Amplification in Extended Transmission Bands Using Bismuth-Doped Optical Fibers

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(Invited Tutorial)

***Abstract*—Bismuth-doped optical glasses emit NIR luminescence in an ultrabroad spectral region of 1000–2000 nm. It makes Bi-doped glasses and glass optical fibers a promising active medium for the creation of Bi-doped fiber lasers and broadband optical amplifiers for this spectral region. Since the first fabrication of Bi-doped fibers in 2005 a large number of papers devoted to the development of Bi-doped fiber lasers and optical amplifiers have been published. It has been shown that Bi-doped fibers are a new breakthrough in active laser materials.**

But there still remains one important problem—up to now the nature of the Bi-related NIR emitting centers is not clear. This prevents one to optimize the technology and compositions of Bi-doped fibers to improve the parameters of Bi-doped fiber devices.

This paper reviews the recent results on the luminescence properties of various Bi-doped optical fibers and the development of Bi-doped fiber lasers and optical amplifiers for the 1150–1550 nm spectral region.

***Index Terms*—Active optical materials, bismuth-doped fiber, chemistry of glasses, fiber laser, luminescence, optical amplifier, redox equilibrium.**

I. Introduction

SINCE the appearance of the first laser 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. At present, the search of new active optical materials is still a topical task because of growing demand in new lasers and optical amplifiers for many applications, in particular, for advanced optical communication systems. Now the bit rate in commercial systems is up to 10 Tbit/s per fiber, in experimental systems—up to 100 Tbit/s. It is a great achievement. But the growth of information demand in the world has reached 30–40% per year. It means that in 20 years one needs to transmit 100–1000 Pbit/s through one fiber. Several approaches to increasing optical fiber capacity are discussing (see for example [1]), one of them is widening a spectral region for the information transmission. Current high capacity optical communication systems use a narrow spectral region of 1530–1610 nm, determined by the amplification bandwidth of EDFA (Fig. 1).

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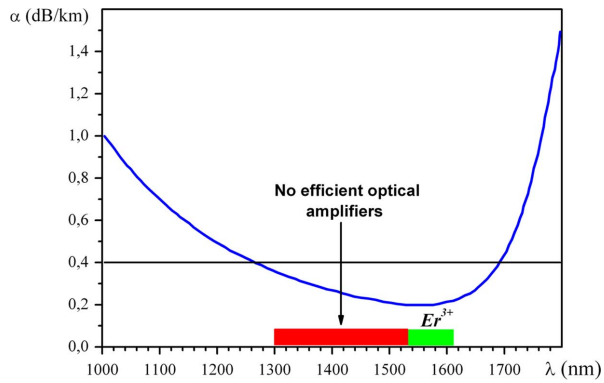

Fig. 1. Low-loss spectrum of silica-based fibers and the spectral region (green) used for high bit rate transmission.

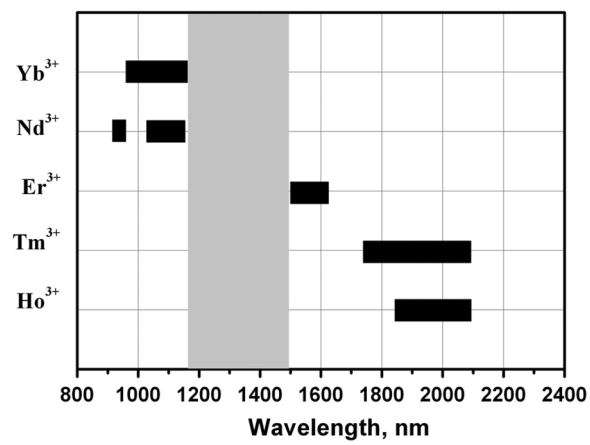

Fig. 2. Spectral region of efficient rate-earth-doped fiber lasers.

But for transmission it is principally possible to use the whole spectral region 1300–1700 nm, where the optical losses of transmission fibers are less than 0.4 dB/km. However at present there are no efficient fiber optical amplifiers for the extended bands 1300–1400 nm, 1400–1500 nm and 1610–1700 nm. Rare-earth-doped glass optical fibers are the most efficient active medium for the near IR spectral region, but it is not possible to construct rare-earth-doped efficient optical amplifiers for the indicated spectral bands (Fig. 2).

So there is a great demand for new active optical materials suitable for the creation of fiber lasers and optical amplifiers operating in extended transmission bands. Some attempts to develop efficient transition metal-doped active materials have

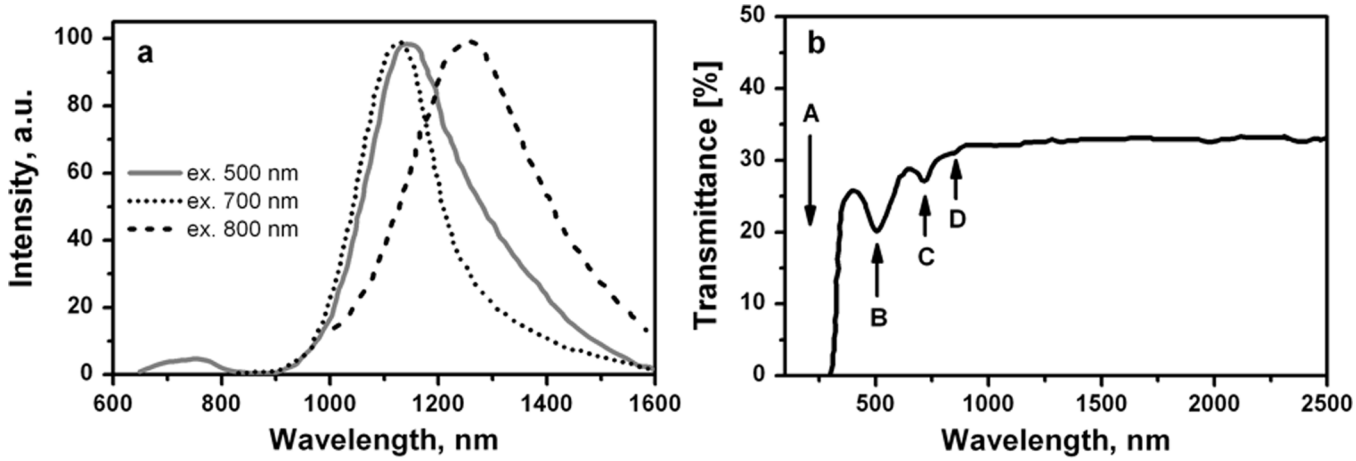

Fig. 3. (a) Luminescence and (b) transmission spectra of Bi-doped Al_2O_3-SiO_2 glass.

been unsuccessful. In 2001, it has been discovered that bismuth-doped aluminosilicate glass emits luminescence in an exceptionally wide region of 1000–1600 nm, the luminescence bands being very broad (200–300 nm) (Fig. 3) [2].

This result has caused significant activity in the fabrication of various Bi-doped glasses. But the interest in Bi-doped glasses increased greatly after the first demonstration of a cw Bi-doped glass fiber laser in 2005 [3]. The luminescence properties of many Bi-doped glasses and crystals have been studied in a spectral region of 1000–2000 nm. The corresponding references can be found in [4]. In this paper the luminescence properties of Bi-doped glasses and the nature of Bi-related near IR emitting centers will be discussed. Then some results on the fabrication and investigation of luminescence properties of various Bi-doped fibers will be presented. At last recent results on the development of Bi-doped fiber lasers and optical amplifiers in extended transmission bands will be demonstrated. A short conclusion will finalize the paper.

II. Luminescence Properties of Bi-Doped Glasses and Nature of Bi-Related Near IR Emitting Centers

During the 10 years after the first demonstration of near IR luminescence in a Bi-doped silica-based glass [2] a large number of papers devoted to various Bi-doped glasses have been published. In these papers near IR emission from Bi-related centers has been reported for silicate, germanate, aluminoborate, aluminosilicate, aluminophosphate, borosilicate and chalcogenide glasses [4]. A brief review of the first results on luminescence properties of various Bi-doped glasses is contained in [5].

Here the most significant results concerning near IR luminescence from Bi-related centers in promising applications glasses are presented. Fig. 4(a) shows the luminescence spectrum of a Bi-doped Li_2O-Al_2O_3-SiO_2 glass [6]. Very broad luminescence (1000–1500 nm) consisting of two overlapping bands with maxima at 1100 and 1350 nm under 900 nm excitation was observed. The emission consists of two Gaussian peaks and the stimulated emission cross-sections at the peaks were calculated as 7.3 10^{-21} and 2.3 10^{-20} cm^2. The intensity relation of the bands depends on a pumping wavelength. The lifetime values for emissions at 1100 and 1350 nm are 549 and 270 μs respectively and almost temperature independent up to 350 K. Ultrabroad emission from Bi-doped chalcogenide glass (gallium lanthanum sulphide) was reported [7]. Fig. 4(b) shows the luminescence spectra of this glass obtained at various pumping wavelengths. It is seen that the luminescence extends up to 2000 nm and beyond. The emission covers the entire telecommunications window (O, E, S, C, L, U). The broad band optical amplification in Bi-doped germanium silicate glass was demonstrated in [8]. Fig. 4(c) shows the luminescence spectra of two Bi-doped glasses: 96.5 GeO_2-3 Al_2O_3-0.5 Bi_2O_3 (GAB) and 79.5 GeO_2-17 SiO_2-3 Al_2O_3-0.5 Bi_2O_3 (GSAB) under 980 nm excitation. Both glasses exhibit broad emission in the 1000–1700 nm wavelength region. The authors measured the gain dependence on pump power at the wavelengths 1300 and 1560 nm in 4 mm thick glass samples (Fig. 4(d)). The maximum gain at 1300 nm in germanium silicate glass reaches 6 dB at the pump power 1 W from a 980 nm laser diode.

The data presented above (together with other data published) show that Bi-doped glasses can indeed be a promising active medium for near IR lasers and broad band optical amplifiers in extended transmission bands. But up to now the nature of Bi-related near IR emitting centers is not clear and this circumstance makes it difficult to create efficient active media on the base of Bi-doped glasses. In fact, laser generation has not yet been possible using bulk Bi-doped glasses. To understand the nature of Bi-related near IR emitting centers and the problems with the creation of efficient Bi-doped glasses and optical fibers it is necessary to present briefly some information concerning the chemistry of Bi and Bi-doped glasses.

Bismuth is a polyvalent element with four oxidation states Bi^{5+}, Bi^{3+}, Bi^{2+} and Bi^{+}. Two processes take place in molten polyvalent element-doped glasses: oxidation (higher valence state) and reduction (lower valence state) [9]. Polyvalent ions in molten glass are in reduction/oxidation (redox) equilibrium, described by the equation:

$$\mathrm{Me^{x+n}} + \mathrm{n/2O^{2-}} \leftrightarrow \mathrm{Me^{x}} + \mathrm{n/4O_2}$$

$\mathrm{Me^{x+n}}$ and $\mathrm{Me^{x}}$ are polyvalent ions in oxidation and reduction states correspondingly, n—number of transferred electrons These processes depend strongly on the melting temperature,

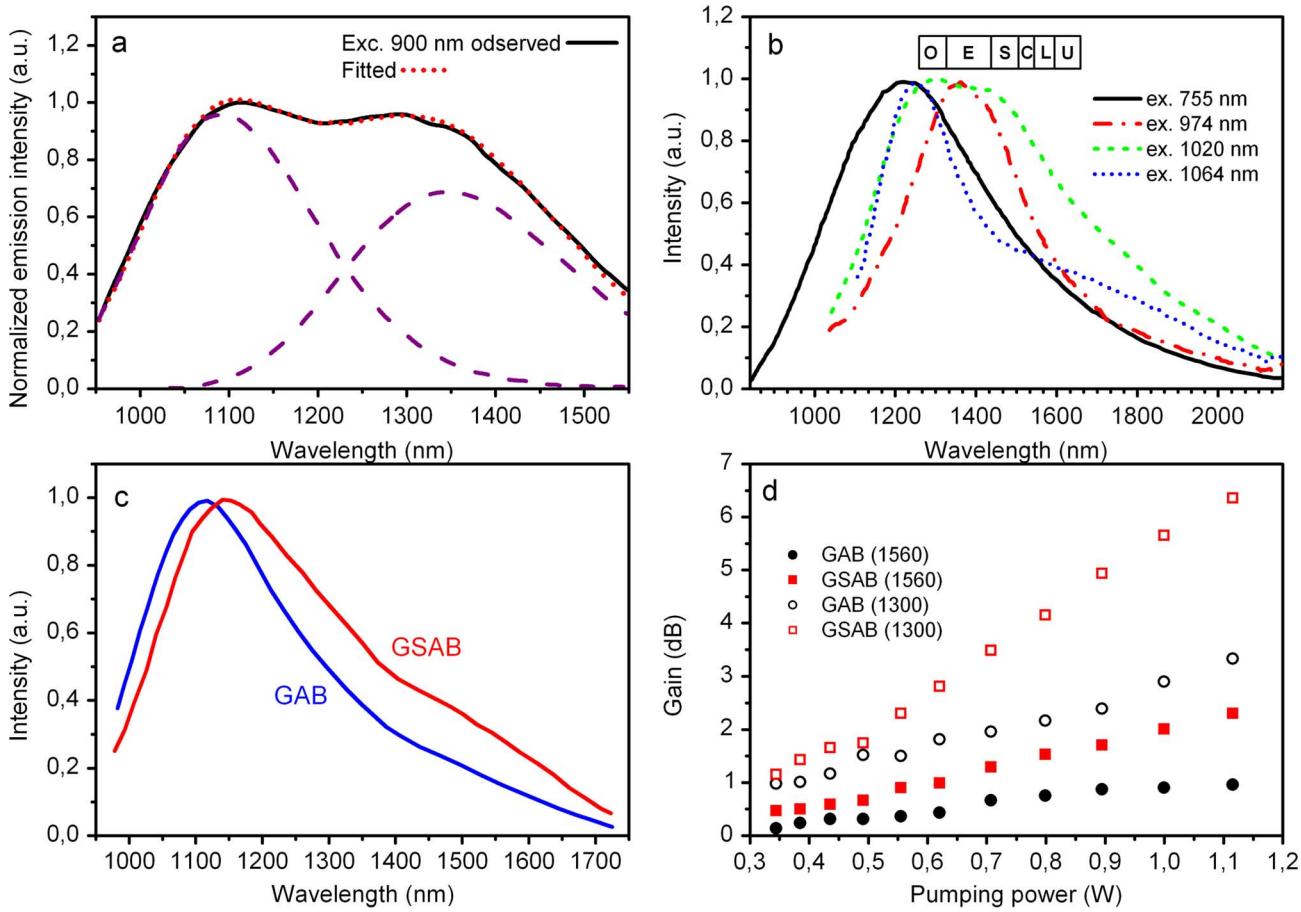

Fig. 4. The luminescence spectra of Bi-doped Li_2O-Al_2O_3-SiO_2 glass (a), chalcogenide glass (b), germanate and germanium silicate glasses (c) and internal gain at 1300 and 1560 nm as a function of pumping power (d). O, E, S, C, L, U—the standard telecommunication bands.

glass composition, atmosphere and polyvalent element concentration. Usually bismuth oxide Bi_2O_3 (oxidation state 3+) is used as a raw material for Bi-doped glass synthesis. Generally the redox equilibrium of metal ions moves towards the reduction side with increasing melting temperature. Bismuth is "the wonder metal": with no other element do reduction reactions proceed so extensively and produce such a variety of products [10]. With increasing melting temperature of Bi-doped glasses the following change in the valence state of bismuth takes place [11]:

$$\begin{aligned} &Bi^{3+} \rightarrow Bi^{2+} \rightarrow Bi^{+} \rightarrow Bi \\ &\quad \rightarrow \text{Bi clusters } (Bi_2, Bi_2^-, Bi_3 \text{ etc}) : \\ &\quad \rightarrow (Bi)_n \text{ metallic colloids} \end{aligned}$$

These features of Bi make it notably difficult to determine the valence state of Bi and, therefore, the exact nature of Bi-related near IR emitting centers in glasses.

But there are two definite experimental facts:

- It is well known that Bi^{3+} and Bi^{2+} ions emit visible luminescence and no near IR luminescence [12]–[15].
- The results of many experiments clearly demonstrate that near IR luminescence is observed because of the reduction of Bi3+ ions to a lower oxidation state. Excessive reduction results in the formation of Bi clusters and colloids and optical losses increase [11], [16].

At present, there are several hypotheses concerning the origin of the near IR emission from Bi-doped glasses: Bi^+, Bi-clusters, BiO, Bi_2^-, BI_2^{2-} point defects and others. But none of them has been directly confirmed. These hypotheses have been analyzed in detail in [4]. Some experiments suggest that the near IR emitting centers in Bi-doped glasses are not sole Bi ions, but clusters consisting of Bi ions and some defects of glasses [17].

III. Bismuth-Doped Optical Fibers: Technology and Luminescence Properties

The first Bi-doped optical fiber was fabricated in 2005 using MCVD technique [18], [19]. The core of this fiber consisted of Bi-doped aluminosilicate glass where near IR luminescence was observed for the first time [2]. A fiber consisting of Bi-doped phosphogermanosilicate glass was also fabricated in [18] to explore the influence of various elements on the luminescence properties.

The core glass compositions of these fibers were as follows (in mol %):

0.03 Bi_2O_3-10 Al_2O_3-90 SiO_2 (fiber A)

0.002 Bi_2O_3-1 Al_2O_3-2 P_2O_5-9 GeO_2-88 SiO_2 (fiber G)

Fig. 5 shows luminescence spectra of these fibers. The spectra resemble those measured in the Bi-doped silica-based glass [2]. The decay of near IR luminescence excited at 1064 nm had a single-exponent shape with the lifetime 800 and 1200 μs for

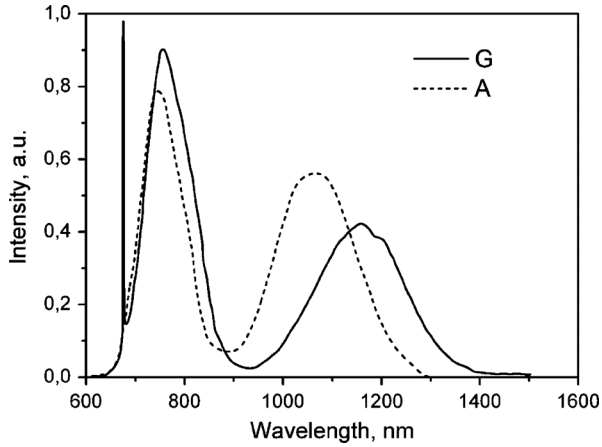

Fig. 5. Luminescence spectra of the first Bi-doped fibers excited at 676 nm.

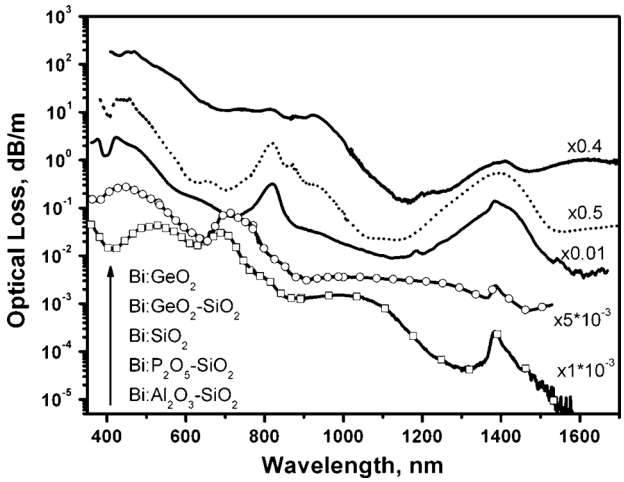

Fig. 6. Optical loss spectra of various Bi-doped fibers. The labels at the right side of curves show the reduction of the absorption values of the corresponding curves for a more convenient comparison of the absorption spectra of these fibers.

fibers G and A respectively. The optical loss spectrum of fiber A is shown in Fig. 6.

Later, various types of Bi-doped optical fibers were developed, including fibers with the cores consisting of Bi-doped SiO_2, Bi-doped GeO_2, Bi-doped P_2O_5-SiO_2, Bi-doped GeO_2-SiO_2 and Bi-doped P_2O_5-GeO_2-SiO_2 glasses. Bi-doped SiO_2 fibers (standard and microstructured) were fabricated by MCVD and "powder in tube" techniques [20], [21], the others-by MCVD. The results of early investigations of the transmission and luminescence properties of various Bi-doped fibers are presented in a number of reviews and papers (see, for example [22]–[26]).

The luminescence spectra of Bi-doped fibers were frequently obtained by excitation only at particular pumping wavelengths and via observation in a limited spectral region. Such measurements don't allow one to get a full luminescence picture for the correct interpretation of luminescence spectra. Recently we carried out the measurement of the luminescence intensity I_{lum} of Bi-doped fibers in dependence on both emission and excitation wavelengths within a wide spectral range of 450–1700 nm. These measurements have allowed us to construct contour plots of the dependence $I_{lum}(\lambda_{em}, \lambda_{ex})$ for the following fibers: Bi-SiO_2, Bi-GeO_2, Bi-P_2O_5-SiO_2, Bi-Al_2O_3-SiO_2 [27].

Fig. 6 shows the optical loss spectra of these Bi-doped fibers. All fibers have several broad absorption bands in visible and near IR regions.

The low curve corresponds to the aluminosilicate fiber, which is the first fiber fabricated and has the well-known absorption bands at 500, 700, 800, 1000 and 1400 nm. In this figure, it is clear that the absorption spectra depend on the core glass composition. The fibers with silica and germanosilicate cores have similar absorption spectra. Fig. 7(a)–(d) shows the contour plots of the luminescence intensity for the indicated fibers. The simplest luminescence picture is for the Bi-doped silica fiber (picture "a"). The well-known red luminescence at 600 nm from Bi^{2+} is visible. A near IR luminescence spectrum consists of two bands: one at 830 nm, excited at 420 and 820 nm and one at 1430 nm, excited by 420, 820 and 1420 nm. These bands will be further considered as related to silica glass. Fig. 7(b) relates to the Bi-doped germanate fiber. The first unexpected result is that there is no red luminescence from Bi^{2+}. Two new bands (in comparison with those of the Bi-doped silica fibers) appeared at 950 and 1650 nm. These bands will be further considered as related to germanate glass. The bands at 830 nm and $\sim$1400 nm, typical for silica glass, are also observed. Their appearance can be explained by the diffusion of a small quantity of silicon from the silica cladding into the germanate core during the fabrication of the fiber.

Fig. 7(c) shows the luminescence picture of the Bi-doped phosphosilicate fiber. The band at $\sim$750 nm excited at 520 nm corresponds to Bi^{2+}. The bands at 830 and 1430 nm, related to silica glass, are visible. There are broad luminescence bands in a spectral region of 1100–1300 nm related to phosphorus.

The luminescence picture for the Bi-doped aluminosilicate fiber is presented in Fig. 7(d). The band at 750 nm corresponds to Bi^{2+}, the band at 820 nm—to silica glass and three broad bands in a spectral region of 1150–1300 nm—to Al. It is interesting that there are no silica-related bands at 1400 nm despite the significant amount of silica glass in the core of this fiber. This result can be explained by strong activity of Al in forming Al-Bi links. Given a small concentration of Bi, practically all of the Bi ions are connected with Al, forming Bi-Al-related emitting centers. However, if the Bi concentration increases (without an increase in the Al concentration) the silica-related band appears at 1400 nm.

Fig. 8 summarizes the results presented. Taking into account the broad luminescence bands of the Bi-doped fibers (100 nm and more) one can see that the luminescence of the Bi-doped fibers extends from 800 to 1700 nm (through the whole spectral region). This figure also shows the lifetimes of the various luminescence bands. For the wavelengths longer than 1000 nm the lifetime values are several hundred microseconds, for shorter wavelengths they are 3–50 microseconds. A detailed discussion of the luminescence properties of Bi-doped fibers can be found in [27].

IV. Bismuth-Doped Fiber Lasers

The first Bi-doped fiber lasers were developed for a spectral region of 1140–1215 nm using Bi-doped aluminosilicate fibers.

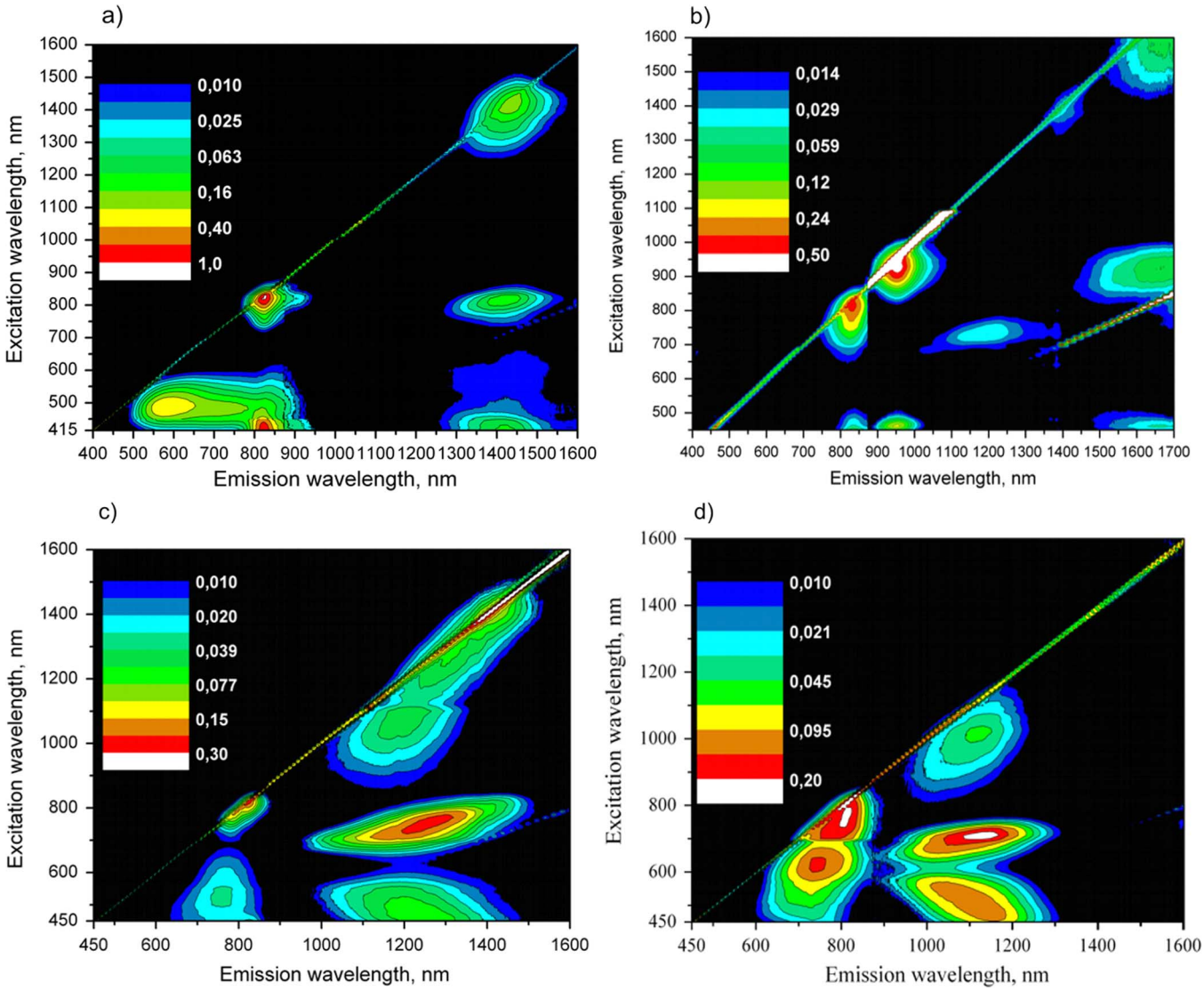

Fig. 7. Contour plots of the luminescence intensity of various Bi-doped fibers.

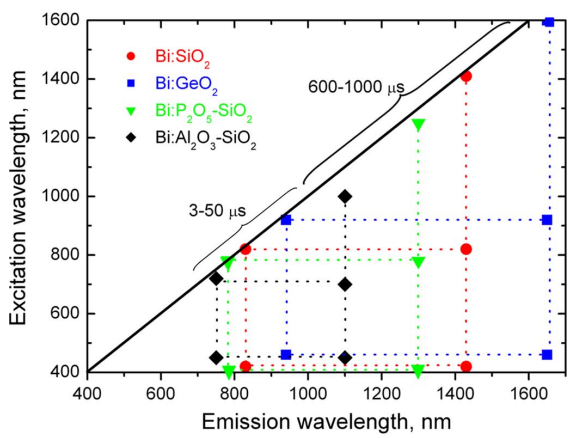

Fig. 8. A summary scheme of the main near IR emission peaks for different Bi-doped fibers. The types of fibers and lifetime values for various luminescence bands are also indicated.

Later, Bi-doped fiber lasers were developed for a spectral region of 1270–1550 nm, using newly developed phosphogermanosilicate, germanosilicate and silica fibers. A review of the results on the development of early Bi-doped fiber lasers is presented in [23].

In this paper we present the recent results on the development of two high-power cw Bi-doped fiber lasers, operating at the wavelengths 1270 and 1460 nm.

A 1270 nm fiber laser is of interest for many applications, in particular, for medical applications (see, e.g., [28]). Besides, the second harmonic of such laser can be used for substitution of the He-Ne gas laser. We used Bi-doped germanophosphosilicate fiber as a gain medium for this laser. A Raman fiber laser at the wavelength 1230 nm with an output power of 25 W was used as a pump source. Fig. 9 shows the output power of the laser as a function of absorbed pump power [29].

Recently, high power and efficient Bi-doped fiber lasers, operating in a spectral region of 1390–1530 nm have been developed [30]–[32]. A Bi-doped germanosilicate fiber with the broad luminescence band at ~1400 nm was used as an active medium. The scheme of the laser operating at 1460 nm is shown in Fig. 10. The length of the Bi-doped fiber was chosen to be 95 m to provide nearly full absorption of the pump radiation at 1340 nm. A phosphosilicate fiber Raman laser was used as

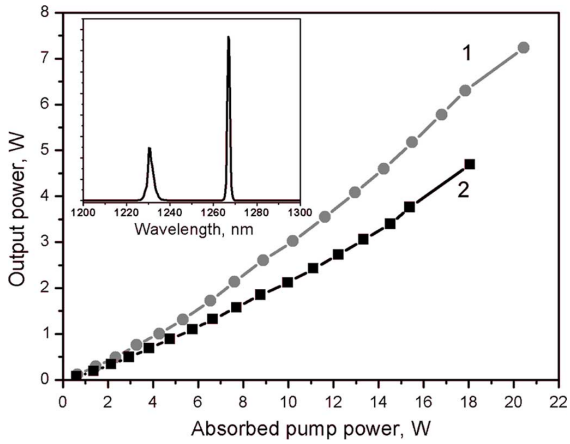

Fig. 9. The output power of the 1270 nm fiber laser as a function of absorbed pump power for the output Bragg grating reflectivity 50% (1) and 25% (2).

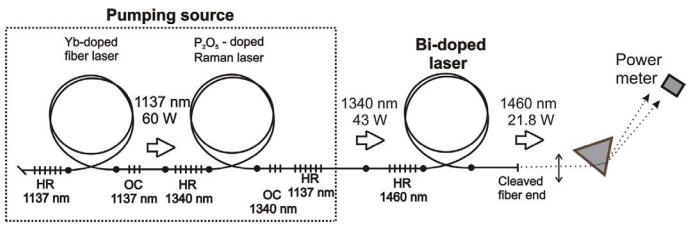

Fig. 10. Bi-doped silica-based fiber laser operating near 1460 nm.

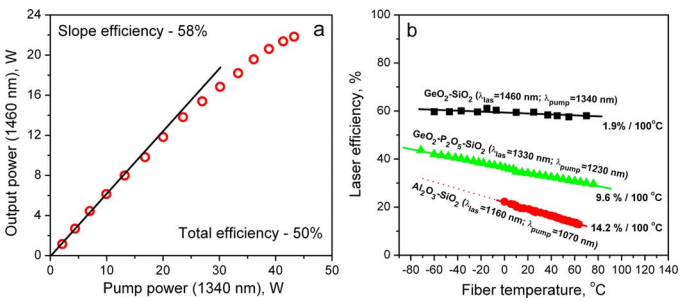

Fig. 11. The output power at 1460 nm in dependence on the pumping power (a) and the efficiency of various Bi-doped fiber lasers as a function of temperature (b).

a pump source. The Raman laser was pumped by a Yb-doped fiber laser, operating at 1137 nm.

Fig. 11(a) shows the output power at 1460 nm in dependence on the pumping power. The conversion efficiency of the laser was 50%. Fig. 11(b) shows the dependence of the laser efficiency on temperature in comparison with that of Bi-doped fiber lasers based on phosphogermanosilicate and aluminosilicate fibers. Clearly, the efficiency of this laser depends only slightly on the temperature within a range of -60–$+800$C.

Fig. 12 summarizes the results regarding the development of Bi-doped fiber lasers. The vertical axis shows the maximum output power of the cw fiber lasers operating at corresponding wavelengths. The circles on the horizontal axis shows the pumping wavelengths, with the color of the circles indicating the corresponding wavelengths generated. At present, the Bi-doped fiber lasers overlap the whole spectral region 1140–1550 nm. However, given the wider spectral region of

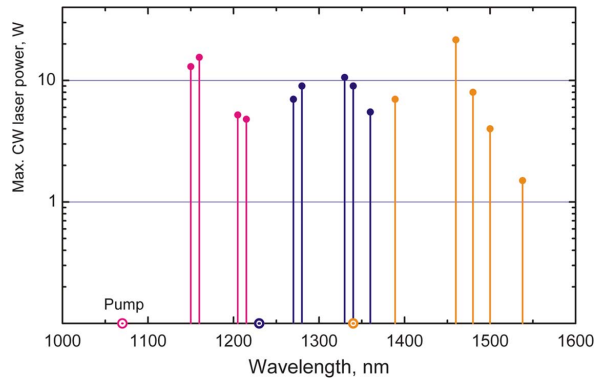

Fig. 12. The output power of various Bi-doped fiber lasers operating in a spectral region of 1150–1550 nm.

the luminescence in Bi-doped glasses and fibers, one might expect extension of the laser generation to shorter and longer wavelengths.

V. Bismuth-Doped Fiber Amplifiers

Optical amplifiers are the most essential element of modern optical fiber communication systems, continuously extending the reach of wavelength division multiplexing (WDM) architectures. At present, commercial systems have a fiber transmission capacity of 10 Terabit/s. The global information demand increases by 30–40 percent per year. It means that in 20 years the fiber transmission capacity will need to be 100–1000 Petabit/s. One of the ways to reach this level of transmission capacity is to widen the transmission bands.

Today, high bit rate communication systems use a narrow spectral region of 1530–1610 nm for the transmission, determined by the amplification bandwidth of the Er-doped fiber amplifier. But it is possible to use a spectral region of 1300–1500 nm, where the optical losses of silica-based fibers are less than 0.4 dB/km. However, there are no efficient optical amplifiers for this spectral region. Nevertheless, it follows from the results presented above that the development of Bi-doped fibers opens the door to the creation of an efficient Bi-doped fiber amplifier (BDFA) for this spectral region.

The first results regarding the development of BDFA were obtained using a phosphogermanosilicate fiber [33]. Though we obtained a gain of more than 20 dB at 1320 and 1430 nm, the pumping power was notably high -460 mW and 190 mW respectively.

Recently, a Bi-doped fiber amplifier, based on a Bi-doped germanosilicate fiber with improved characteristics and a commercial laser diode for pumping has been developed [34]. The scheme of BDFA is shown in Fig. 13.

The pump and the signal were launched through a WDM coupler. The active fiber length was $L = 125$ m. Two different pump sources were used:

1. A home-made Raman fiber laser (RFL) with output power of up to 500 mW,
2. A commercially available single-mode laser diode with output power of up to 80 mW at 1310 nm (LPSC-1310-FC, Thorlabs).

Two different kinds of light sources were used as signals:

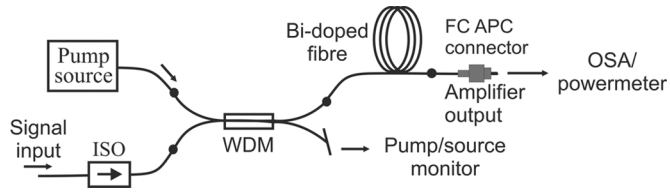

Fig. 13. A Bi-doped fiber amplifier. ISO—optical isolator, WDM—wavelength division multiplexer, OSA—optical spectrum analyzer, FC APC Connector-Fiber-optics for Angled Physical Contact.

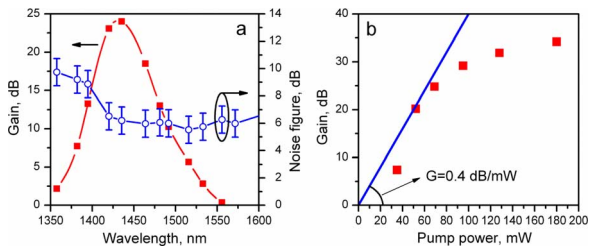

Fig. 14. The gain and noise figure spectra of the BDFA (a) and dependence of gain at 1427 nm on pump power (b).

1. A multi-line signal source based on a super continuum fiber source and a set of HR FBG ($\lambda_s = 1330-1650$ nm, $\Delta\lambda_{\mathrm{FWHM}}\sim 0.7$ nm).
2. A FBG-stabilized diode laser at 1427 nm. We used an optical isolator (ISO in Fig. 13) to suppress optical feedback and to prevent laser generation in the active fiber. The first signal source was used to measure the amplifier gain spectra and noise figure. The second source enabled us to examine the saturation characteristics of the amplifier.

Fig. 14(a) shows the gain spectrum and the noise figure (NF) spectrum of the amplifier pumped by 65 mW at 1310 nm from a laser diode. The peak gain of 24 dB was observed near 1427 nm, the 3 dB bandwidth was 36 nm and NF = 6 dB.

Fig. 14(b) shows the gain at 1427 nm as a function of pump power at 1230 nm. The input signal power in this experiment was $\mathrm{Ps\_in} < -20$ dBm. The maximum gain coefficient (also called the pumping efficiency or gain efficiency) is G = 0.4 dB/mW. The G value achieved is one order of magnitude lower than that of a typical Er-doped fiber amplifier, but one order of magnitude higher than that of RFA and 2–4 times higher than that of Tm-doped fiber amplifiers. We expect that the appropriate optimization of the fiber parameters will allow us to increase the gain coefficient 2–4 times.

VI. Conclusion

Bismuth-doped fibers are a challenging active medium for near IR lasers and optical amplifiers. Bi-doped fiber lasers and optical amplifiers in extended transmission bands have been demonstrated. However, the nature of Bi-related emission centers is not yet clear. Further fundamental research of the nature of Bi emitting centers must be conducted to raise the efficiency of Bi-doped fiber lasers and optical amplifiers to the level of rare-earth-doped fiber devices.

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