplifiers for burst traffic for extended reach PONs." Optics Express, 2020 ,28(13), pp.19362-19373.

[9] M.E. Marhic, K.Y.Wong and L.G. Kazovsky."Wide-band tuning of the gain spectra of one-pump fiber optical parametric amplifiers". 2004, IEEE Journal of Selected Topics in Quantum Electronics, 10(5), pp.1133-1141.

[10] Z. Tong, C. Lundström, P. A. Andrekson, C. J. McKinstrie, M. Karlsson, D. J. Blessing, E. Tipsuwannakul, B. J. Puttnam, H. Toda, and L. Grüner-Nielsen, "Towards ultrasensitive optical links enabled by low-noise phase-sensitive amplifiers," Nat. Photonics 5, 430–436 (2011)

[11] T. Torounidis, P.A. Andrekson, and B.E. Olsson," Fiber-optical parametric amplifier with 70-dB gain. IEEE Photonics Technology Letters", 2006, 18(10), pp.1194-1196.

[12] K.S. Yeo et al, "Fiber optical parametric amplifier with double-pass pump configuration." Optics express, 2013, 21(25), pp.31623-31631.

[13] G.K. Lei, and M.E. Marhic, "Amplification of DWDM channels at 1.28 Tb/s in a bidirectional fiber optical parametric amplifier". Optics Express, 2014, 22(7), pp.8726-8733.

[14] M. Jazayerifar, M., et al, "Impact of Brillouin backscattering on signal distortions in single-fiber diversity loop based polarization-insensitive FOPAs." Journal of Lightwave Technology, 2017, 35(19), pp.4137-4144.

[15] M. E. Marhic, "Fiber Optical Parametric Amplifiers, Oscillators and Related Devices (Cambridge University",2008

[16] 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 25, 10597-10609 (2017)

[17] V. Gordienko et al., "Characterisation of novel polarisation-insensitive configurations of fibre optical parametric amplifiers," 45th European Conference on Optical Communication (ECOC 2019), Dublin, Ireland, 2019, pp. 1-4, doi: 10.1049/cp.2019.0978.