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Bi-doped fiber amplifiers in the E + S band with a high gain per unit length

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We present a bismuth (Bi)-doped fiber amplifier (BDFA) operating in the 1400–1480 nm range using 35 m of Bi-doped germanosilicate fiber. A maximum gain of 23 dB for an input signal of −23dBm at 1440 nm has been achieved, which, to the best of our knowledge, is the highest gain per unit length of 0.66 dB/m reported for a BDFA. The 3 dB bandwidth is measured to be 40 nm (1415–1455 nm), and the gain coefficient is 0.2 dB/mW. A further temperature dependence study of BDFA across the temperature range of −60°C to 80°C also showed a negligible effect of temperature on the E + S band BDFA gain.

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Introduction. Modern communication networks have revolutionized the way people share information, facilitating rapid data transfer globally. The surge in demand for a high-speed data transmission of social networking, cloud services, and online multimedia presents a challenge for existing communication infrastructure. Optical fiber amplifiers play a crucial role in ensuring efficient and reliable data transmission over long distances. However, the current erbium-doped fiber amplifiers (EDFAs) have a limited bandwidth from 1530 to ∼1610 nm, which hinders their ability to meet the growing demand for large-capacity data transmission. To overcome this limitation and expand the bandwidth of optical communication systems, the development of new optical amplifiers operating in the low-loss transmission window (1250–1650 nm) of SMF-28 is crucial.

In recent years, bismuth (Bi)-doped fiber amplifiers (BDFAs) have emerged as promising candidates, benefiting from the wide near-infrared (NIR) luminescence of Bi-doped fibers (BDFs) covering the wavelength regions from 1150 to 1500 nm and 1600 to 1700 nm [1,2], when co-doped with aluminum (Al), phosphorous (P), and germanium (Ge). BDFAs have been successfully demonstrated in various bands, including the O band [3–5], E band [6], and O + E band [7,8] using Bi-doped phosphosilicate fibers (BPSFs), as well as in the E band and S band [9–13] using Bi-doped germanosilicate fibers (BGSFs). Additionally, with the help of Bi-doped aluminosilicate fibers (BASFs) and BGSFs with a high (∼50 mol%) Ge concentration, BDFAs operating at ∼1.2 µm [14] and ∼1.7 µm [15,16] have been reported.

In the E + S band, the maximum gain achieved by BDFAs to date is 38 dB at 1430 nm [12]. However, due to the low Bi concentration used in current BDFs, a significantly long device length of 400 m is required [12]. Recently, we also demonstrated a BDFA with a flat gain of 20.5 ± 1 dB from 1435 to 1475 nm [13], with a long fiber length of 250 m.

In this paper, we present our improvement on a bismuth-doped germanosilicate fiber amplifier (BDFA) that operates within the wavelength range of 1400–1480 nm, utilizing a compact 35 m in-house fabricated BGSF. The BGSF was pumped at 1304 and 1310 nm, with a total power of 365 mW. Our experimental results demonstrate a maximum gain of 18 and 23 dB at 1440 nm for input signal powers of −10 and −23dBm, respectively, which were limited by the available pump power. Importantly, our work represents a significant advancement as, to the best of our knowledge, the highest gain per unit length of 0.66 dB/m has been achieved using BGSF. The BDFA performance was also investigated over the temperature range from −60°C to 80°C, revealing a high level of temperature insensitivity. Specifically, the TDG coefficient varies in the range of −0.03–0.01 dB/°C depending on the input signal power and wavelength.

Experimental setup. We fabricated a Bi-doped germanosilicate preform using the modified chemical vapor deposition (MCVD) combined with a solution doping technique. A GeO_2–SiO_2 soot layer was thermophoretically deposited inside a silica substrate tube (F300 from Heraeus) at a temperature of 1275 ± 15°C and then immersed in a hydrochloric acid (HCl)–ethanol solution containing bismuth. After a sufficient solution doping period and drying process, the glassware was reassembled to the lathe and a solid preform was obtained after high-temperature processes of oxidation, sintering, collapsing, and sealing. The preform was then jacketed and drawn into a single-mode (SM) fiber with a core and cladding diameters of ∼3.6 and 125 µm, respectively. The refractive index difference (Δn) between the core and cladding was 0.02. The LP_{11} mode cutoff wavelength of this fiber was measured to be ∼1140 nm. The absorption values at the pump wavelengths were measured using the cut-back technique, employing a white light source and an optical spectrum analyzer (OSA), and found to be 1.15

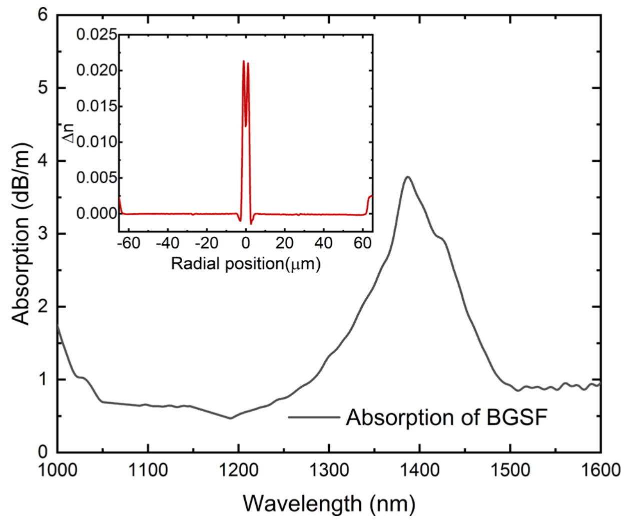

Fig. 1. Absorption of the BGSF from 1000 to 1600 nm. Inset: refractive index contrast of the fiber.

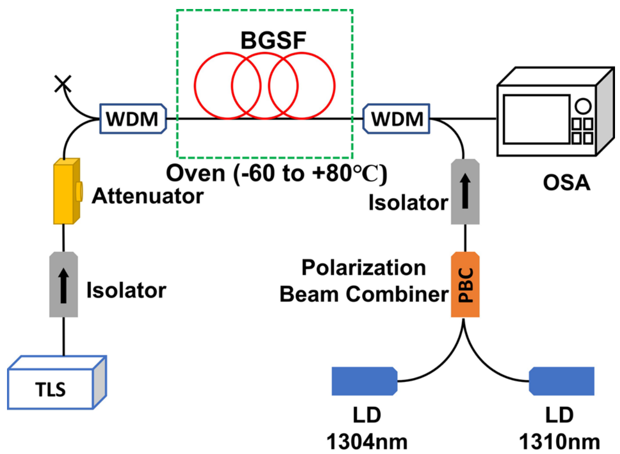

Fig. 2. Schematic of the E + S band BDFA experimental setup.

and 1.25 dB/m at 1304 and 1310 nm, respectively. The unsaturable loss (UL) at the pump wavelengths was ~17%, and the background loss (BL) measured at 1140 nm was ~0.2 dB/m. Figure 1 presents the absorption spectrum of our BGSF in the range of 1000–1600 nm, as well as the refractive index contrast is shown in the inset.

Figure 2 shows the experimental setup of the BDFA in the E + S band. The input signal was provided by a tunable laser source (TLS) with a wavelength range of 1400–1480 nm. It was subsequently adjusted by an attenuator to vary the input signal power from −30 to −5 dBm. BGSFs with different lengths, 35, 40, and 50 m, were tested as the gain media in the amplifier. Two laser diodes (LDs) operating at 1304 and 1310 nm were utilized to pump the BGSF, counter-propagating with the signal. The LDs were combined using a polarization beam combiner (PBC) and provided a total pump power of 365 mW. Two isolators were used to protect the TLS and the LDs. Considering the splice loss between the BGSF with commercial SMF, the input signal was measured after splicing a small piece of BGSF (~5 cm) to the input WDM.

Both input and output signal spectra were measured using an optical spectrum analyzer (OSA, YOKOGAWA AQ6370), with

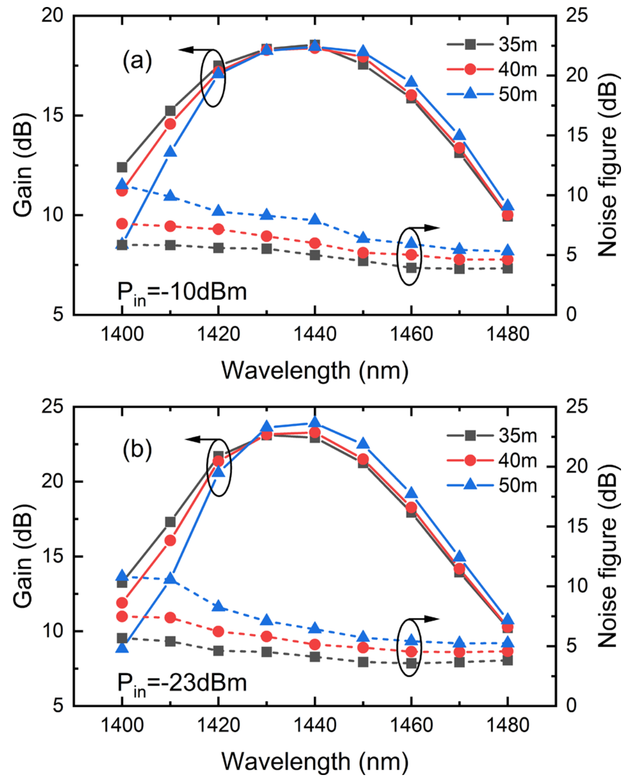

Fig. 3. Gain and NF of the BDFA from 1400 to 1480 nm using 35, 40, and 50 m of BGSF (a: input signal −10 dBm; b: input signal −23 dBm).

a resolution bandwidth of 0.2 nm. The gain and NF characteristics of the BDFA were first measured at room temperature. In addition, the BGSF was placed inside a temperature-controlled oven with an operating temperature range from −60°C to 80°C to study the temperature-dependent gain and NF characteristics of the BDFA.

Result and discussion. Figure 3 depicts the gain and noise figure (NF) spectrum of the BDFA with different lengths of BGSFs used in the setup, with input signal power of −10 and −2 dBm, respectively. At the shorter wavelength edge ranging from 1400 to 1420 nm, the gain exhibits a significant increase when the fiber length is reduced, while a slight decrease is observed at the longer wavelength side.

With a −10dBm input signal, a maximum gain of 18 dB is achieved at 1440 nm for all three BGSF lengths, corresponding to gain coefficients of 0.51, 0.45, and 0.36 dB/m for 35, 40, and 50 m fibers, respectively. The BDFA with a 35 m BGSF demonstrates a flatter gain profile, resulting in a 3 dB bandwidth spanning 50 nm from 1410 to 1460 nm. The NF exhibits a decreasing trend with a decreasing fiber length. With a 35 m fiber, the NF maintains 4.8 ± 1 dB across the entire 80 nm operating region of the amplifier.

When the input signal power is −23dBm, the gain is 23 dB at 1440 nm for the 35 and 40 m fiber lengths, yielding gain coefficients (gain per unit length) of 0.66 and 0.58 dB/m, respectively. The gain slightly increases to 24 dB when using a 50 m BGSF, and the gain coefficient is 0.48 dB/m. The 35 m BGSF provides a flatter gain profile and a lower NF. The 3 dB gain bandwidth is measured to be 40 nm, spanning from 1415 to 1455 nm. The NF remains within the range of 4.6 ± 1 dB from 1400 to 1480 nm

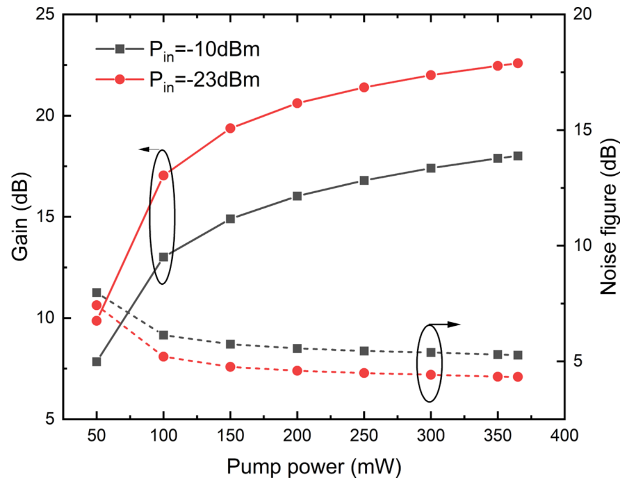

Fig. 4. Gain and NF variation with pump power for −10 and −23 dBm input signals at 1440 nm.

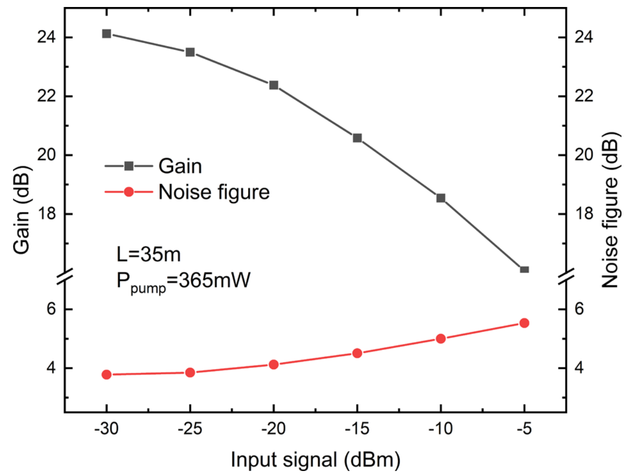

Fig. 5. Gain and NF variation with input signal power from −30 to −5 dBm at 1440 nm.

and varies from 3.6 to 4.6 dB in the 3 dB gain bandwidth. The power conversion efficiency (PCE) is calculated using the signal power increase divided by the launched pump power, which is ~1.84% and ~0.3% at 1440 nm with the three fiber lengths, for −10 and −23 dBm input signals, respectively.

Further characterization was conducted to examine the BDFA dependence on pump and signal power. Given the superior amplifier performance observed with the 35 m fiber length, the measurement was focused only on this BGSF length.

The relationship between gain/NF and pump power is presented in Fig. 4. The power from the two LDs at 1304 and 1310 nm was increased simultaneously in increments of 50 mW. Meanwhile, the signal wavelength was kept constant (−10 or −23 dBm) at 1440 nm, where the highest gain was achieved within the operating wavelength region of 1400–1480 nm. An increase in gain and a decrease in NF is observed as the total pump power increases. The BDFA exhibits a positive gain even at a pump power of 50 mW. The gain coefficient (also called pumping efficiency) with respect to the pump power is calculated to be 0.16 and 0.20 dB/mW for −10 and −2 dBm input signal power, respectively. This improvement can be attributed to both the fiber characteristics and the counter-pumping configuration. Importantly, the BDFA performance in this study did not reach saturation even under the maximum pump power used, suggesting that further improvement can be achieved with the availability of higher pump power.

Figure 5 illustrates the gain and NF at 1440 nm as the input signal power was increased while the pump power was maintained at its maximum of 365 mW. The gain gradually drops from 24 to 16 dB as the signal power is increased from −30 to −5 dBm. Meanwhile, the NF shows an increase from 3.8 to 5.5 dB across the same range of input signal powers. The PCE is found to be 0.07% for a −30 dBm input signal and increases to 3.0% for a −5 dBm input signal.

Furthermore, we examined the temperature-dependent gain and NF characteristics of the BDFA using a fiber length of 35 m. The temperature was regulated by an oven ranging from −60°C to 80°C. The gain and NF spectra of the BDFA for input signal powers of −10 and −23 dBm are shown in Fig. 6.

The BDFA exhibits a high-temperature insensitivity. At signal wavelengths ranging from 1450 to 1480 nm, the gain variation

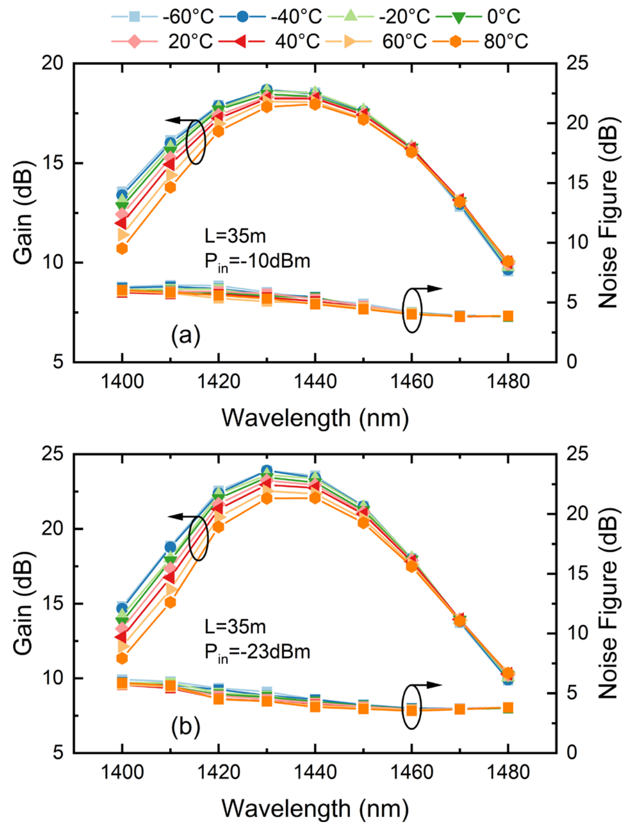

Fig. 6. Gain and NF variation under different temperatures with 35 m of BGSF (a: input signal −10 dBm; b: input signal −23 dBm).

across the entire temperature range of 140°C is within ±0.3 and ±0.6 dB for input power of −10 and −23 dBm, respectively. Interestingly, the gain variation displays different behaviors in different wavelength bands. Specifically, as shown in Fig. 6, with the 35 m fiber, the gain increases when the temperature drops in the wavelength range from1400 to 1460 nm, while an opposite trend was observed in the longer wavelength side from 1460 to 1480 nm, albeit the changes are small in this region. Further study is required to draw conclusions from this observation, as it falls beyond the scope of this work.

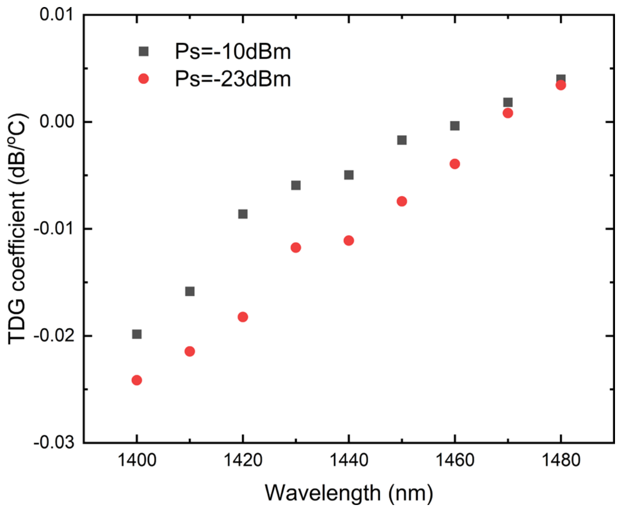

Fig. 7. The TDG coefficients at signal wavelengths from 1400 to 1480 nm for 35 m of BGSF.

The temperature-dependent gain (TDG) coefficient of the amplifier, defined as the amount of signal gain change per unit temperature change in [dB/°C], is presented in Fig. 7 within the entire 80 nm bandwidth. The TDG coefficient was calculated by averaging the total gain variation from −60°C to 80°C. For an input signal of −10 dBm, the TDG coefficient was zero at 1460 nm, while for an input signal of −23 dBm the zero value occurs at 1470 nm. The TDG coefficients for both signal powers of −10 and −23 dBm are within the range from −0.03 to 0.01 dB/°C across the whole wavelength range of 1400 to 1480 nm. In particular, the TDG coefficient within the signal wavelength range of 1430 to 1480 nm is in the range of ±0.01 dB/°C, showing a robust thermal stability of the amplifier.

Summary. We successfully demonstrated a BDFA operating in the E + S band, covering an 80 nm bandwidth from 1400 to 1480 nm, by using 35 m of BGSF, fabricated using the MCVD and solution doping technique. The amplifier showed a maximum gain of 18 and 24 dB for input signal of −10 and −23 dBm, respectively, corresponding to 0.51 and 0.66 dB gain per unit length. The gain was limited by the available pump power. The 3 dB bandwidth was 50 nm (1410–1460 nm) for a −10 dBm and 40 nm (1415–1455 nm) for a −23 dBm input signal. The corresponding NF within the 3 dB bandwidth was maintained at 3.8–5.8 dB and 3.6–4.6 dB for these two input signals. In addition, the BDFA gain coefficient at 1440 nm was measured as 0.16 and 0.20 dB/mW for −10 and −23 dBm signals, respectively.

Furthermore, we studied the BDFA performance under varying temperatures ranging from −60°C to 80°C. The TDG coefficient across the entire wavelength range of 1400 to 1480 nm was found to be within the range of −0.03 to 0.01 dB/C for both −10 and −23 dBm signals, highlighting the excellent temperature stability of the BDFA under different operating conditions.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are available in Ref. [17].

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