Optical amplification in 1430-1495 nm range and laser action in Bi-doped fibers

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Abstract: An emission band with a maximum at 1430 nm and a FWHM of 100 nm was observed in a Bi-doped fiber under core-pumping in the 1340-1370 nm wavelength range. Net gain in 1430-1490 nm and laser action in 1443-1459 nm wavelength range in the Bi-doped aluminosilicate fiber have been demonstrated for the first time to our knowledge.

OCIS codes: (060.2290) Fiber materials; (060.2320) Fiber optics amplifiers and oscillators.

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1. Introduction

Broadband amplifiers in the S-band (1460-1530 nm) and E-band (1360-1460 nm) of the low optical loss telecommunication window based on the active fibers compatible with common telecommunication fibers are required for further increase of telecommunication data traffic [1]. Recently there has been reported on the Bi-doped fiber lasers of 1140-1300 nm operating wavelength range [2]. Authors [3] investigated P_2O_5-GeO_2-SiO_2-Bi_2O_3 core preforms and fibers and reported on the red-shifted broadband fluorescence with peak at 1300 nm observed in glass of such composition. Later a further expansion of lasing diapason up to 1470 nm with a P_2O_5-GeO_2-SiO_2-Bi_2O_3 core fiber was demonstrated [4, 5]. A band with the maximum at even longer wavelength of ~ 1430 nm was observed on the tail of the more intensive 1150 nm

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fluorescence band in an Al_2O_3-GeO_2-P_2O_5-SiO_2-Bi_2O_3 core fiber under excitation at 827 nm [6]. In a fiber of GeO_2-SiO_2-Bi_2O_3 core composition a single broad fluorescence band with the maximum at 1450 fiber was observed at 976 and 808 nm excitation [7]. The authors of [7] also reported that with an addition of Al_2O_3 in the core glass of the fiber the fluorescence at 1450 nm disappeared.

In this paper, we report on the first observation of the wide fluorescence band in a 1400-1500 nm diapason in the Bi-doped aluminosilicate fiber of low non-linearity fully compatible with common telecommunication fibers. The net gain and laser oscillation within this band are demonstrated for the first time to our knowledge.

2. Fiber fabrication and experimental

The preforms of two investigated fibers with cores composition of $4.5Al_2O_3$-$95.5SiO_2$ were fabricated by the MCVD method [2]. Bismuth oxide was incorporated in the core glass of the fiber one by the solution-doping technique. Bi concentration in the core glass did not exceed 0.02 at.% (the detection limit of our X-ray microanalysis). The other preform was made bismuth-free for test measurements. Single-mode fibers with core diameters of ~6 μm were drawn from the preforms.

Optical loss spectra were measured by the cut-back technique using a tungsten lamp as the light source. Single-mode Raman fiber lasers (λ=1343, 1353 and 1372 nm) were used to study the fluorescence of the Bi-doped fiber. The spontaneous emission of the core-excited Bi-doped fiber was measured from the lateral surface of the fiber. A broad-band light source emitting in the 1400-1550 nm wavelength range with overall power less than 100 μW and modulated at 100 Hz frequency was used to measure the light amplification in the fibers. Its emission was launched in the investigated fiber through an optical fiber coupler. The other port of the fiber coupler was used to launch the pump radiation into the fiber. The optical signal emerging from the investigated fiber was transmitted through a monochromator and received by a semiconductor detector. The electrical signal from the detector was detected by a lock-in amplifier (NF Electronic Instruments 5610B). The comparison of the signals with switched on or off pump and the input signal allowed us to calculate on-off and net gains.

The laser oscillation was obtained in a ring cavity constructed with another optical fiber coupler or in a linear cavity formed with UV-written fiber Bragg gratings (FBG) [2]. The electrical fusion splicing of the active fiber to other fibers led to a typical splicing loss of 0.1-0.2 dB caused by the mismatch between the fibers parameters.

The optical spectra of laser emission were recorded with an optical spectrum analyzer (Ando AQ 6310).

3. Results and discussion

The absorption of the active fiber is represented by broad bands around 500, 700 and 1000 nm with a shoulder at 800 nm [8] and a firstly noticed in [9] weak band at 1400 nm. The last band (Fig. 1) strongly overlaps with OH-groups absorption which spectrum measured in the Bi-free fiber is also shown in the Fig. 1. Direct excitation of this band produces a broad emission shown in the inset of Fig. 1. The emission band has a maximum at 1430 nm and a full width at half maximum (FWHM) of 100 nm and covers both S and E telecommunication bands. The typical on-off gain spectrum measured in a piece of the fiber of 10 m length is shown in Fig. 2. The peak gain amounted to approximately 1.4 dB is close by magnitude to the absorption value at the pump wavelength (1343 nm), 1.3 dB. The relatively low absorption at the pump wavelength in this piece of the fiber allows us to estimate a saturation pump power of the gain by studying the dependence of the peak gain at 1435 nm on the pump power, see Fig. 2, inset. It was about 10 mW. This value correlates well with the absorption saturation measurements. The saturated absorption measured at 300 mW of pump power amounted to 0.5 dB and at 10 mW of pump power the absorption was 0.9 dB. If we assume that the passive loss are equal to 0.5 dB, then the small-signal active absorption (1.3 dB - 0.5 dB = 0.8 dB) reduces twice (1.3dB - 0.9 dB = 0.4 dB) at 10 mW of pump power, i.e. this power corresponds to the absorption saturation power. The relatively high residual absorption probably is produced by

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the 1000 nm absorption band tail and OH-groups absorption. Note, that the passive loss at 1550 nm wavelength is about 10 dB/km, so the optical quality of the active fiber is good enough.

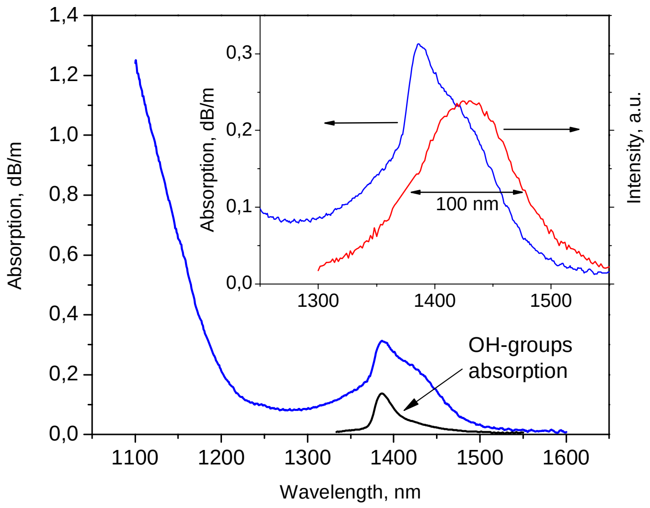

Fig. 1. Absorption of the Bi-doped fiber and its emission under excitation at 1372 nm wavelength. OH-groups absorption measured in the Bi-free fiber is also shown for comparison.

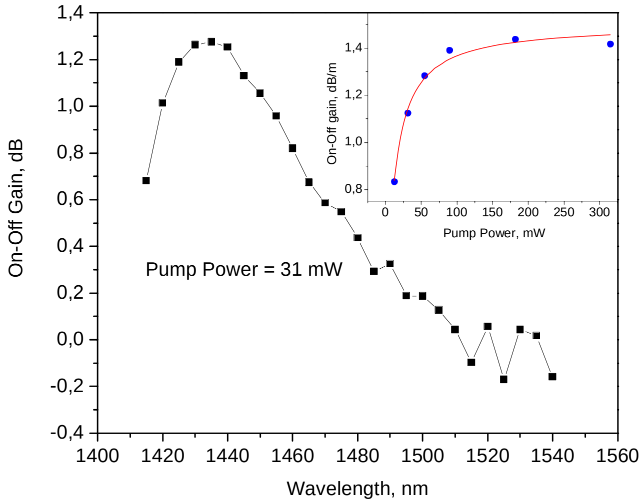

Fig. 2. Typical on-off gain spectrum for the piece of the Bi-doped fiber of 10 m length pumped at 1343 nm wavelength and the dependence of its maximum (1435 nm) on the pump power (inset).

Although the non-linearity of bismuthate glasses is rather high, the non-linearity of our fiber apparently should be quite small, nearly equal to silica glass because the concentration of

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Bi is extremely low (<0.02 at.%). In our fiber of the maximal length of 38 m the Raman gain estimated from the data published in [10] should not exceed 1% at 300 mW pumping at 1350 nm wavelength. To demonstrate it experimentally we also studied two pieces of 10 and 50 m lengths of the bismuth-free fiber. The on-off gain in the 1430-1500 nm range in the fibers pumped at 1343 nm wavelength with a power of up to 300 mW was less than the experimental accuracy of 1.5%.

The maximum net gain obtained in the piece of the fiber of 38 m length with approximately of 300 mW of launched pump power is presented in Fig. 3. The positive net gain is observed in the range 1430-1495 nm which is promising for development of Bi-doped fiber amplifiers operating in S and E telecommunication bands.

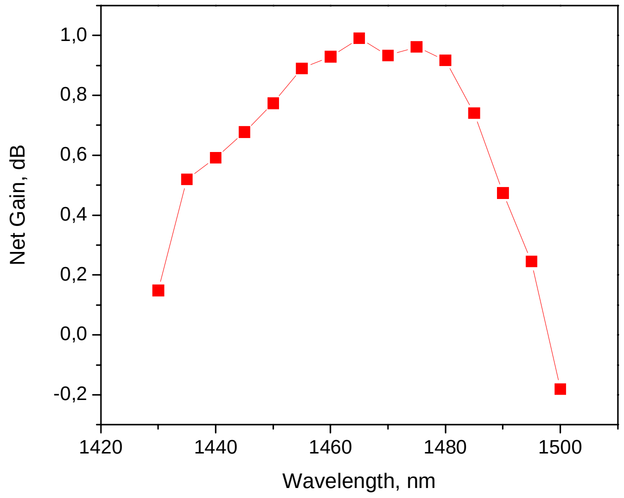

Fig. 3. Net gain for the Bi-doped fiber piece of 38 m length pumped at 1343 nm wavelength.

The CW laser oscillation was obtained at room temperature in this piece of the fiber in ring cavity at wavelength of 1443 or 1444.5 nm under pumping at 1343 or 1356 nm, respectively. The difference between the net gain shown in Fig.3 and the inserted in the cavity losses by the coupler transmission and the splices was positive in the 1435-1455 nm range with a maximum between 1440 and 1445 nm thus explaining the spectral position of laser action. The coupling at both wavelengths of the laser emission was nearly equal and amounted to 98%. The FWHM of the emission line at 1443 and 1444.5 nm was about 1.5 nm and 1.2 nm, respectively. The laser emission spectra are presented in Fig. 4. The efficiency of the laser action measured for the case of 1356 nm pump (taking into account both laser outputs) was about 0.15% with a threshold of 230 mW (Fig. 5). Cooling of the active fiber to -90^{0}C resulted in an insignificant change of the laser efficiency to 0.16% but the threshold became two times smaller, about 110 mW. The laser emission moved to the wavelength of 1445 nm and became narrower, of 0.5 nm FWHM (Fig. 4). The difference in the peak position and the FWHM of laser line in these experiments can be associated with possible change of the gain shape and magnitude with the change of the pump wavelength and temperature.

The laser action was also obtained in the linear cavity at 1459 nm wavelength with the same piece of the fiber pumped at 1356 nm wavelength. The available at the moment output coupler of 25% transmission was used. The loss per round trip inserted in the cavity by the output coupler and by the splices was about (1.85 ± 0.2) dB and the corresponding net gain at room temperature (Fig. 3) amounted to 1.86 dB (per round trip). In accordance to these calculations it was not possible to achieve a laser oscillation in the cavity at room temperature. But lowering the temperature to -30°C resulted in laser action at 1459 nm at absorbed pump power of 250 mW approximately. The emission line-width in this case was about 0.12 nm due to spectrally selective couplers. The efficiency of the lasing was estimated to be less than 0.1%.

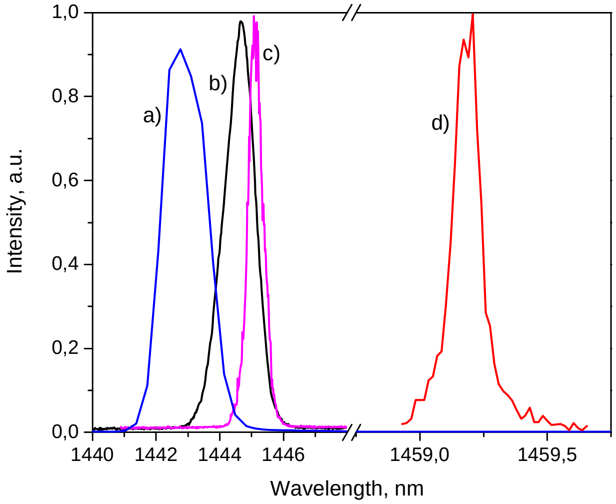

Fig. 4. Spectra of the laser emission: a) 1343 nm pump wavelength, ring cavity, room temperature, b) 1356 nm pump wavelength, ring cavity, room temperature, c) 1356 nm pump wavelength, ring cavity, -90°C, d) 1356 nm pump wavelength, linear cavity, -30°C.

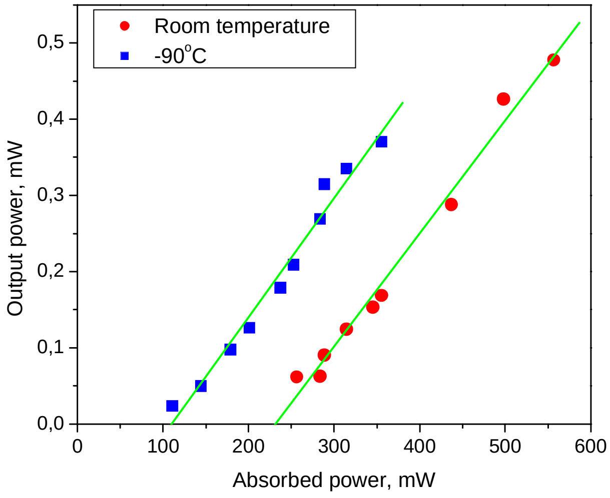

Fig. 5. Output power vs. absorbed pump power for the ring Bi-doped fiber laser pumped at 1356 nm wavelength.

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The results show a high sensitivity of the active medium to the temperature. Although the laser efficiency at the moment is low, it could be improved by optimizing the lasers parameters. Generation of laser emission in the used "short" piece of the Bi-doped fiber with the low maximal net gain (0.65 and 0.93 dB at 1445 and1459 nm wavelengths, respectively, Fig. 3) comparable to the inserted in the cavity loss requires high population of the excited state of the active ions which evidently reduces the population of ground state and active absorption. So, the pump is mainly spent on the passive loss. Moreover, the low gain requires high coupling which also led to the low efficiency because the generated emission is also mainly spent on the intracavity loss. We expect a significant improvement of the laser characteristics by using a longer piece of the same fiber to increase the gain and more transparent output couplers. Further improvement should be done by developing the technology, i.e., increasing the concentration of the active center with simultaneous eliminating of the water from the core glass and reduction of the absorption of other Bi-related centers.

Nevertheless, the results look very promising for a creation of the bismuth-doped fiber amplifiers for the S and E telecommunication bands.

4. Conclusion

In this paper, we reported a first, to our knowledge, observation of the fluorescence with maximum at 1435 nm and the FWHM of 100 nm from the Bi-doped aluminosilicate fiber, the detection of the net gain and the realization of CW Bi-doped fiber lasers operating within this emission band.

The emission band was produced in the Bi-doped aluminosilicate fiber prepared by MCVD technique by excitation of the 1400 nm broad absorption band at wavelengths of 1343, 1356 or 1372 nm. The positive net gain was recorded in the range of 1430-1495 nm wavelengths by pumping the fiber at 1343 nm wavelength. By pumping the fiber at 1343 or 1356 nm wavelength we were able to achieve the laser action in the ring and linear cavity schemes at the wavelengths of 1443-1445 nm (room temperature) and 1459 nm (-30^{o}C).

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