Bi-doped fiber lasers and amplifiers for a spectral region of 1300–1470 nm

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Bismuth-doped fiber lasers operating in the range 1300–1470 nm have been demonstrated for the first time, to our knowledge. It has been shown that Bi-doped alumina-free phosphogermanosilicate fibers reveal optical gain in a wavelength range of 1240–1485 nm with pumping at 1205, 1230, or 808 nm. © 2008 Optical Society of America

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Bi-doped glass optical fibers are a very promising active laser medium. In 2001 Fujimoto and Nakatsuka discovered wideband (200–300 nm) near-IR luminescence from Bi- and Al-codoped silica glass, which takes place in a spectral region of 1100–1500 nm [1]. This achievement caused great interest in the development of fiber lasers and ultrawideband fiber amplifiers for this spectral region. A large number of papers devoted to the investigation of the near-IR luminescence in various Bi-doped glasses, Bi-doped glass optical fiber fabrication, and the development of Bi-doped fiber lasers have been published (see, e.g., [2] and references therein).

Laser generation in Bi-doped fibers has been reported so far (to our knowledge) only in the wavelength region up to 1.3 μm [3–8]. Such Bi-doped fiber lasers were based mainly on aluminosilicate Bi-doped (ASB) fibers. Considerable attention was paid to the investigation of the optical gain at the wavelength near 1.3 μm in various glasses (see, e.g., [9–11] and references therein). It is worthwhile to note some interesting results on the fabrication of Bi- and Er-codoped silica glass, which emits the near-IR luminescence with a FWHM of 420 nm in the region 1100–1600 nm [12]. But no results on laser generation in these glasses at the wavelength 1.3 μm and beyond have been published, to our knowledge. In this Letter we report on the laser generation in Bi-doped optical fibers in the spectral region 1300–1470 nm.

To extend the luminescence band of Bi-doped fibers to longer wavelengths, we used a different glass composition in the fiber core: alumina-free Bi-doped phosphogermanosilicate glass (PGSB). It should be noted that the near-IR luminescence with a peak at about 1300 nm was observed earlier in optical-fiber preforms of similar composition. However, this luminescence disappeared after the fiber-drawing process [7].

We fabricated the preforms for the PGSB fibers by the modified-chemical-vapor-deposition technique. Bi concentration in the fiber core glass was lower than the sensitivity threshold (~0.1 wt.%) of the JEOL JSM 5910LV scanning electron microscope equipped with an Oxford Instruments energy-dispersive x-ray analyzer. The single-mode fibers drawn from these preforms had a core diameter of 4.5 μm and a mode-field diameter of 4.9 μm at a wavelength of 1.3 μm.

The absorption spectra of ASB and PGSB fibers are essentially different (Fig. 1). ASB fibers are known to feature the absorption bands at approximation 500, 700, 800, and 1000 nm [1,2]. Regarding the PGSB fibers, the bands at 500 nm, 700, and 1000 nm appear to be absent; however, one can see the bands at 450, 800, and 950 nm and a complex band in a region of 1100–1500 nm (Fig. 1). The main contribution to the latter band appears to be due to bismuth-associated active centers (bismuth centers, BCs), although this band also comprises the known OH-group absorption bands at about 1240 and 1380 nm. Therefore, BCs can emit IR luminescence when pumped in the 1100–1500 nm absorption band. In fact, we observed wideband luminescence in a region of 1200–1450 nm (FWHM) upon pumping at 1230 nm in both preforms and fibers (curve 1 in Fig. 2).

Near-IR luminescence was also observed in both PGSB preforms and fibers upon pumping at 808 nm, the luminescence spectra of the preforms and fibers being virtually identical. The emission luminescence spectrum peaks near 1375 nm (curve 2 in Fig. 2). Next we measured the temporal dependence of the BC's luminescence decay in the PGSB fibers at the wavelength of 1300 nm upon pumping at 808 nm. It

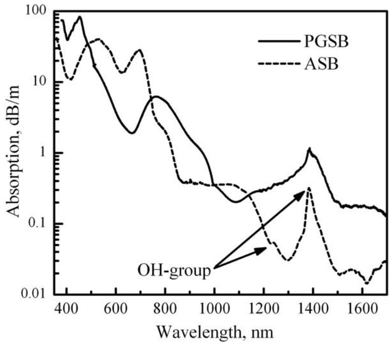

Fig. 1. Absorption spectra of ASB and PGSB fibers.

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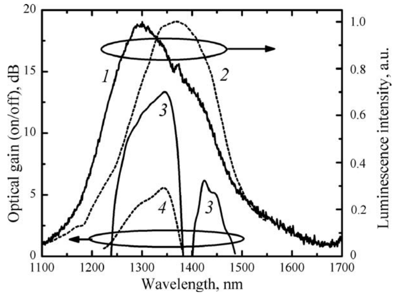

Fig. 2. Emission spectra of PGSB fibers pumped (1) at $\lambda_p=1230$ nm and (2) $\lambda_p=808$ nm; variation of the on/off gain with signal wavelength for a PGSB fiber pumped at (3; fiber length $L=30$ m) $\lambda_p=1230$ nm and (4; $L=13$ m) $\lambda_p=808$ nm. The pump power in the on/off gain measurements was 50 mW.

turned out that this dependence could be satisfactorily approximated with a single exponent, its time constant being 600 μs.

The on/off gain spectra $g(\lambda)$ were measured in the PGSB fibers with a pump at either $\lambda_p=808$ nm or $\lambda_p=1230$ nm. The measured $g(\lambda)$ dependences are shown in Fig. 2, curves 3 and 4. The optical amplification with $\lambda_p=1230$ nm was observed in the wide wavelength region, from 1240 to 1485 nm, with a dip near 1380 nm. Apparently, this dip can be associated with a large OH-group concentration in the fiber core, the corresponding optical losses at 1380 nm being about $\geqslant 0.1$ dB/m). The interaction between OH groups and BCs could result in the suppression of gain in a vicinity of 1380 nm. If so, the reduction of OH concentration via improvement of the technological procedure can lead to the elimination of the dip in the gain spectrum.

With $\lambda_p=808$ nm, the $g(\lambda)$ dependences behaved in a similar way for $\lambda<1380$ nm, whereas amplification in the range $\lambda>1400$ nm did not exceed the detection threshold (Fig. 2).

The above data allowed us to demonstrate several bismuth fiber lasers (BFLs) with various generation wavelengths using the PGSB fiber. All the BFLs were assembled in accordance with the common linear scheme consisting of an active fiber and fiber Bragg gratings (BGs) spliced to the fiber ends (Fig. 3). In some cases, BGs were written directly in the PGSB fibers in order to reduce the intracavity optical losses. The lasing wavelength λ_s was determined by the BGs resonance wavelength. We used a Raman fiber laser ($\lambda_p=1230$ nm), a Bi-doped fiber laser ($\lambda_p=1205$ nm [6]), and a single-mode laser diode $\lambda_p=808$ nm) as pump sources and a 13-m-long PGSB fiber pumped at $\lambda_p=1230$ nm and $\lambda_p=1205$ nm and a 30-m-long PGSB fiber pumped at $\lambda_p=808$ nm as an active medium. One of the BGs had reflectivity R close to 100% [high-reflection Bragg grating (HRBG), Fig. 3], whereas the second one [output coupler formed by a Bragg grating (OCBG)] had $R=50\%$ in the BFLs emitting at $\lambda_s=1310$ and 1345 nm and $R=98\%$ in the BFLs emitting at $\lambda_s=1300$, 1320, 1330, 1427, and 1470 nm. The spectral bandwidth of all BGs was ≈ 0.5 nm. The output BFL spectra are shown in Fig. 4. The dependences of the BFL output power on the absorbed pump power for four laser schemes are shown in Fig. 5. These dependences are nearly linear in the pump-power range under consideration.

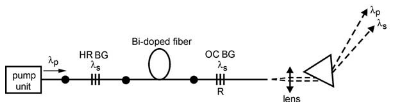

Fig. 3. Scheme of the Bi-doped fiber laser.

The slope efficiency of the BFL at $\lambda_s=1310$ with respect to the absorbed power amounted to 3.2% with $\lambda_p=1230$ nm (Fig. 5, laser 2) and 1.4% with $\lambda_p=1205$ nm (Fig. 5, laser 1) at the temperature $T=300$ K. It turned out that the slope efficiency of a PGSB fiber laser depends strongly on the fiber temperature (as in the case of ASB fiber lasers [5,6]). On cooling the PGSB fiber to $T=77$ K, the slope efficiency increased to 5.0% (laser 1) and 5.4% (laser 2), while the threshold pump power decreased to 100 mW ($\lambda_p=1230$ nm, laser 2) and 170 mW ($\lambda_p=1205$ nm, laser 1).

The slope efficiency of BFL 3 ($\lambda_s=1345$ nm) turned out to be much lower, just 0.8% at $T=300$ K, the threshold power being 200 mW (Fig. 5). Unlike the preceding cases, the slope efficiency of this BFL did not increase on cooling to $T=77$ K but went down to 0.6%, the threshold power growing to 350 mW. The maximal slope efficiency of 3.4% ($T=300$ K) was achieved for $\lambda_s=1470$ nm and $\lambda_p=1230$ nm (Fig. 5), and the threshold pump power in this case amounted to 145 mW.

In BFL 6 (Fig. 4), the active fiber was placed in a cavity formed by three pairs of BGs with resonance wavelengths of 1300, 1330, and 1470 nm. Upon pumping at $\lambda_p=1230$ nm, lasing was achieved at the three wavelengths simultaneously. This fact as well as the dip in the gain line of a PGSB fiber in a vicinity of 1400 nm (Fig. 2, curve 3) testify to a significant inhomogeneous broadening of the gain band formed by one or maybe several different types of BCs.

We have also investigated the possibility of lasing in a region of 1.3 μm with pumping at a shorter wavelength. It has been established that pumping at 1058 nm does not yield lasing with a pump power of up to 12 W. However, we succeeded in obtaining las-

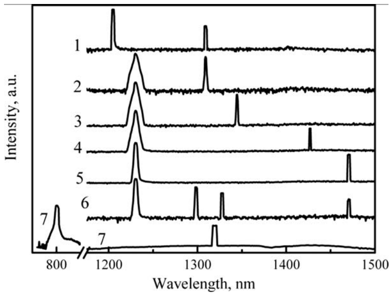

Fig. 4. Output emission spectra of BFLs 1–7: 1, pump wavelength $\lambda_p=1205$ nm, lasing wavelength $\lambda_s=1310$ nm; 2, $\lambda_p=1230$ nm, $\lambda_s=1310$ nm; 3, $\lambda_p=1230$ nm, $\lambda_s=1345$ nm; 4, $\lambda_p=1230$ nm, $\lambda_s=1427$ nm; 5, $\lambda_p=1230$ nm, $\lambda_s=1470$ nm; 6, $\lambda_p=1230$ nm, $\lambda_{s1}=1300$ nm, $\lambda_{s2}=1330$ nm, $\lambda_{s3}=1470$ nm; 7, $\lambda_p=808$ nm, $\lambda_s=1320$ nm.

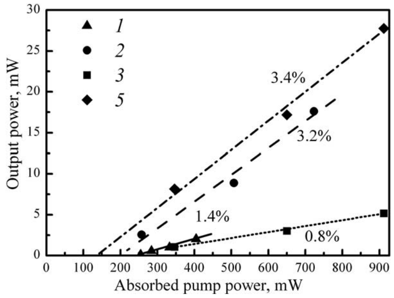

Fig. 5. Output power of BFLs 1–3 and 5 as a function of absorbed pump power: 1, $\lambda_p = 1205$ nm, $\lambda_s = 1310$ nm; 2, $\lambda_p = 1230$ nm, $\lambda_s = 1310$ nm; 3, $\lambda_p = 1230$ nm, $\lambda_s = 1345$ nm; 5, $\lambda_p = 1230$ nm, $\lambda_s = 1470$ nm.

ing at $\lambda_s = 1320$ nm when pumping in the 800 nm absorption band. A 808 nm single-mode fiber-pigtailed laser diode was used as a pump source. The threshold pump power turned out to be ~200 mW. Because this value was virtually the limiting output power of the laser diode used, we failed to measure the dependence of the BFL output power on the pump power. The output spectrum of this BFL is shown in Fig. 4, curve 7.

The low slope efficiency of our first BFLs (1–3%) may be due to either a high level of BC-unrelated loss in PGSB fibers or a possible pump–power dissipation in the BCs themselves. Significant changes in the slope efficiency by varying the pump and lasing wavelengths, as well as distinctions among the slope efficiency dependences on the temperature for different pump and lasing wavelengths, point to a very complicated nature of BCs.

Thus we have fabricated and investigated phosphogermanosilicate bismuth-doped fibers that show near-IR luminescence and optical gain in the range 1240–1485 nm. For the first time to our knowledge, the BFLs, radiating in the range from 1300 to 1470 nm, have been created with pumping at various wavelengths. These results appear to be an important advance in solving the problem of highly efficient fiber lasers and wideband optical amplifiers for the spectral range, very promising for future optical fiber-communication systems.

References

1. Y. Fujimoto and M. Nakatsuka, Jpn. J. Appl. Phys. **40**, L279 (2001).
2. E. M. Dianov, Proc. SPIE **6890**, 68900H-1 (2008).
3. E. M. Dianov, V. V. Dvoyrin, V. M. Mashinsky, A. A. Umnikov, M. V. Yashkov, and A. N. Guryanov, Quantum Electron. **35**, 1083 (2005).
4. I. Razdobreev, L. Bigot, V. Pureur, A. Favre, G. Bouwmans, and M. Douay, Appl. Phys. Lett. **90**, 031103-1 (2007).
5. V. V. Dvoirin, V. M. Mashinsky, and E. M. Dianov, IEEE J. Quantum Electron. **44**, 834 (2008).
6. E. M. Dianov, A. V. Shubin, M. A. Melkumov, O. I. Medvedkov, and I. A. Bufetov, J. Opt. Soc. Am. B **24**, 1749 (2007).
7. L. Bigot, I. Razdobreev, V. Pureur, A. Favre, G. Bouwmans, and M. Douay, in *15th International Laser Physics Workshop* (EPFZ, 2006), p. 224.
8. S. Yoo, M. P. Kalita, J. Sahu, J. Nilsson, and D. Payne, *Proceedings of the Conference on Lasers and Electro-Optics/Quantum Electronics Conference* (Optical Society of America, 2008), paper CFL4.
9. Y. Fujimoto and M. Nakatsuka, Appl. Phys. Lett. **82**, 3325 (2003).
10. Y. Seo, Y. Fujimoto, and M. Nakatsuka, *Proceedings of the Conference on Lasers and Electro-Optics* (Optical Society of America, 2006), paper CTuI6.
11. J. Ren, Y. Qiao, C. Zhu, X. Jiang, and J. Qiu, J. Opt. Soc. Am. B **24**, 2597 (2007).
12. Y. Kuwada, Y. Fujimoto, and M. Nakatsuka, Jpn. J. Appl. Phys. **46**, 1531 (2007).