Efficient Bismuth-Doped Fiber Lasers

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***Abstract*—Bismuth-doped fiber lasers with efficiency of up to 32% at room temperature and up to 52% at 77 K have been developed. The dependence of the efficiency on the pump power and the pump wavelength is interpreted on the basis of spectroscopic measurements.**

***Index Terms*—Fluorescence spectroscopy, infrared spectroscopy, optical fiber lasers, optical fiber materials.**

I. Introduction

FIBER lasers are becoming quite attractive owing to their compactness, robustness and simplicity. Rare-earth-doped fiber lasers cover a spectral range in the 1–2 μm range with a gap in the 1150–1450 nm region where no active fibers compatible with common telecommunication fibers exist [1]. However, further expansion of the telecommunication transmission window necessitates broadband amplifiers in the spectral range of 1300–1450 nm [2]. In addition, light sources in the yellow range (575–590 nm), which are of great importance in dermatology [3], ophthalmology [4] and laser guide star experiments in astronomy [5], can be fabricated by frequency doubling of fiber lasers operating in the 1150–1180 nm range.

We have already reported the first realization of CW and pulsed bismuth-doped (Bi-doped) fiber lasers operating in the 1140–1300 nm range [6], [7]. Spectroscopic estimations [8], have shown that one can expect to expand of this spectral range up to 1.7 μm. Thus, this new laser medium is thought to be very promising for fiber lasers and amplifiers. However, previous preliminary results [6], [9], [10] have reported a moderate lasing efficiency, which makes it necessary to perform a further complex study of spectroscopic and laser parameters of this medium. In this paper, we describe 1160- and 1200-nm Bi-doped fiber lasers with improved efficiencies and propose a model to explain this improvement.

II. Fiber Fabrication and Experimental

The preform of the Bi-doped fiber was fabricated by the modified chemical vapor deposition (MCVD) method, [6] with the core formed by the chemical vapor deposition of aluminum and silicon oxides (the refractive index difference between the core and the cladding was about 0.005 and corresponded to an Al_2O_3 concentration of 2.5 mol.%). Bismuth oxide was incorporated in the core glass by the solution-doping technique. The concentration of Bi atoms in the core glass did not exceed 0.02 at.% (the detection limit of our X-ray microanalysis). A single-mode fiber with a cut-off wavelength of $\sim$1 μm was drawn from the preform. The mode field diameter of the fiber was 6.8 μm at the wavelength of 1.1 μm.

Optical loss spectra were measured by the cut-back technique using a tungsten lamp as the light source. A YAG:Nd^{3+} laser ($\lambda = 1064$ nm) and an Yb^{3+} -doped fiber laser ($\lambda = 1050$ to 1100 nm) were used to study the fluorescence of the Bi-doped fiber. To minimize re-absorption, the fluorescence signal from the core-excited Bi-doped fiber was received from the lateral surface of the fiber. Fluorescence decay was measured under excitation with a CW YAG:Nd^{3+} laser modulated by an electro-optical modulator. The time resolution of this measurement was about 10 μs. The other experimental techniques used in this work are described elsewhere [11], [12].

The Bi-doped fiber laser cavity was formed by fusion splicing both ends of the active fiber to germanosilicate fiber containing a UV-written fiber Bragg grating (FBG). One of the FBGs was highly reflective (HR). The mismatch between the parameters of the germanosilicate and the Bi-doped fibers led to a splicing loss of 0.1–0.2 dB. The length of the Bi-doped fiber was optimized experimentally in each case to obtain a maximum output power.

The Bi-doped fiber laser was core-pumped through the HR FBG by an Yb^{3+} -doped fiber laser [13]. Being pumped at 976 nm into the cladding by a laser diode, the Yb^{3+} -doped fiber laser generated up to 20 W with a $\sim$75% efficiency in the 1070–1090 nm spectral range, depending on the FBGs used.

III. Spectroscopy

A. Optical Loss (Absorption)

Bi active centers in our samples are represented by wide absorption bands at 500, 700, 1000, and 1400 nm and a shoulder at 800 nm [12]. The ratios of the intensities of the bands at 500, 700, and 1000 nm are constant for all the investigated fibers. Thus, we assume that these bands belong to the same active center.

The temperature dependence of the 1000-nm absorption band for the fiber described in this paper is shown in Fig. 1. A temperature increase leads to a rise in absorption in the short-wavelength edge of the band, probably owing to broadening of the intense 700-nm band. As this broadening takes place, the long-wavelength edge of the band changes insignificantly. The optical loss of the fiber at 1300 nm, where Bi absorption is negligible, is 13 dB/km.

The absorption in the 1000-nm band saturates with increasing pump intensity. The residual loss measured at the pump intensity of about 15 MW/cm^2 is shown in Table I and Fig. 1. It is

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TABLE I
SMALL-SIGNAL AND RESIDUAL OPTICAL LOSS IN THE Bi-DOPED FIBER

Wavelength, nm	1064.4		1075	1090
Small-signal loss, dB/m	300 K	0.32	0.28	0.24
	77 K	0.34	0.3	0.25
Residual loss, dB/m	300 K	0.12	0.1	0.075
	77 K	0.09	–	–

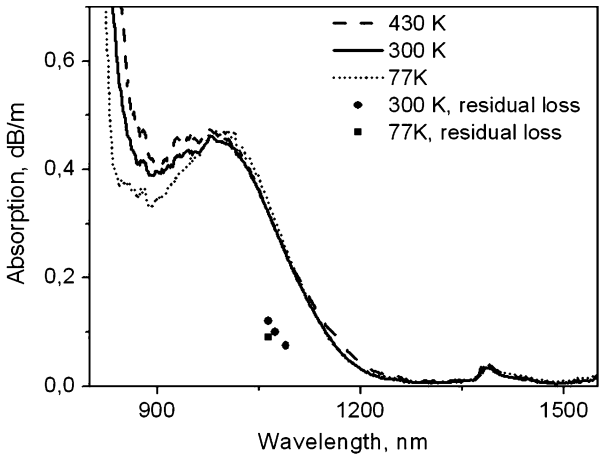

Fig. 1. Loss spectra of the Bi-doped fiber and its residual loss (measured at light intensity of about 15 MW/cm^2).

seen that the level of the residual loss decreases at longer wavelengths and at a lower temperature. Similar results were reported in [9].

B. Fluorescence

Two fluorescence bands are observed under excitation in the visible range [11]. The first band has a maximum at about 1100 nm and the second one at 750 nm. Only the first fluorescence band is observed under excitation in the 1000-nm absorption band. The shape of this fluorescence band remains unchanged under excitation in the 1064–1090 nm range.

The temperature dependence of the fluorescence was investigated under excitation at 1064 nm and at a temperature of either 77 K, or 300–600 K (Fig. 2). The unabsorbed pump power was almost independent of temperature because the absorption coefficient depends only weakly on temperature at this wavelength. The relative fluorescence intensity calculated as an integral over the spectral curve does not change between 77 and 300 K, within our measurement accuracy of 5%. At higher temperatures the integrated fluorescence intensity (measured with lower accuracy, up to 20% at 600 K) also did not change. The conclusion can be drawn that in the temperature range under investigation (77 to 600 K), the fluorescence quantum efficiency changes only slightly. As this takes place, a temperature increase results in an evident blue shift of the fluorescence band (see Fig. 2).

The differences between the fluorescence spectra measured at different temperatures clearly show that the changes in band shape can be explained by a variation of the intensities of two contributions to this band (Fig. 3). The first component grows

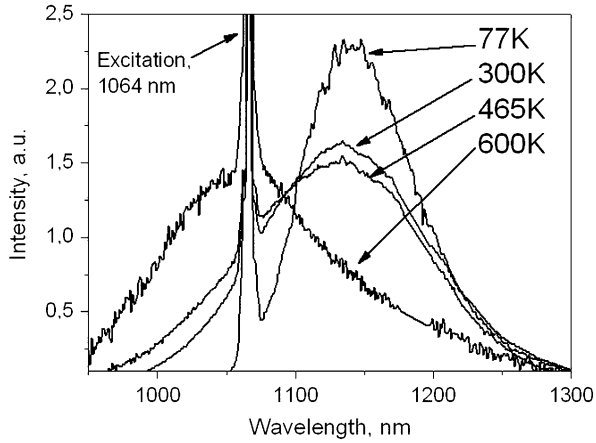

Fig. 2. Temperature dependence of the fluorescence excited at the wavelength of 1064 nm.

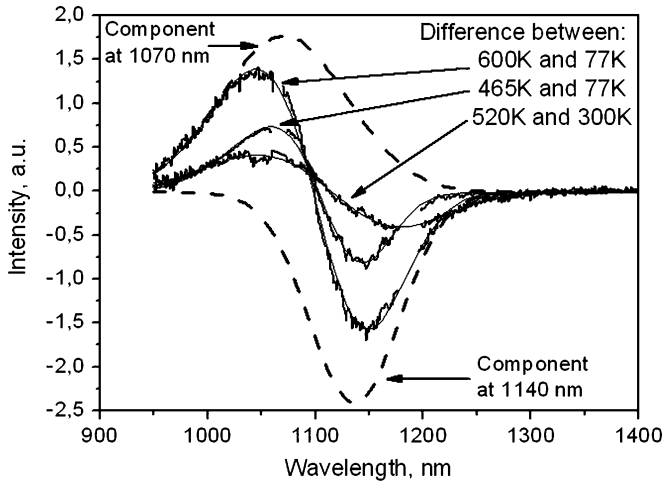

Fig. 3. Difference between luminescence spectra of various temperatures. The components of the fitting by two Gaussian bands are shown for the difference between the spectra measured at 600 K and 77 K.

with temperature, while the second one decreases. As follows from a Gaussian deconvolution of this band, the first component has a maximum at about 1070 nm and a full-width at half-maximum (FWHM) of 140 nm; the second one peaks at 1140 nm and has a FWHM of 100 nm.

The fluorescence decay was measured to be a single exponential with a time constant of 880 μs at room temperature and 890 μs at 77 K. A weak temperature dependence of both fluorescence intensity and its time constant lead us to believe that the fluorescence decay is mainly radiative. The emission cross-sections (Fig. 4) were calculated from the Füchtbauer–Ladenburg equation under the assumption of thermalization of all the states involved into the fluorescence.

Fluorescence intensity saturation was studied under 1064-nm excitation. The saturation intensity was determined to be equal to $\sim$30 kW/cm^2. We could not determine the absorption cross section correctly, because the fiber is single-mode and the active centers distribution across the core is unknown. Nevertheless, the emission cross section spectrum of Fig. 4 and the saturation intensity agree well with earlier published data for a Bi-doped

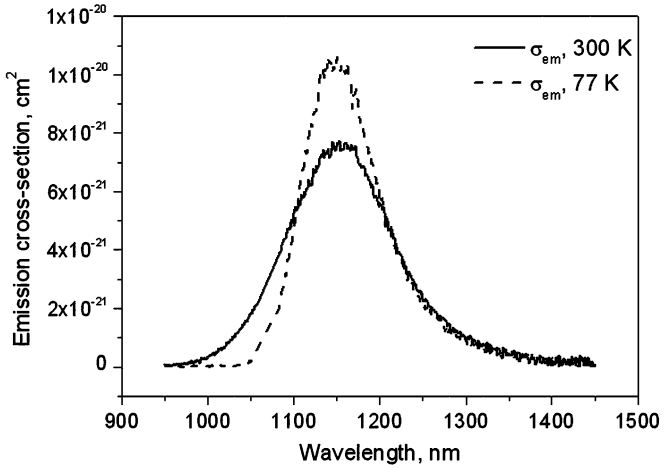

Fig. 4. Emission cross section spectra.

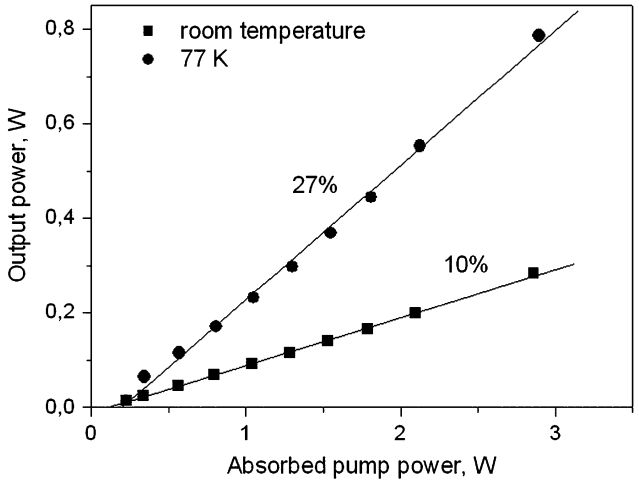

Fig. 5. Efficiency of a 1160-nm laser pumped at 1064 nm with a pump power of up to 3 W. The laser has a 3-dB output coupler and a 64-m active fiber length.

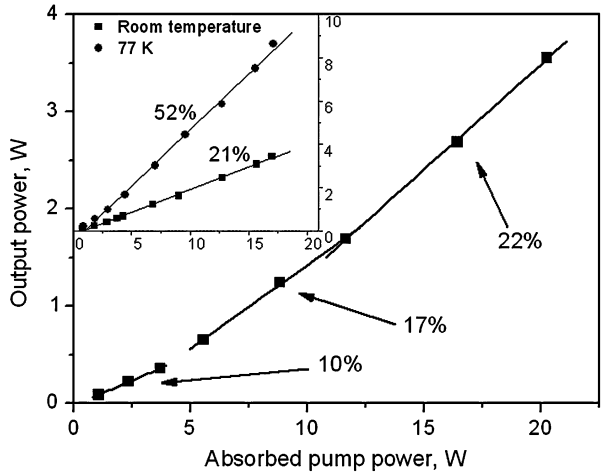

Fig. 6. Efficiency of 1160-nm lasers pumped at 1068 nm at room temperature and at two temperatures at 1075 nm (inset). The lasers had a 3-dB output coupler and a 75-m active fiber length.

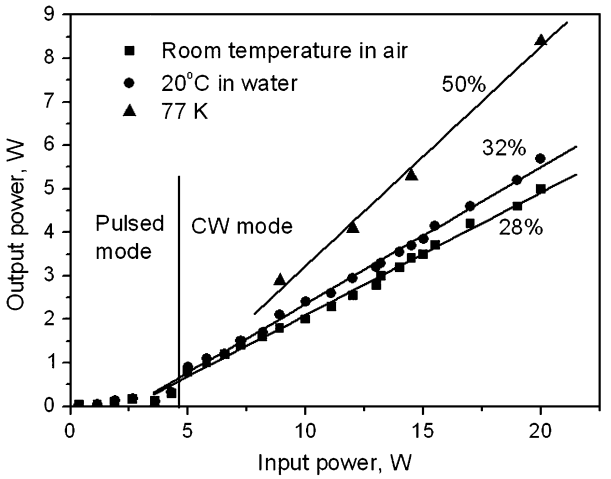

Fig. 7. Efficiency of 1160-nm laser pumped at 1090 nm. The laser has 2.5-dB output coupler and 55-m active fiber length. FBG reflecting the rest of pump at 1090 nm was spliced to its output.

multimode fiber with a similar core composition [6]. The estimation of the active centers concentration using the absorption cross section published in [6] gives the value of $10^{18} - 10^{17}$ cm^{-3}, which corresponds to $10^{-3} - 10^{-4}$ at.%.

The shape of the fluorescence band is weakly sensitive to the excitation intensity up to ~2500 kW/cm^2 at 1068 nm. One can conclude from this observation that inhomogeneous broadening of the fluorescence band (and also of its components) is much less than its spectral width.

IV. Laser Oscillation

A. *Efficiency at 1160 and 1200 nm*

The lasing slope efficiency at room temperature that we reported earlier [6] was weakly sensitive to the pump wavelength in the range of 1050–1100 nm and was around 10% at a pump power of up to 5 W.

In this paper, a temperature decrease to 77 K led to a sizeable improvement in the efficiency at 1160 nm wavelength, from 10% to 27% at a pump power of up to 3 W at 1064 nm (Fig. 5). In addition, at higher pump power the laser efficiency increases, as shown in Fig. 6. A change was noticed at a pump power of about 5 W.

The same behavior was observed under pumping at 1075 nm (see Fig. 6, insert). At 77 K, the efficiency increases up to 52%. The tendency of the efficiency to increase with pump power remains the same. Maximum output power was 3.6 W at room temperature and to 8.6 W at 77 K.

A further increase of the pump wavelength to 1090 nm led to an efficiency of up to 28% at room temperature, but at 77 K the change of efficiency was insignificant (Fig. 7). The HR FBG at 1090 nm ($\mathrm{HRFBG_{pump}}$) was spliced to the laser output in order to increase the output power at 1160 nm. The output power reached about 5 W at room temperature and 8.4 W at 77 K.

It was evident that the Bi-doped fiber was heated up during the laser generation experiments. In addition, the laser output power dropped by a factor of more than two when the fiber was placed in a hot air flow with a temperature of ~50 °C that was in agreement with the earlier observation of a decrease in efficiency of the Bi-doped fiber laser when it was heated from 0°C to 60 °C [9]. Based on these observations, a spool of this fiber

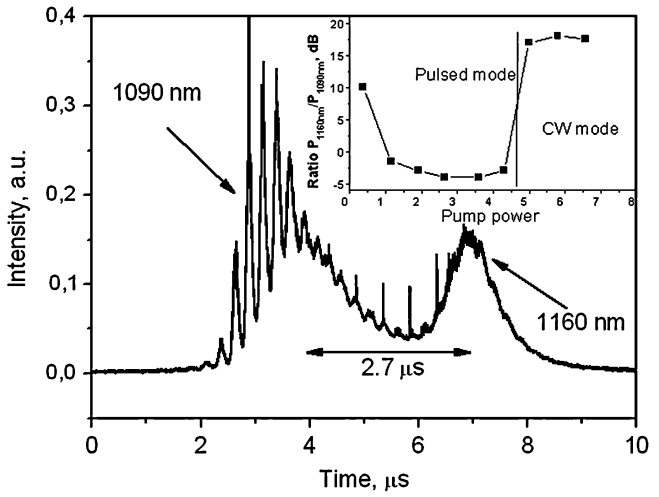

Fig. 8. Pulsed laser action at 1160 nm with pump power of 2.65 W. A pump pulse at 1090 nm transmitted through reflecting pump FBG is observed. The ratio of 1160-nm output power to 1090-nm pump power transmitted through reflecting pump FBG is shown in the inset.

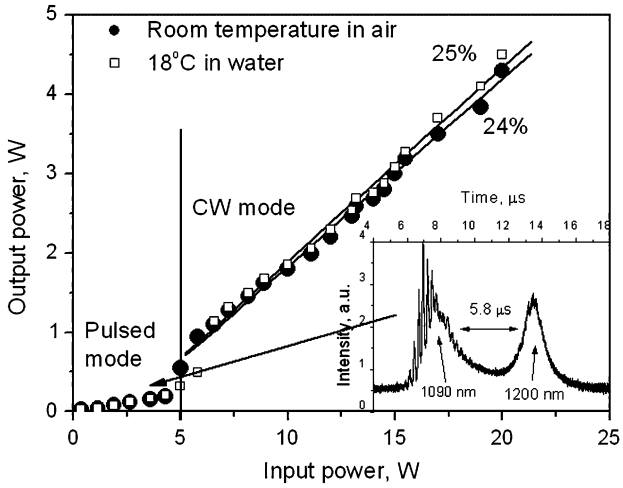

Fig. 9. Efficiency of 1200-nm laser pumped at 1090 nm. The laser has 3 dB output coupler and 55-m active fiber length. Reflecting pump FBG was spliced to its output. Pulse shape at pump power of 3.6 W is shown in the inset. A pump pulse at 1090 nm transmitted through reflecting pump FBG is observed.

was placed into a water tank at room temperature in order to provide a more effective heat removal. As a result, the laser efficiency increased to 32% and the output power reached 5.75 W.

The $\mathrm{HRFBG_{pump}}$ at the laser output produced pulsed lasing at low pump power, as was discussed in [7]. In this case, the Bi-doped fiber acted as a saturable absorber for the Yb^{3+} -doped laser causing pulsed action of both lasers. The pulse shape is shown in Fig. 8. The pump power transmitted through the $\mathrm{HRFBG_{pump}}$ was high enough, owing to strong spectral broadening of the pump pulse at high peak power. At a pump power of about 5 W, the lasing switched to CW mode, which was accompanied by a more than threefold increase in the output power at 1160 nm. The laser efficiency increased and simultaneously the pump power transmitted through the $\mathrm{HRFBG_{pump}}$ decreased to about 20 dB below the laser output power at 1160 nm because of laser line narrowing (see Fig. 8). It appears that the main factor for the lower efficiency in the pulsed mode is that the absorption saturates at high pump pulse energy, and the energy is spent mainly on the residual loss.

The pump laser was then tuned to the wavelength of 1075 nm with a corresponding change of the $\mathrm{HRFBG_{pump}}$ resonant wavelength. In this manner, we were able to correctly compare two lasers operated with two different pump wavelengths. The slope efficiency in the continuous-wave (CW) mode at high pump power remained about 20% (see Fig. 6) indicating that the FBG reflecting the pump did not significantly influence the CW lasing efficiency.

Finally, the laser was tuned to 1200 nm and pumped at 1090 nm. Its efficiency was about 24% in air and about 25% in the water tank (Fig. 9). The output power reached 4.5 W. The laser showed the same features as the laser operating at 1160 nm. The pulse shape at low pump power is also shown in Fig. 9. The laser switched into CW mode at a pump power of about 5 W, with a sharp rise in the output power at 1200 nm.

B. Linewidth Broadening

The spectra of the 1160-nm CW laser at room temperature under 1090-nm pump are presented in Fig. 10. The corresponding HR and output FBGs had FWHMs of 0.4 and 0.2 nm, respectively. The laser linewidth broadened up to 0.3 nm at an output power of 5 W, at a constant rate of 0.025 nm/W. The dip in the line shape originating from the output coupler becomes distinct at a sufficiently high output power. The widths of the lines shown in Fig. 10 are larger than the output coupler width. At an output power of 5 W, the reflection from the FBG was estimated to decrease to 0.6 dB from its maximum reflection of 2.5 dB. At the same time, the unabsorbed pump power measured experimentally changed insufficiently, from 13% to 16%. In the case of the 1200-nm lasing, the output coupler reflection also decreased from 3 dB at the lasing threshold to approximately 1 dB at an output power of 4.4 W.

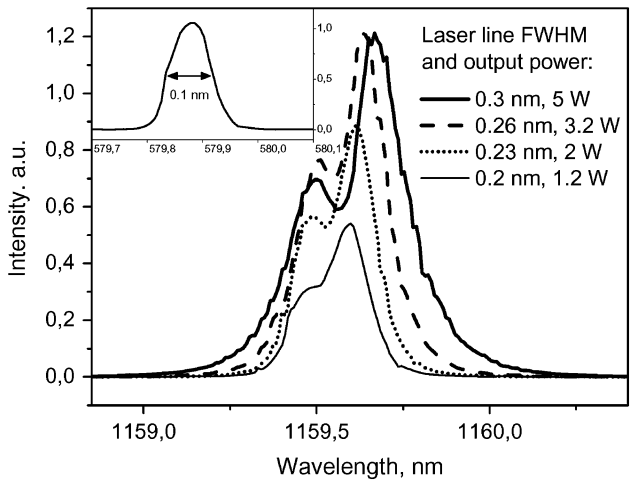

Fig. 10. Spectra of laser emission at 1160 nm. Spectrum of 200 mW second harmonic obtained with 4.5 W pump power is shown in the inset.

The broadening of the laser linewidth also resulted in a leakage of the laser emission in back direction through HR FBG. Therefore, the power transmitted through the HR FBG was monitored in order to estimate its influence on the laser efficiency. However, this power was always less than 6% of the output power and therefore was ignored.

In spite of a strong tendency to linewidth broadening Bi-doped fiber lasers are convenient for yellow light generation. To demonstrate this potential we frequency-doubled the unpolarized 1160-nm laser emission with a commercial 30-mm-long periodically poled lithium niobate crystal with a fiber input (Global Fiberoptics, Ltd., Japan). We obtained 200 mW at 580 nm with a FWHM of 0.1 nm at a pump power of 4.5 W at 1160 nm with a FWHM of 0.3 nm (Fig. 10). This corresponds to a conversion efficiency of ~4.5%.

V. Discussion

We believe that the main factor that currently limits the efficiency of Bi-doped fiber lasers is the residual loss [9]. We do not know the exact origin of this loss. It could be a passive loss or excited-state absorption. In both cases, it is preferable to decrease a population inversion of the active media for a more effective conversion of the absorbed pump power to the laser emission. The increase of the population of the ground state results in an increase of the active centers' absorption and the contribution of the passive loss in the overall absorption of the active media becomes lower. Simultaneously, the decrease of the population of the excited state decreases the excited-state absorption. Thus, the decrease of the population inversion leads to a more effective conversion of the absorbed pump power to the laser emission.

This can be done by lowering the fiber temperature because emission cross section increases at 1160 nm but decreases at 1060–1090 nm (Fig. 4). Combined with the small reduction in residual loss at lower temperature (see Table I), we suppose that this improvement produces a ~50% efficiency at 77 K.

The most interesting feature of Bi-doped fiber lasers is the dependence of their slope efficiency on the pump power. The estimated impact of Raman scattering and four-wave mixing is insignificant in our basically silica fiber. In particular, for a 43-m fiber length and an excitation power of 20 W at 1090 nm, the Raman gain at 1160 nm was estimated not to exceed ~0.5 dB. In the other cases (other wavelengths and lower pump power) the impact of Raman gain is even smaller.

By the other hand, the laser slope efficiency becomes higher with increasing of the output coupler transmission. Such increasing takes place when the laser line broadens. A twofold increase in the efficiency requires at least a twofold reduction in the output FBG reflection. But, to compensate for the increased transmission the output coupler, the population inversion in the active medium required to reach threshold must be increased, and consequently the absorption is reduced. The pump absorption must be at least 25% smaller, as can be estimated from the emission and absorption cross-sections. Here we do not take into account the fact that the efficiency will be affected more strongly by the "residual loss" at a higher inversion. Surprisingly, the unabsorbed pump power almost does not depend on the incident pump power. Thus, the growth of the laser efficiency with pump power cannot be explained only by the laser line broadening.

We suggest an explanation of this phenomenon on the basis of an assumption that the fluorescence band consists of two bands belonging to two different energy terms of the active center (see Fig. 3). A qualitative energy level structure is shown in Fig. 11, where the ground state is indicated as 1, and the energy terms

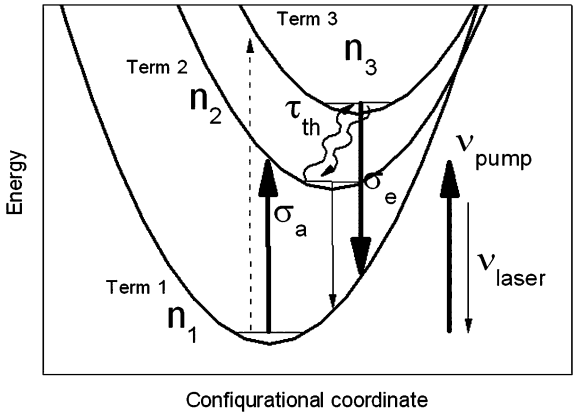

Fig. 11. Qualitative scheme of the active center energy levels involved into the fluorescence (arbitrarily scaled).

responsible for the emission as 2 and 3. The emission from the term 2 produces the main contribution to the laser action. It is important to note that the pump wavelengths correspond to the emission peak of the term 3. If at a pump wavelength the absorption into the term 3 is much less than that into the term 2, then the upper term 3 must be populated through the lower term 2 via the establishment of thermal equilibrium.

In order to show qualitatively the dependence of the gain on the pump power in this system, let us simplify it to a non-degenerate quasi-four-level system with an additional level situated slightly higher than the first excited state (Fig. 11). For simplicity, we neglect with the absorption in term 2. We assume also that the time to reach thermal equilibrium is much less than the excited state lifetime, $\tau_{\rm th} \ll \tau$, and that at equilibrium the populations of both upper levels, n_2 and n_3, are equal. Let us designate the cross-sections of emission and absorption as σ_e and σ_a, the concentration of active centers as n_0, the population of the ground state as n_1, the pump intensity as J and its frequency as ν. Then, the population of the two upper levels at moderate excitation intensity (when $\tau^{-1} \ll \sigma\ J/h\nu \ll \tau_{\rm th}^{-1}$) approaches to

$$N_{2,3} = n_0/(1 + 0.5\sigma_e/\sigma_a), \quad n_2 = n_3 = 0.5N_{2,3}. \tag{1}$$

At high excitation intensity (when $\sigma J/h\ \nu \gg \tau_{\rm th}^{-1}$) the populations of the levels become

$$\begin{aligned} n_2 + n_3 &= N_{2,3}[1 + 0.5\sigma_e/\sigma_a(1 + J_s/J)^{-1}] \\ n_3 &= 0.5N_{2,3}(1 + J/J_s)^{-1} \\ n_2 &= 0.5N_{2,3} + (n_0 - 0.5N_{2,3})(1 + J_s/J)^{-1} \end{aligned}$$

where $J_s = {\rm h}\nu/\sigma_{\rm eff}\tau_{\rm th}, \sigma_{\rm eff} = 0.5\sigma_e\sigma_a/(0.5\sigma_e + \sigma_a)$.

As the pump power approaches infinity ($J \to \infty$) the level populations become

$$\begin{aligned} n_3 &= 0 \\ n_2 &= n_0. \end{aligned} \tag{2}$$

The ratio of (2) and (1) shows that the second level population n_2 increases more than twofold at the high pump power as compared to the case of the moderate pump

$$n_0/(0.5N_{2,3}) = 2 + \sigma_e/\sigma_a. \tag{3}$$

The exact value of the constant on the right-hand side of (3) depends on the energy difference between the levels, the temperature and the degeneracy of the levels. The same relation applies in the presence of a signal at the laser wavelength (we assume that the stimulated emission from the term 3 at the signal wavelength is negligible). If the pump absorption for both moderate and high pump powers remains the same, then in the latter case the starting level of laser action will be populated more strongly than in the former case, as follows from (3). Evidently, the gain rises in the same manner. Thus, an increase in output coupler transmission is compensated by a higher gain. As this takes place, no significant absorption reduction occurs, which provides the efficiency increase.

The efficiency increase with a pump wavelength increase cannot be explained by a decrease in the residual loss, because the absorption changes almost in the same way. On the other hand, it is possible to assume that the absorption into the higher lying term increases at shorter wavelengths. Taking this absorption into account, one can conclude that the population of the higher lying level 3 in the high-pump-power limit is non-zero.

The above concept of three levels interacting with each other and with the pump radiation would be confirmed by the observation of a strong change in the band shape at high pump intensity (>10 MW/cm^2). However, we failed to observe such an effect, because scattering of the intense pump radiation is stronger than the fluorescence signal. Further spectroscopic investigation of this new laser ion is under way.

An overall optical conversion of the laser can be estimated from the obtained results. We demonstrated a single-mode output power of 5.75 W at 1160 nm with a launched laser-diode pump power of 29 W at 976 nm. This corresponds to the overall optical conversion of 20%. At the laser wavelength of 1200 nm, the corresponding values were 4.4 W and 15%.

VI. Conclusion

In this paper, we reported a CW Bi-doped fiber laser with a slope efficiency of 32% and 25% at 1160 and 1200 nm wavelengths, respectively, at room temperature. At 77 K, the slope efficiency at 1160 nm reached 50%. The highest output power at room temperature was 5.75 W and 4.4 W at 1160 and 1200 nm, respectively, for launched pump power of 20 W. At liquid nitrogen temperature the output power increased to 8.6 W at 1160 nm.

Yellow light generation at 580 nm with a power of 200 mW was demonstrated by frequency doubling of a 1160-nm fiber laser emitting 4.5 W.

Spectroscopic investigations show that the emission band of the Bi-doped fiber consisted of two bands with maxima at 1070 and 1140 nm belonging to two different energy terms of the same active center. A level structure model has been proposed to explain the dependence of the laser efficiency on the pump power.

This work is an important step to understand the physics of this new laser ion. These results open up a number of possible practical applications for Bi-doped fiber lasers.

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References

[1] *Rare-Earth-Doped Fiber Lasers and Amplifiers.* , M. J. E. Digonet, Ed.. New York: Marcel Dekker, 2001.

[2] E. Desurvire, "Optical communications in 2025," in *Proc. 31st Eur. Conf. Opt. Communi.*, Glasgow, U.K., 2005, pp. 5–6.

[3] N. S. Sadick and R. Weiss, "The utilization of a new yellow light laser (578 nm) for the treatment of class I red telangiestasia of the lower extremities," *J. Dermatol. Surg.*, vol. 28, pp. 21–25, 2002.

[4] C. F. Blodi, S. R. Russell, J. S. Pudilo, and J. C. Folk, "Direct and feeder vessel photocoagulation of retinal angiomas with die yellow laser," *Ophthalmology*, vol. 97, pp. 791–797, 1990.

[5] C. E. Max, S. S. Olivier, H. W. Friedman, J. An, K. Avicola, B. V. Beeman, H. D. Bissinger, J. M. Brase, G. V. Erbert, D. T. Gavel, K. Kanz, M. C. Liu, B. Macintosh, K. P. Neeb, J. Patience, and K. E. Waltjen, "Image improvement from a sodium-layer laser guide star adaptive optics system," *Science*, vol. 277, pp. 1649–1652, 1977.

[6] E. M. Dianov, V. V. Dvoyrin, V. M. Mashinsky, A. A. Umnikov, M. V. Yashkov, and A. N. Guryanov, "CW bismuth fibre laser," *Quantum Electron.*, vol. 35, pp. 1083–1084, 2005.

[7] V. V. Dvoyrin, V. M. Mashinsky, and E. M. Dianov, "Yb-Bi pulsed fiber lasers," *Opt. Lett.*, vol. 32, pp. 451–453, 2007.

[8] M. Peng, J. Qiu, D. Chen, X. Meng, I. Yang, X. Jiang, and C. Zhu, "Bismuth- and aluminum-codoped germanium oxide glasses for superbroadband optical amplification," *Opt. Lett.*, vol. 29, pp. 1998–2000, 2004.

[9] E. M. Dianov, A. V. Shubin, M. A. Melkumov, O. I. Medvedkov, and I. A. Bufetov, "High-power CW bismuth fiber lasers," *J. Opt. Soc. Amer. B.*, vol. 24, pp. 1749–1755, Aug. 2007.

[10] I. Razdobreev, L. Bigot, V. Pureur, A. Favre, G. Bouwmans, and M. Douay, "Efficient all-fiber Bi-doped laser," *Appl. Phys. Lett.*, vol. 90, p. 031103, 2007.

[11] V. V. Dvoyrin, V. M. Mashinsky, E. M. Dianov, A. A. Umnikov, M. V. Yashkov, and A. N. Guryanov, "Absorption, fluorescence and optical amplification in MCVD Bi-doped silica glass optical fibres," in *Proc. 31st Eur. Conf. Opt. Commun.*, Glasgow, U.K., 2005, vol. 4, pp. 949–950.

[12] V. V. Dvoyrin, V. M. Mashinsky, L. I. Bulatov, I. A. Bufetov, A. V. Shubin, M. A. Melkumov, E. F. Kustov, E. M. Dianov, A. A. Umnikov, V. F. Khopin, M. V. Yashkov, and A. N. Guryanov, "Bismuth-doped-glass optical fibers—a new active medium for lasers and amplifiers," *Opt. Lett.*, vol. 31, pp. 2966–2968, 2006.

[13] I. A. Bufetov, M. M. Bubnov, M. A. Mel'kumov, V. V. Dudin, A. V. Shubin, S. L. Semenov, K. S. Kravtsov, A. N. Gur'yanov, M. V. Yashkov, and E. M. Dianov, "Yb-, Er-Yb-, and Nd-doped fibre lasers based on multi-element first cladding fibres," *Quantum Electron.*, vol. 35, pp. 328–334, 2005.

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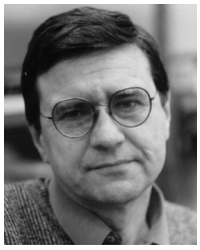

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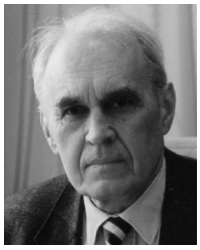

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