Journal of the Optical Society of Korea, Vol. 11, No. 2, June 2007, pp. 63-66

9.6 dB Gain at a 1310 nm Wavelength for a Bismuth-doped Fiber Amplifier

Young-Seok Seo* and Changhwan Lim

Quantum Optics Center, Korea Atomic Energy Research Institute, 150-1 Deokjin-Dong, Yuseong, Daejeon, 305-353, Rep. of Korea

Yasushi Fujimoto and Masahiro Nakatsuka

Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka 565-0871, Japan

(Received June 5, 2007 : revised June 18, 2007)

A 9.6 dB gain is observed at 1310 nm in a 5.0 cm bismuth-doped silica fiber. A launched pump power of 100 mW was obtained using an 810-nm laser diode. We demonstrated the simultaneous optical amplification at two wavelengths near second telecommunication windows, which is the range of zero-dispersion for silica fibers.

OCIS codes : 160.6030, 060.2290, 140.4480

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 a silica fiber, has become an important issue for ultrawide 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 [1]. There are several reports on an infrared luminescence from bismuth-doped glasses [2-11] (germanate, phosphate, borate *et al.*). 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.

Silica glass is one of the most attractive materials for high-peak-power or high-average-power lasers, because it has favorable thermal and mechanical toughness, a high optical transmittance from an ultraviolet to an infrared region, and a low nonlinear refractive index when compared to the other commercial laser glasses. We have developed a new laser material based on silica [12,13]. 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 [14-17]. Absorption spectra peak at 500 nm, 700 nm and 800 nm with broad bandwidths. Its 800 nm absorption band makes this material have a potential to be pumped by commercialized powerful laser diodes (LDs). In addition, cw lasing has been obtained in the spectral region between 1150 and 1300 nm in a bismuth-doped aluminosilicate glass fiber [18,19]. However, the origin of the luminescence mechanism is still unclear.

Bismuth-doped silica glass 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 μs of luminescence make such a fiber promising for the development of lasers and amplifiers. In this paper, we demonstrate an optical amplification at the 1260~1360 nm region (O-band) in bismuth-doped silica fibers (BiDF), which is more than the previous results [16,20]. The LD pumped fiber amplifier at 1310 nm showed 9.6 dB gains with a 5.0-cm length BiDF and a wide-band tuned amplification through an over 100-nm bandwidth. We also report on a simultaneous amplification results for BiDF at two different wavelengths in the 1300 nm region. This technique can be useful for wavelength division multiplexing (WDM) optical amplifiers at the second telecommunications window.

BiDF sample was fabricated by a modified rod-in-tube method [21]. Glass core was inserted into a tube of glass cladding to form a preform, which was drawn by a heating in a drawing furnace. A fiber with a refractive index difference, $\Delta n \sim 0.017$, was drawn from the preform. Its core diameter and outer diameter were 1.54 μm and 125 μm, respectively.

The experimental setup for the optical gain measurement in the BiDF is shown in Fig. 1. An 810-nm cw

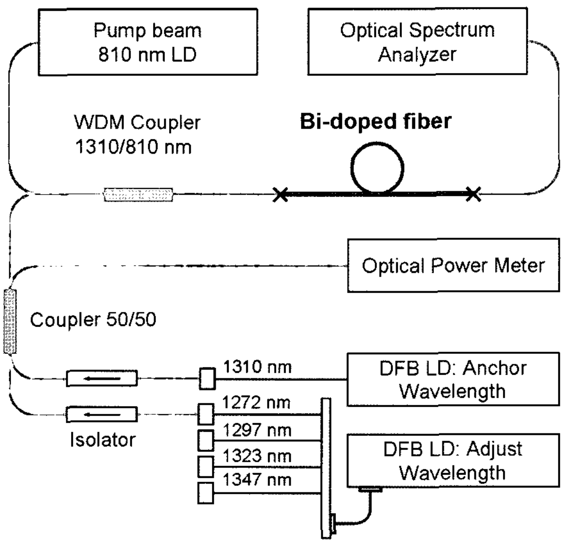

FIG. 1. Schematic diagram for the optical gain measurement of a bismuth-doped silica fiber.

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 the output coupler with a single-mode fiber (SMF). The combined beam goes through into the BiDF, and the gained probe beam was detected by an optical spectrum analyzer (Ando: AQ6317B). The excitation beam is manually chopped to make the state of a probe beam without excitation $P_{s,in}$ and a probe beam with excitation $P_{s,out}$. The definition of gain is $G = P_{s,out} / P_{s,in}$, and is often given in the logarithmic dB unit of G (dB) $= 10\log_{10}G$. The optical gain coefficient was defined as $g = (1 / l) \ln (I / I_0)$, where l is the length of the BiSG sample.

The optical amplification in a 5.0-cm long BiDF sample at a single wavelength, 1310 nm, is shown in Fig. 2. 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 dBm / -20.4 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 [14]. Because the specific gain coefficient of the bulk sample was 0.62 cm^{-1}/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.

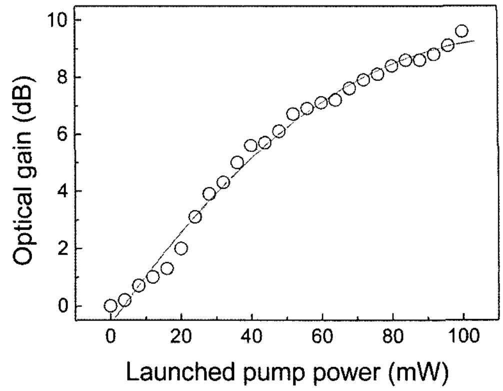

FIG. 2. Optical gain profile of the bismuth-doped silica fiber at a length of 5.0 cm.

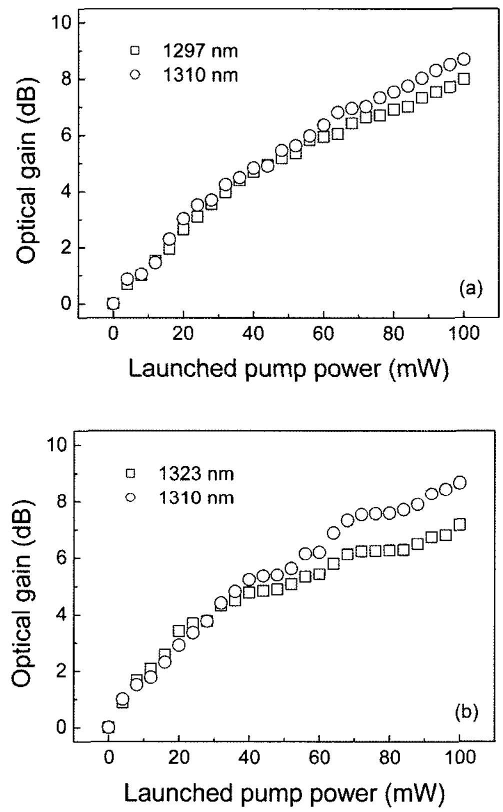

FIG. 3. Simultaneous optical amplification properties at two wavelengths of the 1300-nm range: (a) 1310 nm and 1297 nm; (b) 1310 nm and 1323 nm.

Figure 3 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).

Performance of a fiber amplifier largely depends on the fiber specification used. 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. This result is much smaller than that for EDF or PDFFA in a practical use. The smaller core cross section provides a promising potential for a practical gain performance. The gain characteristics will be further improved by optimizing the fiber's structure, such as a partially doped core structure and a deformed shape of the first clad layer for an efficient pumping.

The origin of a light emission in a BiSG, which is still unclear, is thought to be the valence electrons of the bismuth ions. We are considering more important reasons why aluminum ions are needed to generate a BiSG luminescence. Aluminum is expected to have a special role in the formation of a Bi luminescent center. Therefore, discovering the aluminum's status in a BiSG, especially the aluminum's coordination state, will help us understand the unknown luminescent center. Aluminum coordination state can be investigated by using ^{27}Al-NMR and XAFS. Co-doping of Al and Bi is indispensable for a broadband infrared luminescence of BiSG. The aluminum ion has certain roles in BiSG: assisting in the configuration of the peculiar luminescent center of the Bi ion with some coupling effect, and increasing its compatibility with the silica network [22].

In conclusion, we have demonstrated an optical amplification in a bismuth-doped silica glass and fiber at the second telecommunication window. We have reported on the optical amplification phenomenon in a 5.0-cm long bismuth-doped silica fiber at 1310 nm with an 810-nm excitation 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.

*Corresponding author: physys@kaeri.re.kr

REREFENCES

[1] C.-R. Yang and W.-W. Kim, "GC-EDFA for a Burst Packet Mode Optical Switching System," *J. Opt. Soc. Korea*, vol. 11, pp. 44-48, 2007.

[2] Y. Fujimoto and M. Nakatsuka, "Infrared Luminescence from Bismuth-Doped Silica Glass," *Jpn. J. Appl. Phys.*, vol. 40, pp. L279-L281, 2001.

[3] M. Peng, J. Qiu, D. Chen, X. Meng, I. Yang, X. Jiang, and C. Zhu, "Bismuth- and aluminum-codoped germanium oxide glasses for super-broadband optical amplification," *Opt. Lett.*, vol. 29, pp. 1998-2000, 2004.

[4] M. Peng, J. Qiu, D. Chen, X. Meng, and C. Zhu, "Superbroadband 1310 nm emission from bismuth and tantalum codoped germanium oxide glasses," *Opt. Lett.*, vol. 30, pp. 2433-2435, 2005.

[5] X. Meng, J. Qui, M. Peng, D. Chen, Q. Zhao, X. Jiang, and C. Zhu, "Near infrared broadband emission of bismuth-doped aluminophosphate glass," *Opt. Express*, vol. 13, pp. 1628-1634, 2005.

[6] X. Meng, J. Qui, M. Peng, D. Chen, Q. Zhao, X. Jiang, and C. Zhu, "Infrared broadband emission of bismuth-doped barium-aluminum-borate glasses," *Opt. Express*, vol. 13, pp. 1635-1642, 2005.

[7] M. Peng, C. Wang, D. Chen, X. Jiang, and C. Zhu, "Investigations on bismuth and aluminum co-doped germanium oxide glasses for ultra-broadband optical amplification," *J. Non-Cryst. Solids*, vol. 351, pp. 2388-2393, 2005.

[8] M. Peng, J. Qiu, D. Chen, X. Meng, and C. Zhu, "Broadband infrared luminescence from Li_2O-Al_2O_3-ZnO-SiO_2 glasses doped with Bi_2O_3," *Opt. Express*, vol. 13, pp. 6892-6898, 2005.

[9] V. V. Dvoyrin, V. M. Mashinsky, E. M. Dianov, A. A. Umnikov, M. V. Yashkov, and A. N. Guryanov, "Absorption, Fluorescence and Optical Amplification in MCVD Bismuth-Doped Silica Glass Optical Fibres," *in proc. 31st ECOC*, Glasgow, Scotland, Paper Th3.3.5, vol. 4, pp. 949-950, 2005.

[10] V. V. Dvoyrin, V. M. Mashinsky, E. M. Dianov, A. A. Umnikov, M. V. Yashkov, and A. N. Guryanov, "Bi-Doped Silica Fibers: A New Active Medium for Tunable Fiber Lasers and Broadband Fiber Amplifiers," *OFC/NFOEC 2006*, San Diego, USA, Paper OTuH4, 2006.

[11] T. Suzuki and Y. Ohishi, "Ultrabroadband near-infrared emission from Bi-doped Li_2O-Al_2O_3-SiO_2 glass," *Appl. Phys. Lett.*, vol. 88, pp. 191912.1-191912.3, 2006.

[12] Y. Fujimoto, K. Murata, and M. Nakatsuka, "New material for high average power laser based on silica glass," *Fusion Eng. Des.*, vol. 44, pp. 431-435, 1999.

[13] M. Nakatsuka, H. Yoshida, Y. Fujimoto, K. Fujioka, and H. Fujita, "Recent Topics in Engineering for Solid-State Peak-Power Lasers in Repetitive Operation," *J. Korean Phys. Soc.*, vol. 43, pp. 607-615, 2003.

[14] Y. Fujimoto and M. Nakatsuka, "Optical amplification in bismuth-doped silica glass," *Appl. Phys. Lett.*, vol. 82, pp. 3325-3326, 2003.

[15] Y. Fujimoto and M. Nakatsuka, "Spectroscopic analysis of bismuth and aluminum co-doped silica glass emitting 1000-1600 nm radiation," *XX International Congress*

on Glass 2004, Kyoto, Japan, Paper O-07-077, 2004.

[16] Y.-S. Seo, Y. Fujimoto, and M. Nakatsuka, "Simultaneous Amplification at Two Wavelengths Near 1300 nm in a 6.5-cm-Long Bismuth-Doped Silica Glass," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 1901-1903, 2006.

[17] Y.-S. Seo, Y. Fujimoto, and M. Nakatsuka, "Optical amplification in a bismuth-doped silica glass at 1300 nm telecommunications window," *Opt. Commun.*, vol. 266, pp. 169-171, 2006.

[18] E. M. Dianov, V. V. Dvoyrin, V. M. Mashinsky, A. A. Umnikov, M. V. Yashkov, and A. N. Guryanov, "CW bismuth fibre laser," *Quantum Electronics*, vol. 35, pp. 1083-1084, 2005.

[19] V. V. Dvoyrin, V. M. Mashinsky, and E. M. Dianov, "Yb-Bi pulsed fiber lasers," *Opt. Lett.*, vol. 32, pp. 451-453, 2007.

[20] Y.-S. Seo, Y. Fujimoto, and M. Nakatsuka, "Optical amplification in a bismuth-doped silica fiber," *Proceedings of SPIE*, vol. 6351, pp. 63512C.1-63512C.8, 2006.

[21] S. Kishimoto, M. Tsuda, K. Sakaguchi, Y. Fujimoto, and M. Nakatsuka, "Novel bismuth-doped optical amplifiers for 1.3-micron telecommunication band," *XX International Congress on Glass 2004*, Kyoto, Japan, Paper O-14-029, 2004.

[22] Y. Fujimoto and M. Nakatsuka, "^{27}Al NMR structural study on aluminum coordination state in bismuth doped silica glass," *J. Non-Cryst. Solids*, vol. 352, pp. 2254-2258, 2006.