Bismuth activated alumosilicate optical fibers fabricated by surface-plasma chemical vapor deposition technology

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Plasma chemical technology is experimentally applied to the fabrication of a Bi-activated alumosilicate-core pure-silica-cladding fiber preform. To the best of our knowledge, this is the first time this technology has been applied in this way. We measure gain efficiency at pumping by a 1058 nm wavelength Yb fiber laser in a piece of a newly obtained fiber 20 m in length within 100–1200 nm wavelengths band. The gain efficiency reaches as high as 0.2 dB/mW. Bi-activated alumosilicate-core pure-silica-cladding fiber that is not more than 12 m in length serves a basis for a 1 W output power fiber laser emitting at the wavelength of 1160 nm with 8% slope efficiency. We also measure the photoluminescence spectrum and kinetics of Bi centers responsible for laser emission under the excitation of 193 nm wavelength ArF laser pulses.

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1. Introduction

Since Fujimoto and Nakatsuka discovered a wide-band (220–300 nm) infrared photoluminescence in bismuth containing alumosilicate glass centered in a 1.1–1.25 μm wavelength band [1], researchers have focused on investigating of this luminescence in oxide silicate glasses of various compositions (see, e.g., [2–6]). Interest to this effect is mainly associated with possible application of Bi-doped optical fibers in the amplification of optical signals in a band of 1300–1500 nm. To add, a potentially wide Bi-doped glass spectral band of amplification is suitable for the fabrication of femtosecond lasers.

Despite the presence of luminescence associated with Bi centers in glasses of various compositions, their origin, energy scheme of electron states, as well as structural position in silicon dioxide glass network remain uncertain. The role of aluminum additive in formation of luminescence centers is also unclear. Finally, in a number of publications amplification in Bi-doped glasses[7–9] and fabrication of Bi-activated optical fibers [10–12] are reported, but only in [13–15] was it possible to develop lasers based on this fiber.

In all the above cases Bi-doped fibers for lasers are pulled from preforms fabricated by a thermodynamically equilibrated modified chemical vapor deposition (MCVD) method. It was possible to gain laser emission only in such fiber samples where Bi doping level of the core glass was low. For the purposes of these experiments, relatively long (reaching several tens of meters) active fibers are used (see [13–15]). However, these lasers, being relatively long bring about threshold power reduction for various nonlinear effects [16]. Therefore possible applications of such Bi fiber lasers are restricted to corresponding moderate subthreshold output power range.

At present it is a rather challenging task to single out factors affecting the state of Bi species in glass networks. That is why there is good reason to test

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Bi-doped fibers fabricated by a technology significantly different from the MCVD.

In the present work, for the first time to the best of our knowledge, we applied surface-plasma chemical vapor deposition (SPCVD) technology [17] to synthesize a Bi-doped alumosilicate core fiber preform. This technology has already been used for production of Er-activated fiber preforms. Details and advantages of this process can be found in [18]. Unlike MCVD, halides' conversion in the SPCVD occurs at a reduced pressure and a low temperature of gas mixture in the microwave-induced plasma. An important feature of the SPCVD process is the incomplete and partial oxidation of metal species in the gas phase when the composition of an oxide layer is finally formed on the inner surface of a substrate tube. It is the attachment of absent oxygen atoms in a heterogeneous reaction that brings about such oxide layer stoichiometry. This feature of the process offers great opportunities in managing stoichiometry of deposited oxides, and in particular to synthesize glasses under reducing conditions by means of oxygen deficiency formation in the gas phase [19]. As is shown in [6], it is the presence of reducing conditions during alumosilicate glass synthesis that may be crucial in the appearance of Bi-associated centers responsible for the infrared luminescence.

Our experiments are targeted at the estimation of possibilities and peculiarities of the SPCVD technology application to the fabrication of Bi-activated optical fiber, investigation of luminescent, and absorption characteristics of a fiber thus made, as well as measurement of its gain spectrum and evaluation of its prospects for fiber laser fabrication.

2. Experiment

Bi-doped fiber is drawn from a preform synthesized by the SPCVD method under oxygen deficiency. Core glass is composed by 97 mol.% SiO_2 and 97 mol.% Al_2O_3. Bismuth concentration in the core glass is $3 \times 10^{18} cm^{-3}$. Glass composition and bismuth concentration are determined by an x-ray microprobe analysis. Uncertainty in aluminum content determination does not exceed 10%. Uncertainty in determination of bismuth concentration is much larger, which is associated with its rather low value close to the sensitivity limit of x-ray microanalysis equipment employed. A standard 125 μm in outer diameter fiber has core diameter of 8.4 μm, core/cladding refractive index difference $\Delta n = 5.5 \times 10^{-3}$, and cutoff wavelength of 1100 nm. Fiber loss spectrum is measured by the conventional cutback method using optical spectrum analyzers (OSA) Agilent 86140 B in the infrared, and Ocean Optics S2000 spectrometer in the visible and near UV bands.

Spectrum and kinetics of luminescence are recorded with the help of a setup depicted schematically in Fig. 1. Luminescence is excited by a side illumination of an uncoated fiber piece by 8 ns pulses of an ArF CL5000 excimer laser (193 nm wavelength), with a repetition rate of 100 Hz. The average excitation fluence

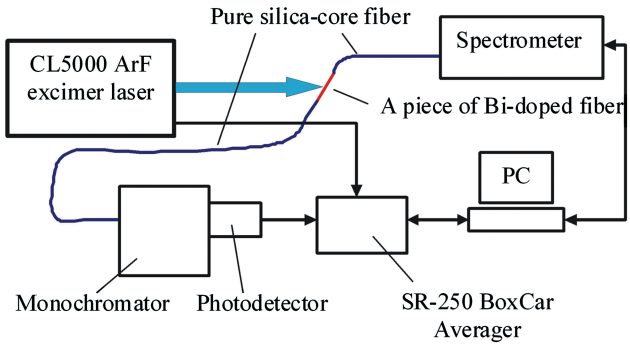


Fig. 1. (Color online) Schematic diagram of photoluminescence recording system.

does not exceed 20 mJ/cm^2. It is experimentally evidenced that with a fluence increase to 100 mJ/cm^2, the luminescence signal increases linearly and reversibly, which testifies to the absence of possible irreversible glass structure rearrangement under the action of the UV laser irradiation.

To observe luminescence in visible and near infrared spectral bands, a piece of fiber under investigation is spliced to a fiber, and the opposite end is connected to an optical spectrum analyzer (OSA). The distance between excitation and splice points does not exceed several millimeters, yielding minimum spectral distortion associated with reabsorption. OSA Agilent 86140 B is used in 900 nm $< \lambda <$ 1300 nm wavelengths band and Ocean Optics S2000 at $\lambda <$ 900 nm for luminescence spectrum recording. Data acquisition is performed with a large time constant, which allows one to operate with a pulsed-periodic signal as if it were a DC one.

The luminescence signal is delivered to the Ocean Optics spectrometer via pure silica core fluorine-doped silica cladding fiber that is 100 μm core in diameter made of KU-1 (high OH content) UV grade silica. A standard single mode SMF28 fiber is used for this purpose together with OSA Agilent in the infrared band.

The fiber delivers the luminescence signal to the input slit of the MDR23 grating monochromator to record kinetics (Fig. 1). Depending on the spectral band, the luminescence intensity at the output slit of the mochromator is registered by different photoreceivers. A multialkaline cathode photomultiplier is used for wavelengths $\lambda <$ 600 nm, an O-Cs cathode photomultiplier for wavelengths 600 nm $< \lambda <$ 900 nm, and a GaAs-based photodiode at $\lambda >$ 1000 nm. Photomutipliers are loaded with 50 ohm resistors, which yield for a recording system time constant of a value not

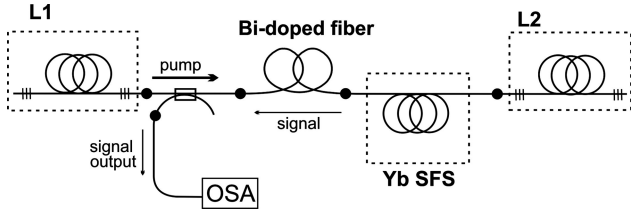


Fig. 2. Scheme for Bi-doped fiber gain spectrum measurements.

exceeding 100 ns. In the case of photodiode, the time constant does not exceed 10 ms. Photoreceiver signals are recorded by a boxcar averager.

Gain performance of the obtained Bi-doped fiber is tested with the help of a setup shown in Fig. 2. A single mode Yb fiber laser, $L1$ at a wavelength of 1058 nm is used as a pump source. A super fluorescent emitter (super fluorescent source, SFS) made from a piece of Yb fiber ~100 m in length is used as a signal light source. The other Yb laser ($L2$) emitting at a wavelength of 1085 nm is used to pump the SFS. Total power of the broad band (1100–1400 nm) SFS does not exceed 12 μW. Optical gain is measured on a piece of Bi-doped fiber 20 m in length with the OSA. The Bi-doped fiber is chosen to be long enough (20 m) to reduce the interplay between laser $L1$ and the SFS, optical loss at the wavelength of 1058 nm being ≥14 dB (unbleachable optical losses) or ≥28 dB (at a low pump level). An additional 5 dB attenuator is formed at the splicing point between $L1$ and the WDM coupler. In addition to optical losses mentioned above the isolation between $L1$ and $L2$ is increased by the SFS fiber absorption at laser wavelengths (≥40 dB).

Gain constant is determined as signals ratio with and without pump $L1$ ("on/off" gain). Such a scheme makes it possible to measure gain spectrum for all wavelengths of the SFS far enough from the $L1$ pump source wavelength.

3. Results

Figure 3 shows absorption and luminescence spectra. In the absorption spectrum all three previously discovered bands [1] associated with the presence of bismuth in alumosilicate glass are well distinguished. On the whole, from the viewpoint of bands' intensities, the absorption spectrum is similar to the one of sample #25 from [4]. Loss level at a wavelength of 1550 nm beyond the Bi-associated absorption bands does not exceed 10 dB/km, which is indicative of a rather high core glass quality in the preform synthesized by SPCVD.

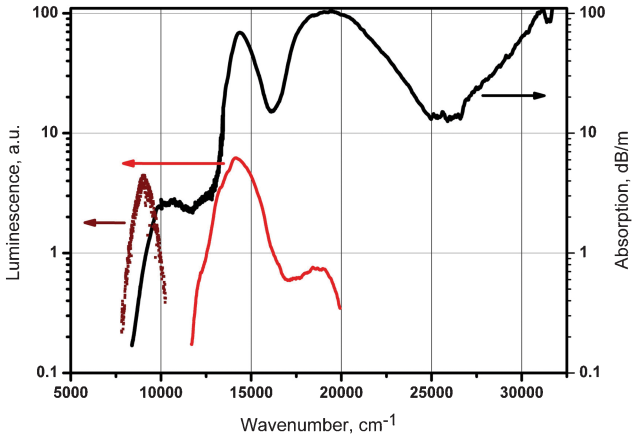


Fig. 3. (Color online) Spectral dependences of absorption and luminescence in a Bi-doped alumosilicate core fiber.

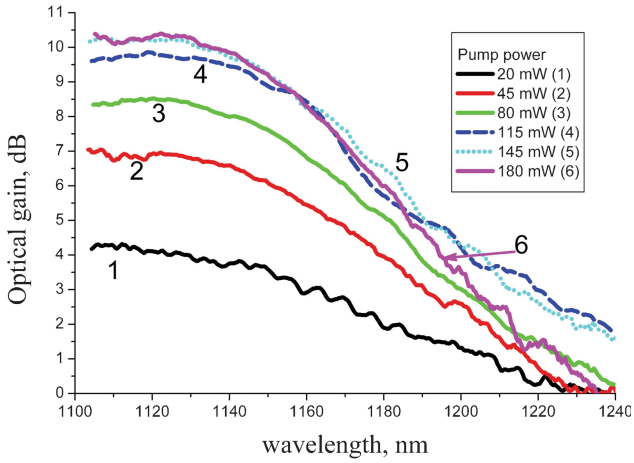
The fiber luminescence spectrum excited by an excimer laser turned out to be rather complicated. Apart from the luminescence contribution of bismuth located in alumosilcate glass of the core, a significant portion of light associated with the luminescence of undoped silica in the cladding is present in a short wavelength region of the spectrum. Key luminescence centers in this glass are intrinsic defects, specific photoluminescence spectrum and kinetics of which at the 193 nm wavelength excimer laser excitation one can find in [20]. Taking into account that the cladding of our fibers consists of F-300 type of silica, the luminescence spectrum of a fiber totally composed of this silica type with no additives has been obtained to isolate and estimate contribution of the luminescence associated with Bi centers. We subtracted spectrum of pure F300 fiber from the luminescence spectrum of the fiber that contains bismuth in the core.

Thus, a developed spectrum consists of three clearly defined groups of bands, spectrally correlated with the absorption bands positions (see Fig. 3). Fitting each of these groups by sets of Gaussian lines shows that the infrared band is well approximated by a single Gaussian line centered at 9068 cm^{-1}. The band in the $12,000–15,000\ cm^{-1}$ region is a superposition of three lines centered at 12,200, 13,100, and $14,200\ cm^{-1}$. Full widths at half-maximums (FWHMs) for these lines are 710, 340, and $1660\ cm^{-1}$, respectively. A nonbridging oxygen luminescence band centered at $15,367\ cm^{-1}$ (FWHM = $2072\ cm^{-1}$) also contributes to this region. A line centered at $18,592\ cm^{-1}$ (FWHM = $2228\ cm^{-1}$) is well distinguished in a short wavelength part of the spectrum. It is worth noting that the spectra obtained are not normalized with respect to the photo detectors' sensitivity and, for this reason, do not allow one to compare emission intensities in different bands.

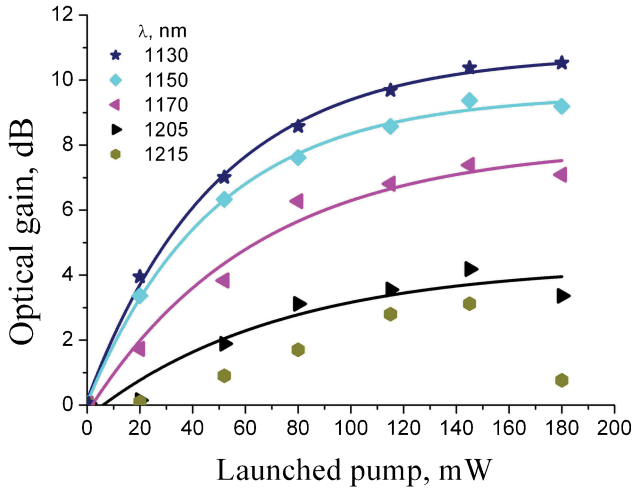
We succeeded in recording the decay kinetics of luminescence signals at 9000, 14,000, and $18,500\ cm^{-1}$ frequencies. Decay curves at each of the first two frequencies are well approximated by single exponential dependencies, specific times being 950 and 4 ms, respectively. Decay at a frequency of $18,500\ cm^{-1}$ is bi-exponential with a larger specific decay time of 1.3 ms.

Figure 4 shows the results of Bi-doped fiber gain measurements. Figure 4(a) demonstrates gain coefficient spectral dependencies in the wavelength band from 1100 to 1240 nm at different pump powers. It is seen that the gain spectrum reaches a maximum at a wavelength of ~1120 nm. At larger wavelengths gain coefficient decreases, approaching zero in the vicinity of the 1240 nm wavelength.

Dependence of gain coefficient on pump power saturates at power ~100 mW, as is seen from Fig. 4(b). In the ~1220 nm wavelength region one can see some decay of the gain coefficient at pump powers exceeding ~200 mW. This agrees with peculiarities of the output-versus-input power dependence in this wave-



(a)



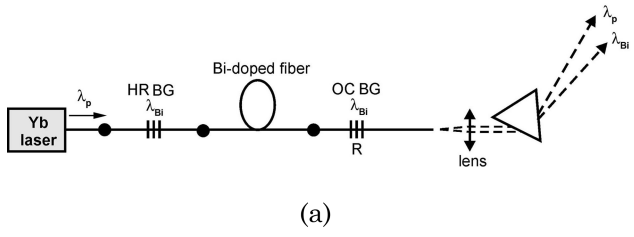
(b)

Fig. 4. (Color online) (a) Dependence of gain coefficient (on/off) on wavelength for various pump powers. (b) Gain coefficient as a function of pump power at various wavelengths.

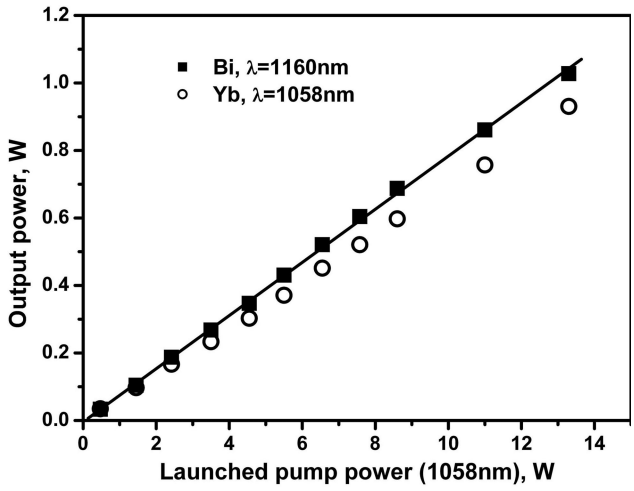
length region for the fiber laser developed on the basis of Bi-doped fiber fabricated by MCVD technology [14].

At low pump levels gain efficiency is as high as 0.2 dB/mW, which is lower if compared to Er-doped fiber amplifiers, but is significantly higher if compared to Raman ones [21].

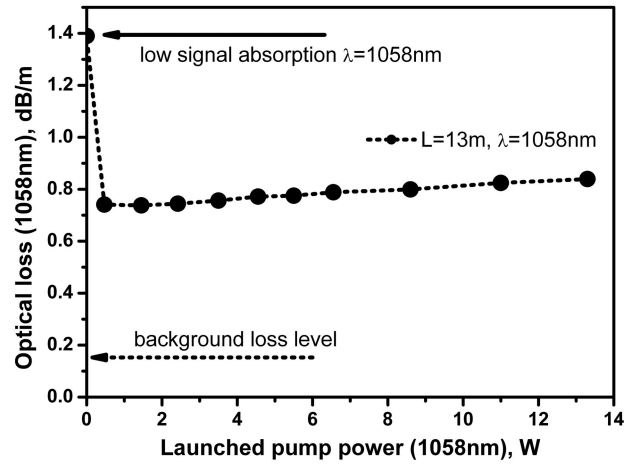
High gain coefficients (up to 10 dB in a single pass) of Bi-doped fiber achieved by the SPCVD along with relatively low optical losses in the vicinity of the 1160 nm wavelength permit one to get lasing on the basis of this fiber using a scheme shown in Fig. 5(a). A single mode fiber laser at a wavelength of 1058 nm is used as a pump source. Its radiation is launched in the Bi-doped fiber core through a piece of fiber with a high reflective (HR) Bragg grating [Fig. 5(a)]. 50% Bragg grating is used as the output coupler of laser cavity. As a small signal absorption coefficient at the pump wavelength amounts ~1.4 dB/m, length of the Bi-doped fiber for the fiber laser is set equal to 12 m. The spectrum of the observed Bi-doped fiber laser



(a)



(b)



(c)

Fig. 5. (a) Scheme of the Bi-doped fiber laser. (b) Output power as a function of launched pump power for Bi-doped fiber laser. (c) Photo-bleaching effect in Bi-doped fiber as a function of launched pump power.

generation is similar to the one of a previously published CW Bi fiber laser (e.g., [14], Fig. 5). It is defined essentially by the Bragg gratings' parameters, which in our case yield the laser wavelength = 1160 nm and FWHM ≈ 0.5 nm.

Laser characteristics are shown in Figs. 5(b) and 5(c). Output power increases linearly with the launched pump power and reaches ~1 W at pump power ~14 W [Fig. 5(b)]. Presuming active Bi centers concentration to be proportional to the absorption coefficient

in the band centered in the vicinity of 1 μm wavelength, one can state that, in the present work, a Bi-doped laser is developed with the fiber containing about an order of magnitude greater active Bi centers as compared to the fiber used in [14].

In this experiment ~1 W unabsorbed pump power is present at the laser output. In absence of the output Bragg grating, no lasing is observed regardless of launched pump power level. Here fiber photo bleaching at pump wavelength is observed, but only to ~50% of the small signal absorption level with a graduate loss increase at a further pump power increase [see Fig. 5(c)]. It should be noted that similar optical losses unsaturated with power increase are also observed in fibers of the same composition fabricated by MCVD technology [14]. At significantly smaller bismuth concentration those losses amount ~30% of their initial value. The presence of a mechanism responsible for such unsaturated losses appears to explain a relatively low laser efficiency of about 8% with respect to launched pump power.

4. Conclusion

We have demonstrated that the application of SPCVD technology makes it possible to produce Bi-doped alumosilicate-core/pure-silica-cladding fibers. These fibers feature an optical gain in 1100–1250 nm wavelength range and are applicable for fiber laser development in this spectral band, with the active part of the fiber being about 10 m. Qualitatively absorption luminescence spectra and the shape of gain spectrum in the above wavelengths do not differ from the ones, measured in similar fibers produced by the MCVD technology.

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 ~0.5 dB/m. As concerns Bi-doped fiber gain efficiency, it amounts to 0.2 dB/mW, which is significantly smaller as compared to Er-doped fiber amplifiers, but approximately by an order of magnitude larger than that for Raman fiber amplifiers.

In an additive-free alumosilicate glass network, a long wavelength edge of bismuth center gain spectrum (pump wavelength is 1058 nm) is situated at a wavelength of ≈1240 nm with its maximum at a wavelength of about 1100 nm. Depending on glass network structure, one can expect differences in gain spectra widths including a red edge shift to longer wavelengths.

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