A highly temperature-insensitive Bi-doped fiber amplifier in the E+S-band with 20 dB flat gain from 1435-1475 nm

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Abstract: We report a bismuth-doped fiber amplifier operating in the E+S-band providing a 20.5±1dB flat gain with 5.5±2dB NF from 1435-1475nm for -10dBm input signal. The gain coefficient and temperature-dependent-gain coefficient are 0.065dB/mW and -0.005±0.001dB/°C, respectively.

1. Introduction

The global data traffic in communication networks is growing continuously at a rate of 30-40% per year. The Covid-19 pandemic has accelerated this growth to 40-50% and 2020 witnessed an unprecedented spike in capacity demand. The growth is driven by the increases in global internet users, social networking, cloud services, and online multimedia such as emerging ultrahigh-definition videos. The next-generation of optical communication systems are expected to offer per-fiber transmission capacity in the 1-10Pb/s range [1]. However, one critical obstacle to realizing this requirement is the limited waveband (1530-1610nm) supported by currently used optical amplifiers. The development of optical amplifiers capable of operating in the low-loss window (1260-1700nm) of transmission fibers beyond the C+L-bands would provide an immediate way to increase the capacity of installed fibers. In recent years, bismuth (Bi)-doped silica (SiO_2) fibers have shown wideband near-infrared (NIR) luminescence extending from 1150-1700nm [2,3], providing the opportunity to explore various Bi-doped fibers and develop Bi-doped fiber amplifiers (BDFAs) in different wavebands. Using Bi-doped phosphosilicate fibers (BPSFs), BDFAs have been successfully demonstrated in the O-band [4-7], O+E-band [8-10], and E-band [11]. Using Bi-doped germanosilicate fibers (BGSFs), BDFAs have also been demonstrated in the E-band and S-band [12-16]. In addition, BDFAs operating in the 1.18μm band [17] and in the 1.7μm band [18,19] have been reported using Bi-doped aluminosilicate fibers (BASFs) and Bi-doped germanosilicate fibers with high GeO_2 concentration (BHiGSFs), respectively. To date, the maximum gain reported from an E+S-band BDFA is 38dB at 1430nm for a -20dBm signal, with a 3-dB bandwidth of 35nm [14], and the maximum bandwidth reported so far from an E+S-band BDFA is 55nm for >20dB gain from 1405-1460nm [16]. However, the reported BDFA gains and 3-dB bandwidths are focused in the E-band (near the 1.43μm band) have not so far supported extension to the S-band or been shown to operate at wavelengths above 1.46μm. In addition, there are only a few reports concerning the thermal stability of BPSF amplifiers in the O-band [7,9] and E-band [9,11] and BHiGSF amplifier in the 1.7μm band [19] and, to the best of our knowledge, no one has reported the temperature dependent gain characteristics for BGSF amplifiers in the E-band and S-band.

In this paper, a BDFA operating across the boundary of the E+S-band is demonstrated with a flat gain of 20.5±1dB from 1435-1475nm for an input signal power of -10dBm using a bi-directional pumping scheme at dual pump wavelengths of 1310nm and 1270nm. The 3-dB bandwidth of the E+S-band BDFA is 50nm from 1430-1480nm and the in-band optical signal-to-noise-ratio (OSNR) in the wavelength band 1425-1490nm ranges from 25-35dB. The temperature dependent gain performance is also characterized over the temperature range from -60℃ to +80℃. The gain variation across the whole 140℃ temperature span is within ±0.5dB for a -10dBm signal, and the temperature-dependent-gain (TDG) coefficients from 1435-1475nm are found to be -0.005±0.001dB/℃, which indicates an incredibly high insensitivity of the BDFA gain characteristics with respect to environmental temperature.

2. Bi-doped germanosilicate fiber amplifier in E+S-band

A Bi-doped germanosilicate preform was fabricated in-house using modified chemical vapor deposition (MCVD) in combination with solution doping and then drawn into a fiber with core and cladding diameters of 7μm and 100μm, respectively. The maximum index difference (Δn) between the core and cladding is 0.01. The absorption at the pump wavelengths of 1270nm and 1310nm was measured by the cut-back technique as 0.13dB/m and 0.2dB/m, respectively. The unsaturable loss (UL) at 1310nm was measured to be 22%, and the background loss at 1100nm was found to be 36dB/km.

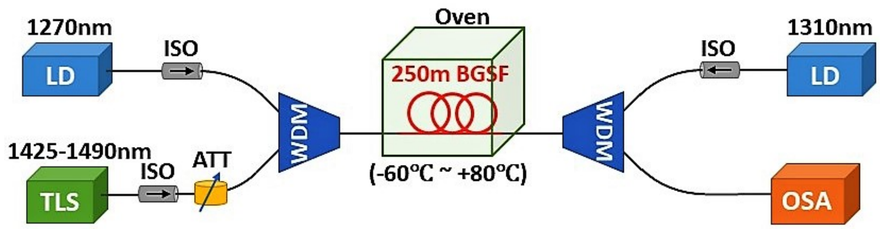

Fig. 1. Experimental setup of the E+S-band Bi-doped germanosilicate fiber amplifier.

Using the experimental setup shown in Fig. 1, the amplifier gain characteristics of the BGSF were tested in the E+S-band. Established from different measurements using various pump wavelengths ranging from 1270-1420nm, we identified an optimal pumping configuration of using bi-directional pumping at pump wavelengths of 1270nm and 1310nm from a gain flatness perspective. A 250m length of the BGSF was found to be optimal in terms of the maximum gain achieved and was used in this work. As shown in Fig. 1, fiber pigtailed laser diodes (LDs) operating at 1270nm and 1310nm can provide a total pump power of 700mW to the BDFA. A tunable laser source (TLS) with an operating wavelength covering from 1425-1490nm was used to provide the signals to be amplified. Three isolators (ISOs) were used to protect the TLS and the pumps. By setting the output power from the TLS and adjusting the attenuator (ATT), we selected a constant input signal power of -10dBm. The input and output signal spectra were recorded using an optical spectrum analyzer (OSA, YOKOGAWA AQ6370) with a resolution bandwidth of 0.2nm. In addition, the BGSF was placed inside a temperature-controlled oven with an operating temperature range from -60°C to +80°C.

3. Results and discussions

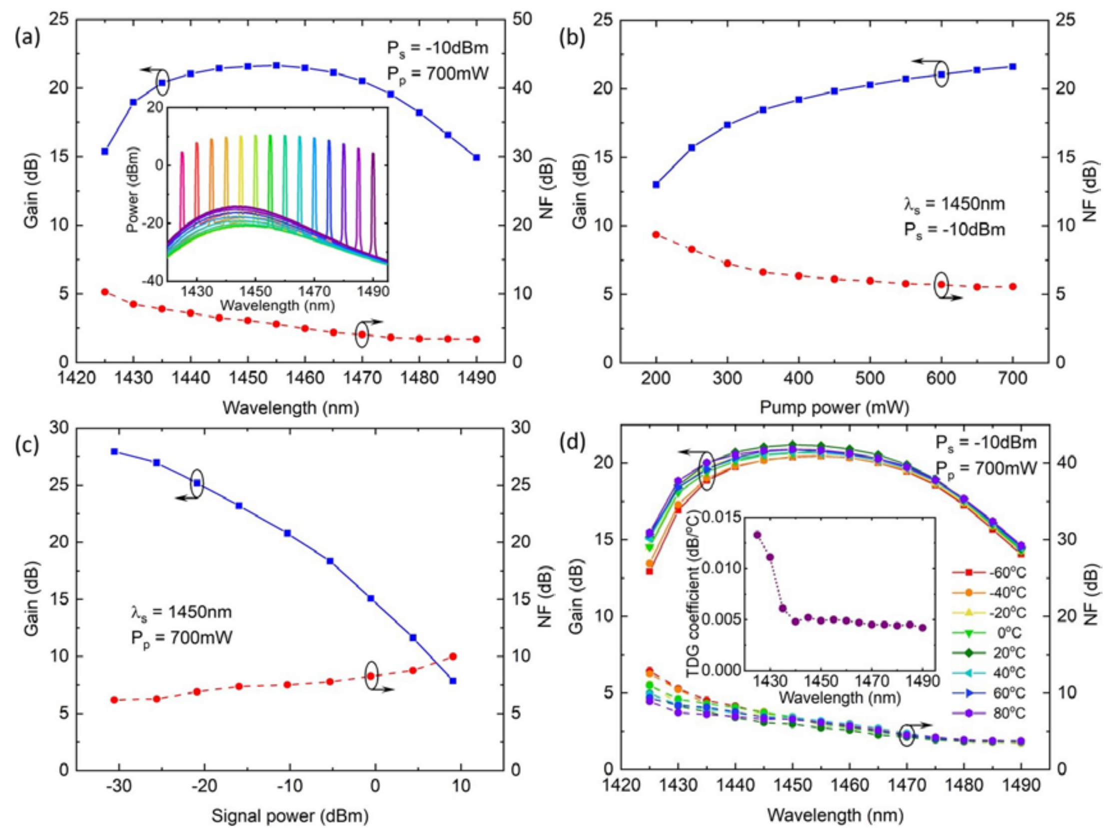

Fig. 2. (a) Gain and NF spectrum from 1425nm to 1490nm at RT for a -10dBm signal (the inset shows the signal and noise spectra from which the in-band OSNR is derived); (b) Gain and NF variation with pump power for a -10dBm signal at 1450nm; (c) Gain and NF variation with signal power at 1450nm; (d) Gain and NF spectra in the temperature range from -60°C to +80°C at intervals of 20°C for a -10dBm signal (the inset shows the calculated TDG coefficient spectrum from 1425-1490nm).

The gain and NF spectrum of the E+S-band BDFA was firstly characterized at RT, as shown in Fig. 2(a). For a signal power of -10dBm, a flat gain of 20.5±1dB was achieved from 1435-1475nm with a NF in the range of 3.6-7.8dB. The optical technique used herein for NF measurements has been verified against an electrical method, and no significant difference was observed [20]. The 3-dB bandwidth of the gain spectrum was 50nm from 1430-1480nm. The in-band OSNR was measured to be in the range of 25-35dB across the wavelength band from 1425-1490nm, as shown in the inset of Fig. 2(a). The gain and NF characteristics at 1450nm were measured with respect to variation of pump power. As shown in Fig. 2(b), an increase in gain and a decrease in NF were observed with an increase in total pump power. At 1450nm, the gain coefficient was calculated to be 0.065dB/mW for a -10dBm signal. Also, the gain and NF characteristics at 1450nm were measured as a function of signal power. As shown in Fig. 2(c), the gain increased with a decrease in NF as the signal power was reduced from +10dBm to -30dBm. For a small signal power of -30dBm, a gain of 28dB with a NF of 6.2dB was achieved at 1450nm.

Next, the temperature dependent gain and NF spectra of the E+S-band BDFA were characterized in the temperature range from -60℃ to +80℃ at intervals of 20℃ for a signal power of -10dBm, as shown in Fig. 2(d). As can be seen, the gain variation across the whole 140℃ temperature span is within ±0.5dB. The BDFA gain and NF showed relatively insignificant changes with increasing temperature from -60℃ to +80℃. As shown in the inset of Fig. 2(d), the TDG coefficient, defined as the amount of signal gain change per unit temperature change in [dB/ºC], was calculated over the -60℃ to +80℃ temperature range, and was found to vary from -0.004dB/℃ to -0.014dB/℃ for a -10dBm signal in the wavelength band 1425-1490nm. In particular, the TDG coefficient from 1440-1490nm covering the E+S-band is extremely low – all under -0.005 dB/℃, which represents a higher thermal stability than most EDFAs [21] can offer and likewise other reported BDFAs in different wavebands [7,9,11,19].

4. Conclusions

In summary, we have demonstrated a Bi-doped germanosilicate fiber amplifier operating in the E+S-band providing a >15dB gain from 1425-1490nm. A flat gain of 20.5±1dB with a NF of 5.5±2dB was achieved from 1435-1475nm for a signal power of -10dBm. The 3-dB bandwidth of the E+S-band BDFA was 50nm at RT from 1430-1480nm and the in-band OSNR across the wavelength band from 1425-1490nm was in the range of 25-35dB. The gain and NF characteristics were studied with respect to variation of pump power and signal power, respectively. The gain coefficient at 1450nm was found to be 0.065dB/mW for a -10dBm signal. The temperature dependent gain and NF spectra were characterized from 1425-1490nm over the temperature range of -60℃ to +80℃. To the best of our knowledge, it is the first time the temperature dependent characteristics of Bi-doped germanosilicate fiber amplifiers operating in the E+S-band has been reported. The TDG coefficient across the signal wavelengths in the E- and S-band from 1440nm to 1490nm was found to be below -0.005dB/℃ for a -10dBm signal. Moreover, like our previous O-band [22,23] and O+E-band [24] BDFAs, the flat gain characteristics and the high temperature-insensitivity of the proposed E+S-band BDFA suggest the feasibility of undertaking WDM data transmission experiments to assess the amplifiers potential for applications in optical communications.

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5. References

[1] M, Toshio, in 2009 14th OECC, 1-2, 2009.

[2] E. M. Dianov, *J. Light. Technol.* **31**(4), 681-688, 2013.

[3] N. K. Thipparapu, *et al.*, *Opt. Mater. Express* **9**(6), 2446-2465, 2019.

[4] N. K. Thipparapu, *et al.*, *Opt. Lett.* **41**(7), 1518-1521, 2016.

[5] N. K. Thipparapu, *et al.*, *Opt. Lett.* **44**(9), 2248-2251, 2019.

[6] S. V. Firstov, *et al.*, *Sci. Rep.* **10**(1), 1–9, 2020.

[7] Y. Wang, *et al.*, *Opt. Lett.* **44**(23), 5650–5653, 2019.

[8] Y. Wang, *et al.*, in 2020 OFC pdp, paper Th4B.1, 2020.

[9] Y. Wang, *et al.*, *J. Light. Technol.* **39**(3), 795-800, 2021.

[10] Y. Ososkov, *et al.*, *Opt. Express* **29**(26), 44138–44145, 2021.

[11] Y. Wang, *et al.*, in 2021 OFC, paper Tu1E.1, 2021.

[12] M. A. Melkumov, *et al.*, *Opt. Lett.* **36**(13), 2408-2410, 2011.

[13] V. Dvoyrin, *et al.*, in 2020 OFC, paper W1C.5, 2020.

[14] A. Donodin, *et al.*, *Opt. Mater. Express* **11**(1), 127–135, 2021.

[15] A. Vakhrushev, *et al.*, *Opt. Express* **30**(2), 1490–1498, 2022.

[16] A. Donodin, *et al.*, in 2022 48th ECOC, paper Tu5.5, 2022.

[17] N. K. Thipparapu, *et al.*, *Opt. Lett.* **40**(10), 2441–2444, 2015.

[18] S. V. Firstov, *et al.*, *Sci. Rep.* **6**(1), 1-6, 2016.

[19] S. V. Firstov, *et al.*, in 2017 OECC and PGC, 1-2, 2017.

[20] N. Taengnoi, *et al.*, *Opt. Express* **29**(10), 15345-15355, 2021.

[21] N. Kagi, *et al.*, *J. Light. Technol.* **9**(2), 261-265, 1991.

[22] Y. Hong, *et al.*, *J. Light. Technol.* **38**(8), 2278-2284, 2020.

[23] Y. Hong, *et al.*, *Opt. Express* **30**(18), 32189-32203, 2022.

[24] Y. Hong, *et al.*, in 2021 CLEO/Europe-EQEC, paper CI-1.1, 2021.