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Bismuth-doped Silica Fiber Amplifier

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1. Introduction

To accommodate rapidly increasing quantities of information and communication, optical fiber transmission technology with high-speed high-capacity is demanded. The development of an optical gain medium and fiber amplifiers to cover the 1250~1650 nm region, which is the entire optical telecommunication windows of silica fiber, becomes an important issue for ultra-wide broadband optical communication. Bismuth-doped glasses exhibit a broadband luminescence in the near infrared region. Thus, they are potential gain media for extending the spectral bandwidth of the current erbium-doped silica fiber amplifiers. There are several reports on an infrared luminescence from bismuth-doped glasses such as germanate, phosphate, borate et al. (Meng et al., 2005ab; Peng et al., 2005abc; Suzuki & Ohishi, 2006). According to their research, bismuth-doped glasses are therefore very promising for creating broadband amplifiers for fiber telecommunication lines and tunable or femto-second lasers.

There are two useful wavelengths for optical communication. One is the 1550 nm, erbium-doped fiber amplifiers (EDFAs) working wavelength, which has minimum losses. EDFA developments within the third telecommunication window have contributed to the rapid growth of wavelength division multiplexing (WDM) transmission systems. The L-band (1570~1605 nm) of EDFA can be used in WDM systems in conjunction with C-band (1530~1560 nm). However, efforts to use WDM techniques to exploit this capability have been hampered by nonlinear fiber effects such as four-wave mixing. In addition, the amplification bandwidth of silica-based EDFA is as small as ~70 nm (Yamada et al., 1998). A broadband amplifier with a gain bandwidth of more than 70 nm was reported by the integration of EDFA with thulium-doped fiber amplifiers or fiber Raman amplifiers (FRAs) (Yamada et al., 1998).

The other useful wavelength (1300 nm) for optical communication is O-band, between 1260 and 1360 nm, which is the natural zero-dispersion region of silica glass fiber where the temporal distortion of transferred optical pulses can be minimized. For example, praseodymium-doped fluoride fiber amplifiers (PDFFAs) and FRAs have been successfully used for 1300 nm amplification, but it also suffer from narrow bandwidth (~25 nm) in operating wavelength and low efficiency (Miyajima et al., 1991; Whitley, 1995). In addition, a PDFFA normally made from fluoride glass, which is very brittle and cannot be fusion spliced to the silica glass fiber. An alternative core fiber material and fiber amplifier for 1300 nm amplification is expected.

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High-average-power lasers are widely used for material processing, thin film fabrication with ablation, generation of extreme ultraviolet light sources for lithography, and various scientific research purposes. As there are so many applications of high-power lasers, demand is growing rapidly for more powerful lasers; therefore, the requirements for thermally resistant laser media are becoming tougher. Some of the absorption energy created in a laser medium by excitation with flash lamps or laser diodes is extracted as an output of laser energy, but most of the absorption energy generates heat accumulation in the medium. This heat accumulation causes a thermal lensing effect and a thermal birefringence in the medium; of course, the excess heat accumulation leads to destruction of the medium. Therefore, laser media must be operated under strict conditions during excitation.

Silica glass is one of the most attractive materials for high-peak-power or high-average-power lasers because it has favourable thermal and mechanical toughness, high optical transmittance from the ultraviolet to the infrared regions, and a low nonlinear refractive index compared to the other commercial laser glasses. These properties are indispensable to the laser driver for inertial confinement fusion because phosphate laser glasses have such weak thermal shock toughness that they cannot work at a high repetition rate (Fujimoto et al., 1999).

Bismuth-doped silica glass (BiSG) is a new material that emits a broadband fluorescence peak at around 1250 nm with a bandwidth over 300 nm. We suggested BiSG which can complement the problems of the other optical amplifiers (Fujimoto & Nakatsuka, 2001; 2003). It is important to understand the optical properties of the BiSG for technological applications such as optical fiber amplifier and fiber laser. It is well known that bismuth ions contribute to increase the refractive index of the glass and give no specific absorption band in the visible and near infrared region. However, BiSG has three excitation bands at 500, 700 and 800 nm showing the luminescent bands at 750, 1120 and 1250 nm respectively. Its 800 nm absorption band makes this material have a potential to be pumped by commercialized powerful laser diodes. In addition, cw lasing has been obtained in the spectral region between 1150 and 1300 nm in a bismuth-doped aluminosilicate glass fiber (Dianov et al., 2005; Dvoyrin et al, 2006; 2007).

We previously reported a new infrared luminescent BiSG that had a possibility of being a high-power laser material and a possibility of being an optical fiber amplifier. Also, we achieved optical amplification in a BiSG and bismuth-doped silica fiber (BiDF) at 1310 nm with 810-nm excitation. BiSG has many attractive features, which make it suitable as a core fiber material of an optical fiber. The near-infrared spectral regions with a wide luminescence in the range from 1000 ~ 1600 nm and a long lifetime of about 100~600 μ s of luminescence make such a fiber promising for the development of lasers and amplifiers.

In this chapter, we demonstrate an optical amplification at the 1260~1360 nm region (O-band) in various BiSG and fiber. The optical amplification was observed at five different wavelengths between 1260 and 1360 nm with 810 nm excitation. The optical gain profile is similar to the fluorescence spectrum and the amplification bandwidth is greater than 75 nm in the 1300 nm region. The laser diode pumped fiber amplifier at 1310 nm showed gain characteristics with a 5.0, 8.0-cm length BiDF and a wide-band tuned amplification through an over 100-nm bandwidth. We also report on a simultaneous amplification results for BiSG and fiber at two different wavelengths in the 1300 nm region. Simultaneous amplification of 25 nm bandwidth in four different wavelength regions was obtained. This technique can be useful for WDM optical amplifiers at the second telecommunications window.

2. Optical amplification in a BiSG

2.1 Sample preparation and experimental setup

The sample compositions (mol %) of BiSG are shown in Table 1. In the case of sample A, bismuth-oxide (Bi_2O_3 ; 99.9 %), aluminum-oxide (Al_2O_3 ; 99.99 %) and silica powder (SiO_2 ; 99.8 %) were mixed and kneaded in a mortar. The mixture compound of Bi_2O_3 : 1.0 mol %, Al_2O_3 : 7.0 mol %, and SiO_2 : 92 mol % was put in an alumina crucible and then melted at 1750 °C for 50 hour in the air atmosphere. In the case of sample B, lithium oxide (Li_2O) was added and the mixture was put in an alumina crucible and then melted at 1700 °C for 30 hours. The composition of the sample B was Bi_2O_3 (1.0 mol %), Al_2O_3 (7.0 mol %), SiO_2 (92-x mol %) and Li_2O : (x = 1, 5, and 10 mol %). The samples were cut in the pieces (0.5 cm × 0.5 cm × 0.24 cm) and optically polished. The color of the prepared samples was reddish brown but transparent, with a transmittance of ~90 % at 1300 nm region.

Sample	Bi_2O_3 (mol %)	Al_2O_3 (mol %)	SiO_2 (mol %)	Li_2O (mol %)
A	1	7	92	
	1	7	91	1
B	1	7	87	5
	1	7	82	10

Table 1. Glass composition of bismuth-doped silica glass and added in lithium oxide, Li_2O .

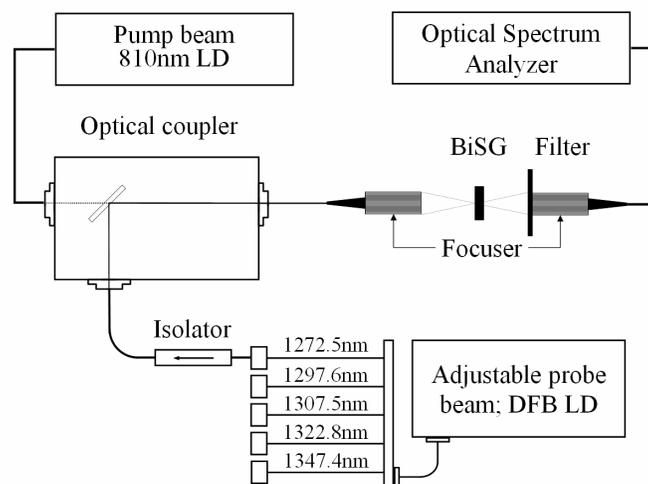


Fig. 1. The experimental setup for the optical amplification in a bismuth-doped silica glass.

The experimental setup for optical gain measurement is shown in Fig. 1. The 810 nm semiconductor laser (Unique Mode: UM2500-50-15) was used as an excitation source. Distributed feedback (DFB) semiconductor lasers (Mitsubishi Electric Corp.: FU-436SDF-EW41Mxx) with five different wavelengths were used as probe beams. The wavelengths of the five DFB semiconductor lasers were 1272.5, 1297.6, 1307.5, 1322.8 and 1347.4 nm, and these probe beams can be adjusted using a single laser driver. The probe laser beams were combined with the excitation beam using an optical coupler (OFR: 810/1310 nm), and then focused into the multi-mode fiber (MMF) with an output focusing lens (focuser). The

combined beam was focused into the BiSG sample surface by the focuser and the probe beam was detected by an optical spectrum analyzer (Ando: AQ6317B) using a pigtail focuser. The excitation beam is manually chopped to make the state of a probe beam without excitation I_0 and a probe beam with excitation I . The optical gain coefficient was defined as $g = (1/l) \ln (I/I_0)$, where l is the length of the BiSG sample.

The transmittance and the fluorescence spectra were measured using U-4100 spectrometer (Hitachi Ltd.) and SS-25 spectrometer (JASCO Corp.) with 150 W Xe lamp excitation. The transmittance of the new sample in the region of 1000 to 2500 nm was 90 % at maximum, which is higher than previous result (Fujimoto & Nakatsuka, 2001). The fluorescence spectra of BiSG samples with 800 nm excitation have a peak at ~1250 nm and the broad emission with a FWHM of ~300 nm. The strong absorption at 300 nm is considered to be the absorption edge of the Bi₂O₃-containing glass system (Sugimoto et al, 1996). However, we could not find any luminescence derived from previously reported Bi³⁺ luminescence and the infrared emission was hardly observed from the sample without aluminum (Parke & Webb, 1973; Weber & Monchamp, 1973).

2.2 Gain characteristics of the bulk-type BiSG

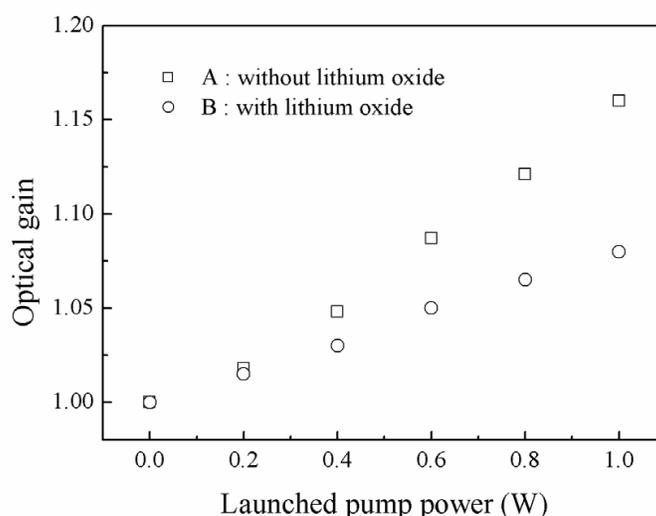


Fig. 2. Optical gain profiles of each sample at thickness 0.24cm.

We have measured the gain characteristics of the BiSG samples over a useful part of the 1300 nm optical communication window. The probe beam (1307.5 nm) and the excitation beam (810 nm) were focused onto the sample surface. Between the two MMF pigtail focuser, we measured amplified signals in BiSG samples with the maximum launched pump power (1.0 W) at 810 nm. Figure 2 shows the optical gain profile of two samples at 1307.5 nm. The optical gain increases linearly with excitation power up to 1.0 W. In the case of sample A, the maximum optical gain and the gain coefficient was 1.16 and 0.62 cm⁻¹, respectively. The absorbed energy was calculated as 42 % of excitation power, which is 0.42 W at 1.0 W excitation for a 0.24 cm thick sample. If the excitation length such as fiber core material becomes longer, the absorption will increase then the gain will be larger than that is demonstrated in this experiment. In the case of sample B, the maximum optical gain and the gain coefficient was 1.08 and 0.32 cm⁻¹, respectively.

The spectral dependence of the optical gain is important if optical fiber amplifier is to be incorporated in broadband WDM system. As shown in Fig. 3, the measured spectral dependence of the optical gain shows a close resemblance to the fluorescence spectrum, as shown by the dotted line. The optical gain was observed at five wavelengths, 1272.5, 1297.6, 1307.5, 1322.8 and 1347.4 nm. The optical gain spreads widely between 1260 and 1360 nm. A maximum optical gain and gain coefficient was 1.18 and 0.70 cm^{-1} respectively at the 1272.5 nm wavelength region, which is closed to the peak wavelength of the fluorescence spectrum. Moreover, the broad fluorescence spectrum suggests that optical gain in excess of 1.09 (0.35 cm^{-1}) should be available over a bandwidth as large as $\sim 75 \text{ nm}$ (Seo et al., 2006a).

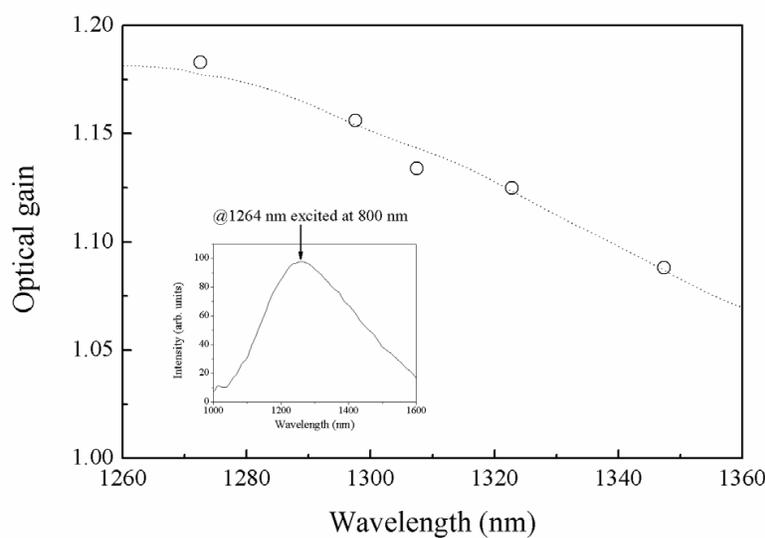


Fig. 3. Optical gain as a function of different signal wavelength 1272.5, 1297.6, 1307.5, 1322.8 and 1347.4 nm. Points and curve represents experimental measurements and fluorescence spectrum at 800 nm excitation, respectively.

3. Optical amplification in a 6.5-cm-long BiSG

3.1 Sample preparation and experimental setup

The composition of this sample was Bi_2O_3 (1.0 mol %), Al_2O_3 (7.0 mol %), and SiO_2 (92.0 mol %). The BiSG can be drawn by pulling the melted material upward using an alumina bar. The fabricated sample was cut in the same shape of 6.5-cm-long with an elliptical cross section ($250 \times 450 \mu\text{m}$). The BiSG was optically polished at both ends to provide good optical transmission. The experimental setup for optical amplification in a BiSG is shown in Fig. 4. For the probe beam, a 1308 nm distributed feedback (DFB) semiconductor laser (Afonics: FXP0034, peak at 1308 nm) and four DFB semiconductor lasers (Mitsubishi Electric Corp.: FU-436SDF-EW41Mxx) with different wavelengths 1272.5, 1297.6, 1322.8, and 1347.4 nm respectively, were combined using a singlemode fiber (SMF) WDM coupler. And the probe beams can be adjusted using a single driver. The DFB semiconductor laser of 1308 nm was used as the anchor wavelength. The probe laser beam was combined with the excitation beam in the optical coupler (OFR: 810/1310 nm) and then focused into the MMF with an output focusing lens (focuser). The combined beam was focused into the BiSG sample by the focuser, and the gained probe beam was detected by an optical spectrum analyzer (Ando: AQ6317B) using another pigtail focuser.

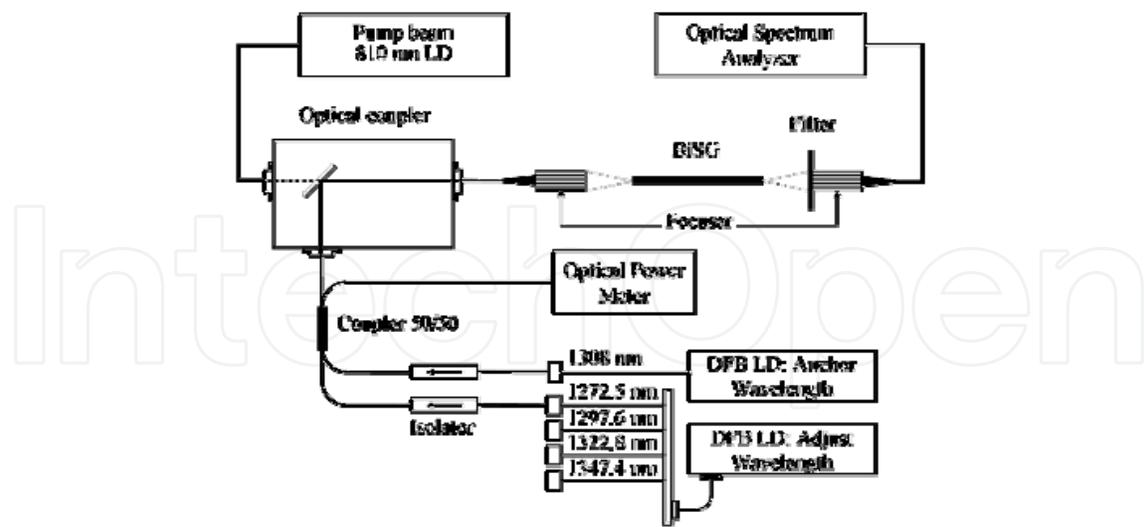


Fig. 4. Experimental setup for optical amplification in a 6.5-cm-long bismuth-doped silica glass

3.2 Gain characteristics of the rod-type BiSG

We measured the gain characteristics of the BiSG at 1300 nm optical communication window. By pigtail focuser, the probe beam (1308 nm) and excitation beam (810 nm) were focused onto the sample surface. The maximum optical gain was calculated to be 4.79 (6.80 dB) and therefore, gain coefficient g was 0.24 cm^{-1} . The optical gain increases linearly with excitation power up to 360 mW. The measured signal input/output power for BiSG was $-8.3 \text{ dBm} / -1.5 \text{ dBm}$ (@ 1308 nm), exhibiting much lower power conversion efficiency. The optical gain in the previous result with a bulk-type BiSG was 1.19 with excitation power of 2.0 W, though the sample thickness was 0.26 cm (Fujimoto & Nakatsuka, 2003). Because the optical gain coefficient of bulk sample was 0.13 cm^{-1} at 360 mW excitation power, the fiber shape clearly affects the gain increment due to beam mode matching between the pump and the probe. If the excitation length is longer, absorption power will increase greatly, and then the gain will be larger than that demonstrated in this experiment.

Between the two MMF pigtail focusers, we measured optical amplification in the BiSG with a threshold of 360 mW launched pump power at 810 nm. Figure 5 shows simultaneous amplification at two wavelengths near 1300 nm second telecommunication window. The wavelength of the excitation beam was 810 nm, and the sample length was 6.5 cm. The probe wavelengths to measure the simultaneous amplification in the BiSG sample were adjustable wavelengths (1272.5 nm, 1297.7 nm, 1322.8 nm and 1347.4 nm) and anchor wavelength (1308 nm). For the four cases of amplification experiments, the maximum optical gain at these wavelengths were 3.30 (5.19 dB), 3.18 (5.02 dB), 3.05 (4.84 dB) and 2.87 (4.58 dB) respectively and 3.12 (4.94 dB) at the anchor wavelength was obtained. The optical gain shown in simultaneous measurements of two wavelengths suggests that it is possible to realize WDM optical fiber amplifiers in O-band (1260~1360 nm) by using this gain material.

The spectral dependence of optical gain is an important consideration if a fiber amplifier is to be incorporated in a broadband WDM system. As shown in Fig. 6, the measured spectral dependence of the optical gain coefficient appears to closely resemble the fluorescence

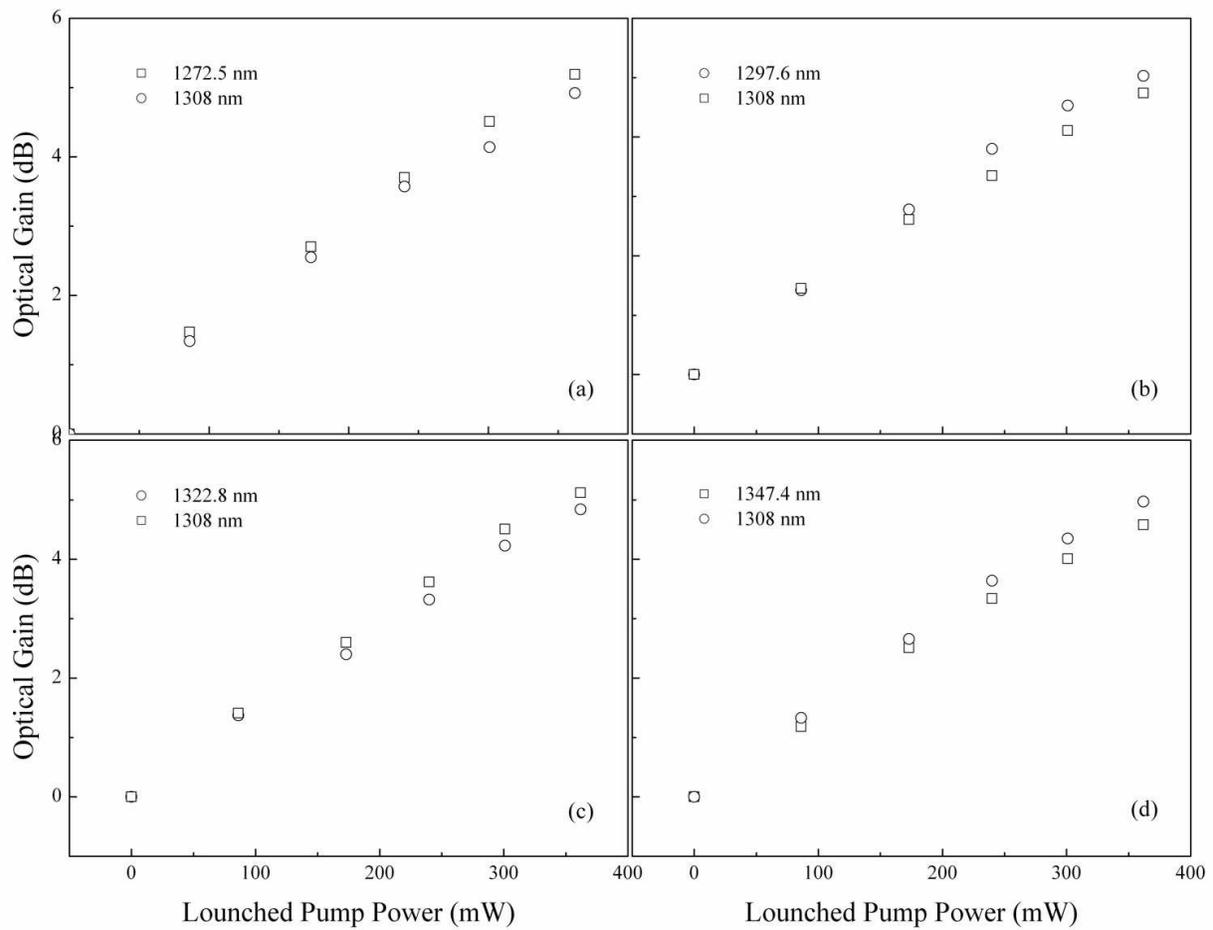


Fig. 5. Simultaneously optical amplification properties at two wavelengths of 1300 nm range: (a) 1308 nm and 1272.5 nm; (b) 1308 nm and 1297.6 nm; (c) 1308 nm and 1322.8 nm; and (d) 1308 nm and 1347.4 nm.

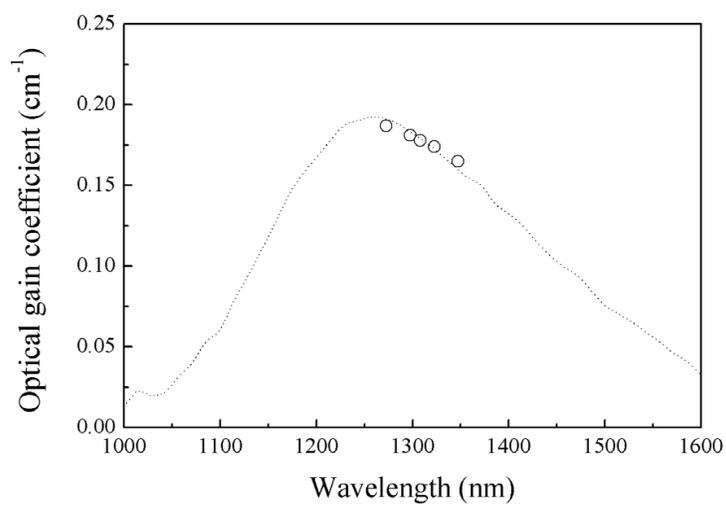


Fig. 6. Optical gain coefficient as a function of different signal wavelengths: 1272.5, 1297.6, 1308.0, 1322.8 and 1347.4 nm. Points and curve represent experimental measurements and fluorescence spectrum at 800 nm excitation, respectively.

spectrum, as represented by a dotted line. The optical gain spread widely from 1250 to 1360 nm. The maximum optical gain was obtained at 1272.5 nm. This wavelength is close to the peak wavelength of the fluorescence spectra. Moreover, broad fluorescence spectrum suggests that optical gain coefficient exceeding 0.165 cm^{-1} should be available over a bandwidth as large as 75 nm (Seo et al., 2006b).

4. Optical amplification in a multi-mode BiDF

4.1 Sample preparation and experimental setup

BiDF sample was fabricated by modified rod-in-tube method. The mixture compound of this sample was Bi_2O_3 : 1.0 mol %, Al_2O_3 : 7.0 mol %, and SiO_2 : 92 mol %. Glass core was inserted into a tube of glass cladding to form a preform, which was drawn by heating in the drawing furnace. The fiber with refractive index difference, $\Delta n \sim 0.017$, was drawn from the perform. The 8.0 cm long sample was optically polished at both ends to provide good optical transmission. Its core diameter and outer diameter was 13 μm and 230 μm , respectively.

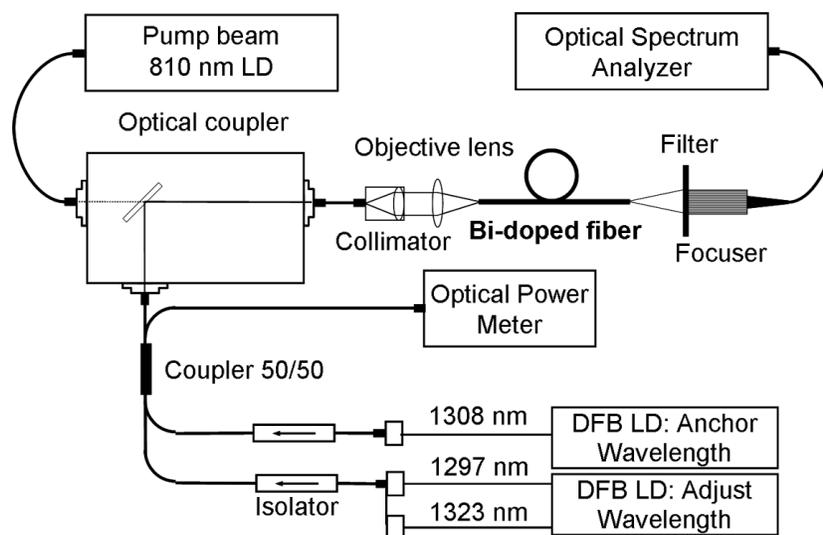


Fig. 7. Schematic diagram for optical gain measurement in bismuth-doped silica fiber.

The experimental setup for optical gain measurement in BiDF is shown in Fig. 7. An 810-nm CW laser diode was used as the pump source. A 1308 nm distributed feedback (DFB) laser diode and two laser diodes with different wavelengths were used as probe beam. The wavelengths of the two laser diodes were 1297 nm and 1323 nm, respectively, and these probe beams can be adjusted using a single driver. The probe laser beam was combined with the excitation beam in the optical coupler (OFR 810/1310 nm), and focused on an end of the fiber by an objective lens. The amplified probe signal was observed with an optical spectrum analyzer, and an optical low path filter cut out the unused pump light.

4.2 Gain characteristics of the multi-mode BiDF

Glass core was the optical amplification in an 8.0 cm long BiDF sample at single wavelength, 1308 nm, is shown in Fig. 8. The maximum optical gain was calculated to be 3.76 (5.8 dB) and therefore, gain coefficient was 0.038 dB/mW. The optical gain increased linearly with

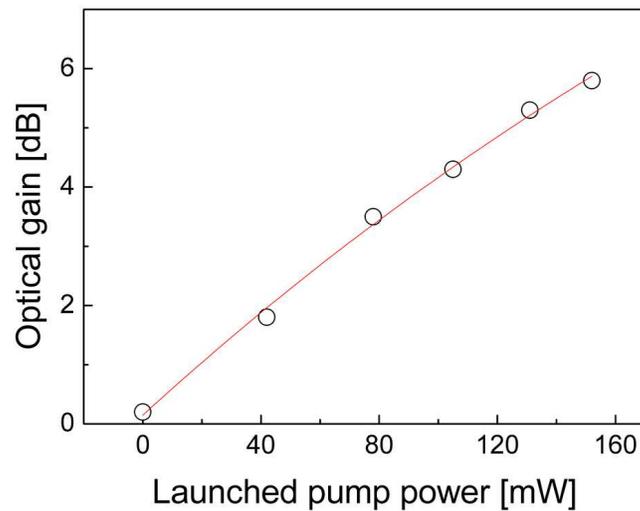


Fig. 8. Optical gain profile of an 8.0 cm long bismuth-doped silica fiber.

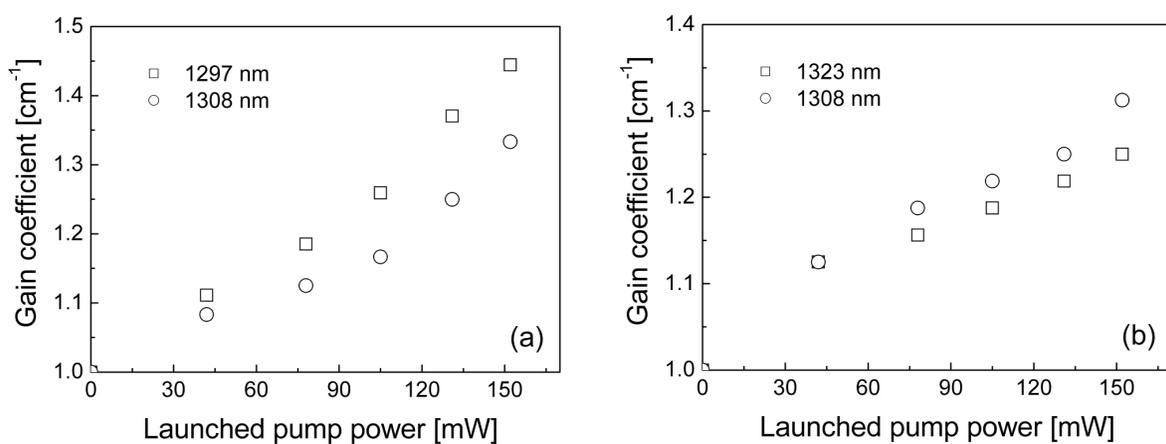


Fig. 9. Simultaneous optical amplification properties at two wavelengths of 1300-nm range: (a) 1308 nm and 1297 nm; (b) 1308 nm and 1323 nm.

excitation power up to 152 mW. The measured signal input/output power for BiDF was -29 dBm / -23 dBm (@ 1308 nm), exhibiting much lower power conversion efficiency. The optical gain in the previous result with a bulk-type BiSG was 1.16 with excitation power of 1.0 W, though the sample thickness was 0.24 cm. Because the specific gain coefficient of the bulk sample was 0.62 cm⁻¹/W, the fiber shape affects the gain increment due to beam mode matching between the pump and the probe.

Figure 9 shows simultaneous amplification at two wavelengths near the 1300 nm region. The signal wavelengths to measure the simultaneous amplification in the BiDF were adjustable wavelengths (1297 and 1323 nm) and anchor wavelength (1308 nm). For the two cases of amplification experiments, the maximum gain coefficients at the adjustable wavelengths (0.046 and 0.036 cm⁻¹) and the anchor wavelength (0.036 and 0.034 cm⁻¹) were obtained. The optical gain shown in simultaneous measurements of two wavelengths suggests that it is possible to realize WDM optical fiber amplifiers in O-band (1260~1360 nm). Performance of fiber amplifier largely depends on the fiber specification. Optical gain

in this experiment was much smaller than that for EDF or PDFFA. The smaller core cross section gives promising potential to the practical gain performance. The gain characteristics will be further improved by optimizing the fiber structure, such as a partially doped core structure and deformed shape of first clad layer for efficient pumping (Seo et al., 2007a).

5. Optical amplification in a single-mode BiDF

5.1 Sample preparation and experimental setup

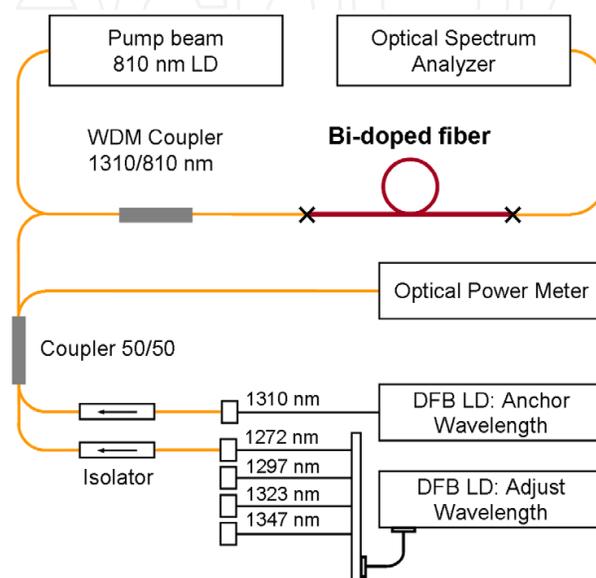


Fig. 10. Schematic diagram for the optical gain measurement of a bismuth-doped silica fiber.

BiDF with a refractive index difference, $\Delta n \sim 0.017$, was drawn from the preform. Its core diameter and outer diameter was $1.54 \mu\text{m}$ and $125 \mu\text{m}$, respectively. The experimental setup for the optical gain measurement in the BiDF is shown in Fig. 10. An 810-nm cw laser diode was used as a pump source. A 1310 nm distributed feedback (DFB) laser diode and four laser diodes with different wavelengths were used as a probe beam. The wavelengths of the four DFB laser diodes were 1272, 1297, 1323 and 1347 nm, and these probe beams can be adjusted by using a single laser driver. The probe laser beams were combined with an excitation beam using a WDM coupler (810/1310 nm). BiDF was fusion spliced (FSM-40PM, Fujikura) to output coupler with a SMF. The combined beam goes through into the BiDF, and the gained probe beam was detected by an optical spectrum analyzer (Ando: AQ6317B).

5.2 Gain characteristics of the single-mode BiDF

The optical amplification in a 5.0-cm long BiDF sample at a single wavelength, 1310 nm, is shown in Fig. 11. The maximum optical gain was calculated to be 9.6 dB and therefore, the gain coefficient was 0.442 cm^{-1} . The optical gain increased linearly with an excitation power up to 100 mW. The measured signal input/output power for the BiDF was $-30.0 \text{ dBm} / -20.4 \text{ dBm}$ (@ 1310 nm), exhibiting a much lower power conversion efficiency. The optical gain in the previous result with a bulk-type BiSG was 1.16 with an excitation power of 1.0 W, though the sample thickness was 0.24 cm (Seo et al, 2005; 2006a). Because the specific gain coefficient of the bulk sample was $0.62 \text{ cm}^{-1}/\text{W}$, the fiber shape clearly affects the gain increment due to a beam mode matching between the pump and the probe. If the excitation

length is longer, absorption power will increase greatly, and then the gain will be larger than that demonstrated in this experiment.

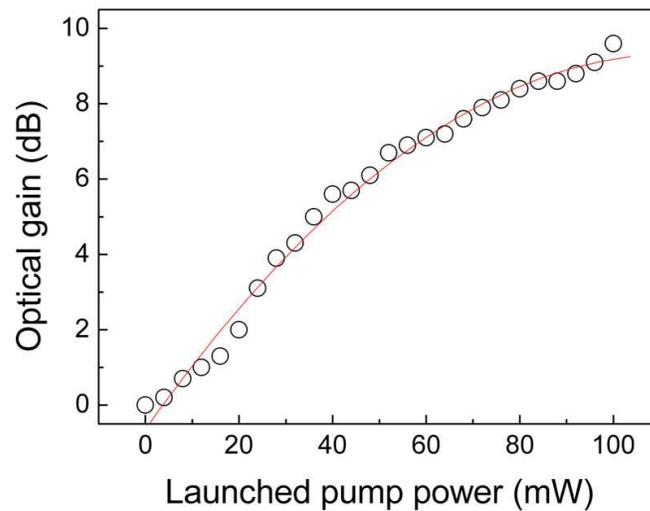


Fig. 11. Optical gain profile of the bismuth-doped silica fiber at a length of 5.0 cm.

Figure 12 shows a simultaneous amplification at two wavelengths near the 1300 nm region. The wavelength of the excitation beam was 810 nm, and the sample length was 5.0-cm. The signal wavelengths to measure the simultaneous amplification in the BiDF were adjustable wavelengths (1297 nm and 1323 nm) and an anchor wavelength (1310 nm). For the two cases of amplification experiments, the maximum optical gain at these wavelengths were 7.99 dB and 7.17 dB respectively and 8.69 dB at the anchor wavelength was obtained. The optical gain shown from the simultaneous measurements of two wavelengths suggests that it is possible to realize WDM optical fiber amplifiers in the O-band (1260~1360 nm). One of the most fundamental parameters, the pump efficiency is defined as the net gain per unit pump power. Net gain is obtained for over a 100-mW pump power. The pump efficiency is 0.095 dB/mW (Seo et al., 2007b).

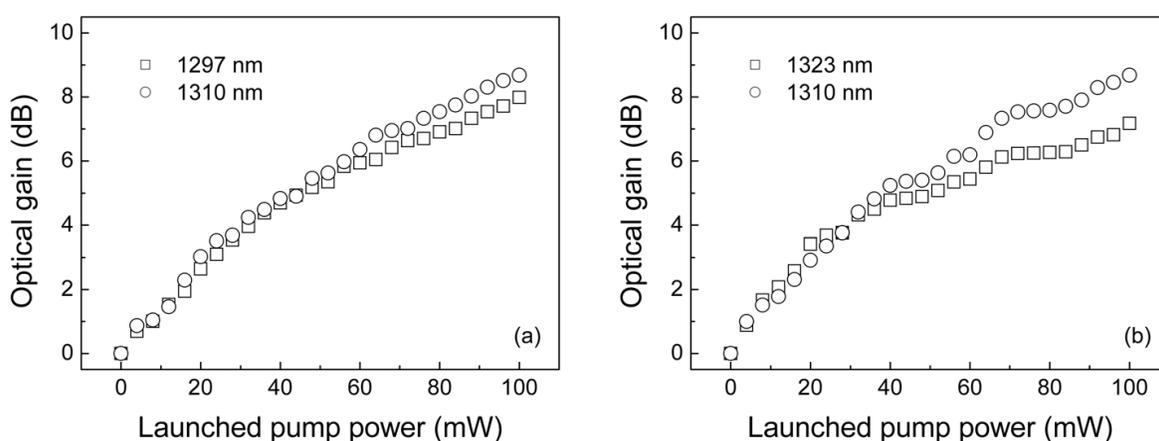


Fig. 12. Simultaneous optical amplification properties at two wavelengths of the 1300-nm range: (a) 1310 nm and 1297 nm; (b) 1310 nm and 1323 nm.

6. Conclusion

The BiSG can complement other optical fiber amplifiers by solving such problems as fusion splicing and wideband amplification. Understanding the optical properties of BiSG is important due to its potential technological applications in optical fiber amplifiers and fiber lasers. The spectroscopic properties of the investigated BiSG are different from those of the previously reported luminescence from Bi³⁺ ions ((Parke & Webb, 1973; Weber & Monchamp, 1973). The peaks of absorption and emission spectra of BiSG exist in the visible and infrared regions, respectively. The absorption cross section of the ¹S₀→³P₁ allowed transition for Bi³⁺ ions was estimated to be 2.4×10⁻¹⁷ cm²; that for bismuth ions of BiSG is 1.2×10⁻²⁰ cm² at best. The Stokes shift between absorption and emission in a BiSG sample is much larger than rare earth ions. Because of the large Stokes shift, population inversion can be realized, and optical amplification occurs via the stimulated emission process.

The origin of light emission in a BiSG, which is still unclear, is the valence electrons of the bismuth ions. We are considering more important reasons why aluminum ions are needed to generate BiSG luminescence. Aluminum ions are needed to generate BiSG luminescence. Aluminum is expected to have a special role in the formation of Bi luminescent center. Therefore, discovering the aluminum status in BiSG, especially the aluminum coordination state, will help us understand the unknown luminescent center. Aluminum coordination state can be investigated by using ²⁷Al-NMR and XAFS. Co-doping of Al and Bi is indispensable for the broadband infrared luminescence of BiSG. The aluminum ion has to roles in BiSG: assisting the configuration of the peculiar luminescent center of Bi ion with some coupling effect, and increasing compatibility with the silica network (Fujimoto & Nakatsuka, 2006; Ohkura et al., 2007).

There are many attractive characteristics of BiSG for a laser application, such as, a long emission lifetime (over 600 μs) and a high absorption cross-section which enable an effective pumping and a short pulse generation. It is important to measure the quantum yield, because the performance of a laser amplification and oscillation is very sensitive for the quantum yield. The quantum yield is defined as the rate of the emitted photon number to the absorbed photon number. The quantum efficiency of the BiSG was measured as 60-70 % (Fujimoto et al, 1999).

BiSG has many attractive features that make it suitable for use in an optical fiber amplifier. First, because BiSG is a silica-based material, it can be transformed to an optical fiber and easily fusion connected to the silica fibers of a network system. Second, the peak wavelength is at 1250 nm, and the bandwidth is 300 nm of FWHM, which is five or six times wider than erbium-doped silica fibers. Third, as the simultaneous amplifying signals near the 1300 nm region (~75 nm), BiSG fiber amplifier is considered a more effective solution for WDM broadband systems. Fourth, a common commercial semiconductor laser (~808 nm) can be used for excitation of this medium. As discussed above, BiSG is a promising candidate for the core fiber material of an optical amplifier at a natural zero-dispersion wavelength, 1300 nm, of silica glass fiber (Fujimoto & Nakatsuka, 2001; 2003).

In conclusion, we have demonstrated optical amplification in a bismuth-doped silica glass and BiDF at second telecommunication window. The amplification was obtained at five different wavelength and the amplification bandwidth is greater than 75 nm (1272.4 ~ 1347.4 nm) in a 0.24 cm BiSG. And we demonstrated simultaneous optical amplification at two wavelengths of the 1300 nm region in a BiSG. Simultaneous amplification was obtained at four different wavelengths, and the amplification bandwidth was greater than 75 nm. This

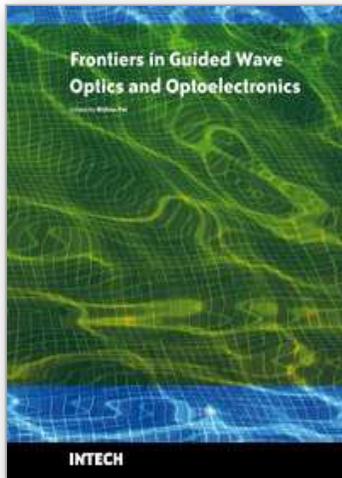
technique can be useful for WDM optical amplifiers at 1300 nm second telecommunication windows. Therefore, this gain medium is expected to be useful for applications in ultrawide broadband optical communication.

Also we reported optical amplification in a BiDF. The optical gain obtained in an 8.0-cm-long multi-mode BiDF at 1308 nm with 810-nm excitation and discussed simultaneous amplification at two wavelengths of the 1300 nm region. And we have demonstrated on the optical amplification phenomenon in a 5.0-cm-long single-mode BiDF at 1310 nm and discussed a simultaneous amplification at two wavelengths of the 1300 nm region. These spectroscopic characteristics and the amplification observed at the 1300 nm range have shown that such fibers are good candidates for cw and pulsed fiber lasers and fiber amplifiers for a spectral range of 1100~1400 nm.

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As the editor, I feel extremely happy to present to the readers such a rich collection of chapters authored/co-authored by a large number of experts from around the world covering the broad field of guided wave optics and optoelectronics. Most of the chapters are state-of-the-art on respective topics or areas that are emerging. Several authors narrated technological challenges in a lucid manner, which was possible because of individual expertise of the authors in their own subject specialties. I have no doubt that this book will be useful to graduate students, teachers, researchers, and practicing engineers and technologists and that they would love to have it on their book shelves for ready reference at any time.

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