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Polarised luminescence of bismuth active centres in germanosilicate glasses

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Abstract. **We have studied polarised luminescence of bismuth active centres in germanosilicate glasses. The 1.4-μm luminescence components with orthogonal polarisation states under excitation with linearly polarised light at $\lambda = 1.26$ μm have been shown to differ in intensity. The degree of polarisation reaches ~0.12. Increasing the concentration of bismuth active centres leads to a decrease in the degree of polarisation of luminescence in the range studied.**

Keywords: *polarised luminescence, anisotropy of optical centres, bismuth, active fibre.*

1. Introduction

A great deal of attention is currently paid to the development of broadband fibre-optic amplifiers and tunable lasers for the near-IR spectral region. In this context, it is promising to use gain media in the form of bismuth-doped fibres, which have broad near-IR gain bands. To date, a large number of bismuth-doped fibre laser devices for the spectral range 1150–1750 nm have been demonstrated [1, 2]. As shown in studies of fibre amplifiers and superluminescent fibre sources (SFS's) [3], the degree of polarisation of the SFS output signal depends on the polarisation state of the pump light, and the gain coefficient depends on the mutual orientation of the signal and pump polarisation directions. These findings suggest that the absorption and luminescence cross sections of the bismuth active centres involved are not isotropic. The polarisation-dependent gain effect has been rather well studied for rare-earth-doped fibres [4]. Extensive studies have been concerned with polarised luminescence [5] in bulk glasses doped with Pr^{3+}, Nd^{3+}, Eu^{3+}, Er^{3+} and Tm^{3+} ions [6–8]. At the same time, neither absorption nor emission anisotropy of active centres in bismuth-doped glasses or fibres has been studied in detail.

2. Subject of investigation and experimental procedure

The samples for this investigation had the form of bismuth-doped fibre preforms produced by the MCVD process. The cladding consisted of pure silica glass, and the core, of bismuth-doped germanosilicate glass. The preform diameter was ~12 mm and the core diameter was 2 mm. A typical refractive index profile of the samples is shown in Fig. 1a. The core–cladding index difference Δn was $(7-9)\times10^{-3}$. All the samples contained less than 0.1 wt% Bi because effective amplification and lasing are only possible in optical fibre with low bismuth concentration. Figure 1b shows typical absorption and luminescence spectra of the bismuth active centres (BACs). In this study, the centres were excited by 1260-nm radiation and luminescence was detected in the range 1300–1600 nm.

Figure 2 shows a schematic of the experimental setup. As a signal source, we used a Fianium FemtoPower 1060 supercontinuum source, which generated quasi-continuous ultra-

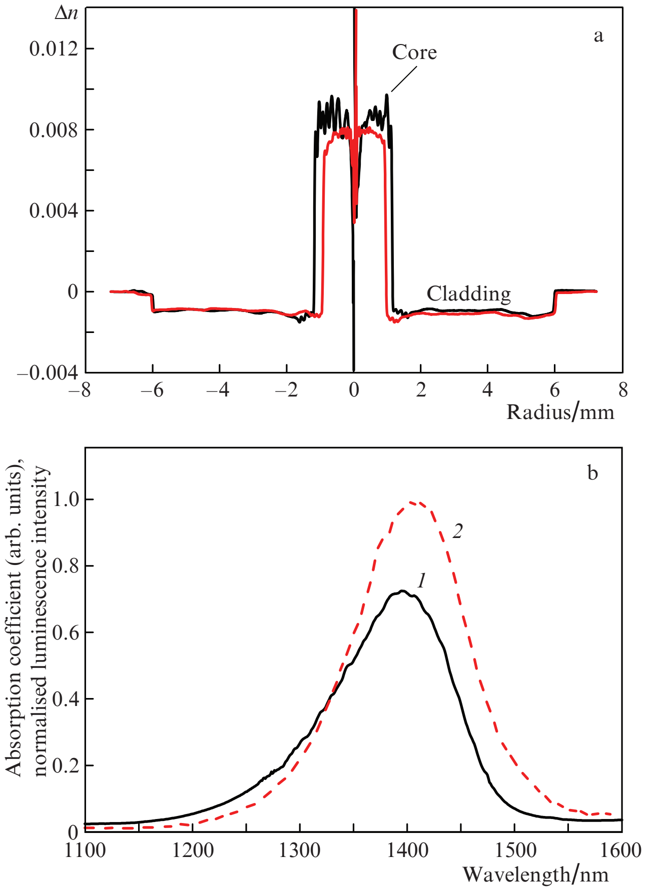

Figure 1. (a) Typical refractive index profiles of the samples and (b) absorption (*1*) and luminescence (*2*) spectra of the BACs.

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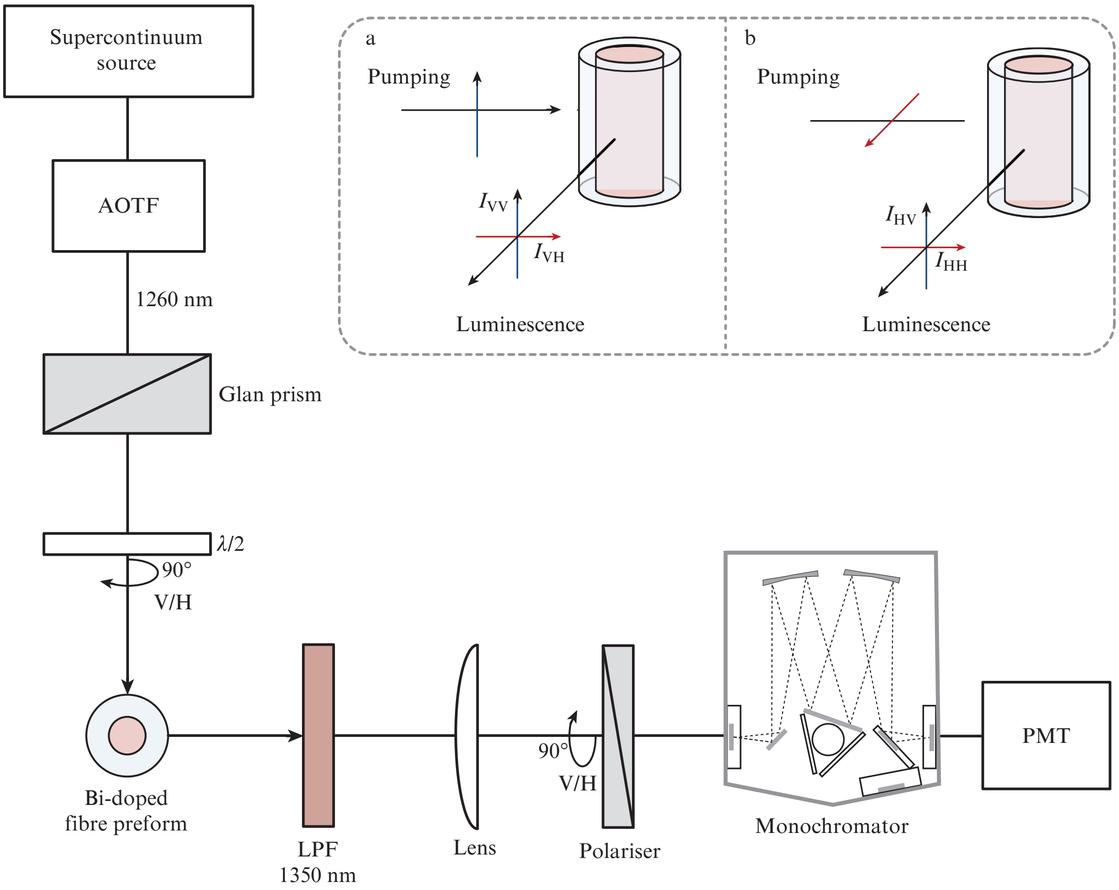

Figure 2. Schematic of the experimental setup (LPF = long-pass filter).

broadband light in the range 450–1800 nm with a power spectral density of ~1 mW nm^{-1}. The supercontinuum source had an output fibre pigtail for connecting to an acousto-optic tunable filter (AOTF), which allowed one or a few lines 5 nm or more in width in the range 1100–1700 nm to be separated from the broad spectrum of the supercontinuum source. In our experiment, we used a wavelength of 1260 nm, corresponding to the excitation band of BACs in germanosilicate glasses. The AOTF output was a narrow collimated partially polarised light beam. Linearly polarised light was separated by a Thorlabs GL10 Glan prism of laser grade calcite, with extinction of at least 100 000 : 1 in the range 350–2300 nm. The plane of polarisation of pump light was rotated by a Thorlabs AHWP10M-1600 achromatic half-wave plate, operating in the range 1100–2000 nm. The luminescence of the samples was focused onto the entrance slit of a monochromator by a plano-convex quartz glass lens. The front surface of the lens was located 70 mm from the central part of the sample. To suppress the scattered pump light, a Thorlabs FEL1350 filter (Fig. 2, LPF) was placed between the lens and sample, which cut wavelengths under 1350 nm. The luminescence polarisation was controlled by a Thorlabs LPIREA050-C polariser, which had an extinction coefficient above 1000 : 1 in the operating wavelength range 1050–1700 nm. The setup included a symmetric Czerny–Turner monochromator with a ruled grating (830 lines/mm) having a blaze wavelength of 1200 nm, optimised for operation in the range 500–1800 nm. The luminescence signal was detected by a Hamamatsu R5509-72 liquid nitrogen-cooled photomultiplier (300–1700 nm).

The half-wave plate was mounted so that the plane of polarisation of excitation light was oriented vertically (Fig. 2, inset a). We measured I_{VV} and I_{VH} luminescence intensities (where the first letter in the subscript refers to the plane of polarisation of pump light, and the second, to the plane of polarisation of luminescence; V = vertical and H = horizontal) at two orientations of the polariser, corresponding to transmission of the vertically and horizontally polarised luminescence components. The degree of polarisation was calculated as $P = (I_{VV} - I_{VH}G)(I_{VV} + I_{VH}G)^{-1}$. Some components of the setup had polarisation-dependent transmission, so the above formula includes a correction coefficient, G, which was evaluated by measuring the I_{HV} and I_{HH} intensities. Given that, under excitation with horizontally polarised light (Fig. 2, inset b), the vertically and horizontally polarised luminescence components have equal intensities, the ratio of their measured intensities (at the output of the system) characterises the polarisation selectivity of the system: $G = I_{HV}/I_{HH}$. This coefficient is essentially identical to the extinction coefficient of the monochromator grating and varies from 2.25 to 2.7 in the range $\lambda = 1.35–1.45$ µm.

To ascertain whether the experimental setup operated properly and assess the measurement accuracy ensured by it, we used Er^{3+}-doped glass samples with a known degree of polarisation of their luminescence. Our measurements showed that the degree of polarisation in the test samples was within 1%, in agreement with experimental data reported by Rokhmin et al. [7]. Thus, our setup allowed the degree of polarisation of luminescence to be measured with an accuracy of 1% or better.

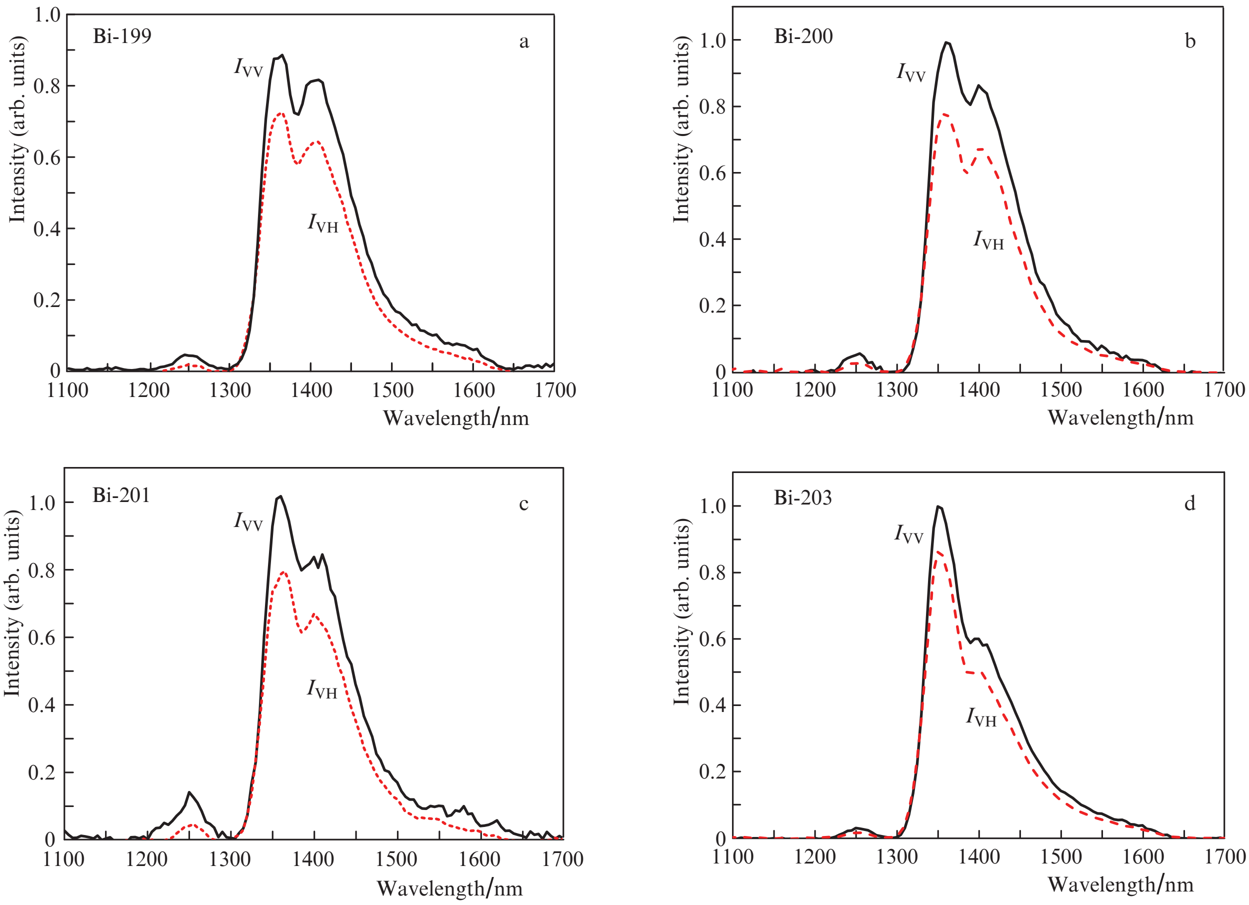

Figure 3. Polarised luminescence spectra of BACs in the (a) Bi-199, (b) Bi-200, (c) Bi-201 and (d) Bi-203 samples under excitation at λ = 1260 nm.

3. Measurement results

Figure 3 shows polarised luminescence spectra of different bismuth-doped fibre preforms. The peak at $\lambda \sim 1.25$ μm is due to the pump light partially transmitted through the LPF, and the main luminescence peak, located at 1.4 μm, has a small dip at $\lambda \approx 1.385$ μm, attributable to the presence of OH groups in the lenses and filters mounted in the path of the luminescence.

Our measurements demonstrate that, under excitation with linearly polarised light having vertical polarisation, the vertically and horizontally polarised luminescence components differ significantly in intensity. Table 1 presents the degree of polarisation of luminescence and the absorption coefficient of BACs at $\lambda \approx 1.4$ μm in our samples. The absorption coefficient of the BACs characterises the relative concentration of active bismuth in the core. It was measured in fibres drawn out from the preforms under study because this was significantly easier and more accurate than loss measurements in the preforms. Drawing the preforms was assumed to cause no appreciable transformation of the BACs.

The above data suggests that the absorption and luminescence cross sections of the bismuth active centres are not spatially isotropic. The degree of polarisation of luminescence of the BACs in germanosilicate glasses is an order of magnitude higher than that in Er^{3+}-doped glasses. It follows from the present results that the polarisation-dependent gain in bismuth-doped germanosilicate core fibres should exceed that in Er-doped fibres by about one order of magnitude. Therefore, in designing and fabricating bismuth-doped fibre devices increased attention should be paid to polarisation dependences, including the degrees and states of polarisation of signal and pump light. In connection with this, polarisation-dependent gain measurements in a polarisation-maintaining bismuth-doped germanosilicate fibre are planned in our future work.

It is worth noting that, as seen from Table 1, the degree of polarisation of luminescence in our experiments decreases slightly with increasing BAC concentration, which can be interpreted as evidence of nonradiative excitation transfer between active centres in the case of an increased BAC concentration. Such a process will be accompanied by ‘loss of information’ about the polarization state of excitation light, and the experimentally observed degree of polarisation of luminescence will decrease. The present data leads us to conclude that, in the concentration range studied, the fraction of BACs that exchange energy with each other is relatively small. Photon-mediated energy transfer between BACs is essentially ruled out because the samples have a small optical thickness (no greater than 0.0045 mm).

Table 1. Spectral characteristics of the BACs at $\lambda \approx 1.4$ μm.

Sample	Absorption coefficient/dB m^{-1}	Degree of polarisation
Bi-199	2.2	0.12
Bi-200	1.65	0.12
Bi-201	1.4	0.12
Bi-202	18	0.09
Bi-203	4	0.09

Thus, we have studied polarised luminescence of bismuth active centres in germanosilicate glasses and demonstrated partial polarisation of luminescence near $\lambda = 1.4$ μm under excitation with linearly polarised light at $\lambda = 1.26$ μm. The degree of polarisation reaches ~0.12. Raising the concentration of bismuth active centres in the range studied leads to a slight decrease in the degree of polarisation.

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