Abstract: The recent results on the new laser material – Bi-doped glasses and optical fibers are reviewed. First, luminescence properties of various Bi-doped glasses are discussed. At last the results of investigations of Bi-doped fiber lasers covering a wavelength range of 1150 – 1550 nm are presented.

Bi-doped fiber lasers

I.A. Bufetov* and E.M. Dianov

Fiber Optics Research Center, Russian Academy of Sciences, 38, Vavilov Str., Moscow 119333, Russia

Received: 26 February 2009, Accepted: 1 March 2009
Published online: XXXXXXXX 2009

Key words: bismuth, fiber laser, IR luminescence

PACS: 42.55.Wd, 42.55.Zz, 42.70.Hj, 42.70.Ce

1. Introduction

Since the appearance of the first lasers in 1960 great attention has been paid to the search and the creation of new active laser media. This made it possible to improve the characteristics of the existing lasers and to develop new ones. Active glass optical fibers are one of the most efficient laser media. Fiber lasers have excellent beam quality and the highest efficiency among solid-state lasers. Laser diodes with a fiber output are used as a pumping source. Fiber Bragg gratings form a laser cavity. Such all-fiber monolithic construction provides small size and weight and high reliability. Because of the large surface area of a fiber with respect to its volume, cooling of fiber lasers is very efficient, even at high power levels.

The first fiber laser was constructed by E. Snitzer in 1961 [1]. He used a Nd-doped glass optical fiber as an active medium. However, at that time this avenue of laser physics was not pursued and it is evidently why. The advent of modern high-efficiency fiber lasers was possible only owing to the development of low-loss glass optical fibers in the early 1970s and the subsequent rapid development of optical fiber communication. The latter became the decisive factor in the development and industrial production of long-lived high-brightness laser diodes, various specialty optical fibers and other fiber-based devices. These components were the base for the production of fiber lasers.

* Corresponding author: e-mail: iabuf@fo.gpi.ru
Table 1 Luminescence properties of Bi-doped glasses

<table>
<thead>
<tr>
<th>No.</th>
<th>Composition, mol%</th>
<th>(\lambda_p), nm</th>
<th>(\lambda_c), nm</th>
<th>FWHM, nm</th>
<th>(\tau), (\mu)s</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>95.7 SiO(_2) – 2.2 Al(_2)O(_3) – 0.3 Bi(_2)O(_3)</td>
<td>500</td>
<td>750</td>
<td>140</td>
<td>3.62</td>
<td>[2]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1140</td>
<td></td>
<td>220</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>700</td>
<td>1122</td>
<td>160</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>800</td>
<td>1250</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>96 GeO(_2) – 3 Al(_2)O(_3) – 1Bi(_2)O(_3)</td>
<td>800</td>
<td>1300</td>
<td>320</td>
<td>255</td>
<td>[4]</td>
</tr>
<tr>
<td>3</td>
<td>96 GeO(_2) – 3 Ga(_2)O(_3) – 1 Bi(_2)O(_3)</td>
<td>808</td>
<td>1325</td>
<td>345</td>
<td>500</td>
<td>[16]</td>
</tr>
<tr>
<td>4</td>
<td>96 GeO(_2) – 3 Ta(_2)O(_3) – 1 Bi(_2)O(_3)</td>
<td>808</td>
<td>1310</td>
<td>400</td>
<td>&gt;200</td>
<td>[17]</td>
</tr>
<tr>
<td>5</td>
<td>75 GeO(_2) – 20 MgO – 5Al(_2)O(_3) – 1Bi(_2)O(_3)</td>
<td>980 (808)</td>
<td>1150 (1290)</td>
<td>315 (330)</td>
<td>264</td>
<td>[18]</td>
</tr>
<tr>
<td></td>
<td>75 GeO(_2) – 20 CaO – 5Al(_2)O(_3) – 1Bi(_2)O(_3)</td>
<td>(808)</td>
<td>1150 (1290)</td>
<td>440 (300)</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 GeO(_2) – 20 SrO – 5Al(_2)O(_3) – 1Bi(_2)O(_3)</td>
<td>(808)</td>
<td>1150 (1290)</td>
<td>510 (225)</td>
<td>1725</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>82 P(_2)O(_5) – 17 Al(_2)O(_3) – 1 Bi(_2)O(_3)</td>
<td>405</td>
<td>1210</td>
<td>235</td>
<td></td>
<td>[19]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>514</td>
<td>1173</td>
<td>207</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>808</td>
<td>1300</td>
<td>300</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>63 SiO(_2) – 23 Al(_2)O(_3) – 13 Li(_2)O – 1 Bi(_2)O(_3)</td>
<td>700</td>
<td>1100</td>
<td>250</td>
<td></td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800</td>
<td>1250</td>
<td>450</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>900</td>
<td>1100</td>
<td>500</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>59 P(_2)O(_5) – 12 B(_2)O(_3) – 15 La(_2)O(_3) – 6 Al(_2)O(_3) – 17 Li(_2)O – 1 Bi(_2)O(_3)</td>
<td>530</td>
<td>690</td>
<td>100</td>
<td>4</td>
<td>[21]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800</td>
<td>1150</td>
<td>290</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>980</td>
<td>1125</td>
<td></td>
<td>290</td>
<td></td>
</tr>
</tbody>
</table>

Until 2005 all fiber lasers were based on rare earth-doped fibers. At present high-power rare-earth-doped fiber lasers with the wavelengths of generation in the near IR region have found a widespread use in optical communication, medicine, material treating and other applications.

Fig. 1 shows the spectral regions of the existing efficient fiber lasers based of rare earth ions. It is seen that there is a spectral region of 1150 – 1500 nm where no fiber lasers (and any other efficient lasers) exist. But this spectral region is very promising for a number of important applications, such as advanced optical communication systems, medicine, astrophysics.

Fortunately, it has been discovered recently, that some Bi-doped glasses (silica-based, aluminophosphate, germanate, and others) emit luminescence in an exceptionally wide region of 1100 – 1600 nm, the luminescence bands being very broad – 200 – 300 nm [2–4] (Fig. 2). These results showed a possibility for the development of fiber lasers and ultrawide band optical fiber amplifiers in this spectral region.

The first Bi-doped fiber optical fibers were fabricated in 2005 using MCVD technique [5,6]. On the base of these fibers the first Bi-doped fiber laser was demonstrated the same year [7]. These achievements have opened a prospect for the creation of a new class of advanced fiber lasers.

It is interesting to note, that the first Bi lasers, using the Bi atoms and molecules in a gas phase as an active medium, were demonstrated in visible and IR regions 25 – 40 years ago (see for example [8–11]).

In this paper the recent results on the new type of solid state lasers – Bi-doped fiber lasers are reviewed. Sec. 2 discusses the luminescence properties of various Bi-doped glasses and fibers. Sec. 3 is concerned with the optical gain in Bi-doped glasses and fibers. Various designs of Bi fiber lasers are described in Sec. 4. This section embraces both Bi fiber lasers for a spectral region of 1140 – 1215 nm, and recently demonstrated Bi fiber lasers for a region of 1300 – 1520 nm A short summary is provided in Sec. 5.
2. Luminescence properties of various bi-doped glasses and fibers

Visible luminescence from Bi$^{2+}$- and Bi$^{3+}$-doped glasses and crystals is well known (see for example [12–14]). In 2001 Y. Fujimoto and M. Nakatsuka discovered a new near-infrared luminescence from a Bi-and Al-codoped silica glass [2] and demonstrated optical amplification in this glass at 1300 nm with 800 nm excitation in 2003 [15]. Thorough spectroscopic investigations of the glass, the measurements of luminescence lifetime and electron spin resonance allowed the authors to conclude that the observed luminescence was not connected with Bi$^{2+}$ and Bi$^{3+}$. After this a large number of papers (more than thirty) devoted to the near infrared luminescence in various Bi-doped glasses, have been published.

Table 1 shows compositions of some selected glasses and their luminescence properties. $\lambda_p$ and $\lambda_e$ – excitation (pump) and emission peak wavelengths correspondingly, FWHM – full-width at half maximum of luminescence bands, $\tau$ – lifetime of Bi luminescence.

The selection of glass compositions was made taking into account the following considerations.

First, it seemed proper to show the variety of Bi-doped glasses, in which the near infrared luminescence was observed. That’s why silica- and germania-based glasses, aluminophosphate, boroaluminophosphate, and lithiumaluminosilicate glasses are placed in the table.

Second, it seemed important, for one basic glass (e.g. germanate glass), to show the influence of various glass components on the luminescence properties (glasses 2 – 5 in the table).

The glasses were prepared by the conventional melting-quenching technique on a 20 – 30 g scale and for each series of glasses samples of typical dimensions $10 \times 10 \times (2 – 5)$ mm$^3$ were also prepared for the transmission and luminescence measurements.

Four Bi absorption bands were observed in the transmission spectra of practically all glasses at approximately 500, 700, 800, and 1000 nm. Most luminescence measurements were carried out with excitation at these bands.

The analysis of the luminescence properties of the Bi-doped glasses from Table 1 allows one to make a number of interesting conclusions:

- the luminescence spectra consist of several bands and the spectral position of the bands is determined by the excitation wavelength and depends slightly on glass composition;
- the luminescence bands are very broad (up to 500 nm), the bandwidth depending on the glass composition and the excitation wavelength;
- the lifetime of the near infrared luminescence is two orders of magnitude longer than that of Bi$^{3+}$-doped glasses;
- the absorption bands are situated in a spectral region of 800 – 1000 nm where long-lived high-brightness laser diodes developed for the pumping of lasers and amplifiers are available;
- in most Bi-doped glasses strong near IR luminescence was observed only if the glasses contained Al; in Bi-doped germania-based glasses the luminescence was also observed when these glasses contained B, Ga, and Ta.

These unique properties of the Bi-doped glasses discussed above show a great potential for the creation of a new generation of fiber lasers and ultrawideband optical amplifiers for a spectral region of 1150 – 1500 nm.

All the results discussed above have been obtained in bulk glasses. The question was if it would be possible to fabricate high quality long fibers with similar lumines-
I.A. Bufetov and E.M. Dianov: Bi-doped fiber lasers

<table>
<thead>
<tr>
<th>No.</th>
<th>Core glass composition, mol.%</th>
<th>Bi concentration, at.%, and doping technique</th>
<th>Loss at 1000 nm, dB/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>88.2 SiO$_2$ – 1 Al$_2$O$_3$ – 6.6 GeO$_2$ – 4.2 P$_2$O$_5$</td>
<td>&lt; 0.02, solution</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>83.8 SiO$_2$ – 15 Al$_2$O$_3$ – 1.2 GeO$_2$</td>
<td>&lt; 0.02, solution</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>96.7 SiO$_2$ – 3.3 Al$_2$O$_3$</td>
<td>0.15, solution</td>
<td>≈ 20</td>
</tr>
<tr>
<td>17</td>
<td>94.2 SiO$_2$ – 5 Al$_2$O$_3$ – 0.8 GeO$_2$</td>
<td>&lt; 0.02, vapor</td>
<td>2.2</td>
</tr>
<tr>
<td>25</td>
<td>98 SiO$_2$ – 2 Al$_2$O$_3$</td>
<td>&lt; 0.02, vapor</td>
<td>1.06</td>
</tr>
<tr>
<td>33</td>
<td>95 SiO$_2$ – 5 Al$_2$O$_3$</td>
<td>&lt; 0.02, solution</td>
<td>1.8</td>
</tr>
<tr>
<td>430</td>
<td>75 GeO$_2$ – 19 SiO$_2$ – 5 Ta$_2$O$_5$ – 1 P$_2$O$_5$</td>
<td>&lt; 0.02, vapor</td>
<td>∼ 0.02</td>
</tr>
</tbody>
</table>

Table 2 Fiber preforms

**Figure 5** (online color at www.lphys.org) Absorption spectra of fibers 5, 25, 33, and 430. Short wavelength part of spectrum 5 was measured in a slice cut from a perform.

**Figure 6** (online color at www.lphys.org) Luminescence spectra of Bi-doped fibers no. 1, no. 4, and no. 430 excited at 676 (a) and 1064 nm (b).

Luminescence properties using Bi-doped glasses. And in case of a positive answer, if it would be possible to create efficient fiber lasers.

In 2005 these questions were answered positively by developing the first low-loss Bi-doped silica-based fibers [5,6] and fiber lasers [7]. Later the similar Bi-doped fibers were fabricated in other laboratories [22–24].

The first Bi-doped fiber preforms were fabricated by MCVD technique using a silica substrate tube which served as a reflecting cladding of fibers [5,25]. Aluminum was used as a dopant in the silica core of fibers to provide Bi luminescence and to create a core – cladding index difference of 0.006–0.030. Ge and P were added for the study of their possible influence on the luminescence properties of Bi centers. Bi and Al were incorporated by a solution technique or from a vapor phase. Other dopants were deposited from a vapor phase. Table 2 shows the core compositions of the first preforms fabricated. Optical fibers with a core diameter of 5 – 20 µm were drawn using these preforms. Fig. 3 shows an electron image of the cross section. Profiles of Al and Bi concentrations and a profile of the refractive index difference in preform 5 are shown in Fig. 4. Fig. 5 gives typical absorption spectra of fibers with different core glass compositions. It is seen that these fibers have the same absorption bands of Bi centers as in crucible-melted glasses. But one can see one more Bi absorption band at 1400 nm overlapping with the OH absorption band.

The luminescence spectra of fibers 1, 4, and 430 are shown in Fig. 6. The excitation at 636 nm results in two luminescence bands at about 750 and 1050 – 1200 nm with a bandwidth of about 100 and 200 nm respectively (Fig. 6a). Only one luminescence band at approximately 1200 nm is excited by pumping in 1000 nm absorption band (Fig. 6b). The peak position of this band shifts to a longer wave-
The bright and broad luminescence band centered at 1300 nm was first observed in Bi,Ge,P-doped silica fiber perform [22,30]. But fibers drawn from this perform do not reveal luminescence in this wavelength region. But during the progress of the investigation of similar type fibers we succeeded in obtaining samples with luminescence in near IR.

Optical properties of such fibers with various concentrations of phosphorus pentoxide and germania were investigated [31]. The preforms for the fibers were fabricated by the MCVD technology. The Bi concentration in the fiber core glass was lower than the sensitivity threshold of our equipment (~0.1 wt.%). But in the process of perform fabrication all measures have been taken to obtain similar Bi concentrations in all fibers. The fibers drawn from these preforms had a second mode cutoff wavelength of ~1.1 µm.

Fig. 8 shows luminescence and loss spectra of the following fibers (see Table 3): 1. Bi-doped phosphogermanosilicate (PGSB) fiber (Fig. 8a); 2. Bi-doped germanosilicate (GSB) fiber (Fig. 8b); 3. Bi-doped phosphosilicate (PSB) fiber (Fig. 8c); and Fig. 8d represents the same parameters of an ASB fiber. Luminescence of PGSB, GSB, and PSB fibers was registered under the pump radiation with the wavelength 1.23 µm. The ASB fiber was pumped at 1.058 µm and 1.372 µm.

The absorption spectra of the ASB and PGSB fibers are essentially different. We observe here the strong dependence of the absorption spectra on the core composition. The ASB-fibers are known to feature absorption bands at ~500, 700, 800, and 1000 nm [2,33] (see Fig. 5). As regards the PGSB-fibers, the amplitudes of 500-nm, 700-nm, and 1000-nm bands appear to be noticeably decreased, however, one can see bands at 450, 800, and 950 nm and a complex band in the region of 1100 – 1500 nm (Fig. 8a).

So, if we want to pump the Bi-doped fiber into the absorption band directly linked to IR luminescence, the absorption bands 1.1 – 1.5 µm in PGSB fibers, 1.2 – 1.5 µm in GSB fibers, and 0.9 – 1.4 µm in PSB fibers can be used. In a similar way, the absorption bands around 1 µm and, as it was shown recently [34], around 1.4 µm (see Fig. 8d) can be used in ASB fibers.

For this reason the 1230 nm laser radiation was used for luminescence excitation in PGSB, GSB, and PSB types of fibers. The PGSB fiber sows a very broad luminescence band 1200 – 1500 nm. The reduction of the phosphorus content in the fiber core results in narrowing down and in changing the 1100 – 1500 nm absorption band shape. Besides, we observe narrowing down of the luminescence spectra (GSB fiber, Fig. 8b).

---

**Table 3** Designations and compositions of Bi-doped fibers

<table>
<thead>
<tr>
<th>Mark</th>
<th>Core glass composition, (concentration in mol.%, if available)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M48</td>
<td>SiO$_2$ – GeO$_2$ – P$_2$O$_5$</td>
<td>[22,30]</td>
</tr>
<tr>
<td>PGSB</td>
<td>83.5 SiO$_2$ – 1.5 P$_2$O$_5$ – 15 GeO$_2$</td>
<td>[27,28]</td>
</tr>
<tr>
<td>GSB</td>
<td>85 SiO$_2$ – 15 GeO$_2$</td>
<td>[31]</td>
</tr>
<tr>
<td>PSB</td>
<td>92.5 SiO$_2$ – 7.5 P$_2$O$_5$</td>
<td>[31]</td>
</tr>
<tr>
<td>AGSB</td>
<td>95.6 SiO$_2$ – 1.1 Al$_2$O$_3$ – 3.3 GeO$_2$</td>
<td>[32]</td>
</tr>
<tr>
<td>ASB</td>
<td>97 SiO$_2$ – 3 Al$_2$O$_3$ (1)</td>
<td>[31]</td>
</tr>
<tr>
<td></td>
<td>95.5SiO$_2$ – 4.5Al$_2$O$_3$ (2)</td>
<td>[34]</td>
</tr>
</tbody>
</table>

---

**Figure 7** (online color at www.lphys.org) Emission spectra (normalized) of Bi-doped aluminosilicate fiber pumped at different wavelengths.
In the case of PSB fiber, the elimination of germania and the increase of a P-doping (in comparison with PGSB fiber) results in the formation of the broad absorption band between 0.9 and 1.4 µm in IR part of spectrum (Fig. 8c). Luminescence spectrum represents wavelength band with maximum at 1300 nm (under excitation at 1230 nm).

According to [34], ASB2 fiber pumped at 1372 nm demonstrate an emission band with a maximum at 1430 nm and a full width at half maximum of 100 nm (Fig. 8d). The luminescence spectrum of this fiber looks like luminescence spectrum of the GSB fiber (Fig. 8b).

Comparing luminescence spectra of PGSB, GSB, PSB and ASB fibers we can say the following. It looks like the short wavelength wing of the 1100–1500 nm absorption band of the PGSB fiber (Fig. 8a) can be attributed to bismuth-associated active centers (bismuth center, BC) combined with P atom (luminescence band with maximum at 1300 nm, Fig. 8c). Whereas the long wavelength wing of this band can be attributed to BC combined with Ge and Si (luminescence band with maximum at 1400 nm, Fig. 8b and Fig. 8d, dashed lines). In such a case Fig. 8d indicate that absorption band at ~1000 nm and 1050–1250 nm luminescence band in ASB fibers are associated with BC combined with Al.

So, the IR luminescence in Bi-doped optical fibers can be obtained in a spectral region of 1050 – 1500 nm by varying core composition and pump wavelengths. Differences between luminescence spectra of bulk Bi-doped glasses and fibers of a similar composition (compare e.g. Fig. 2 and Fig. 7) can be attributed to the different technologies of sample preparation and to the different conditions of luminescence excitation because the pump radiation intensity in single mode fibers usually higher than in bulk glasses.

3. Optical gain in bi-doped glasses and fibers

Luminescence in optical medium is necessary but not sufficient condition for achieving optical gain in this medium. Optical pump on/pump off gain in Bi-doped glasses was first observed in 2003 [15]. Since then, the amplification was registered as in a number of various bulk glasses [35–38], as well as in Bi-doped optical fibers of various composition [3,5,39]. In all these experiments except [5] the on/off gain was measured in the vicinity of 1300 nm under optical pumping at 800 nm. In [5] optical amplification at 1300 nm was measured in a Bi-doped fiber pumped at 1064 nm.

Figure 8 (online color at www.lphys.org) Optical losses (1, 1') and luminescence spectra (2, 2') of PGSB (a), GSB (b), PSB (c), and ASB (d) fibers [31,34]. Vertical arrows indicate the pump wavelengths. Dashed lines refer to ASB2 fiber pumped at 1372 nm. Curve 1' in Fig. 8d was multiplied by a factor of two for better legibility of the figure.

Figure 9 (online color at www.lphys.org) Gain coefficient of ASB fiber at the wavelength 1130 nm as a function of pump power. Fiber length is 20 m.
Gain saturation observed at the pump power increase leads us to the conclusion that maximum gain in the Bi-doped fiber under investigation is about $\sim 0.5 \text{ dB/m}$. At low pump levels gain efficiency is as high as 0.2 dB/mW (at 1120 nm), which is lower if compared to Er-doped fiber amplifies, but is significantly higher if compared to Raman ones [41].

Fig. 10 demonstrates gain coefficient spectral dependences for three types of Bi-doped fibers [28,32,40]. The luminescence spectra of the same fibers are also shown for comparison. It is seen that the gain spectrum in ASB fibers pumped at $\lambda_p \approx 1.06 \mu\text{m}$ reaches maximum at a wavelength of $\sim 1120$ nm. At larger wavelengths gain coefficient decreases, approaching to zero in the vicinity of 1240 nm wavelength. So, ASB-fibers demonstrate reasonable optical gain in the wavelength region 1100–1200 nm being pumped at $\sim 1 \mu\text{m}$.

**Broadening of the luminescence spectra in ASB fibers** is observed on addition of several mol% of germania to the core composition (Fig. 10b). But the on/off gain spectrum of such fiber (AGSB fiber, Table 3) is approximately the same as in ASB fiber. This phenomenon could be explained as follows [42]. In fibers of this composition the IR luminescence band can consist of two different superimposed bands (see e.g. Fig. 11). One of these bands is long-lived (decay time $\sim 1$ ms) and another band is short lived (luminescence decay time less than 4 $\mu$s). Presence of the short-lived luminescence band can reduce optical gain itself and restrict the optical gain spectral region.

The on/off gain spectra $g(\lambda)$ were measured also in the PGSB single mode fibers with a pump at $\lambda_p = 1230$ nm [28]. The measured $g(\lambda)$ dependences are shown in Fig. 10c. The optical amplification with $\lambda_p = 1230$ nm was observed in a wide wavelength region, from 1240 to at least 1500 nm. The essential reduction of the accu-

---

**Figure 10** (online color at www.lphys.org) Luminescence (1) and on/off gain (2) spectra of Bi-doped silica-based fibers. (a) – ASB fiber, $L = 20$ m, $\lambda_p = 1058$ nm, $P_p = 80$ mW; (b) – AGSB fiber, $L = 100$ m, $\lambda_p = 1058$ nm, $P_p = 180$ mW; (c) – PGSB fiber, $L = 30$ m, $\lambda_p = 1230$ nm, $P_p = 50$ mW

---

**Figure 11** (online color at www.lphys.org) Spectra of slow and fast decay luminescence bands exited in a Bi-, Al-, and Ti-doped silica fiber by 975 nm pump radiation. Spectra are obtained using time resolved spectroscopy. AGSB fiber reveals similar luminescence properties [42]
4. Laser generation in Bi-doped fibers

4.1. Bi fiber lasers for a spectral region of 1140 – 1215 nm

The first bismuth fiber laser was constructed using the Bi-doped alumosilicate optical fibers [7]. CW laser generation with quite high slope efficiency of 10 and 14% was obtained at 1146 and 1215 nm correspondingly. A Nd:YAG laser with a wavelength of 1064 nm was used as a pump source. The fiber parameters and laser construction were not optimized and the results obtained were not a record. But it was the first confirmation of the feasibility of Bi-doped fibers as an active laser medium. After this a number of bismuth fiber lasers have been developed, among them CW high-power lasers [22,23,44–46], Q-switched and mode-locked lasers [47–49], frequency-doubled bismuth fiber laser [44,50–52]. Most investigations, which gained insight into the physics of the laser generation, were carried out with CW bismuth fiber lasers.

4.1.1. CW Bi fiber lasers

A CW Bi-doped fiber laser in a wide range of lasing wavelengths and pump powers was investigated in [44]. A single-mode ASB fiber (the same fiber was used in [7]) with a cutoff wavelength of 1.1 \( \mu \text{m} \) was used as an active medium. The mode field diameter at 1.1 \( \mu \text{m} \) was 6.8 \( \mu \text{m} \).
The concentration of Bi in the aluminosilicate core glass didn’t exceed $2 \times 10^{-2}$ at.%. The absorption spectrum of this fiber in the spectral region 1000 – 1700 nm is shown in Fig. 14. The absorption band with a maximum near 1000 nm and a long wavelength edge near 1200 nm corresponds to BC absorption. It is necessary to note that optical losses at a wavelength of about 1300 nm are less than 10 dB/km. This means that background losses in the Bi-doped fiber under investigation are no larger than this value. The absorption of the pump radiation is equal to 0.29 dB/m for 1070 nm and 0.26 dB/m for 1085 nm. For this reason, the length of the fiber $L = (50 – 80)$ m used in Bi-laser schemes was long enough for efficient pump radiation absorption. The luminescence spectrum of the Bi-doped fiber consists of one band with a peak wavelength of 1150 nm under 1070 nm excitation.

The scheme of a CW bismuth fiber laser is shown in Fig. 15. A CW Yb fiber laser with an output power of 80 W at 1070 nm was used as a pump source. In some experiments, a laser with a lower power at 1085 nm was used. The pump radiation was launched into the core of Bi-doped fiber. The cavity of the Bi-fiber laser was formed by two fiber Bragg gratings (FBGs). FBGs were written in sections of special photosensitive Ge-doped fibers and then spliced with the Bi-doped fiber. The output coupler (OC) FBG has a reflectivity $R=50\%$ in most experiments. The spectral width of the FBGs was $\sim 1$ nm, except for the experiments on yellow-light generation. A dispensing prism was used for the separation of the pump and the Bi-laser radiation at the output of the Bi-laser.

The radiation of the Bi-fiber laser and the unabsorbed pump radiation were observed at the output of the laser scheme. Fig. 16 shows the dependences of the unabsorbed pump power $P_{up}$ and the laser radiation power $P_{Bi}$ on the pump power ($P_m$) launched into the Bi-laser fiber for four versions of the Bi-laser at wavelengths of 1150, 1160, 1205, and 1215 nm.

The Bi-fiber laser at 1150 and 1160 nm demonstrated the maximal efficiency of 19 and 22%, and the maximal output power of 13 and 15 W respectively. Most of the pump radiation was absorbed in the Bi-doped fiber. The longer the lasing wavelength in the region of 1150 – 1205 nm, the lower the efficiency of the Bi-fiber laser was. Up to the wavelength of 1205 nm the $P_{Bi}(P_m)$ dependence remains close to a linear one. Already in 10 nm...
The spectral band 1 in Fig. 17 is the pump radiation at the wavelength $\lambda_p = 1070$ nm. Band 2 has a two-maxima structure, which is a characteristic feature of the Raman spectrum in silica. The frequency shift between the pump band and the maxima of the central band is 452 and 490 cm$^{-1}$, which agrees satisfactorily with the main Raman shifts in silica (440 and 490 cm$^{-1}$). The cavity for Raman generation is formed apparently by two cleaved fiber ends. The spectrum line 3 at 1215 nm in Fig. 17 is the Bi-laser radiation.

In all the experiments described above, the Bi-doped fiber was initially kept at room temperature ($T = 25^\circ C$). But it turned out that the output power of the Bi fiber laser essentially depends on the temperature of the Bi-doped fiber. The dependence of the output power of the Bi laser on the fiber temperature in the range of 0 – 60$^\circ C$ was measured. This dependence is shown in Fig. 18. This dependence is nearly linear and shows a $\approx 40\%$ reduction of the output power with a temperature increase from 0 to 60$^\circ C$.

The measured values of the Bi-lasers efficiency are essentially lower than, e.g. the efficiencies of widely used Yb or Nd-fiber lasers. To find the mechanism of energy loss, we measured the absorption of pump radiation in the Bi-doped fiber. The experimental scheme used was similar to the scheme of Bi-laser shown in Fig. 15, but both FBGs were excluded. The measurements on Bi-doped fiber spans, 26 and 47 m in length, using the pump wavelengths of 1070 and 1085 nm, showed that there was an unsaturable absorption even for high input powers (up to 50 W, i.e., much higher than the saturation power of $\approx 10$ mW). In the entire range of pump powers, we did not observe any lasing effects in these experiments. The results of these measurements are shown in Fig. 19. The presence of unsaturable optical losses, $\sim 100$ dB/km in magnitude, can explain the observed value of Bi-laser efficiency.

The unsaturable losses in the Bi-doped fiber proved to depend on the temperature of the fiber. We measured the value of these losses using a 47 m fiber span. The measurements of the pump-power transmission were carried out at temperatures of 0, 24, and 50$^\circ C$. During the measurement...
ments, the fiber was temperature stabilized. The results obtained are shown in Fig. 20. The observed dependence of the unsaturable optical losses in the Bi-doped fiber is in accordance with the temperature dependence of the laser output power.

The results of the investigation of the output power and unsaturated losses dependences on the temperature open a possibility to increase the efficiency of Bi-doped fiber lasers. One way is to keep a Bi-doped fiber at room temperature during the laser operation [13]. In fact it doesn’t considerably complicate a laser construction. The other way is to keep a Bi-doped fiber at 77 K. The experiments carried out have shown the slope efficiency 32 and 50% correspondingly [46].

4.1.2. Frequency-doubled bismuth fiber laser

Efficient solid-state (fiber) yellow laser sources are becoming now indispensable for numerous applications. It is known that the 570–590 nm band is very promising for ophthalmology and dermatology applications [53,54]. There is a very interesting and important application of high-brightness 589 nm sources to generate laser guide stars for adaptive optics correction of large telescopes [55]. Yellow lasers can also be used for wavelength-multiplexed holographic memory [56].

At present there are several methods of generating yellow light radiation: frequency doubling of Yb solid-state (fiber) lasers, frequency doubling of Raman-shifted Yb (Nd) solid-state (fiber) lasers, sum-frequency generation of two solid state lasers. All these methods have their advantages and drawbacks. Bi-doped fiber lasers operating in the vicinity of 1160 nm give us another opportunity for yellow light generation as second harmonic of these lasers. And this opportunity was demonstrated in several experiments [44,50–52] using nonlinear crystals. It is interesting to note an investigation of the attractive possibility of constructing yellow all-fiber Bi laser with frequency doubling in a periodically poled optical fiber [57].

In [44] the effective 1160 nm Bi-fiber laser was used to demonstrate the possibility of yellow-light generation using frequency doubling of the CW Bi laser radiation.

For this aim, we used a commercial 30 mm long periodically poled lithium niobate crystal with a fiber input (Global Fiberoptics, Ltd.). The expected efficiency of second-harmonic generation (SHG) (λ = 580 nm) was ≈ 20% at 5 W linear polarized laser radiation with a wavelength bandwidth of less than 0.05 nm. The output radiation of all our Bi-fiber lasers was nonpolarized. For this reason, we were able to use no more than a half of the laser power for frequency doubling. The next question was the bandwidth of the Bi laser. To reduce the laser bandwidth, we used FBGs (HR and OC) with a spectral width of ≈ 0.1 nm. However, owing to a low concentration of Bi ions in the fiber core, the length of the active fiber was sufficiently large (L = 78 m). Under these conditions nonlinear processes result in broadening the laser spectrum, and the bandwidth of the spectrum depends on the fiber length and the output power of the laser. The data obtained in our experiments with lasers 52 and 78 m in length are shown in Fig. 21. The results obtained in our experiment are shown in Fig. 22. The maximal yellow CW radiation power obtained in our experiments was 300 mW. The expected efficiency of SHG (λ = 580 nm) was ≈ 20% at 5 W linear polarized laser radiation with a wavelength bandwidth of less than 0.05 nm. Similar experiments were fulfilled in [51]. It is anticipated that obtained results could be significantly improved by construction of a Bi fiber laser with linear output polarization and a narrow linewidth.
4.1.3. Pulsed Bi fiber lasers

Two types of pulsed Bi-doped fiber lasers have been demonstrated recently – a mode-locked Bi-doped fiber laser [48,49] and a Q-switched Yb-Bi fiber laser [47].

A mode-locked Bi-doped fiber laser

A mode-locked soliton Bi-doped fiber laser delivering stable ~0.9-ps pulses with a repetition rate of 7.5 MHz and tunable from 1153 nm to 1170 nm was demonstrated [49]. The short pulse operation is initiated by a fast dilute nitride based SESAM. The operation in soliton regime was achieved using careful dispersion management with a transmission grating pair and an improved Bi-doped fiber allowing for the cavity with a reduced length.

The schematic of the bismuth doped fiber laser is shown in Fig. 23. The laser cavity comprised 12 meters of Bi-doped silicate glass fiber with absorption of ~1.2 dB/m at the pump wavelength of 1062 nm [40], a 1062/1165 pump coupler, and a fiber loop output mirror with ~95% reflectivity at the lasing wavelength. The laser was core-pumped with a 1 W Yb-doped single-mode fiber laser.

The length of the doped fiber was optimized in order to achieve efficient pump absorption and, consequently, sufficient gain, while keeping the length and dispersion of the fiber section of the cavity to be low. The splice loss to a standard single mode fiber was ~0.3 dB due to some mode field mismatch. The overall cavity losses were further minimized using the loop mirror and the pump coupler with high reflectivity and extinction ratio, respectively. An additional dichroic fiber coupler was used at the output of the laser to separate the residual pump and the signal light.

The normal group velocity dispersion (GVD) of the optical fiber at 1.16 µm wavelength range was compensated by a transmission grating pair with 1250 lines/mm and a grating separation of ~19 mm. Polarization controller was used to prevent the decrease in the diffraction efficiency of the grating pair. AsN-based semiconductor saturable absorber mirror grown by solid source molecular beam epitaxy ensured the self-starting passive mode-locking [12]. The SESAM consisted of 4 GaInNAs quantum wells with a width of 6 nm grown on top of 24.5 pair GaAs/AlAs DBR. The DBR stopband had a center wavelength of ~1140 nm with an approximately 150-nm bandwidth.

An optimized cavity design and alignment allow for stable short-pulse operation with a repetition rate of 7.5 MHz. A typical pulse train observed with an oscilloscope is shown in Fig. 24. Autocorrelation trace seen in Fig. 25, reveals pulse duration of 0.94 ps. The aperture of the objective, focusing the beam onto SESAM, was chosen to provide spatial filtering of wavelength components dispersed by the grating pair. The continuous wavelength tuning, therefore, could be achieved in the range of 1153–1170 nm by moving the objective in the transverse direction. The overall cavity dispersion was estimated to be...
Figure 25 (online color at www.lphys.org) Autocorrelation trace of Bi-doped fiber pulses. The pulse width is 0.93 ps

Figure 26 (online color at www.lphys.org) Scheme of Yb–Bi fiber laser. 1 – high-reflective coupler of Yb-doped fiber cavity, 2 – output coupler of Bi-doped fiber cavity, 3 – high-reflective coupler of Bi-doped fiber cavity, 4 – output coupler of Yb-doped fiber cavity (cleaved fiber end). The single-cavity scheme did not contain elements 2 and 3

~ −0.4 ps$^2$ using the soliton sidebands in the spectrum. The typical pulse energy of the laser was ~0.2 nJ. At the loop mirror output the pulses acquire a small chirp resulting in a time-bandwidth product of 0.40. This small chirp could be expected from the cavity dispersion map which includes pulse propagation over long fiber in the cavity and in an output pigtail that comprises an additional fiber coupler for separation of residual pump light.

Yb-Bi pulsed fiber laser

The absorption wavelength band of the ASB fibers covers the generation wavelength region of Yb fiber lasers. This makes possible to use ASB as saturable absorber for Q-switch Yb fiber laser cavity that was demonstrated in [47].

But a BC lifetime of ~1 ms should lead to poor efficiency at high repetition rates exceeding ~1 kHz because the active centers cannot fully relax from an excited state during the time between two pulses. To overcome this drawback ASB fiber placed the in a separate resonator to achieve laser action and consequently to decrease the lifetime of bismuth associated active centers in the excited state (see Fig. 26). A similar two-cavity bulk laser scheme was earlier used for reduction of lifetime of saturable absorber active centers [58].

Stable pulsed action was obtained at the wavelengths of 1050, 1064, 1066, 1070, and 1080 nm. The laser efficiency in the pulsed operation mode was about 50% relative to the input pump power and about 80% of the CW mode efficiency in the absence of the saturable absorber. A typical pulse train is shown in Fig. 27.

Maximum average output power reached 7.5 W at 1064 nm wavelength with 16.5 W of pump power and was about 3.5 W at 1066, 1070, and 1080 nm wavelengths, corresponding to 8 W of pump power approximately. An increase of average output power was accompanied by a pulse energy saturation and pulse shortening due to a higher gain; the peak power also rose accordingly. No switch of the pulsed operation mode into a CW mode was observed.

Depending on the specific laser parameters, the Bi-doped fiber laser pulse had a width of 1 – 5 µs and a delay of 5 – 10 µs relative to the pulse of the Yb-doped fiber laser. The ratio of output intensities of this laser and the Yb-doped fiber laser was about −20 dB at both wavelengths, 1160 and 1215 nm. The output power of the Bi-doped fiber laser was low because the portion of the Yb-doped fiber lasing power absorbed was small, estimated to be about 10%, and because of its relatively low efficiency, which had been about 10% in CW operation mode. To increase the output power at 1160 nm, a piece of the same Bi-doped fiber was spliced to the laser output, acting as an amplifier.

Such a simple technique allowed one to improve the laser performance. The energy extraction in this amplifier was about 10%, and the pulse energy reached 6.5 µJ with a 1.5 µs pulse width. The average output power at 1160 nm reached 400 mW, and peak power was about 4 W with nearly 10 W of 975 nm wavelength pump.
4.2. Bi fiber lasers for a spectral region of 1300 – 1550 nm

All Bi-doped fiber lasers, considered in the previous section, were based on Bi-doped aluminosilicate fibers pumped at ~1 μm. Laser generation in a spectral region of 1300 – 1550 nm was demonstrated by Bi-doped fiber lasers based on PGSB [27,28,59], GSB [31], and ASB [34] fibers.

Laser generation in a very broad wavelength region was obtained using PGSB fiber lasers. Optical parameters of PGSB fibers allowed one to demonstrate a variety of BFLs generating in 1300 – 1550 nm region. All the BFLs were assembled in accordance with the common linear scheme (see Fig. 15). In some cases, FBGs were written directly in the PGSB-fibers, in order to reduce the intracavity optical loss. The lasing wavelength \( \lambda_s \) was defined by the FBGs resonance wavelength. As pump sources a Raman fiber laser (\( \lambda_p = 1230 \) nm [60]), or a BFL based on an ASB-fiber and emitting at \( \lambda_p = 1205 \) nm [40] was used in a set of similar experiments. As the BFL active medium we used a 30-m long PGSB or GSB fiber with \( \lambda_p = 1230 \) nm and \( \lambda_s = 1205 \) nm. One of the FBGs had reflectivity \( R \) close to 100%, whereas the second (output) FBG had \( R \) in the range from 50 up to 98%.

Lasing was obtained at a set of wavelengths \( \lambda_s \) between 1300 and 1520 nm. The output BFLs spectra with \( \lambda_s = 1230 \) nm and 1205 nm are shown in Fig. 28. The dependences of the BFL output power on the absorbed pump power for four laser schemes are shown in Fig. 29. These dependences are nearly linear in the pump power range under consideration.

The slope efficiency of the BFL at \( \lambda_s = 1310 \) nm with respect to the absorbed power amounted to 3.2% with \( \lambda_p = 1230 \) nm (Fig. 29, laser 2) and 1.4% with \( \lambda_p = 1205 \) nm (Fig. 29, laser 1) at a temperature \( T = 300 \)K. It turned out that the slope efficiency of a PGSB-fiber laser strongly depends on the fiber temperature (as in the case of ASB-fiber lasers [44,46]). On cooling the PGSB-fiber to \( T = 77 \) K, the slope efficiency increased to 5.0% (laser 1) and 5.4% (laser 2), while threshold pump power decreased to 100 mW (\( \lambda_p = 1230 \) nm, laser 2) and 170 mW (\( \lambda_p = 1205 \) nm, laser 1).

It should be noted that Raman gain can in some cases take essential part in lasing processes in Bi-doped fibers. For example, the PGSB fiber laser at 1310 nm pumped at 1230 nm demonstrated at higher pump intensities the nonlinear increase of slope efficiency up to 29% [27]. To exclude the interference of Raman scattering the pump powers in experiments illustrated by Fig. 29 were restricted to the values ~ 1 W.

The slope efficiency of the BFL no. 3 (Fig. 29, \( \lambda_s = 1345 \) nm) turned out to be much lower: just 0.8% at \( T = 300 \)K, the threshold power being 200 mW. 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%. As this took place, the threshold power grew 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. 29),

The double-cavity performance allowed one to realize effective pulsed laser action in a simple scheme and to expand the usual spectral range of Yb fiber lasers to the long-wavelength side. Pulsed laser action is obtained in a spectral range of 1050 – 1200 nm with a pulse energy up to 100 μJ, peak power of up to 65 W, a pulse width about 1 μs, and a repetition rate of 10 – 100 kHz.
Figure 30 (online color at www.lphys.org) Output power of BFLs based on PGSB fibers as a function of absorbed pump power

Figure 31 (online color at www.lphys.org) Spectra of BFL output radiation: 1 – 1500 nm BFL based on PGSB fiber; 2 – 1520 nm BFL based on PGSB fiber; 3 – 1500 nm BFL based on GSB fiber. Pump wavelength was 1230 nm, \( T = 300\) K

and the threshold pump power in this case amounted to 145 mW.

In the BFL no. 6 (Fig. 28, curve 6), the active fiber was placed in three cavities at once, one cavity inside the other. The cavities were formed by three matched pairs of FBGs 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 testifies to significant inhomogeneous broadening of the gain line.

For a more precise location of the long wavelength edge of this line the possibility of lasing at wavelengths of \( \lambda_s = 1500, 1520, \) and 1550 nm was investigated in the same experimental conditions.

Lasing at wavelengths \( \lambda_s = 1500\) and 1520 nm at room temperature with the threshold pump power \( \sim 200 – 300\) mW (see Fig. 30 and Fig. 31) was obtained. And we failed to obtain the laser generation at \( \lambda_s = 1550\) nm. The pump threshold power at this wavelength was higher than 4 W. The dependences of the BFL output power on the absorbed pump power for BFLs at 1500 and 1520 nm are shown in Fig. 30. It is of interest that the change of the slope efficiency of 1500 nm fiber laser at a pump power of \( \sim 1\) W was observed.

A lasing at the wavelength \( \lambda_s = 1500\) nm was also obtained in the same scheme of the fiber laser but with a GSB fiber of the same length (see Fig. 31, curve 3). The threshold pump power at \( \lambda_p = 1230\) nm was \( \sim 60\) mW, the slope efficiency of the laser was \( \sim 3\%\).

We have also investigated the possibility of lasing in the region of 1.3 \( \mu m\) with PGSB fiber pumped 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. And it is clear because wavelength 1058 nm is placed between absorption bands of PGSB fiber. However, we succeeded in obtaining lasing at \( \lambda_s = 1320\) nm when pumping in the 800-nm absorption band. An 808-nm single-mode fiber-pigtailed laser diode was used as the pump source. As the BFL active medium we used a 13-m long PGSB-fiber. The output FBGs had reflectivity R=98%. The threshold pump power turned out to be \( \sim 200\) mW. Because this value was virtually the limiting output power of the laser diode used, we failed to construct the dependence of the BFL output power on the pump power. The output spectrum of this BFL is shown in Fig. 32.

To reach the longer wavelengths by Bi-doped fiber lasers the luminescence of PGSB fibers under different excitation wavelengths was investigated [59]. Fig. 33 shows the luminescence spectra of SM PGSB fiber pumped at 532, 800, 925, and 1230 nm. The luminescence spectra are normalized to 1 with respect to the luminescence bands in the range \( \lambda > 1000\) nm. Pumping at various wave-
Luminescence, a.u.
1.0
0.5
0
2.0
4.0
6.0
400 600 800 1000 1200 1400 1600
Wavelength, nm
1
2
3
4
3
4

Power, dB
-50
-45
-55
-60
-65
-70
-80
-75
-40
-35
-30
1600 800 900 1000 1100 1200 1300 1400 1500
Wavelength, nm
1
2
3
4
3
4

Figure 33 (online color at www.lphys.org) Luminescence spectra of single mode PGSB-fibers excited at the different wavelengths: 1 – 532 nm, 2 – 925 nm, 3 – 800 nm, and 4 – 1230 nm.

Figure 34 (online color at www.lphys.org) Output emission spectra of a BFL with $\lambda_p = 925$ nm and $\lambda_s = 1550$ nm. $T = 300$ K. The inset shows the laser spectrum with resolution.

Laser generation at 1550 nm was obtained using 30 m long PGSB fiber with BGs (HR and OC with $R = 92\%$), pumped at 925 nm (Nd fiber laser at the wavelength 925 nm was used as pump source). The threshold pump power turned out to be $\sim 200$ mW. The output spectrum of radiation at the output of the fiber laser is shown in Fig. 34. The efficiency of the 1550 nm fiber laser was not measured because the available pump power was of the order the threshold one.

Laser generation in the wavelength band 1442 – 1460 nm was demonstrated also in ASB fibers pumped at 1343 – 1356 nm [34]. The efficiency of lasers in these first experiments was estimated to be less than 0.1%.

So, the obtained laser generation in a broad spectral band indicates that Bi-doped fibers can be used as an optical gain medium in a broad-band region of 1140 – 1550 nm, including the O-, E-, and S-bands of the fiber-optic transmission window.

5. Summary

Since 2001 great attention has been paid to investigations of near IR luminescence in various glasses doped with Bi.

It has been shown that the near IR luminescence can be observed in a spectral region of 1000 – 1600 nm depending on the glass composition and the excitation wavelength. Since 2005 Bi-doped optical fibers have been fabricated. In the first Bi-doped fibers (with silica-based Al-doped glasses as a core material) the near IR luminescence was observed in a spectral region of 1100 – 1200 nm.

Using these fibers a family of Bi-doped fiber lasers has been developed for the spectral region 1150 – 1215 nm. The slope efficiency of CW lasers was up to 30%.

Later Bi-doped fibers with Al-free silica-based core glass were fabricated [24,28,61]. These fibers exhibit the near IR luminescence in the spectral region 1300 – 1600 nm. The first laser generation in this spectral region from Bi-doped fibers has been successfully demonstrated recently [28]. The slope efficiency of the lasers in this first experiment was not high (1 – 3%). The realizability of fiber lasers based on ASB fibers $\sim 1450$ nm being pumped at $\sim 1350$ nm was also shown [34]. The review picture of Bi-doped fiber lasers demonstrated up to now is shown in Fig. 35.

Despite great progress in the development of various Bi-doped optical fibers and Bi-doped fiber lasers, generating in the whole spectral region 1150 – 1500 nm, a big problem remains: the nature of luminescence Bi-related centers is not clear.

There are several well-grounded proposals to attribute the near IR luminescence to Bi$^{5+}$ [2,62], Bi$^+$ [17,24,25,30], Bi$^{3+}$, Bi$^{5+}$, Bi$^+$/Bi$^2$ [63,64], and others. But up to now there has been no direct confirmation of any of these centers.

Taking into account strong dependence of near IR luminescence features on the glass composition, the glass structure and details of the Bi-doped glass technology one can suggest that each of these centers can be formed in glasses and emit the luminescence under proper conditions.
Figure 35 (online color at www.lphys.org) Laser generation wavelengths obtained in Bi-doped fibers at different pump wavelengths on the background of the loss spectra of Bi-doped fibers. Arrows indicate pump wavelengths; laser and corresponding pump wavelengths are shown by lines of the same type. Thin and thick lines refer to Bi-doped aluminosilicate and phosphogermanosilicate fibers, correspondingly.

But there is another point of view. Point defect optical centers caused by the presence of 6p (Bi, Pb) and 5p (Sn, Sb) ions are proposed for the explanation of the near IR emission [65].

Further fundamental researches of mechanisms of the near IR luminescence in Bi-doped glasses and fibers are necessary.

No doubt it would be possible to improve strongly the Bi-doped fiber laser efficiency by carefully controlling fiber compositions and fabrication conditions.

Acknowledgements The authors gratefully acknowledge the many colleagues at the FORC and the ICHPS, who have contributed to the work on the Bi-doped fibers and fiber lasers research and development.

References
