Abstract: The Bi-doped fiber lasers operating at wavelengths of 1280 nm, 1330 nm, 1480 nm, and 1500 nm with a maximal output power of up to 2 W and a slope efficiency of 14–25% have been demonstrated for the first time. We have also investigated the influence of the doping concentration (GeO$_2$ and P$_2$O$_5$) on the optical and laser generation properties of Bi-doped phospho-germanosilicate fibers.

1. Introduction

Bi-doped silica-based glasses and fibers are promising materials for tunable and ultra-short-pulse lasers and optical amplifiers in wavelength range 1150–1550 nm [1,2]. In 2005, Bi, Al-codoped silicate fiber lasers operating at 1140 nm (~10% efficiency) and 1215 nm (~14% efficiency) were demonstrated for the first time [3]. Later it was shown that doping of aluminum into the fiber core was not necessary for the appearance of IR luminescence [4–6]. However, if Ge and/or P instead of Al were added to the silica fiber core, then IR luminescence of bismuth active centers (BAC) shifted towards the long-wavelength range, to 1300–1500 nm. Al$_2$O$_3$-free Bi-doped phospho-germanosilicate fibers were used as active media for first fiber lasers generating in the wavelength range 1300–1550 nm [7–11]. The slope efficiency and the threshold of such lasers were ~3% and ~200 mW under 1230-nm pumping, respectively. In addition, the optical gain in the wavelength range 1430–1495 nm and laser generation at 1440–1460 nm in Bi-doped silica fibers codoped with Al were revealed [12]. The slope efficiency of such Bi-doped
fifth to seventh modes of single-mode Bi-doped phosphogermanosilicate fibers.

The experimental samples were single-mode Bi-doped silica-based fibers codoped with different concentrations of germanium and/or phosphorus. The preforms of fibers were fabricated by the MCVD-process. The composition of the core glass is given in Table 1. The concentrations of the dopants were evaluated by an Oxford Instruments JSM 5910LV scanning electron microscope with an X-ray spectrum analyzer. In all the samples, the bismuth concentration is lower than the detection threshold, which is about 0.02 at.%. It is worth noting that the composition of fibers F3 and F2 are the same, but the bismuth concentration in the core of fiber F3 is greater than that in fiber F2 and in the other fibers of this series.

The absorption spectra in the visible and near-IR wavelength range were measured using the “cut back” technique by optical spectrum analyzers: HP 70950B for the IR region and Ocean Optics 2000 for the visible region. Luminescence was observed through the lateral fiber surface. The luminescence spectra were recorded by the above spectrum analyzers. The sources of luminescence excitation were a fiber-coupled laser diode operating at 808 nm (∼100 mW output power), a Raman laser at 1230 nm (up to 10 W), the second harmonic of a Nd:YAG laser (532 nm, 300 mW), and a CW Nd-doped fiber laser emitting at 925 nm [14].

The luminescence decay of BAC in the region 1300–1500 nm was detected using an InGaAs photodiode with a response time of ∼4 μs [15], a detailed description of the experimental setup is given. At the wavelength of 808 nm, BACs were excited with rectangular pulses with a duration of 1 ms. The luminescence decay time at 750 nm was measured using a Si-photodiode (response time ∼6 ns) with pulses of the second harmonic of a Q-switched Nd:YAG (527 nm) laser as the pump source (duration ∼10 ns). The signals were recorded using a digital oscilloscope (Le Croy Wavepro 7100) with sufficient time resolution.

A broadband light source operating at 1250–1550 nm was used as the signal source for the optical gain measurements of the fibers. A Raman laser emitting at 1230 nm served as the pump source. The optimum length of the B-doped fiber was determined from the small-signal absorption at the excitation wavelength. The optical gain in the Bi-doped fibers was calculated as the signal intensity ratio with the pump switched on and switched off, respectively (“on/off gain”).

We have constructed a number of fiber lasers based on Bi-doped fibers. The simple linear laser cavity was formed by two fiber Bragg gratings with the reflection coefficients R₁ = 99.5% and R₂ = 4% or 50%. The Raman lasers operating at 1230 nm, 1310 nm, and 1340 nm were used as pump sources. All measurements were carried out at room temperature.

### 3. Experimental results

Fig. 1 shows the absorption spectra measured in the visible and near-IR ranges for Bi-doped fibers with different core glass composition (Table 1). It is seen that the absorption spectrum of fiber F1 consists of broad bands peaking at ∼450 nm, 800 nm, a weak shoulder at ∼950 and

<table>
<thead>
<tr>
<th>Title of fiber</th>
<th>Concentration</th>
<th>∆n × 10⁻³</th>
<th>Mode field diameter at 1.3 μm, μm</th>
</tr>
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<tbody>
<tr>
<td>Ge, at.%</td>
<td>P, at.%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>4.3</td>
<td>–</td>
<td>19</td>
</tr>
<tr>
<td>F2</td>
<td>4.4</td>
<td>0.5</td>
<td>22</td>
</tr>
<tr>
<td>F3</td>
<td>4.3</td>
<td>0.6</td>
<td>18.5</td>
</tr>
<tr>
<td>F4</td>
<td>2.9</td>
<td>1.9</td>
<td>14.5</td>
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<tr>
<td>F5</td>
<td>0.5</td>
<td>2.7</td>
<td>8.5</td>
</tr>
<tr>
<td>F6</td>
<td>0.3</td>
<td>3.9</td>
<td>9</td>
</tr>
<tr>
<td>F7</td>
<td>–</td>
<td>3.7</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 1 The title, composition and optical parameters of single-mode Bi-doped phosphogermanosilicate fibers

![Figure 1](http://www.lphys.org) The absorption spectra of the Bi-doped silica-based fibers codoped with Ge and/or P (for clarity of figure the absorption spectra of all the fibers were multiplied by applicable coefficient: F1 − 1, F2 − 0.85, F3 − 0.6, F4 − 15, F5 − 30, F6 − 250, F7 − 200)
Luminescence spectra of Bi-doped fibers upon excited at 1230 nm (∼300 mW) (a) and 808 nm (∼70 mW) (b). A comparison of these luminescence spectra allows to conclude that the relative intensity of the ∼1300 nm and ∼1400 nm bands depends on the ratio of the P$_2$O$_5$ and GeO$_2$ concentrations. In particular, we observed an increase of bands ∼1300 nm and 1400 nm with increasing the P$_2$O$_5$ and GeO$_2$ doping level, respectively. Fig. 2b shows the luminescence spectra upon excitation at ∼808 nm. The spectra also consist of the same two bands centered at 1300 nm and 1400 nm. We believe that the absorption and luminescence bands peaking at 1300 nm and 1400 nm belong to bismuth active centers associated with P (1300 nm) and Ge, respectively. The band peaked at ∼1400 nm in the luminescence spectra of the fiber F7 (Ge-free) originates apparently from the BAC associated with Si.

In the case of 0.925-μm excitation, the emission spectrum consisted of two wide bands in the near-IR range, at ∼1150 and 1600 nm for fibers F2–F4 and a single band at ∼1120 nm for fibers F5–F7. On the contrary, sample F1 does not show any near-IR emission upon excitation at 925 nm (Fig. 3a). Besides a new emission band at ∼940 nm arises in fibers F1–F3. However, this band is absent in the luminescence spectra of fibers F4–F7.
Upon excitation at 532 nm, two emission bands centered at ~750 nm and in the region 1150–1200 nm are observed in fibers F2–F7. The shape of the 750 nm band for samples F2–F5 is similar. In fiber F1, the band peaking at 800 nm was observed instead of the 750 nm band. It can be seen that fiber F1 also reveals weak luminescence in the region 1000–1350 nm when excited at 532 nm (Fig. 3b).

We also carried out luminescence decay measurements for all samples, and the results for fibers F2, F7 are shown in Fig. 4a and Fig. 4b. The luminescence decay at 750 nm (fiber F2) consists of two components with decay times: $\sim 6$ ns (time response of Si detector is up to 6 ns) and $\sim 5 \mu$s (Fig. 4a). For samples F2 and F7 excited at 808 nm, the monitoring wavelengths were 1400 nm and 1300 nm, respectively. The luminescence decay of F2 and F7 fibers exhibits a single-exponential decay with characteristic times of $\sim 600$ and $\sim 800 \mu$s, respectively (Fig. 4b). The luminescence lifetimes of the rest fibers lie between 600 and 800 $\mu$s.

It was expected that these fibers could have some amplification, because the short-lived BACs were absent [15]. Indeed, we could detect amplification in Bi-doped phosphogermanosilicate fibers. The gain spectra of some fibers are given in Fig. 5. Note that the gain coefficient was measured with an accuracy of $\sim 15\%$ in the wavelength regions 1250–1360 nm and 1425–1550 nm. The gain coefficient in the spectral region of 1360–1435 nm was not defined because of high OH-group absorption. We found that the gain spectra strongly depend on the composition of the fiber core: the gain spectra maxima in fibers F1–F3 lie in wavelength range of 1360–1420 nm, and in fibers F5–F7, at the wavelength of 1280 nm upon excitation at wavelength of 1230 nm. It can be seen that the magnitude of the long-wavelength tail (1425–1550 nm) of the gain spectra increases as a result of doping of the fiber core with GeO$_2$, whereas the gain of fiber F7 in the range $\lambda > 1430$ nm decreases monotonically almost to the detection threshold.

Thus, the above data allowed us to make a number of bismuth fiber lasers (BFL) based on phosphogermanosilicate fibers. All the BFLs were assembled in accordance with the common linear scheme consisting of an active fiber and fiber Bragg gratings (FBGs) spliced to the fiber ends. Earlier the first BFLs based on the fiber F2 operating in spectral region 1300–1550 nm were demonstrated [7–10,16]. The Raman fiber laser at 1230 nm was used as a pumping source for lasers based on F2 fiber. The slope efficiency of these BFLs was rather low $\sim 3\%$. It has been
shown above that there are three kinds of BACs in the fiber core glass with different optical properties. Upon pumping at 1230 nm, the major part of BACs bonded with phosphorous and a small part of BACs bonded with germanium have been excited. Probably, the low efficiency of BFLs is connected with smallness of the P$_2$O$_5$ concentration in F2 fiber and inefficient transfer of excitation energy between active bismuth centers. Changing of the excitation wavelength allows us to increase the BFL efficiency. Indeed, under pumping at 1310 nm, the laser generation slope efficiency of ~17% at wavelength of 1480 nm was obtained. The lasing output power with respect to the absorbed pump power is presented in Fig. 6a (for comparison, the same dependence for 1480 nm laser with a pump wavelength of 1230 nm is also shown). In both the cases, we used the same fiber laser cavity consisting of two pairs of Bragg gratings (BG) with reflection coefficients R ~ 100% and 50% and a 30-m long Bi-doped fiber (sample F2). For better absorption of pump radiation, the 90-m piece of fiber was used in the next experiment. As a result, the slope efficiency of BFL (~50% output coupler) pumped at 1340 nm was ~23% (Fig. 6b). The maximal output power was ~2 W. After removing the output coupler we also obtained lasing with a slope efficiency of ~18% in the cavity formed by HR BG (R ~ 100%) and a cleaved fiber endface (Fig. 6b). Moreover, the laser with a cleaved fiber end as an output coupler demonstrated a 14 dB round trip optical net gain in the laser cavity.

The slope efficiency of a 1.5-µm BFL based on the fiber F3 with a pump wavelength of 1230 nm was measured to be ~0.3%. Therefore, increasing the bismuth concentration in the fiber core leads to a decrease of the lasing efficiency.

In addition, the 1500-nm laser slope efficiency of ~14% was achieved at a pump wavelength of 1310 nm (BFL was based on 70-m long F1 fiber). In this case, the output coupler had the reflection coefficient of ~92%. The power thresholds for all the above BFLs amounted to ~100–200 mW.

It was expected that upon pumping at 1230 nm, the slope efficiency of the BFLs based on fibers containing a high concentration of P$_2$O$_5$ and a low concentration of GeO$_2$ (fibers F5–F7) operating in the wavelength region 1260–1340 nm would be higher. The slope efficiency of BFLs based on 30-m long fiber F5 emitting at wavelengths of 1280 nm and 1330 nm (upon 1230 nm excitation) amounted to ~12%. An increase of the laser length to ~100 m led to an increase of the slope efficiency up to ~24%, and an increase of the laser output at 1330 nm up to ~2.5 W (Fig. 6b). On shifting the pump wavelength to the short-wavelength region (1058 and 1085 nm), the slope efficiency of 30-m long fiber F5 emitting at the wavelength of 1330 nm went down by more than an order of the magnitude.

4. Conclusion

We have investigated the influence of the fiber core composition on optical and lasing properties. From a comparison of the luminescence and absorption spectra, it has been shown that fiber core contains three kinds of active bismuth centers associated with Ge, P, and Si. It was demonstrated that the slope efficiency of BFLs strongly depends on the pump and lasing wavelengths and on the fiber core composition. The slope efficiencies of BFLs operating at 1280, 1330, 1480, and 1500 nm amounted to 14–20%. The maximal output power from BFL emitting at 1330 nm and 1480 nm was as great as ~2.5 W and 2 W, respectively. The net gain in a Bi-doped fiber of 14 dB was achieved at the wavelength 1480 nm. Demonstration of an increased efficiency of lasers based on Bi-doped phosphogermanosilicate fibers in the spectral range ~1300–1500 nm appears to be an important advance in solving the problem of high-efficiency wideband optical amplifiers for this spectral range.
References