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Bi-doped fibre lasers operating in the range 1470 – 1550 nm

E.M. Dianov, S.V. Firstov, V.F. Khopin, O.I. Medvedkov, A.N. Guryanov, I.A. Bufetov

***Abstract*. Lasing in bismuth-doped optical fibres in the range 1470 – 1550 nm has been demonstrated for the first time. The gain media were Bi-doped phosphogermanosilicate and, for the first time, germanosilicate glass fibres. The gain spectrum of the phosphogermanosilicate fibres extends from 1300 to 1550 nm, the range which can be used in next-generation optical fibre communication systems.**

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

The IR luminescence of bismuth-doped glasses has been the subject of much attention since 2001 [1], in particular because it suggests the possibility of achieving optical gain and laser action in such materials, which is no doubt of interest for extending the wavelength range of optical fibre communication systems. Recent work has shown that bismuth-doped glasses exhibit IR luminescence at wavelengths from 1000 to 1600 nm, depending on glass composition and excitation wavelength (see [2] and references therein). In 2005, the first bismuth-doped optical fibres were fabricated and were shown to lase [3]. Until recently, appreciable optical gain and lasing in bismuth-doped aluminosilicate glass fibres were demonstrated only in the range 1.15 – 1.215 μm [3 – 6], with slope efficiencies of up to ~ 30 %.

For optical fibre communication applications, the range 1300 – 1530 nm is of most interest. To achieve optical gain and lasing in this range, we used bismuth-doped phosphogermanosilicate (PGSB) glass as fibre core material. Such fibres have recently been demonstrated to lase in the range 1300 – 1345 nm [7] and up to 1470 nm [8]. In addition, we studied bismuth-doped germanosilicate (GSB) glass fibres, which differed from PGSB fibres only in that they contained no phosphorus in their core. The aim of this work was to find out how far the gain band of bismuth-doped fibres can be extended to longer wavelengths. To this end, we examined the possibility of creating bismuth-doped fibre lasers operating at 1500, 1520 and 1550 nm. Note that 1500-nm lasing of PGSB fibres was briefly reported in [7]. Moreover, bismuth-doped aluminosilicate fibres were reported to lase in the range 1440 – 1460 nm [9].

Fibres for this investigation were prepared by the MCVD process. The fibre core was made of silica glass doped with 5 at % Ge, 0.5 at % P and 0.02 at % Bi (the last concentration is the detection limit of Bi with our equipment). The absorption spectrum of a single-mode PGSB fibre is displayed in Fig. 1. The spectrum contains bands centred at 450, 770 and 950 nm and a composite band in the range 1100 – 1500 nm. To determine the optimal pump wavelength for long-wavelength lasing of the PGSB fibre, we measured its luminescence spectra under excitation in different absorption bands. The luminescence spectra of the PGSB fibre pumped at $\lambda_p = 532$, 800, 925 and 1230 nm are also presented in Fig. 1. The spectra are normalised to the luminescence bands in the range $\lambda > 1000$ nm.

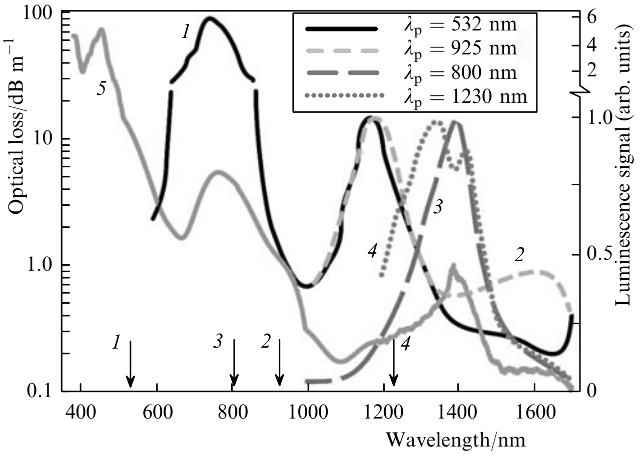

Figure 1. Luminescence spectra of a single-mode PGSB fibre under excitation at (*1*) 532, (*2*) 925, (*3*) 800 and (*4*) 1230 nm; (*5*) optical loss spectrum of the PGSB fibre. The arrows indicate the pump wavelengths.

At $\lambda_p = 532$ nm, luminescence is observed in a very broad spectral range, from 600 to 1700 nm. Pumping at $\lambda_p = 532$ and 925 nm gives rise to a luminescence band with $\lambda_{max} = 1180$ nm. A longer wavelength band (1200 – 1500 nm, $\lambda_{max} = 1400$ nm) is excited at $\lambda_p = 800$ and 1230 nm. At $\lambda_p = 800$ nm, we observe only its longer wavelength component, which is due to bismuth centres associated with germanium and silicon atoms in the core material [10]. At $\lambda_p = 1230$ nm, both the longer and shorter

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E.M. Dianov, S.V. Firstov, O.I. Medvedkov, I.A. Bufetov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia; e-mail: iabuf@fo.gpi.ru;
V.F. Khopin, A.N. Guryanov Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, ul. Tropinina 49, 603600 Nizhnii Novgorod, Russia

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wavelength components of this band are excited, which points to excitation of the bismuth centres bonded to both phosphorus and germanium atoms [10]. In addition, 925-nm excitation of the PGSB fibre produces a luminescence band with $\lambda_{\max} \approx 1600$ nm. (A similar luminescence band of bismuth-doped germanosilicate fibres pumped at 976 nm was first reported by Qui and Shen [11].)

Note that the shape of the luminescence spectrum of the PGSB fibre core (especially the intensity ratio of the bands with $\lambda_{\max} \approx 1180$ and ~ 1600 nm) depends significantly on the pump intensity I_p (Fig. 2). At a relatively low 925-nm pump intensity, the spectra of the PGSB glass core in a fibre preform and multimode fibre are dominated by the 1600-nm emission (Fig. 2, spectra *1*, *2*). With increasing pump intensity, the relative intensity of the peak at $\lambda_{\max} \approx 1180$ nm increases in both the multimode and single-mode fibres, whereas that of the 1600-nm luminescence in the single-mode fibre is lower by about a factor of 2.5, which may be interpreted as evidence that the transitions of the bismuth centres responsible for these luminescence bands differ in saturation intensity.

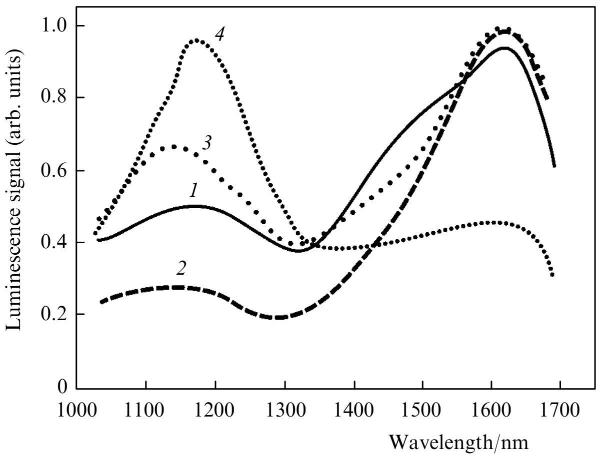

Figure 2. Luminescence spectra of the PGSB core glass pumped at 925 nm: (*1*) preform, $I_p = 50$ W cm^{-2}; (*2*) multimode fibre, $I_p = 80$ W cm^{-2}; (*3*) multimode fibre, $I_p = 4$ kW cm^{-2}; (*4*) single-mode fibre, $I_p = 400$ kW cm^{-2}.

The above results led us to use pump wavelengths $\lambda_p = 925$ and 1230 nm in subsequent experiments with PGSB fibre lasers.

The bismuth-doped fibre lasers (BFLs) had a linear-cavity design, typical of such experiments, with fibre Bragg gratings (FBGs) as mirrors (detailed description of the laser configuration can be found, e.g. in [8]). The lasing wavelength λ_g was determined by the FBG resonance wavelength. The pump source was a Raman fibre laser with $\lambda_p = 1230$ nm or a neodymium fibre laser [12] with $\lambda_p = 925$ nm. In both cases, the pump radiation was single-mode and was launched directly into the core of an active bismuth-doped fibre. We used 30- and 13-m-long PGSB fibres at pump wavelengths of 1230 and 925 nm, respectively. The reflectivity of one FBG was close to 100 %, and that of the other FBG was ~ 90 %.

At $\lambda_p = 1230$ nm, we observed room-temperature lasing at $\lambda_g = 1500$ and 1520 nm, with a threshold pump power of 200–300 mW. Figure 3 shows the output power as a function of pump power for the BFLs and their optical spectra. We failed to obtain lasing at 1550 nm under similar conditions. The lasing threshold at this wavelength was above 4 W.

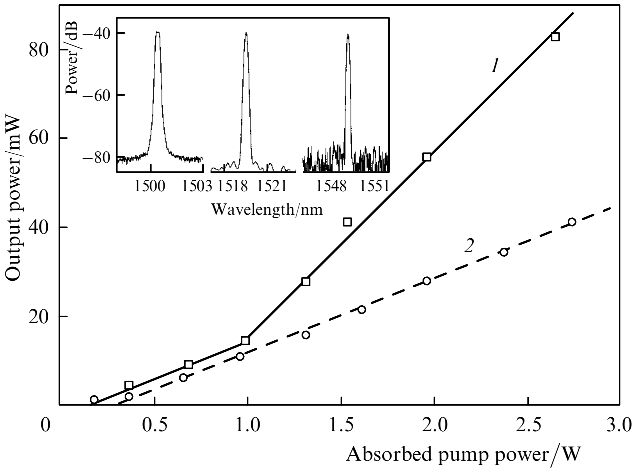

Figure 3. BFL output power as a function of 1230-nm pump power: (*1*) $\lambda_g = 1500$ nm, 4.2% slope efficiency; (*2*) $\lambda_g = 1520$ nm, 1.6 % slope efficiency. Inset: optical spectra of the PGSB fibre lasers with $\lambda_g = 1500$ nm ($\lambda_p = 1230$ nm), $\lambda_g = 1520$ nm ($\lambda_p = 1230$ nm) and $\lambda_g = 1550$ nm ($\lambda_p = 925$ nm).

The absorption spectrum of the GSB fibre (Fig. 4) is similar to that of the PGSB fibre and also shows an IR band in the range 1200–1500 nm. Excitation in this band gives rise to IR luminescence in the range 1300–1500 nm. Using 1230-nm pumping and the above fibre laser configuration, we achieved 1500-nm lasing in a 30-m-long GSB fibre. The lasing threshold was 60 mW, and the room-temperature slope efficiency was 3 %.

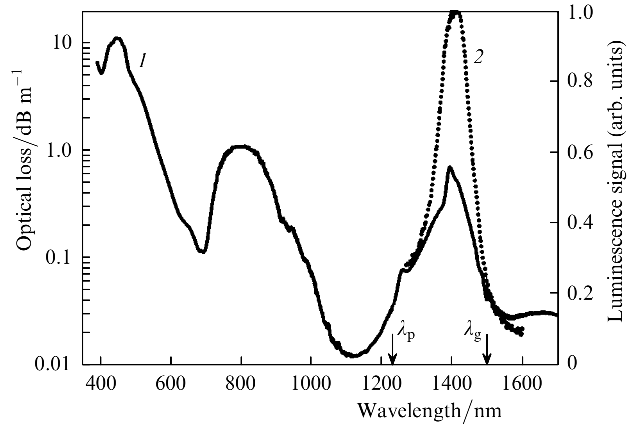

Figure 4. (*1*) Optical loss and (*2*) luminescence spectra of the GSB fibre pumped at $\lambda_p = 1230$ nm.

To obtain lasing at even longer wavelengths, we used a pump wavelength $\lambda_p = 925$ nm. Under 925-nm pumping, the PGSB fibre was made to lase at 1550 nm, with a threshold pump power of 200 mW. The laser output spectrum is displayed in the inset in Fig. 3. We failed to determine the laser efficiency because the highest pump power in those experiments only slightly exceeded the lasing threshold.

Thus, the first bismuth-doped fibre lasers operating in the range 1470–1550 nm were demonstrated. The absorption band centred at ~ 950 nm was used to pump PGSB fibre lasers. Lasing in bismuth-doped fibres in the range 1300 – 1550 nm, demonstrated in this study and previously [7 – 9], provides direct evidence of a real optical gain at these wavelengths. Therefore, bismuth-doped fibres can, in principle, be used as broadband amplifiers in the range 1300 – 1550 nm, i.e. in the O, E, and S bands and a part of the C band of the second and third telecom windows.

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