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Bi-doped fibre lasers and amplifiers emitting in a spectral region of 1.3 μm

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***Abstract*. A bismuth-doped fibre laser emitting at wavelengths within the second transparency window of silica fibres is fabricated. It is shown that Bi-doped aluminium-free phosphogermanosilicate fibres pumped in the regions of 800 and 1200 nm have the amplification band at 1275 – 1375 nm.**

Keywords: *bismuth laser, fibre laser, fibre amplifier, fibre optics.*

The investigation of the nature of the broadband IR luminescence discovered not long ago in Bi-doped glasses and fibres (see [1] and [2] and references therein) is of much scientific interest, because an adequate model for the bismuth active center (BC) is still absent. In addition, the related problem of the development of optical amplifiers operating within the second transparency window of silica fibres (1260 – 1360 nm) and at longer wavelengths is very important for the creation of extremely broadband fibreoptic communication systems.

The real optical gain (the excess of the gain over losses) has been demonstrated so far in Bi-doped glass fibres only in the wavelength region of 1.15 – 1.225 μm, where lasers based on alumosilicate Bi-doped fibres (hereafter, ASB fibres) [3] emit quite high powers [4]. In this work, we investigated the possibility of shifting the amplification band of Bi-doped glasses and fibres to the longer IR region between 1260 and 1700 nm. This wavelength band is used now only partially, but can be used in the future extremely broadband fibreoptic communication systems.

The luminescence spectrum of ASB fibres in which lasing was observed covers the wavelength range from 1000 to 1300 nm [Fig. 1, curve (*1*)]. To extend the luminescence band of Bi-doped fibres to longer wavelengths, we used alumina-free Bi-doped phosphogermanosilicate (PGSB) glass. The preforms for the PGSB fibres were fabricated by the MCVD method. The Bi concentration in the fibre core was lower than the sensitivity threshold (~ 0.1 %) of a JEOL JSM 5910LV scanning electron microscope equipped with an Oxford Instruments X-ray analyser. The single

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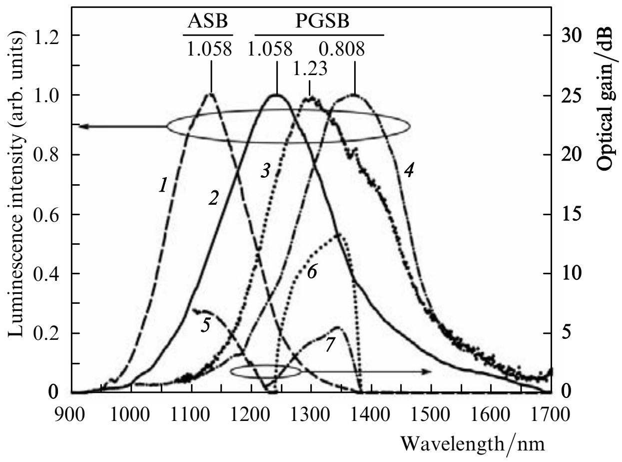

Figure 1. Luminescence spectra of ASB and PGSB fibres pumped at different wavelengths (*1* – *4*) (pump wavelengths are indicated over the curves in μm); (*5* – *7*) gain spectra in the ASB fibre [(*5*) – fibre length $L = 20$ m, $\lambda_p = 1058$ nm)] and PGSB fibres [(*6*) – $L = 30$ m, $\lambda_p = 1230$ nm; (*7*) – $L = 13$ m, $\lambda_p = 808$ nm)]. The pump power in all cases was 50 mW.

mode fibres drawn from these preforms had a core diameter of 4.5 μm and a mode-field diameter of 4.9 μm at the wavelength of 1.3 μm.

Infrared luminescence was observed in PGSB preforms and fibres upon pumping at 808 nm or 1058 nm, the luminescence spectra of the preforms and fibres being almost identical [curves (*2*, *4*) in Fig. 1]. One can see that the luminescence spectrum of PGSB fibres is shifted to the red compared to that of ASB fibres. The absorption spectra of the ASB and PGSB fibres are also considerably different (Fig. 2). The ASB fibres have the absorption bands at 500, 700, 800, and 1000 nm. The PGSB fibres have no 500-nm and 700-nm absorption bands, but exhibit absorption bands at 450, 800, and 950 nm and a complex band in the region of 1100 – 1500 nm (Fig. 2), which probably also includes the 1240-nm and 1400-nm absorption bands of OH groups contained in the fibre core. Bismuth centres probably also make a considerable contribution to this absorption band, and therefore, their IR luminescence should be observed upon pumping into this band. Indeed, broadband luminescence was observed between 1260 and 1460 nm upon pumping preforms and fibres at 1230 nm [curve (*3*) in Fig. 1].

We measured the relaxation dynamics of BC luminescence in PGSB fibres at a wavelength of 1300 nm upon

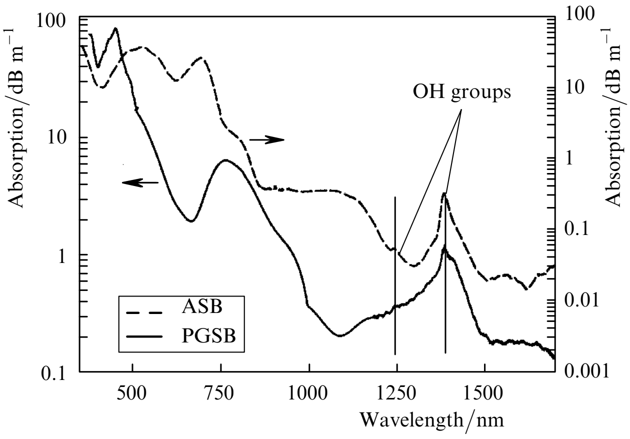

Figure 2. Optical losses in ASB and PGSB fibres.

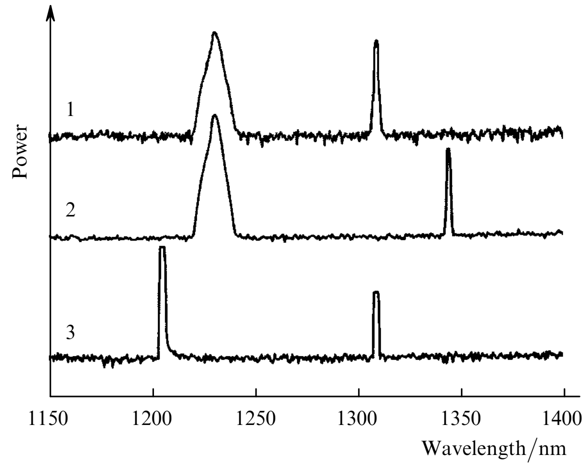

Figure 3. Spectra of a Bi-doped fibre laser emitting at $\lambda_g = 1310$ nm and pumped at $\lambda_p = 1230$ nm (laser 1), $\lambda_g = 1345$ nm and $\lambda_p = 1230$ nm (laser 2), $\lambda_g = 1310$ nm and $\lambda_p = 1205$ nm (laser 3).

pumping at 808 nm. The luminescence decay was well described by a single exponential with the decay time $\sim$ 600 μs. Note that the 1300-nm luminescence decay curve did not contain a fast component (with the relaxation time no more than 5 μs), in contrast to germanoalumosilicate fibres [5]. We measured the small-signal gain spectra in the 1100 – 1400-nm band of PGSB fibres and, for comparison, in ASB fibres [curves (*5 – 7*) in Fig. 1].

Based on the data obtained in the study, we fabricated a PGSB fibre laser. The laser was assembled by using a standard scheme (see, for example, [4]), and was pumped by a single-mode Raman fibre laser at 1230 nm [6] or by an ASB fibre laser at 1205 nm [4]. The active medium of the bismuth fibre laser was a 30-m long PGSB fibre with spliced fibre Bragg gratings (FBGs) as mirrors. One of the FBGs had the reflectance R close to 100 %, whereas the other (output) FBG had $R = 50$ %.

We obtained lasing in the gain band of the PGSB fibre in three schemes of fibre lasers with different FBG resonance wavelengths and different pump wavelengths (Fig. 3). Laser 1 pumped at 1230 nm emitted at 1310 nm. The threshold pump power P_{th} was $\sim$ 150 mW. The slope efficiency η of the laser with respect to the absorbed pump power was $\sim$ 3.2 % at room temperature and pump power $P_p < 1$ W. The slope efficiency of the PGSB fibre laser strongly depended on the fibre temperature (as in the case of ASB fibre lasers [4, 7]) and the pump power. As the PGSB fibre was cooled down to 77 K, the slope efficiency at $P_p < 1$ W increased to 5.4 %, while P_{th} decreased to 100 mW. At higher pump powers, the slope efficiency increased and amounted to 19 % at $P_p = 6$ W ($T =$ 300 K) and 29 % ($T = 77$ K), i.e a nonlinear dependence of the laser output power on the pump power was observed. The maximum output power of the laser was 400 mW ($T = 300$ K) and 1.6 W ($T = 77$ K). The increase in η with the pump power is explained by the fact that the frequency shift between pump and lasing radiation in laser 1 corresponded to the maximum fibre Raman gain in silica fibres (in this case 490 cm^{-1}). The Raman gain strongly affected lasing at high pump powers. This conclusion is based on the numerical simulation of the bismuth laser operation taking into account Raman amplification, as was done in [4].

To reduce drastically the influence of Raman amplification in the fibre we increased the difference between the pump ($\lambda_p = 1230$ nm) and laser wavelengths $\lambda_g = 1345$ nm, laser 2. In this case, the frequency shift between the laser and pump radiation was 700 cm^{-1}, which reduced the Raman gain in the fibre by more than an order of magnitude. In addition, the wavelength 1345 nm corresponded to the maximum gain in the Bi-doped fibre [see curve (*6*) in Fig. 1]. In laser 2, the linear dependence of the output power on the pump power was observed in all the range of pump powers. The slope efficiency of this laser was considerably lower, being 0.8 % at $T = 300$ K. The pump threshold was $\sim$ 200 mW and P_{max} was 30 mW at $P_p =$ 3.7 W. Unlike the preceding case, the slope efficiency of laser 2 did not increase upon cooling to $T = 77$ K, but decreased down to 0.6 %, while the threshold power increased to 350 mW.

We also investigated the possibility of pumping the PGSB fibre laser by the shorter-wavelength radiation. Laser 3 was pumped by a 1205-nm ASB fibre laser, while the cavity of laser 3 was tuned to a wavelength of 1310 nm (as in the case of laser 1). The slope efficiency of laser 3 was 1.4 % at room temperature for $P_{th} \sim 200$ mW. Upon cooling the active fibre down to $T = 77$ K, the slope efficiency increased to 5 %, while P_{th} decreased to 170 mW. The pump power of laser 3 did not exceed 400 mW andP_{max} at 1310 nm was 2 mW at 300 K and 6 mW at 77 K.

Thus, we have fabricated bismuth-doped phosphogermanosilicate fibres demonstrating IR luminescence and optical gain within the second transparency window of silica fibres. The fibres have absorption bands at 450, 800, 950, and 1100 – 1500 nm. By pumping fibres at wavelengths 808 and 1230 nm, we observed the amplification of optical signals in the range between 1275 and 1375. The gain in this band upon pumping at 1205 and 1230 nm exceeds losses in the fibre, which allowed us to obtain for the first time lasing in bismuth lasers above 1300 nm. The low lasing efficiency ($\sim$ 1 %) may be due to either a high level of nonresonance losses in first experimental fibres, or the pump power dissipation in the BCs themselves. The significant changes in the slope efficiency upon varying the pump and lasing wavelengths, and the considerable difference between the dependences $\eta(T)$ observed in this case suggest that BCs have a complicated structure. The demonstration of the optical gain in Bi-doped fibres in the spectral range used in fibre communication systems is an important advance in solving the problem of fabricating efficient broadband optical amplifiers for this spectral range*.

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* Notes of the authors during the paper editing: While the article was in the process of publication the laser generation at the wavelengths 1427, 1470 and 1501 nm was observed using the same PGSB fibre and the same pump source, the slope efficiency being several percent for all wavelengths. So, the PGSB fibre demonstrates optical amplification from 1300 nm up to 1500 nm except a narrow dip near 1380 nm apparently associated with a large OH-group concentration in the fibre core.