Broadband Bismuth-Doped Fiber Amplifier With a Record 115-nm Bandwidth in the O and E Bands

Y. Wang, N. K. Thipparapu, D. J. Richardson, and J. K. Sahu
Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
yw9n17@soton.ac.uk

Abstract: We report a bismuth-doped fiber amplifier providing >20dB gain from 1345nm-1460nm with 31dB maximum gain and 4.8dB NF at 1420nm for a -23dBm signal. The gain coefficient and temperature-dependent-gain coefficient are 0.042dB/mW and -0.015dB/°C, respectively.

1. Introduction

The explosive growth of data transfer over the global internet resulting, for example, from increased use and development of online multimedia applications, cloud services and associated data center interconnection means that the capacity demands on modern optical fiber communication systems are continuously increasing. The development of efficient amplifiers capable of operating outside of the currently used C+L-bands (1530nm-1625nm) extending from the O-band to the U-band (1260nm-1675nm) where the transmission loss in existing silica optical fibers is ≤0.4dB/km would provide an immediate opportunity to access additional bandwidth [1, 2]. The broadband near-infrared (NIR) luminescence properties of bismuth (Bi)-doped silica fibers, which span the O-, E-, S- and U-bands indicate that Bi is a promising dopant to develop amplifiers in these wavebands [3]. Recently amplifiers operating in the O-band [4-7] and E-band [8, 9] have been demonstrated using silica based Bi-doped fibers (BDFs). To date the maximum bandwidth reported so far for >20dB gain in a BDF is 40nm for the 1430nm band [8].

In this paper, we report an ultra-broadband Bi-doped fiber amplifier (BDFA) that provides for >20dB gain over a 115nm bandwidth from 1345nm to 1460nm, which covers part of the O-band and the entire E-band. A maximum gain of 31dB with a noise figure (NF) of 4.8dB at 1420nm for a signal power of -23dBm was achieved. In addition, we measured the temperature-dependent-gain (TDG) and NF performance from 1350nm to 1460nm over the temperature range from -40 to +60°C. The TDG coefficient for -23dBm signal was found to be -0.015dB/°C at a signal wavelength of 1420nm. The TDG coefficient of the BDFA in the entire E-band was in the range from -0.076dB/°C to -0.012dB/°C, which is similar to that of a typical erbium (Er)-doped fiber amplifier (EDFA) [10].

2. Bi-doped phosphosilicate fiber amplifier

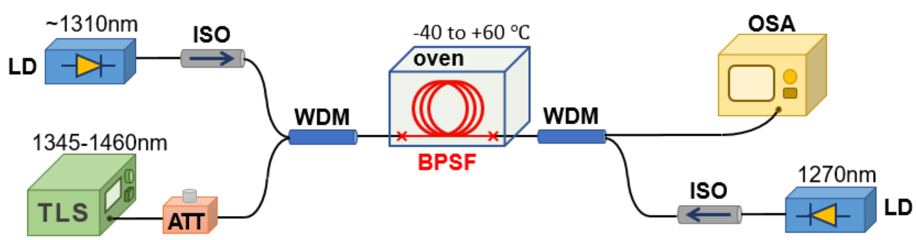

Fig. 1. Experimental setup of Bi-doped phosphosilicate fiber amplifier.

Building upon our extensive past experience in making Bi-doped fibers, a Bi-doped phosphosilicate fiber (BPSF) preform was fabricated in-house using the modified chemical vapor deposition (MCVD)-solution doping technique with a refractive index difference (Δn) of ~0.004, and then drawn into fiber with core and cladding diameters of 11 and 150µm, respectively. The absorption at the pump wavelengths of 1270nm and ~1310nm was measured using the cut-back method and was found to be 0.57dB/m and 0.52dB/m, respectively, and the background loss at 1550nm was measured to be 0.01dB/m. The unsaturable loss (UL) at 1240nm was measured to be 16.4%. The OH concentration of the BPSF, measured from the absorption peak at 1380nm, was ~1ppm. Note that no special measures were incorporated in the fabrication process to reduce the OH content for this current generation fiber.

The experimental setup used to demonstrate and characterize the Bi-doped phosphosilicate fiber amplifier is shown in Fig. 1. A 220m length of BPSF was found to be optimal in terms of overall gain performance and was used in the experiments described herein. Laser diodes (LDs) operating at ~1310nm and 1270nm were utilized to provide bidirectional pumping and to enhance the broadband gain performance. The total pump power that could be launched into the BPSF was 850mW (475mW from the forward pump and 375mW from the backward pump). A tunable laser source (TLS) with a linewidth of 400kHz and an operating wavelength spanning the range 1345nm-1460nm was used to provide the signal to be amplified. By setting the output power from the TLS and adjusting the attenuator (ATT) the signal power was set to -23dBm at the input of the BPSF. Two isolators (ISOs) were used to protect the LDs from any back reflections, while two wavelength division multiplexers (WDMs) were used to combine or separate the pump and signal wavelengths. The input and output signal spectrum were recorded by an optical spectrum analyzer (OSA, YOKOGAWA AQ6370) using a resolution bandwidth of 0.02nm.

3. Results and discussion

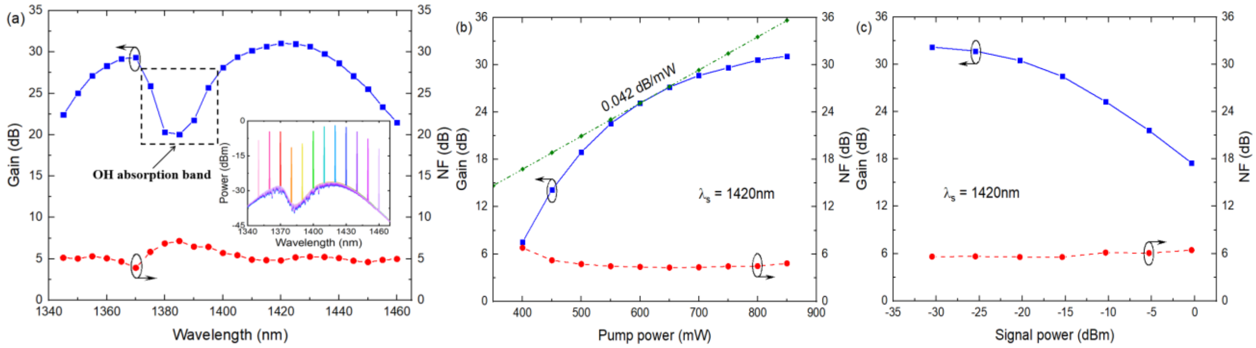

Fig. 2. (a) Gain and NF spectrum from 1345nm-1460nm for a fixed signal power of -23dBm (the inset shows the signal and noise spectrum from which the in-band OSNR is derived); (b) Gain and NF variation with pump power for a -23dBm signal at 1420nm (where the slope of the dashed line represents the gain coefficient); (c) Gain and NF variation with signal power at 1420nm.

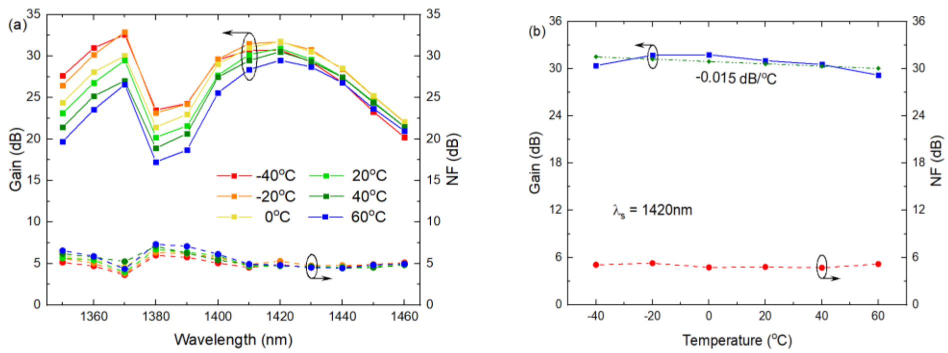

Fig. 3. (a) Temperature dependent gain and NF characteristics from 1350nm-1460nm in the temperature range from -40 to +60°C for a signal power of -23dBm; (b) Gain and NF from -40 to +60°C at 1420nm for -23dBm signal (where the slope of dashed line represents the TDG coefficient).

We first measured the gain and NF characteristics for a signal power of -23dBm from 1345nm to 1460nm at room temperature, as shown in Fig. 2(a). The BDFA can provide an ultra-wide gain of >20dB and a NF of 4.6~7.1dB from 1345nm to 1460nm, where a maximum gain of 31dB with a NF of 4.8dB was achieved at 1420nm. Note that the lowest gain of ~21dB and a correspondingly higher NF of ~7dB was obtained at ~1380nm. This compromised performance is due to the OH content in our current BPSF, which induced a loss of ~11dB over the 220m BPSF used in the experiment. The in-band OSNR for a -23dBm signal was found to be >22dB across the wavelength band of 1345nm-1460nm, as shown in the inset of Fig. 2(a). For a signal power of -10dBm, the OSNR was >35dB from 1345nm-1460nm. We next measured the gain and NF characteristics at 1420nm as a function of pump power. As shown in Fig. 2(b), an increase in gain and a slight decrease in NF were observed as the total pump power was increased. At a signal wavelength of 1420nm, the gain coefficient was calculated to be 0.042dB/mW for a -23dBm signal. Also, the gain and NF variation was characterized as a function of signal power. As shown in Fig. 2(c), the gain showed an increase and the NF showed only a negligible change when the signal power was decreased from 0dBm to -30dBm. For a small signal power of -30dBm, a gain of 32dB with a NF of 5.6dB was achieved at the signal wavelength of 1420nm.

Next, the BPSF was heated inside a temperature-controlled oven with an operating temperature range from -40 to +60ºC (see Fig. 1). We studied the temperature dependent gain and NF characteristics for a -23dBm signal in the wavelength region from 1350nm to 1460nm, from -40 to +60° C at intervals of 20°C. As presented in Fig. 3(a), the gain showed a linear increase whereas the NF remained almost constant when the ambient temperature decreased from +60 to -40°C. The gain variation with temperature was larger on the shorter wavelength side and smaller at the longer wavelength side. To quantify the temperature dependent gain characteristics, we calculated the TDG coefficient (defined as the amount of signal gain change per unit of temperature change, in dB/ºC) over the -40 to +60°C temperature range. As shown in Fig. 3(b), the amount of change in gain and NF was insignificant at 1420nm. The TDG coefficient at 1420nm was found to be -0.015dB/°C for -23dBm signal, and for a signal power of -10dBm the BDFA showed an even lower TDG coefficient of -0.01dB/°C. This is much smaller than the TDG coefficients of most EDFAs and the O-band BDFA [10-12], and thus illustrates the excellent thermal stability of the proposed BDFA in the wavelength region from 1350nm-1460nm.

4. Conclusions

We demonstrated an ultra-broadband Bi-doped phosphosilicate fiber amplifier operating in the O+E-band. A gain of >20dB with a NF of 4.6~7.1dB was achieved for a -23dBm signal power across the wavelength band of 1345nm-1460nm. To the best of our knowledge, the bandwidth of 115nm is the widest ever reported from a BDFA. The maximum gain obtained at 1420nm was 31dB with a NF of 4.8dB for a signal of -23dBm. For a smaller signal power of -30dBm, a gain of 32dB with a NF of 5.6dB was achieved at a signal wavelength of 1420nm. The temperature dependent gain and NF characteristics were measured from 1350nm to 1460nm over the temperature range of -40 to +60°C, and the TDG coefficient at 1420nm was found to be -0.01dB/°C and -0.015dB/°C for the -10dBm and -23dBm signals, respectively. Our amplifier exhibits somewhat compromised gain performance at wavelengths around 1380nm due to OH content in our current BPSF, we will in due course improve the drying process (e.g. using Chlorine drying) during preform fabrication to reduce this compromised performance moving forward. In addition, just as for our previous O-band BDFA [7, 13], we will look to undertake both coarse- and dense-WDM experiments to confirm the suitability of our BDFA for data transmission and to ultimately assess the potential for commercialization.

Acknowledgements

This work was supported by the EPSRC funded “AirGuide Photonics” Programme Grant (EP/P030181/1) and through a II-VI Foundation PhD studentship. The data for this paper can be accessed at https://doi.org/10.5258/SOTON/D1119.

5. References

[1] N. K. Thipparapu, Y. Wang, S. Wang, A. A. Umnikov, P. Barua, and J. K. Sahu, “Bi-doped fiber amplifiers and lasers [Invited],” Opt. Mater. Express 9, 2446-2465 (2019).

[2] E. M. Dianov, “Amplification in extended transmission bands using bismuth-doped optical fibers,” IEEE J Lightwave Technol 31, 681-688 (2013).

[3] E. M. Dianov, “Bismuth-doped optical fibers: a challenging active medium for near-IR lasers and optical amplifiers,” Light: Science & Applications 1, 1-7 (2012).

[4] N. K. Thipparapu, A. A. Umnikov, P. Barua, and J. K. Sahu, “Bi-doped fiber amplifier with a flat gain of 25 dB operating in the wavelength band 1320–1360 nm,” Opt. Lett. 41, 1518-1521 (2016).

[5] N. K. Thipparapu, Y. Wang, A. A. Umnikov, P. Barua, D. J. Richardson, and J. K. Sahu, “High gain Bi-doped all fiber amplifier for O-band DWDM optical fiber communication,” in OFC 2019, (OSA, 2019), paper M1J.5.

[6] N. K. Thipparapu, Y. Wang, A. A. Umnikov, P. Barua, D. J. Richardson, and J. K. Sahu, “40 dB gain all fiber bismuth-doped amplifier operating in the O-band,” Opt. Lett. 44, 2248-2251 (2019).

[7] Y. Hong, K. Bottrill, N. Taengnoi, N. K. Thipparapu, Y. Wang, A. A. Umnikov, J. Sahu, D. Richardson, and P. Petropoulos, “Experimental demonstration of dual O+C-band WDM transmission over 50-km SSMF with direct detection,” IEEE J Lightwave Technol (2020).

[8] M. A. Melkumov, I. A. Bufetov, A. V. Shubin, S. V. Firstov, V. F. Khopin, A. N. Guryanov, and E. M. Dianov, “Laser diode pumped bismuth-doped optical fiber amplifier for 1430 nm band,” Opt. Lett. 36, 2408-2410 (2011).

[9] M. A. Melkumov, V. Mikhailov, A. M. Hegai, K. E. Riumkin, P. S. Westbrook, D. J. DiGiovanni and E. M. Dianov, “E-band data transmission over 80 km of non-zero dispersion fibre link using bismuth-doped fibre amplifier,” Electr. Lett. 53, 1661-1663 (2017).

[10] N. Kagi, A. Oyobe, and K. Nakamura, “Temperature dependence of the gain in erbium-doped fibers,” IEEE J Lightwave Technol 9, 261-265 (1991).

[11] Y. Wang, N. K. Thipparapu, A. A. Umnikov, P. Barua, D. J. Richardson, and J. K. Sahu, “Temperature dependent gain and noise figure characteristics of O-band Bismuth-doped fibre amplifier,” in ECOC 2019, (IET Conference Publications, 2019).

[12] 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, 5650-5653 (2019).

[13] N. Taengnoi , K. R. H. Bottrill, N. K. Thipparapu, A. A. Umnikov, J. K. Sahu, P. Petropoulos , and D. J. Richardson, “WDM transmission with in-line amplification at 1.3μm using a Bi-doped fiber amplifier,” IEEE J Lightwave Technol 37, 1826-1830 (2019).