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Fibre optic parametric amplifier for high capacity burst-mode access networks

CHANDRA B. GAUR,[1,*] VLADIMIR GORDIENKO,[1] FILIPE FERREIRA,[1,2] VITOR RIBEIRO,[1] AND NICK J. DORAN[1]

[1] *Aston Institute of Photonics Technology, Aston University, Birmingham, B4 7ET, UK*
[2] *Now with University College London (UCL), Gower Street, London, WC1E 6BT, UK*
[*] *gaurc@aston.ac.uk.*

Abstract: We compare performance of a polarization insensitive fiber optic parametric amplifier (PI-FOPA), a commercial erbium doped fiber amplifier (EDFA) and a discrete Raman amplifier (DRA) in a 50 km long-reach optical access network transmitting bursts of 10 Gbps signal with traffic density ranged from 5% to 97%. We demonstrate that for the same power budget the PI-FOPA allows for transmission of bursty traffic with density up to 97% while DRA and EDFA are limited to 30% and 15%, respectively. Alternatively, we demonstrate PI-FOPA to allow for 3 dB and 5 dB higher power budget than the DRA and EDFA, respectively, for the worst case scenario of 75% traffic density.

1. Introduction

Fiber optic parametric amplifiers (FOPA) are capable of an ultrafast amplification owed to its underlying process – $\chi^{(3)}$ non-linearity in optical fibers [1]. Its response time $\tau_t = 1/|\omega_g - \omega|$ is estimated to be <0.1 fs at frequencies $f < 600$ THz based on the silica bandgap energy E of 9eV [2,3], where ω_g and ω are the bandgap and interaction frequencies. Such a response time can be considered instantaneous for all modern telecom applications and makes FOPA appealing for implementation in burst networks.

FOPA can significantly increase power budget of optical links carrying bursty traffic. Large burst signal net gain of 20 dB by PI-FOPA amplification has been demonstrated by the authors in [4]. A polarization insensitive FOPA (PI-FOPA) [5] employed as a drop-in replacement of Erbium-doped or Raman fiber amplifier has been experimentally demonstrated to enhance receiver sensitivity by >3 dB for burst signal amplification [6]. FOPA can be employed along with either direct or coherent detection. FOPA can amplify both bursty (TDM) and WDM traffic as demonstrated in [7,8]. Amplification of bi-directional C&L band signals by FOPA have been experimentally demonstrated in extended-reach passive optical network (PON) architecture employing WDM and bursty traffic simultaneously [9,10]. Overall, aforementioned features of FOPA prove its feasibility as a drop in amplifier for long-reach optical access links.

In our previous work we demonstrated that FOPA performs better than Erbium doped fiber amplifier (EDFA) and Raman amplifier when amplifying a range of burst durations from 5 µs to 70 µs [6]. FOPA showed less than 1 dB received power penalty in comparison with a back to back (B2B) burst configuration [6], while EDFA and a Raman amplifier suffered from transient effects causing significant burst distortions and resulting in the received power penalty up to ~3 dB [11]. Traffic in burst networks for access, datacenter interconnect or optical free-space communication [12–14] does not only vary in duration but can have a different burst traffic density [15]. Moreover, the traffic density can change randomly essentially in range from 0% to 100%, for example in PON protocols where upstream traffic is sent any time by each client [16] or in energy efficient PON scheme where downstream traffic is bursty [17]. Therefore, a burst

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network capacity and reach depends on an amplifier ability to handle as wide range of traffic densities as possible. We experimentally investigate FOPA amplification of dynamic burst traffic density at a fixed burst duration.

In this paper we extend our previous work [6] and demonstrate for the first time to the best of our knowledge that FOPA can accommodate a much wider range of traffic densities than that supported by EDFAs and Raman amplifiers, without incurring notable signal power penalties. We employ PI-FOPA, EDFA or discrete Raman amplifier to amplify 10 Gbps signal bursts with a short duration of 30 µs and traffic density varied from 5% to 97% in a 50-km reach optical fiber access link and compare their performance. We further demonstrate that when the signal is amplified by EDFA or a discrete Raman amplifier, a receiver sensitivity suffers from significant penalties for burst traffic density over 15% or 30% respectively, and exceeds 5 dB and 3 dB, at traffic density of 75%. On the other hand, FOPA has less than 1 dB receiver sensitivity penalty across all examined traffic densities. Overall, we demonstrate FOPA to multifold improve the receiver sensitivity and the supported traffic density as compared to a commercial EDFA or a discrete Raman amplifier.

2. Experimental setup

Figure 1 shows experimental setup for amplification of 10 Gbps on-off keying (OOK) burst signal in 50 km reach optical fiber access link architecture by different amplifiers under test (AUT). The setup aims to evaluate performance of the AUTs in a generalized burst traffic environment instead of investigating a specific optical link architecture. The transmission setup evaluates specifically, the ability of the AUT to overcome the lump loss of a passive network element, such as an optical splitter or an array wavelength grating optical demultiplexer, after propagation over a long-reach optical fiber trunk.

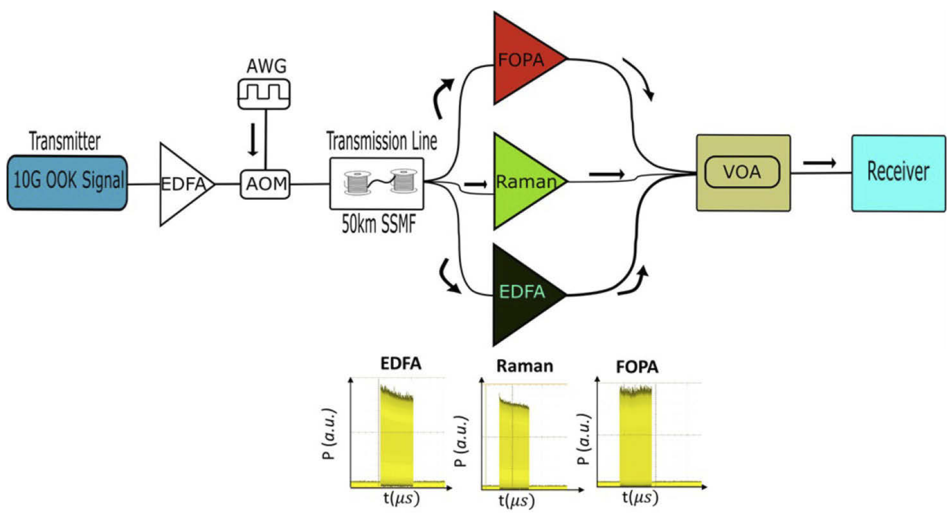

Fig. 1. Experimental long-reach optical fiber access network setup for burst mode amplification via PI-FOPA, EDFA and Raman amplifier

In the transmission setup, the signal was sourced from a continuous tunable laser at wavelength of 1535 nm and modulated using a Mach Zehnder modulator (MZM) driven by a pseudo random bit sequence (PRBS) with length of 2^{11-1}. The signal was amplified by a booster EDFA and passed through an acousto optic modulator (AOM) driven by a square waveform generator to produce signal bursts. The square waveform duty cycle was varied from 5% to 97% to change the signal traffic density. Burst duration of 30 µs was selected based on previous result in [6] – it

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is a duration within the capabilities of all AUTs, at least for repetitions spaced of 100 µs or more. In this paper, we now investigate shorter repetition periods, this is higher traffic densities – likely to be reach towards the end-of-life of a given system. Figure 2 shows schematic representation of emulated signal burst traffic with burst period was adjusted from 600 µs to 31 µs while keeping the burst duration at 30 µs in all cases. The examined range of traffic densities was defined by limitations of our equipment. The signal power during bursts was fixed at 2.3 dBm, so the resulting average signal power for each traffic density is also shown in Fig. 2.

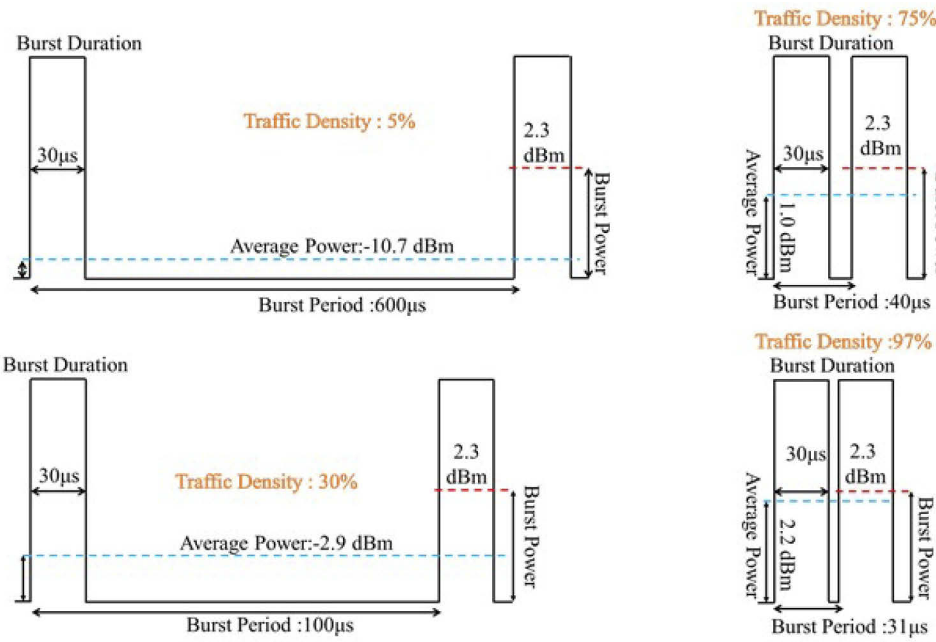

Fig. 2. Schematic representation of emulated signal burst traffic density for 5%, 30%,75% and at 97% with burst periods of 600 µs,100 µs,40 µs and 31 µs at a fixed burst duration of 30 µs. Fixed burst power and corresponding average burst power at respective traffic densities are shown.

The burst traffic was transmitted over 50 km standard single mode fiber (SSMF) and then amplified by individual AUTs at a fixed gain of 13 dB. A variable optical attenuator (VOA) emulates the insertion loss of a network element, for example, an optical splitter [18] or an array wavelength grating optical demultiplexer. The VOA was used to sweep the received signal power. A band pass filter (BPF) with 1 nm bandwidth was used to filter undesired noise from AUT's. The receiver employed a DC-coupled PIN photodetector suitable for bursty traffic. A real time oscilloscope was connected to the receiver to detect and capture traces. An offline digital signal processing detected bursts, discarded the first 100 ns from each detected burst to remove bits corrupted by the AOM, found the decision threshold and finally counted errors to find the bit error rate (BER). BER was calculated over ten burst traces for each received power level. The receiver was synchronized with the PRBS generator 10 GHz clock used to produce 10 G OOK signal. However, the receiver was not synchronized with the AWG driving AOM for burst generation. Inset of Fig. 1 shows typical signal burst waveforms after amplification by each AUT (EDFA, Raman and FOPA). Details of commercial grade EDFA and experimental setup for discrete Raman amplifier are explained in [6].

This experiment employs a reduced nonlinear crosstalk polarization-insensitive half-pass loop FOPA [19]. In this design a signal is split in orthogonal components counter propagating in the loop. Each signal component is equally amplified in a respective length of a highly non-linear fiber, and the amplified signal components are recombined at the FOPA output. The PI- FOPA setup is described in detail in [20]. Figure 3 shows example optical spectra at the PI-FOPA input and output when amplifying a burst signal with 30% traffic density at wavelength of 1535 nm. The PI FOPA net gain was limited to 13 dB for the sake of fair comparison with the discrete Raman amplifier. A residual pump is situated in the middle of the spectrum at 1564.4 nm. An idler at the wavelength of 1589 nm was removed by a BPF in the receiver.

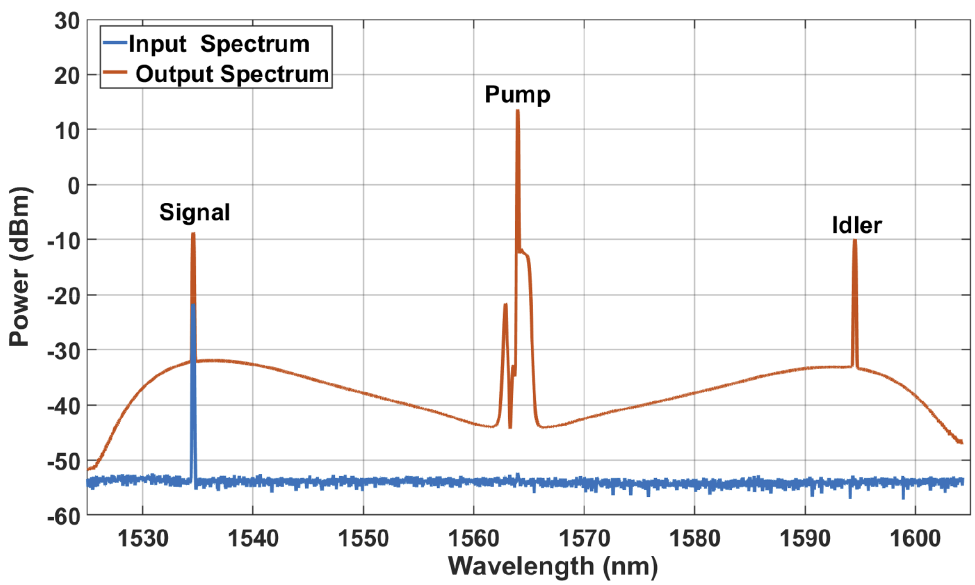

Fig. 3. Optical power spectra at the input and output of the PI-FOPA with 13 dB net gain.

3. Experimental results and discussion

3.1. BER vs received burst power

In this section we discuss Fig. 4 which demonstrates BER vs received burst power for (a) back-to-back (B2B), (b) EDFA, (c) Raman amplifier and (d) FOPA as traffic density is varied from 5% to 97%. The 50 km SSMF span introduced 9.7 dB loss, so the signal power during bursts at the AUTs input was −7.4 dBm. Net gain of all amplifiers was 13 dB. In the B2B case both the 50 km SSMF span and AUT's were omitted.

Figure 4(a) shows BER vs burst power for B2B case and establishes a reference for calculation of receiver sensitivity penalties introduced by AUTs. An increase of traffic density from 5% to 97% introduces received power penalty up to 2 dB in B2B due to penalties associated with the AOM and the receiver although some compensation is provided by discarding the first 100 ns of each burst [6].

Figure 4(b) shows a BER of burst traffic amplified by EDFA. Signals with low traffic density from 5% to 20% have almost overlapping BER curves with received burst powers at the BER threshold of 10^{-3} within range of 1 dB- since at low burst traffic density allows EDFA to reach its steady state before amplifying the next incoming burst. However, by further increasing traffic density the signal burst power required for BER of 10^{-3} increases substantially, peaking for a traffic density of 75% for which ~5 dB extra power is required, for maximum 97% traffic density receiver power penalty in EDFA improved by ~1 dB. This implies that the signal distortion introduced by EDFA transients increases with traffic density but starts to slightly improve as

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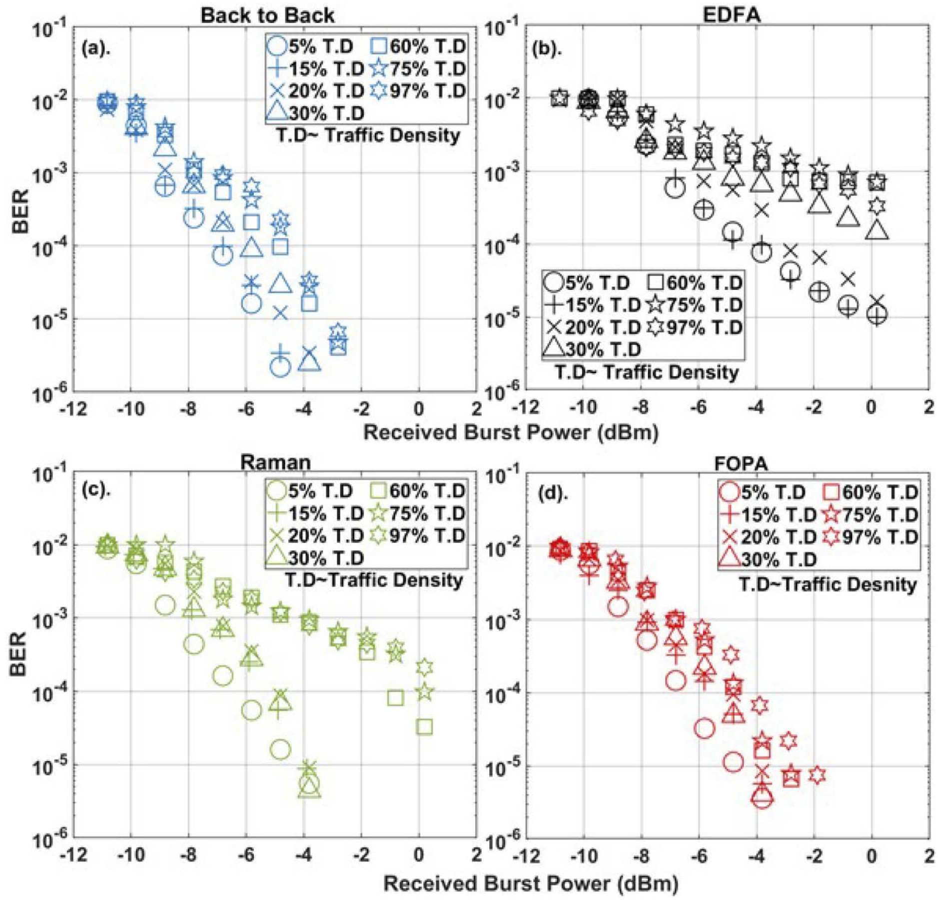

Fig. 4. BER vs burst power comparison for burst traffic density of 5% to 97% in case of (a) B2B, (b) EDFA, (c) Raman and (d) FOPA. Burst Duration was fixed at 30 μs and gain of all AUTs was set at 13 dB.

traffic density approaches 100% which is non- burst. However, even as high bursty traffic density as 97% still introduces penalties.

BER of Raman amplified signal bursts is shown in Fig. 4(c). Raman-amplified signals with low traffic density from 5% to 30% have very close performance – signal power requirements differ by less than 1 dB. On the other hand, a burst power penalty >2 dB was observed for high burst traffic density from 60% to 97%. Received power penalty peaked at 75% traffic density and to reach BER of 10^{-3} ~3 dB extra power is required. We attribute a signal degradation caused by a burst traffic density increase to transient effects in the tested discrete Raman amplifier. Although Raman scattering has a nearly instantaneous response time [21] backward pumped Raman amplifiers can suffer from transient effects linked to a pump propagation time in a long gain fiber [22]. Raman amplifiers demonstrate transients also due to pump depletion effects [23]. The transients in Raman amplifiers are more pronounced in case of forward pumping [23], and the transient time scales with the gain fibre length [22]. Therefore, we expect forward pumped Raman amplifiers and distributed Raman amplifiers to be even more susceptible to transients than the backward pumped discrete Raman amplifier examined in this work.

Figure 4(d) shows BER vs received burst power for FOPA amplified burst traffic. Similar BER curves are observed for all burst traffic densities in the range between 5% and 97%. The received signal power required to reach BER of 10^{-3} increases by <2 dB as the traffic density increases from 5% to 97%. This is very similar to the B2B performance shown at Fig. 3(a) and indicates that FOPA incurs little signal distortions associated with burst traffic density increase.

In addition, Fig. 5 compares FOPA, EDFA and a Raman amplifier in terms of BER vs burst power measured at the lowest traffic density of 5%, the worst case at 75% and at the highest bursty traffic density of 97%. FOPA performance in all three scenarios was very close to B2B. The Raman amplifier performed with little (<1 dB) received signal power penalty as compared to the B2B for low traffic density of 5%. However, the Raman amplifier has significantly degraded performance for high traffic density of 75%: a received signal penalty at BER level of 10^{-3} was around 3 dB. The EDFA has incurred a notable signal BER degradation even at low traffic density causing a received signal power penalty of 1 dB at BER level of 10^{-3} as compared to the FOPA and Raman scenarios. This penalty increased to 5 dB as traffic density reached 75%. Both EDFA and Raman amplifier observed ~2 dB power penalty in comparison with FOPA at 97% burst traffic density as shown in Fig. 5(c). Both EDFA and Raman amplifier still suffer from transient at very high burst traffic density with minor improvement in received power in comparison with worst case of 75% traffic. Overall, it demonstrates that FOPA was the only amplifier able to amplify high traffic density without incurring significant penalties.

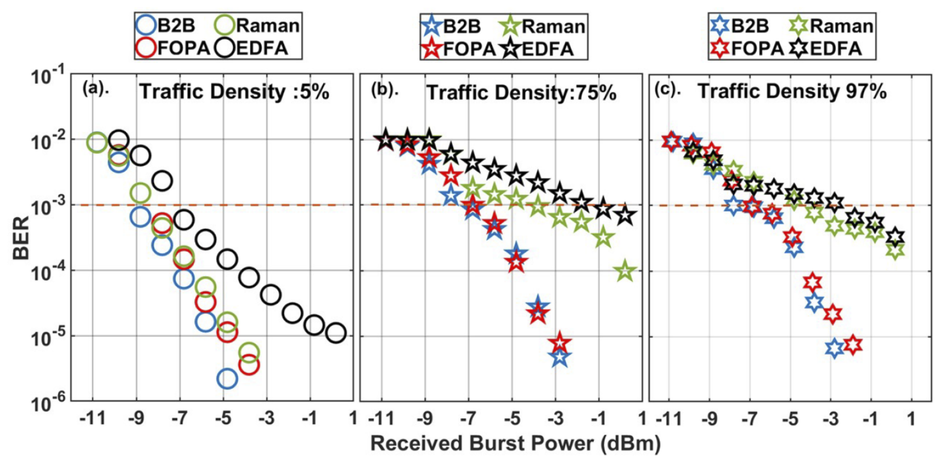

Fig. 5. BER comparison between FOPA, Raman amplifier and EDFA for traffic density of (a) 5%, (b) 75% and (c) 97%

4. Burst traffic density vs receiver sensitivity

One important parameter for performance analysis of optical access links is receiver sensitivity as it defines available power budget. For example, in case of PON it defines the reach and the maximum splitting ratio. In this work we define receiver sensitivity as received burst power required to reach BER level of 10^{-3}. This section discusses receiver sensitivity for burst traffic density from 5% to 97% shown in Fig. 6. The receiver sensitivity is measured for B2B and all AUTs at fixed gain of 13 dB.

The best receiver sensitivity in the B2B scenario was −9 dBm when traffic density was 5% or 15%. An increase of traffic density caused some degradation of the receiver sensitivity. The worst receiver sensitivity of −7 dBm in the B2B case was observed at the traffic density of 75%. The receiver sensitivity degradation in the B2B case is owed to performance limitation of the DC coupled PIN receiver and transients in the transmitter AOM. Further we evaluate AUTs in terms of receiver sensitivity penalty compared to the B2B performance.

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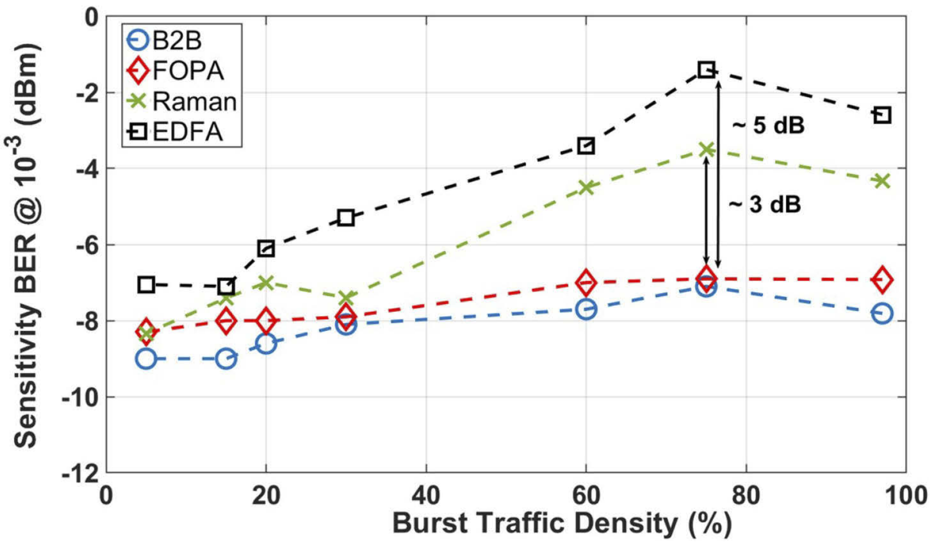

Fig. 6. Receiver sensitivity vs Burst Traffic Density from 5% to 97% at BER level of 10^{-3}.

The best receiver sensitivity in the EDFA case was −7 dBm for traffic densities of 5% and 15%, which corresponds to a penalty of 2 dB introduced by EDFA. A further increase of the traffic density caused a receiver sensitivity penalty up to ~5 dB for traffic density of 75%. This indicates that implementation of EDFA in burst networks can significantly decrease an available link power budget.

The receiver sensitivity in the case of Raman amplification was between −8 dBm and −7 dBm for burst traffic density up to 30%. However, a further increase of the burst traffic density up to 75% has caused the receiver sensitivity degradation up to ~−3 dBm. This implies that although Raman amplifier has introduced a receiver sensitivity penalty of only ~1 dB at low traffic density, the penalty has reached >3 dB for traffic density of 60% and above. On the other hand, FOPA has performed well for all examined traffic densities with receiver sensitivity was always within 1 dB range from that of the B2B scenario.

Figure 6 shows a significant performance degradation with the traffic density increase in the EDFA and Raman scenarios. We then performed receiver sensitivity measurements at the maximum allowed by our waveform generator traffic density of 97%. We observed that receiver sensitivity has been improved by ~2 dB in the EDFA and ~1 dB for Raman scenario. At 97% traffic load repetition rate of 1 µs between bursts has improved EDFA receiver sensitivity by 2 dB, although not sufficient to eliminate transient completely [24]. In [6], we observed that when burst traffic was switched to non-burst traffic receiver sensitivity for EDFA and Raman amplifier improved significantly by ~8 and 6 dB respectively in comparison at 5 µs burst duration, because amplifier transients are mitigated completely for non-burst traffic. Whereas, residual transient effects even at 97% burst traffic was observed for EDFA and Raman amplifiers. FOPA observed ~2 dB receiver sensitivity improvement for 100% traffic. Overall, the traffic density of 75% was the worst performing for the EDFA and the Raman amplifier. On the other hand, FOPA has performed at the maximum traffic density as well as at the 75% traffic density.

We compared receiver sensitivity in cases of burst traffic amplification by FOPA, EDFA and Raman amplifier. Both EDFA and Raman amplifier incurred transient effects degrading the receiver sensitivity with traffic density increase. Conversely, the FOPA ultrafast response time has prevented the receiver sensitivity from degradation for any traffic density in the examined range from 5% to 97%. Consequently, FOPA can allow for >3 dB and >5 dB higher power budget than Raman and EDFA, respectively, based on the worst-case scenario of 75% traffic density. Alternatively, for a sensitivity penalty of ~1 dB and ~2 dB (for BER = 10^{-3}) with Raman and EDFA amplifiers traffic density has to be kept smaller than 30% and 15%, respectively. Overall, for the transmission links following the architecture sketched in Fig. 1, FOPA can enable a link to operate with more than 6 and 3 times higher traffic density than EDFA and Raman amplifier, respectively.

Although the experiment was limited to 10 G because no dispersion compensation was implemented in this 50 km reach PON, all examined amplifiers are suitable for high bit rate signals For example, FOPA operation has been shown with signals carrying up to 256 Gbit/s [25,7]. However, advanced modulation formats are more susceptible to transient effects than 10 G OOK [26]. Since the most significant transients have been observed when employing EDFA or Raman amplifier, we expect the FOPA performance to be even more advantageous for bursty networks employing advanced modulation formats.

5. Conclusion

We demonstrate PI-FOPA with <1 dB receiver sensitivity penalty as compared to the B2B for range of traffic densities from 5% to 97%. On the other hand, EDFA and Raman amplifier suffer from BER degradation as traffic density increases over 15% and 30%, respectively, reaching >5 dB and >3 dB worse sensitivity than FOPA for a 75% traffic density. In addition, and for the generalized optical access link architecture considered here, FOPA allows for 5-times higher traffic density than EDFA for the same power budget. We conclude that FOPA is able to improve a burst network power budget by >5 dB or its traffic capacity by a factor of 6 as compared to a commercial EDFA. Although, FOPA is not yet commercially competitive with other amplifiers studied in this work, we have demonstrated FOPA as compared to currently available amplification technologies to significantly improve throughput for burst traffic. We therefore envisage results of this work to encourage a further development of cost-effective parametric amplification.

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Data Availability. To access the underlying data please see [27].

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