






Bismuth doped fibre amplifier operating in E- and S- optical bands

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Abstract: Bismuth-doped fibre amplifiers offer an attractive solution for expanding the bandwidth of fibre-optic telecommunication systems beyond the current C-band (1530-1565 nm). We report a bismuth-doped fibre amplifier in the spectral range from 1370 to 1490 nm, with a maximum gain exceeding 31 dB, and a noise figure as low as 4.75 dB. The developed system is studied for forward, backward, and bi-directional pumping schemes and three different signal power levels. The forward pumping scheme demonstrates the best performance in terms of the achieved noise figure. The developed amplifier can be potentially used as an in-line amplifier with >20dB gain in the spectral band from 1405 to 1460 nm.

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1. Introduction

An exponentially growing demand for the optical networks capacity is a stable current trend that is likely to continue due to the current deployment of 5G networks, the fast development of cloud and numerous online services, the emerging machine-to-machine communications, and many other bandwidth-hungry applications [1,2]. The conventional optical network systems exploit only about 11 THz of a much larger silica-glass-based optical fibre bandwidth. This is defined by the availability of well-developed and commercially available Er-doped fibre amplifiers operating in C- and L- optical bands (1530-1620 nm). There are currently three main approaches to increasing the capacity of fibre-optic transmission systems and meeting the ceaselessly rising demand: (i) more efficient use of the existing systems, e.g. the development of the new modulation formats; (ii) the development of the spatial division multiplexing (more fibre or new fibres with more spatial channels), and (iii) the development of systems capable to utilise the huge spectral bandwidth of the existing fibre base - the multi-band transmission (MBT). The application of the high-order modulation formats requires increase of the signal-to-noise ratio and this is limited by the nonlinear effects in optical fibre [3], spatial division multiplexing requires either the use of dark-fibres or the deployment of new optical fibre infrastructures, while MBT maximises the return-on-investments in the existing infrastructures [4] by the transmission in the so-called O, E, S, L, and U optical bands.

First commercial MBT systems already coming to the market target transmission in C+L-band systems based on Erbium-doped fibre amplifiers (EDFAs). Operation in the L-band adds 60 nm to the conventional 35 nm C-band. As the next step, it is natural to continue bandwidth expansion into the next closest band that is S-band. However, the transmission in O- and E-bands should be considered as well, as they are very attractive for transmission, especially using special pure

silica fibre with low loss in this spectral region [2]. However, multi-band transmission requires novel types of amplifiers for corresponding spectral bands. Many amplifier technologies were proposed to cover some or multiple bands using neodymium (Nd) [5], praseodymium (Pr) [6], or Tm-doped fibres [7], and Raman fibre amplifiers [8]. It was suggested already a time ago that Pr- as well as Nd-doped optical fibres demonstrate emission in all the O-, E-, and S- telecom bands but suffer from the strong excited-state absorption noticeably spectrally narrowing the net gain and suppressing its magnitude [5,9–12]. A rapid non-radiative transition between G_4 and 3F_4 levels contributes to the poorer (as compared to EDFAs) performance of the Pr-doped fluoride fibre amplifiers [10] and prevents creation of Pr-doped silica fibre amplifiers that would be fully compatible with standard telecom fibres. There is a competition between the ${}^4F_{3/2} - {}^4I_{9/2}$, ${}^4F_{3/2} - {}^4I_{11/2}$, and ${}^4F_{3/2} - {}^4I_{13/2}$ electronic transitions in the Nd-doped optical fibres [5,9,10]. The magnitude of the optical gain observed in the E- and S- telecom bands in the result of the ${}^4F_{3/2} - {}^4I_{13/2}$ transition is substantially limited by the ASE originating from other transitions. In spite of a significant recent progress achieved with a micro-structured Nd-doped silica fibre allowing suppression of the unwanted transitions through spectral filtration [9], such fibres still require further development in order to match the performance of Er-doped fibres. On the other hand, Raman fibre amplifiers have the drawback of high pumping power requirements and relatively higher noise.

Since the first reports [13] Bi-doped fibre amplifiers (BDFAs) have been extensively studied as promising amplification platform for multi-band transmission [14–25]. Using different host materials such as aluminosilicate, phosphosilicate, and germanosilicate glass allows to significantly shift emission spectrum from 1150 to 1500 nm [18,26,27]. Bi-doped fibre amplifier with record bandwidth of 115 nm, 31 db gain, and 4.8 noise figure (NF) in the O and E bands has been recently reported [24]. The first successful data transmission experiment characterised on three signal wavelengths in E-band was reported in [21] and first multi-channel amplification was reported in [20]. Moreover, the performance of Bi-doped fibre amplifier spectrally adjacent to EDFA range was studied in [23] using both backward and forward pumping scheme. The state-of-the-art review on Bi-doped fibre amplifiers and lasers was presented in [18]. Despite the advances in development of BDFAs in the E- and S-bands the direct comparison of different pumping schemes including bi-directional one has not yet been conducted in E and S-bands. In this paper we demonstrate BDFA based on germanosilicate active fibre operating in the spectral range from 1370 to 1490 nm with the maximum gain of 31 dB, a minimum noise figure of 4.75 dB, and >20 dB gain bandwidth of around 55 nm. Moreover, we compare three different pumping schemes including forward, backward, and bi-directional ones, and evaluate the amplifier performance with different signal powers of -20 dBm, -10 dBm, and 0 dBm.

2. Methods and experimental setup

The Bi-doped germanosilicate fibre used in this work was fabricated in Dianov Fiber Optics Research Center using MCVD-solution [28]. The core of fibre consists of 95 mol% SiO₂, 5 mol% GeO₂ and <0.01 mol% of bismuth. The fibre core and cladding diameter are 9 μm and 125 μm, respectively. The numerical aperture (NA) is 0.14, and the cutoff wavelength is around 1.2 μm. The spectral properties of the fibre are similar to one reported in [21,28] The developed Bi-doped fibre amplifier based on 320 m long piece of active fibre and the experimental setup for gain and NF measurements are depicted in Fig. 1. Due to low concentration of Bi-related active centres typical length of Bi-doped fibre in amplifiers exceeds 100 m that might lead to the increased NF due to Rayleigh scattering [29].

Two tunable lasers (TL) operating in spectral ranges of 1340-1440 nm and 1410-1490 nm are used as a signal radiation for characterisation of Gain and NF characteristics of developed amplifier in spectral range of 1370-1490 nm. The first amplifier is used to cover spectral band before 1440 nm, and another one in the band of 1440-1490 nm. The radiation of the TLs pass

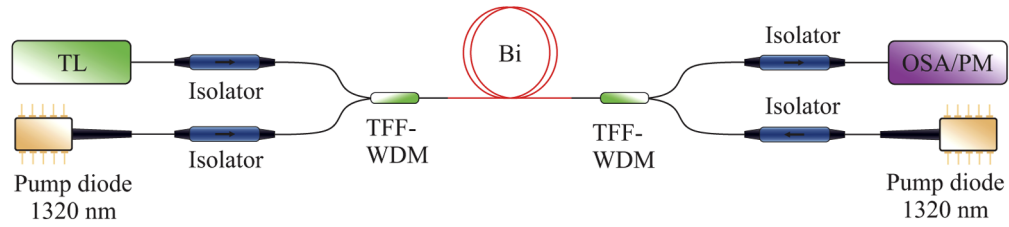


Fig. 1. Scheme of the BDFA. TL: tunable laser; TFF-WDM: thin film filter wavelength division multiplexer; Bi: Bi-doped fibre; OSA: optical spectrum analyser; PM: power meter.

polarisation independent isolator with minimum isolation of 32 dB and internal losses less than 3 dB in spectral band of 1390-1490 nm. After the isolator the radiation is coupled into Bi-doped fibre through thin film filter wavelength division multiplexer (TFF-WDM). The key components of the developed setup are TFF-WDMs with very steep and consistent transmission (1300-1362 nm) and reflection (1370-1565 nm) bands with constant optical loss of 0.1 dB. The radiation of two pump diodes operating at the wavelength of 1320, used as forward and backward pumping, passes 1320 nm polarisation independent isolators and is coupled into the active fibre through TFF-WDMs. After a subsequent amplification in the Bi-doped fibre signal radiation passes another TFF-WDM and the 1390-1490 nm polarisation independent isolator and is detected in either optical spectrum analyser (OSA) or power-meter (PM). The OSA is used for both peak-to-peak gain measurements and the noise spectral power density subtraction for NF calculation that is found using the source subtraction technique described in [30] and using the following equation:

$$NF = 10 \log \left(\frac{\rho_{total}}{G h \nu} + \frac{1}{G} + \frac{\rho_{sse}}{h \nu} \right), \quad (1)$$

where ρ_{total} and ρ_{sse} are the total noise spectral density on the output of the amplifier and the input source noise spectral density, respectively; G is the gain, h is the Planck constant, and ν is the photon frequency. The noise spectral density was achieved from the signal spectrum by approximating of the spectral noise level on the signal wavelength. Moreover, the noise spectral density was calibrated in regards with the power received by the PM. The gain was measured by recording spectra at the input and output of the amplifier and comparing their signal peak power increment.

3. Results

3.1. Forward pumping scheme

The performance of the developed BDFA is characterised for the forward, backward, and bi-directional pumping schemes and three different signal levels of -20 dBm, -10 dBm, and 0 dBm. The gain and NF for the forward pumping scheme and 3 different signal levels are depicted in Fig. 2.

The gain increases with the pump power increase and saturates at high pump powers for all signal power levels in Fig. 2(a,c,e). The maximum gain of 30.36 dB is achieved at the wavelength of 1430 nm, pump power of 470 mW and signal power of -20 dBm. The gain spectrum shows a significant flattening with the increase of signal power leading to an widening of -3dB gain bandwidth from 27.28 to 52.1 nm for -20 dBm and 0 dBm signal power, respectively. Moreover, increase of the signal power leads to consistent gain reduction from maximum value of 30.36 dB to 18.63 dB for -20 dBm and 0 dBm of signal power. This effect also causes the increase of NF value from 4.75 dB to 5.56 dB.

The corresponding NF and is shown in Fig. 2(b,d,e). The NF decreases with the increase of the pump power and saturates along with the gain saturation. The significant increase of NF

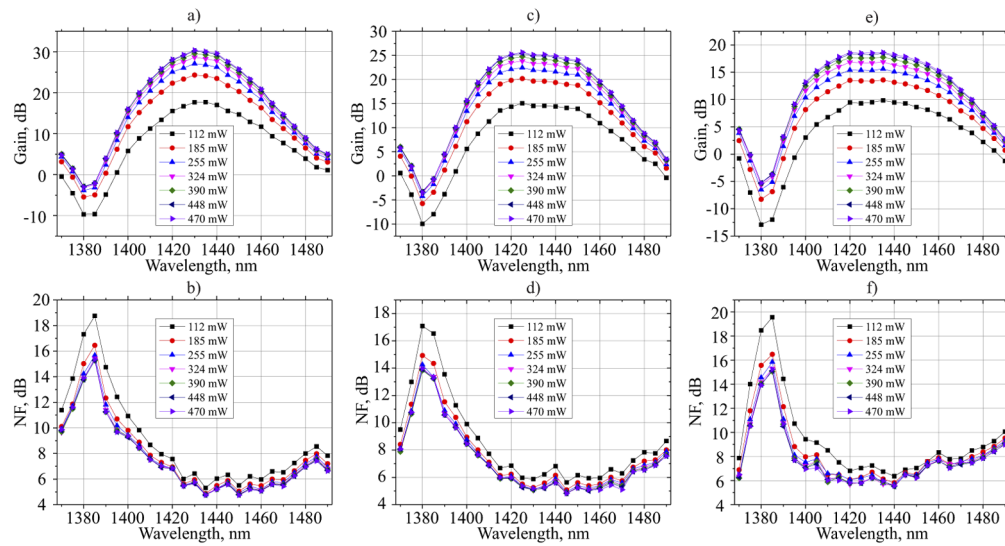


Fig. 2. Dependencies of the measured gain (upper row) and the noise figure (bottom row) on the wavelength for different pump powers in a forward pumping scheme: a,b) gain, NF for -20 dBm input signal power; c,d) gain, NF for -10 dBm input signal power; e,f) gain, NF for 0 dBm input signal power.

closer to 1390 nm corresponds to the amplification at the edge of the gain band, the decrease of the isolator transmission, and the influence of the water absorption tail. The amplification at the 1370 nm occurs due to stimulated emission from the pump level and leads to decreased NF in comparison to the signal amplification at 1390 nm. The amplification beyond the presented spectral band was not possible due to the limitations of the TFF-WDM reflection band starting from the 1370 nm. The minimum NF of 4.75 dB is achieved with -20 dBm signal at the 1435 nm wavelength and 470 mW of the pump power. The comparison between the gain, the gain bandwidth, and the NF for all pumping schemes are presented in Table 1.

Table 1. Characteristics of pumping schemes for different signals for 470 mW of the pump power for forward pumping scheme, 454 mW of the pump power for backward pumping scheme, and 472 mW of the pump power for bi-directional pumping scheme.

Signal power	Pumping scheme	Gain, db	Bandwidth, nm	NF, db
-20 dBm	forward	30.36	27.28	4.75
	backward	30.59	28.98	5.3
	bi-directional	30.52	29.08	5.26
-10 dBm	forward	25.63	42.38	4.82
	backward	26.88	38.19	5.52
	bi-directional	26.57	37.13	5.5
0 dBm	forward	18.63	52.1	5.56
	backward	19.63	44.87	6.43
	bi-directional	19.5	42.93	6.95

3.2. Backward pumping scheme

As the next step, the backward pumping scheme was investigated with all three signal powers, i.e. the optical gain and the NF were measured. The behaviour of the gain and NF spectra is

similar to the backward pumping scheme, with slightly higher gain and lower NF (Fig. 3). The maximum gain for -20 dBm signal power is equal 30.59 dB at the wavelength of 1430 nm and the pump power of 454 mW. The maximum gain bandwidth for -20 dBm is wider than that of the forward pumping scheme and is equal 28.98 nm. However it is also narrower than that of backward pumping scheme in case of 0 dBm signal and is equal to 44.87 nm. The minimum NF magnitude is 5.3 dB for signal power of -20 dBm at the wavelength of 1430 nm and the pump power of 454 mW. The observed higher NF level in comparison to the forward pumping scheme is, indeed, expected for the non-uniformly pumped active fibre [31].

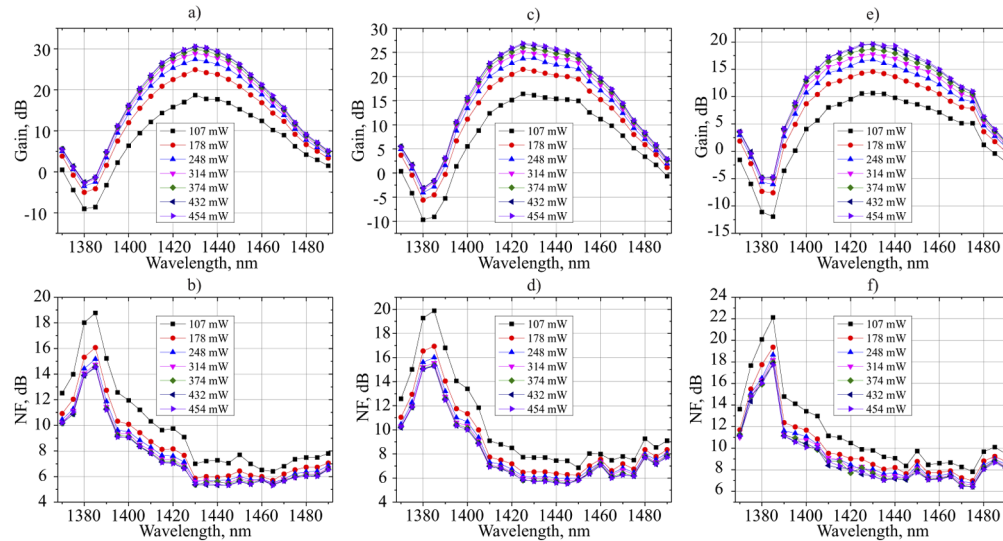


Fig. 3. Dependencies of the measured gain (upper row) and the noise figure (bottom row) on the wavelength for different pump powers in a backward pumping scheme: a,b) gain, NF for -20 dBm input signal power; c,d) gain, NF for -10 dBm input signal power; e,f) gain, NF for 0 dBm input signal power.

3.3. Bi-directional pumping scheme

As the last step, the bi-directional pumping scheme is investigated in terms of gain and NF (Fig. 4). The total pump power of the diodes pumping the active fibre with equal power in both directions is indicated in Fig. 4. As the maximum pump power of the bi-directional pumping scheme is significantly higher than those of both forward and backward pumping schemes, the maximum value of gain and gain bandwidth, and minimum value NF are compared at the similar power of 472 mW (dark blue line with arrows in Fig. 4).

The maximum gain for the -20 dBm signal power is equal 30.52 dB at the wavelength of 1430 nm and the pump power of 472 mW. The maximum gain bandwidth for -20 dBm is the widest than other pumping schemes and is equal 29.08 nm. However, in the case of 0 dBm signal it is also narrower than that of backward pumping scheme and is equal to 42.93 nm. The minimum NF magnitude is 5.26 dB for the signal power of -20 dBm at the wavelength of 1430 nm and the pump power of 472 mW, which is a slightly better value than that of the backward pumping scheme.

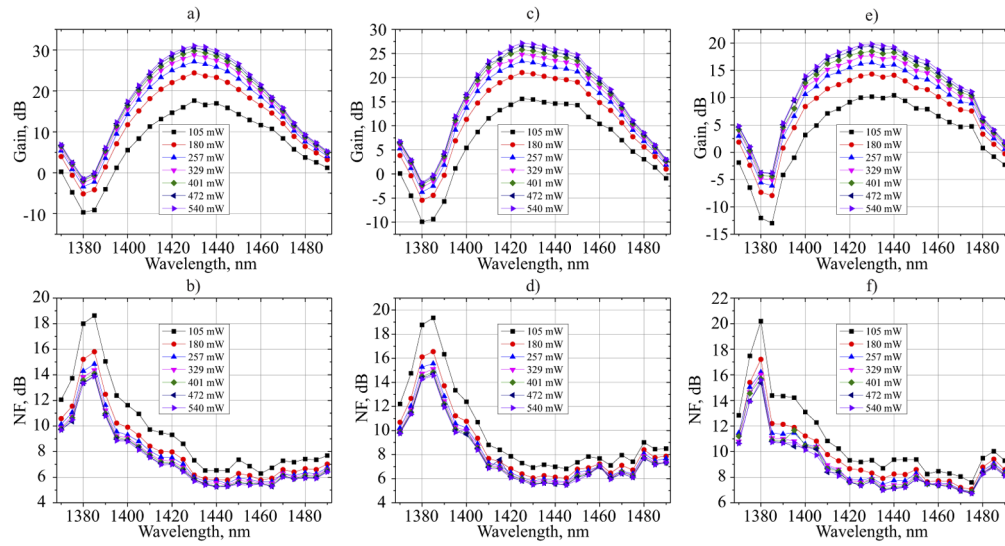


Fig. 4. Dependencies of the measured gain (upper row) and the noise figure (bottom row) on the wavelength for different pump powers in a bi-directional pumping scheme: a,b) gain, NF for -20 dBm input signal power; c,d) gain, NF for -10 dBm input signal power; e,f) gain, NF for 0 dBm input signal power.

4. Discussion

The developed amplifier was studied using different pumping schemes with slightly different pump powers, and we would like to compare the power dependencies of gain and NF characteristics. As the both optical gain and noise figure have also a spectral dependence, we averaged the spectral magnitudes of these parameters in the range of 1400-1480 nm in order to compare an average performance of the pumping schemes. Such dependencies for forward, backward and bi-directional pumping scheme are presented in Fig. 5.

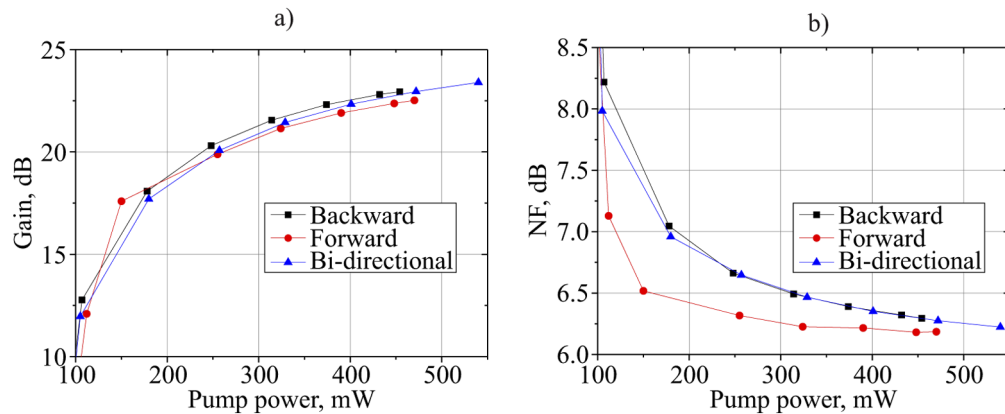


Fig. 5. Dependencies of the Gain (a) and NF (b) on the pump power

The graphs show that, almost for all pump powers, the highest gain was achieved in the backward pumping scheme. The bi-directional pumping scheme showed intermediate gain magnitudes relatively to the backward and forward pumping schemes. The forward pumping

scheme demonstrated a lower optical gain as compared to other pumping schemes. On the other hand, the lowest noise figure is achieved with the forward pumping scheme. The noise figure for bi-directional and backward pumping schemes is almost the same with slightly better performance in the bi-directional scheme with pump powers less than 200 mW. Thus, the uniform pumping plays the crucial role for the amplifier performance in terms of the noise figure. It is worth noting that the NF for the forward pumping shows a noticeable saturation with the pump power as compared to the bi-directional and backward pumping schemes. This indicates that a significant increase in the pump power for the bi-directional and backward pumping schemes will be comparable with the forward pumping NF. The same gain saturation was observed in the backward pumping scheme. Therefore, it is preferable to use the forward pumping scheme in order to achieve a moderate gain and an excellent noise performance with a relatively low pump power. Obviously, NF and gain characteristics should be nearly the same in all pumping schemes when the gain medium is well pumped.

The measured power conversion efficiencies (PCE) for three different pumping schemes are as follows: 15.3% for forward pumping scheme, 16.3% for bi-directional pumping scheme, and 19.8% for backward pumping scheme. The PCE of around 20% is the typical value for L-band EDFAs [32], and less than that of C-band EDFAs. The further increase of the PCE can be performed by using fibre Bragg gratings [33], double pass configuration [34], or shifting pump wavelength closer to the absorption maximum. The maximum output signal power exceeds 100 mW. However, we have recently demonstrated the BDFAs operating in the vicinity of 1.45 μm with output powers of several hundreds of milliwatts [20,23]. Although it is already sufficient for application in practice, further scalability is anticipated, since >50% lasing efficiency with >10-W output power have been already reported [35].

The current results presented in this work show a certain overall increase in the performance of BDFA, i.e. the increase of the maximum gain (or the minimum NF) in comparison to our previous works with 27.8 dB gain and 7.4 dB NF [20], and 27.9 dB gain and 5 dB NF [23]. In [24], a significant optical gain was observed also below 1390 nm down to 1345 nm. The usage of phosphosilicate Bi-doped fibres with a highly pronounced emission band around 1.3 μm could contribute to this phenomenon [26]. The usage of two laser diodes operating at different wavelengths of 1270 nm and 1310 nm could lead to the excitation of two types of Bi-related optical centres. Thus, two types of Bi-related optical centres can be stabilised in the same glass host and a laser action can be achieved for both of them with the change of the pump wavelength [17]. In this work, the left part of the gain spectrum showed a continuous growth; however, a detailed study of this part was impossible due to the increased optical loss of the TFF-WDMs and the isolators in this spectral area. Therefore, the detailed study of the Bi-doped fibres in the shorter-wavelength region is planned in the future.

5. Conclusion

A BDFA with the maximum gain of 31 dB and the minimum noise figure of 4.75 dB has been developed and studied in the forward, backward, and bi-directional pumping schemes. The demonstrated amplifier has a high gain (>20dB) in the whole spectral band of 1405-1460 nm. The three pumping schemes were compared in terms of the average noise figure, optical gain performance, and PCE. It was concluded that the forward pumping scheme is the most promising as the excellent performance can be achieved at lower pump powers. However, it should be improved in terms of PCE, and the possible solutions are covered in the discussion. The high optical gain and the low NF of the BDFA operating in the E- and S-bands reported in this work with the overall BDFA performance comparable to the conventional EDFAs allows to consider BDFAs as a promising in-line amplifier with a potential to double the capacity of conventional C-band EDFA systems.

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Disclosures

The authors declare no conflicts of interest.

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