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High gain E-band amplification based on the low loss Bi/P co-doped silica fiber

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A home-made low loss Bi/P co-doped silica fiber was fabricated using the modified chemical vapor deposition (MCVD) technique combined with the solution doping method, where the background loss at 1550 nm was as low as 17 dB/km. We demonstrated for the first time, to the best of our knowledge, an all-fiber amplifier using the home-made Bi/P co-doped fiber achieving broadband amplification in the E-band. The amplifying performance was evaluated and optimized with different pumping patterns and fiber length. A maximum net gain at 1355 nm close to 20 dB and a minimum noise figure of 4.6 dB were obtained for the first time, to the best of our knowledge, using two 1240 nm laser diodes under bidirectional pumping with the input pump and signal powers of 870 mW and −30 dBm, respectively.

Keywords: bismuth-doped fiber; fiber amplifier; E-band amplification.
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1. Introduction

With the rapid development of Internet, cloud computing, Internet of Things, and other technologies, the conventional erbium-doped fiber amplifiers (EDFAs), which work mainly in the C + L band, cannot meet the growing demand from the capacity of optical fiber communication systems. Thus, it is urgent to research and develop optical fiber amplifiers outside the C + L band. At present, some rare earth-doped fiber amplifiers have been developed, such as praseodymium-doped[1], neodymium-doped[2], and thulium-doped fiber amplifiers[3], but these fiber amplifiers have a narrow gain bandwidth because of the limitation of rare earth ions' 4f–4f transition. In addition, the Raman fiber amplifier is currently the only fiber amplifier that can achieve the full-range amplification of ultra-wideband from 1270 to 1660 nm[4], but its critical drawbacks of complex structure, high pump power, requiring multiple pump sources to work at the same time, and high cost limit its commercial use. A Bi-doped fiber is a potential gain medium for a broadband amplifier because of its broadband near-infrared (NIR) emission covering the O, E, and U bands[5].

Studies have shown that luminescence properties of Bi-doped silica fibers are closely related to the core composition and the valence state of Bi ions[6]. Over the past few decades, lasing and optical amplification between 1100–1800 nm have been reported using the Bi-doped fibers based on different glass hosts (i.e., aluminosilicate, phosphorsilicate, and germanesilicate)[7–11]. Bi-doped fiber amplifiers (BDFAs) operating over the extended transmission bands have been achieved abroad with the gain of 11.5 dB at 1180 nm, 40 dB at 1350 nm, 27.9 dB at 1445 nm, and 25 dB at 1725 nm using Bi-doped aluminosilicate fibers, Bi-doped phosphosilicate fibers, and Bi-doped high germania silica fibers, respectively[12–15]. The researches on the luminescence properties of Bi-doped glass and fibers have been carried out also very early in China. In 2004, Peng *et al.* reported the discovery of ultra-broadband NIR luminescence in Bi-doped aluminum–germanium silicate glass[16]. In 2007, Zhou *et al.* studied the optical amplification properties of Bi-doped germanosilicate glass and observed ultra-broadband optical amplification in the range of 1272–1560 nm. The highest gain of the bulk glass reached 6.73 dB at 1272 nm with a 980 nm laser diode (LD)[17]. In 2009, Jiang modeled a broadband BDFA for the first time, to the best of our knowledge, and predicted that the amplifier can have ultra-broad gain at 1.2–1.62 μm with the pump wavelength of 800–900 nm[18]. In 2012, Luo *et al.* reported a Bi/Er co-doped germanosilica fiber, which has ultra-broadband luminescence

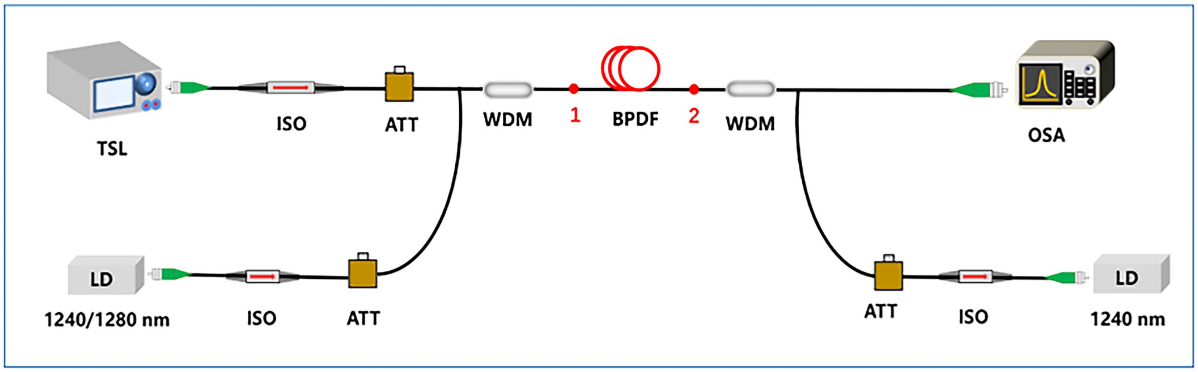

Fig. 1. Experimental setup of the single stage BPDF amplifier. Points 1 and 2 are fusion splicing joints between BPDF and WDMs.

in the range of 1000–1570 nm[19]. In brief, Zhou *et al.* have already carried out in-depth research on the mechanism, optical properties, and preparation of Bi-doped glass and fibers[20–27]. However, to the best of our knowledge, there is no report on the net gain of domestic Bi-doped silica fiber amplifiers.

In this paper, we developed a fiber amplifier operating at 1355–1385 nm using a home-made low-loss Bi/P co-doped silica fiber (BPDF). The amplifying performance at different pumping conditions and fiber lengths was compared, and the gain and noise figure (NF) characteristics with different pump and signal powers were evaluated. Using a bidirectional pumping configuration with two 1240 nm LDs, the maximum gain about 20 dB and the minimum NF of 4.6 dB at 1355 nm were achieved with a total pump power of 870 mW and signal power of −30 dBm.

2. Experiment and Methods

The BPDF was fabricated by the modified chemical vapor deposition (MCVD) technique combined with the solution doping method. The core and cladding diameters were 6 and 125 μm, respectively. The numerical aperture and cutoff wavelength were 0.14 and ~1050 nm. The core background loss and absorption spectra of the fiber were measured by the cut-back method with a white light source (WLS, Thorlabs SLS201L/M).

The experimental setup of the single stage bidirectional pumping BPDF is schematically shown in Fig. 1. A tunable laser source (TLS, Santec) operating in the range of 1355–1485 nm was used as the input signal source with an isolator (ISO) and attenuator (ATT). Two LDs at 1240 and 1280 nm, each with up to ~500 mW output power, were used as the pump sources for the amplifier. Optical ISOs were used to isolate back reflection and residual pump power, and the fiber ATTs were used to regulate the pump and signal powers. The pump and signal lights were coupled into the BPDF through wavelength division multiplexers (WDMs). The BPDF was fusion spliced with the WDMs, and points 1 and 2 are fusion splicing joints. The input and amplified signals were recorded before BPDF (point 1) and after the second WDM for the gain and NF measurements by an optical spectrum analyzer (OSA, Yokogawa AQ6370), respectively. The input insertion loss was measured to be ~0.5 dB.

3. Result and Discussion

Figure 2(a) shows the background loss of the BPDF. The background loss at 1550 nm was as low as ~17 dB/km, which was lower than that of Ref. [28]. Figure 2(b) shows the absorption spectrum of BPDF from 950 to 1650 nm. The core absorption coefficient at 1240 nm was as high as ~461 dB/km, close to that previously reported[28]. Meanwhile, the OH absorption peak at ~1380 nm was weaker than that previously reported, which benefits the achievement of a flattop gain profile[29].

As shown in Fig. 3, two amplified spontaneous emission (ASE) spectra of 190 m BPDF were measured with 1240 and 1280 nm LDs (415 mW pump power). Under the excitation of 1240 or 1280 nm, the ASE spectra both showed a broad band with different peak positions. The peak position of the ASE spectrum under 1240 nm excitation was at ~1323 nm, and that under 1280 nm excitation was at ~1345 nm, where there was a red shift with a longer pump wavelength. As reported, it is due to the strong dependence of the luminescence spectrum of Bi active centers related to phosphorus (BAC-P) on the excitation wavelength[6]. Therefore, using a 1240 nm LD as the pump source was beneficial for the higher gain at the short wavelength, conversely under 1280 nm excitation.

Then, the gain performances of the BPDF pumped by a 1240 nm LD with bidirectional, forward, and backward

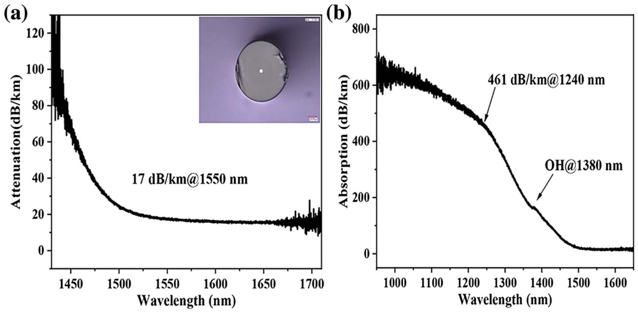

Fig. 2. (a) Background loss and (b) absorption spectrum of the BPDF.

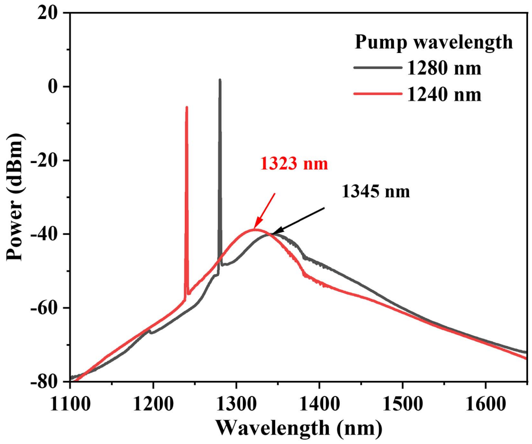

Fig. 3. ASE spectra of the BPDF at 1240 and 1280 nm pumping.

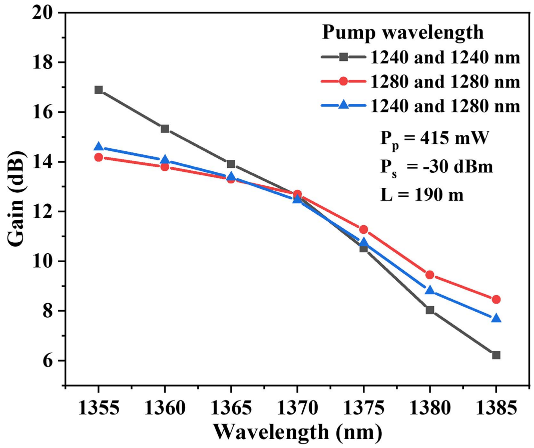

Fig. 5. Gain characteristics under different pump wavelength combinations at fixed pump and signal power as well as fiber length.

pumping configurations were compared. The total pump and signal powers of each pumping configuration were 415 mW and −30 dBm, respectively. The fiber length was optimized to get maximum gain for each pumping configuration, and the optimal fiber lengths of bidirectional pumping and forward or backward pumping were 190 m and 170 m, respectively. Figure 4 shows the gain spectra from 1355 to 1385 nm with a step of 5 nm. It can be obviously seen that the net gain with bidirectional pumping was much higher than that with forward or backward pumping. The bidirectional pumping led to a more uniform average inversion[30]. Meanwhile, the gain with forward or backward pumping was similar due to their almost same upper-state population and inhomogeneous population distribution along the fiber length with the same pump power.

Figure 5 shows the gain performances of three different kinds of pumping wavelength combinations with the bidirectional pumping configuration. The total pump power for each combination was fixed to be 415 mW, and the pump power for forward and backward was equal to a 3 dB optical fiber coupler. For a given total pump power, the gain from 1355 to 1370 nm was the highest with two 1240 nm LDs pumping, while that from 1370 to 1385 nm was the highest with two 1280 nm LDs pumping. Therefore, the result illustrated that using two 1280 nm LDs benefited the achievement of gain at a longer wavelength, whilst improving gain flatness. Using two 1240 nm LDs was beneficial for improving the gain at a shorter wavelength, and a maximum gain of ∼17 dB at 1355 nm was achieved. The result of gain difference was consistent with ASE spectra in Fig. 3[31].

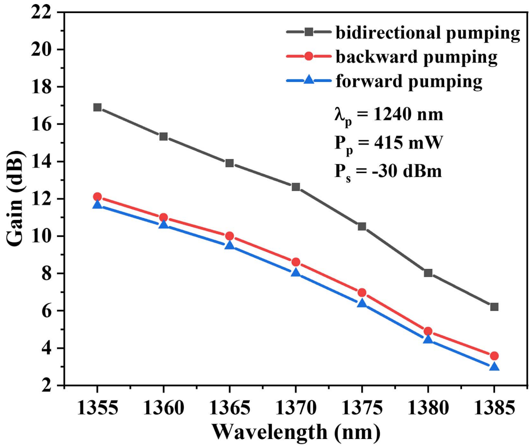

Fig. 4. Gain characteristics of three pumping configurations, bidirectional pumping with the fiber length of 190 m and forward and backward pumping with the fiber length of 170 m.

The optical gain and NF characteristics of BPDF were measured by bidirectional pumping with two 1240 nm LDs, as shown in Fig. 6. It was clear that the optimal length of the fiber was 190 m for getting the maximum gain at 1355 nm [see Fig. 6(a)]. However, limited by the signal source operating at shorter wavelength and the matched WDMs, we cannot further optimize the maximum gain value at shorter wavelength. The gain and NF at different input signal powers of 1355 nm with the fixed pump power of 870 mW are shown in Fig. 6(b). The input signal was recorded before the BPDF (point 1, see Fig. 1), and thus the NF was calculated without considering the insertion loss of the first WDM (0.5 dB). There was no obvious difference of the gain and NF with different input signal powers of −40 and −30 dBm, which indicated that the gain was not saturated. However, as the signal power increased from −30 to −10 dBm, the gain decreased significantly from 19.9 to 17.5 dB, and the NF increased from 4.6 to 5.8 dB because of gain saturation. The upper-state population will decrease, and the inversion will be reduced as fast as the input signal power increases, thus degrading the gain and NF[30]. Figure 6(c) shows the gain and NF at 1355 nm with different pump powers. With an increase in pump power from 415 to 870 mW, the gain increased from 16.9 to 19.9 dB, and NF decreased from 6.8 to 4.6 dB. The highest gain of 19.9 dB and the lowest NF of 4.6 dB were achieved under ∼870 mW pump power. The gain coefficient of pump power at 1355 nm was found to be ∼0.023 dB/mW, and the gain coefficient of fiber length was ∼0.105 dB/m with the pump power of 870 mW.

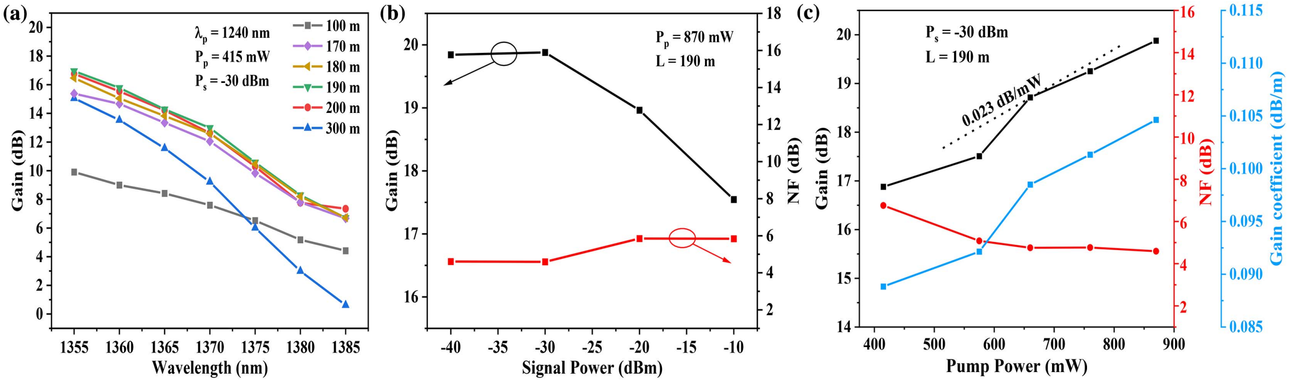

Fig. 6. Gain and NF characteristics under bidirectional pumping with two 1240 nm LDs. (a) Gain versus fiber length with the pump power of 415 mW and the input signal power of −30 dBm. (b) Gain or NF versus signal power with the fiber length of 190 m and the pump power of 870 mW. (c) Gain or NF versus pump power with the fiber length of 190 m and the input signal power of −30 dBm.

4. Conclusion

In this paper, we prepared a low-loss BPDF by MCVD technology, where the background loss at 1550 nm was as low as 17 dB/km. We demonstrated for the first time, to the best of our knowledge, an all-fiber amplifier successfully operating in the E-band using this home-made BPDF. We systemically compared the gain performance of different pumping methods. The bidirectional pumping was of great benefit to achieving higher gain than either forward or backward pumping. The gain characteristics with different pump or signal powers were evaluated. A maximum gain at 1355 nm close to 20 dB and a minimum NF of 4.6 dB were obtained using two 1240 nm LDs under bidirectional pumping with the input pump and signal powers of 870 mW and −30 dBm, respectively. To the best of our knowledge, this is the first net gain ever reported in China based on the home-made BPDF. In future work, the fiber fabrication process and amplifier configuration need to be further optimized to improve the performance of the fiber amplifier.

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References

1. Y. Miyajima, T. Sugawa, and Y. Fukasaku, "38.2 dB amplification at 1.31 μm and possibility of 0.98 μm pumping in Pr^{3+}-doped fluoride fibre," Electron. Lett. **27**, 1706 (1991).
2. M. Brierley, S. Carter, P. France, and J. E. Pedersen, "Amplification in the 1300 nm telecommunications window in a Nd-doped fluoride fiber," Electron. Lett. **26**, 329 (1990).
3. S. Chen, Y. Jung, S. U. Alam, R. Sidharthan, D. Ho, S. Yoo, D. J. Richardson, and J. M. O. Daniel, "Ultra-short wavelength operation of thulium-doped fibre amplifier in the 1628–1655 nm waveband," in *European Conference on Optical Communication* (2018).
4. J. Bromage, "Raman amplification for fiber communications systems," J. Light. Technol. **22**, 79 (2004).
5. Y. Fujimoto and M. Nakatsuka, "Infrared luminescence from bismuth-doped silica glass," Jpn. J. Appl. Phys. **40**, L279 (2001).
6. S. V. Firstov, V. F. Khopin, I. A. Bufetov, E. G. Firstova, A. N. Guryanov, and E. M. Dianov, "Combined excitation-emission spectroscopy of bismuth active centers in optical fibers," Opt. Express **19**, 19551 (2011).
7. I. A. Bufetov, M. A. Melkumov, S. V. Firstov, K. E. Riumkin, A. V. Shubin, V. F. Khopin, A. N. Guryanov, and E. M. Dianov, "Bi-doped optical fibers and fiber lasers," IEEE J. Sel. Top. Quantum Electron. **20**, 111 (2014).
8. N. K. Thipparapu, Y. Wang, S. Wang, A. A. Umnikov, P. Barua, and J. K. Sahu, "Bi-doped fiber amplifiers and lasers," Opt. Mater. Express **9**, 2446 (2019).
9. A. Donodin, V. Dvoyrin, E. Manuylovich, L. Krzczanowicz, W. Forysiak, M. Melkumov, V. Mashinsky, and S. Turitsyn, "Bismuth doped fibre amplifier operating in E- and S- optical bands," Opt. Mater. Express **11**, 127 (2021).
10. Y. Ososkov, A. Khegai, S. Firstov, K. Riumkin, S. Alyshev, A. Kharakhordin, A. Lobanov, A. Guryanov, and M. Melkumov, "Pump-efficient flattop O+E-bands bismuth-doped fiber amplifier with 116 nm -3 dB gain bandwidth," Opt. Express **29**, 44138 (2021).
11. Y. Wang, N. K. Thipparapu, D. J. Richardson, and J. K. Sahu, "Ultra-broadband bismuth-doped fiber amplifier covering a 115-nm bandwidth in the O and E bands," J. Light. Technol. **39**, 795 (2021).
12. N. K. Thipparapu, S. Jain, A. A. Umnikov, P. Barua, and J. K. Sahu, "1120 nm diode-pumped Bi-doped fiber amplifier," Opt. Lett. **40**, 2441 (2015).
13. Y. Wang, N. K. Thipparapu, S. Wang, P. Barua, D. J. Richardson, and J. K. Sahu, "Study on the temperature dependent characteristics of O-band bismuth-doped fiber amplifier," Opt. Lett. **44**, 5650 (2019).
14. V. V. Dvoyrin, V. M. Mashinsky, and S. K. Turitsyn, "Bismuth-doped fiber amplifier operating in the spectrally adjacent to EDFA range of 1425–1500 nm," in *Optical Fiber Communication Conference* (2020).
15. E. M. Dianov, S. V. Firstov, S. V. Alyshev, A. V. Kharakhordin, K. E. Riumkin, M. A. Melkumov, V. F. Khopin, and A. N. Guryanov, "Bismuth-doped optical fibers for the telecommunication L and U bands: effect of laser and thermal treatment on gain characteristics," in *European Conference on Optical Communication (ECOC)* (2018).
16. M. Y. Peng, J. R. Qiu, D. P. Chen, X. G. Meng, I. Y. Yang, X. W. Jiang, and C. S. Zhu, "Bismuth- and aluminum-codoped germanium oxide glasses for super-broadband optical amplification," Opt. Lett. **29**, 1998 (2004).
17. S. F. Zhou, H. F. Dong, H. P. Zeng, G. F. Feng, H. C. Yang, B. Zhu, and J. R. Qiu, "Broadband optical amplification in Bi-doped germanium silicate glass," Appl. Phys. Lett. **91**, 061919 (2007).
18. C. Jiang, "Modeling a broadband bismuth-doped fiber amplifier," IEEE J. Sel. Top. Quantum Electron. **15**, 79 (2009).
19. Y. Luo, J. Wen, J. Zhang, J. Canning, and G. D. Peng, "Bismuth and erbium codoped optical fiber with ultrabroadband luminescence across O-, E-, S-, C-, and L-bands," Opt. Lett. **37**, 3447 (2012).
20. S. Zhou, H. Dong, H. Zeng, J. Hao, J. Chen, and J. Qiu, "Infrared luminescence and amplification properties of Bi-doped $GeO_2-Ga_2O_3-Al_2O_3$ glasses," J. Appl. Phys. **103**, 103532 (2008).
21. J. Wu, D. Chen, X. Wu, and J. Qiu, "Ultra-broad near-infrared emission of Bi-doped SiO_2-Al_2O_3-GeO_2 optical fibers," Chin. Opt. Lett. **9**, 071601 (2011).

22. Y.-S. Wang, Z.-W. Jiang, H.-X. Luan, Z.-X. Zhang, J.-G. Peng, L.-Y. Yang, J.-Y. Li, and N.-L. Dai, "Preparation and spectral characteristics of Bi-doped double cladding fiber," Acta Phys. Sin. **61**, 084215 (2012).
23. Y.-S. Wang, Z.-W. Jiang, J.-G. Peng, H.-Q. Li, L.-Y. Yang, J.-Y. Li, and N.-L. Dai, "Controlling the spectral characteristics of bismuth doped silicate glass based on the reducing reaction of Al powder," Chin. Phys. Lett. **30**, 044207 (2013).
24. J. Wu and X. Wu, "Fabrication of Er/Bi Co-doped silica preforms with a broadband infrared emission," Opto-Electron **4**, 6 (2014).
25. P. Liu, L. Liao, Y.-B. Chu, Y.-B. Wang, X.-W. Hu, J.-G. Peng, J.-Y. Li, and N.-L. Dai, "Irradiation and temperature influence on the Bi-doped silica fiber," Acta Phys. Sin. **64**, 224220 (2015).
26. J. Cao, Z. Zhang, X. Li, and M. Peng, "Abnormal NIR photoemission from bismuth doped germanophosphate photonic glasses," J. Mater. Chem. C **7**, 3218 (2019).
27. Q. Zhao, Q. Hao, Y. Luo, and G. D. Peng, "Thermal-induced luminescence enhancement of BAC-P in bismuth-doped phosphogermanosilicate fibers," Opt. Lett. **45**, 1152 (2020).
28. A. Khegai, Y. Ososkov, S. Firstov, K. Riumkin, S. Alyshev, A. Kharakhordin, E. Firstova, F. Afanasiev, V. Khopin, A. Guryanov, and M. Melkumov, "O-Band bismuth-doped fiber amplifier with 67 nm bandwidth," in *Optical Fiber Communications Conference and Exhibition (OFC)* (2020), p. 3.
29. W. Yu, N. Kumar Thipparapu, D. J. Richardson, and J. Sahu, "Bi-doped fiber amplifiers for ultra-wideband optical communication systems," in *IEEE Photonics Society Summer Topicals Meeting Series (SUM)* (2021), p. 3.
30. P. C. Becker, N. A. Olsson, and J. R. Simpson, *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology* (Academic, 1999).
31. E. M. Dianov, "Bismuth-doped optical fibers: a challenging active medium for near-IR lasers and optical amplifiers," Light Sci. Appl. **1**, e12 (2012).