5.5 W monolithic single-mode fiber laser and amplifier operating near 976 nm

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ABSTRACT

An all-glass Yb-doped single-mode fiber laser and amplifier with output power of more than 5 W near 977 nm have been realized. Both laser and amplifier were based on a specially developed photodarking-free Yb-doped fibers with increased core-to-clad diameter ratio (up to 0.31).

Keywords: Fiber laser, ytterbium-doped fiber, large mode area fiber, three-level laser.

1. INTRODUCTION

Single-mode lasers operating at wavelength near 0.98 μm are widely used in spectroscopy and also have a wide potential application for pumping of Er or Yb doped optical fibers and solid state amplifiers. Narrow line width sources at this wavelength are of great interest for frequency doubling and thus for a replacement of argon solid-state lasers. However, to date only semiconductor laser diodes (pigtailed with singlemode fiber) with output power of less than 1W are commercially available in this wavelength region.

Utilization of Yb-doped fiber lasers and amplifiers operated near 0.98 μm looks promising. Ytterbium ions have a broad band of luminescence from 920 to 1150 nm. Lasing of Yb-ions has been demonstrated for the spectral range of 970 - 1150 nm. It should be noted that the fabrication of effective lasers operating in the 970-980 nm spectral range is challenging due to competition between radiative transitions happening due to the quasi-three-level scheme (970-980 nm) and quasi-four-level transitions at wavelengths of 1010-1150 nm. In this case the most critical requirement to active fiber is the achievement of a high pump power density in the active medium (typically, ratio between density of pump power in the core and the density of signal power must be higher than 0.2-0.5 depending on the laser or amplifier scheme). From this point of view, the simplest way to realize a powerful source at 0.98 μm is to use a scheme where singlemode pump power inject direct in fiber core [1-3]. At the same time the output power of available singlemode lasers at 910-940 nm, acting as a pump sources, is limited to a few watts. That is why the best results of single-mode emission generation at 0.98 microns have not exceeded 2.1 W output power [1]. Moreover, the realization of single-mode pump sources operating in the 910-940 nm spectral region (for example, a single-mode neodymium-doped fiber laser [1,3]), is a same challenge from technological point of view.

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A much more promising approach to increase output power of single-mode lasers at 0.98 μm is fabrication of fiber laser scheme on the base of double clad fibers pumping by multi-mode laser diode into the first cladding [4-9]. However the only special large mode area fibers with decreased inner silica cladding can be used for this aim. Otherwise (in the case of standard fibers) the area of the first cladding and area of the active core differ by more than two orders in magnitude and pump power must significantly exceed power of the generated signal near 0.98 μm (to achieve inversion more than 50%), which leads to a very small efficiency of such lasers. Moreover to avoid the appearance of undesirable lasing at wavelength of near 1030 nm the length of laser cavity is chosen to be short that result in a large portion of unabsorbed pump power. Thus increasing of the ratio of the core and the inner cladding diameters result in efficiency growth of the lasers at 976 nm [10].

The best result in the field of high power singlemode laser fabrication at wavelength of near 0.98 μm (94 W at wavelength of 977 nm) were obtained in a rod type Photonic Crystal Fiber [9]. The core to the inner cladding diameter ratio was about 1:2.5 in this case. The second result (10W optical radiation at 976 nm) belongs to the scheme based on active tapered step-index fiber [6]. Thin fiber end has been adapted for splicing with optical fiber of standard type (with outer diameter of about 125 μm), whereas the thick end of the fiber had a diameter of 1 mm. The core diameter at the thick end exceeded 100 μm and core NA was about 0.15, so that multi-mode pump was coupled directly into the fiber core. Usage of Jacked Air Clad fiber in the amplifier scheme have allowed to the authors of the paper [8] obtain 4.3W single-mode emission at wavelength of 977 nm (the inner cladding diameter was 25 microns).

The main problem of the proposed fiber lasers operated near 0.98 μm was presence of a large number of bulk elements in the laser schemes (lens, [6,8,9], dichroic mirrors [6,8,9], and also mirrors, forming a laser cavity [9])). Non-monolithic laser scheme result in a poor reliability, sensitivity to environmental changes, unhandiness and necessity to couple the radiation back into the single-mode fiber in many applications.

In this paper we report on development of high power all-fiber laser and amplifier operated near 0.98 μm for the first time. For this aim technologically simple optical fiber adapted for efficient lasing at a wavelength of about 0.98 μm was realized.

2. ACTIVE FIBER DESIGN

During the fiber fabrication the photodarking (PD) problem of Yb-ions [11] (the effect of efficiency reducing of Yb-doped fiber lasers) must be take into account. This effect is caused by inducing defects in the core glass matrix during laser operation. The defects characterized with a broad absorption band with a maximum in the visible spectral range [12-13]. It has revealed earlier that the nature of the defects is associated with the formation of oxygen-hole centers as a result of excitation of the charge transfer state of Yb-O-complex [14-17]. It is important that rate of the photodarking loss growth is proportional to the ~ 5^{th} order of inversion [12]. As a result, estimated lifetime of 0.98 μm lasers (operates at inversion >50%) based on standard aluminosilicate glass matrix do not exceed tens of hours (compare with 10-100 thousands of hours lifetime for lasers operated near 1.03-1.06 μm at inversion ~ 2-5%).

Therefore to achieve long term stability of the fiber laser, the core glass matrix, which is not sensitive to the effect of PD should be used as core medium. Among the PD-free glass matrixes the most popular are P-doped [12] and Al-Ce-doped [18] silica glasses. However both of the solutions result in increasing of core refractive index (a high contents of P_2O_5 or Ce_2O_3 are required in both cases), which lead to limitation of the maximum single mode core. A decision of the problem is utilization of recently developed phosphoro-aluminosilicate glass matrix [19-22] for the core. Its main advantages of the P_2O_5-Al_2O_3-SiO_2 glass is possibility to achieve refractive index of the core closed to that of the cladding and suppressed PD effect (for glasses with excess of phosphorous), which opens possibility of fabrication a photodarking-free large-mode area fibers. [21].

As it was mentioned above, one of the main factors determining the efficiency of the fiber laser operating at 976 nm is the core to cladding diameters ratio. The minimum core refractive index (and therefore maximum core diameter) is limited by bend sensitivity of the fiber. In the present work we have used W-shaped refractive index profile of the core: the Yb-doped part of the core had step-index (SI) profile and was surrounded with a low-index F-doped layer. It is well known that cut-off wavelength of such fiber design is lies in a shorter wavelength spectral range compared to the standard SI-fiber (at a same core diameter and refractive index of it). Thus in the case of W-profile, single-mode regime of light propagation can be achieved at larger core diameter. Furthermore W-profile fibers are less sensitive to bending as compared to conventional SI optical fibers.

Active fiber preform was fabricated with MCVD-technology, which was modified to deposit all the components (i.e. Al_2O_3 and Yb_2O_3) from the gas phase. To achieve a low core NA (~0.038) the concentration of the Yb_2O_3 in the core (except Yb-free central part) was reduced to 0.1 wt %. The method of ring doping [10] was used to reduce average signal intensity in the Yb-doped fiber region and by this way to enhance the lasing efficiency near 0.98 μm. To ensure efficient pump mixture a square-shaped cladding was fabricated. The ratio of the core diameter to the average cladding diameter was 0.31.

The fabricated preform was drawn into optical fibers optical fibers with dimensions of silica glass 28/80x80 μm (minimal value compatible with standard fiber cleaver and fusion splicer) and 40/115x115 μm (average clad D~125 μm, which is compatible with a standard pump combiners). The fibers were coated with a low index acrylate coating (NA=0.46). Mode field diameters were estimated to be as large as 18 μm and 25 μm for the 28/80x80 μm and 40/115x115 μm fibers correspondingly. The refractive index profile of the realized fiber (28/80x80 μm) and mode field distribution are depicted in Figure 1. The image of the fiber end, formed by an optical microscope, is shown in the inset of Figure 1. Estimate LP_{11} mode cut-off wavelength was below 0.98 μm for the 28/80x80 μm fiber

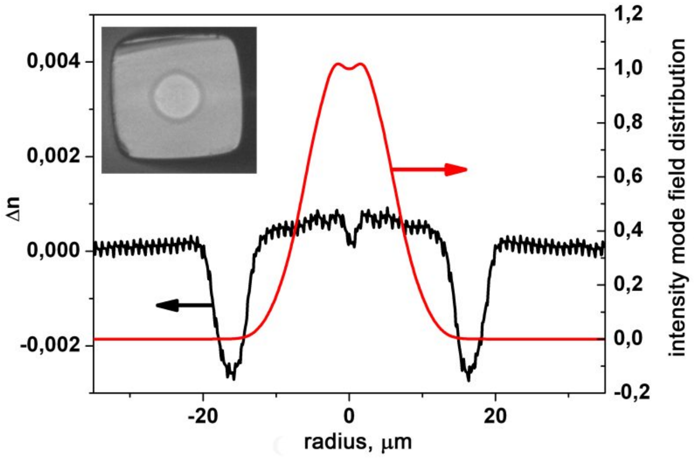

Figure 1. Measured refractive index profile of 80x80 μm fiber; calculated (according to RIP) intensity of mode field distribution; image of fiber end (inset)

3. LASER AND AMPLIFIER BASED ON FABRICATED FIBER

3.1 Laser scheme

The fabricated 28/80x80 μm Yb-doped fiber was tested in the simplest all-fiber laser scheme (Figure 2) that included multimode pump diode (λ= 915 ± 10 nm, NA=0.15, P=33W) pigtailed with 105/125 μm fiber; tapered core-less double-clad fiber for coupling pump irradiation into the laser cavity without power loss; single-mode 20/80 μm fiber with written high-reflection Bragg grating at 977 nm; Yb-doped fiber wounded on a spool with 30 cm diameter and single-mode 20/125 passive fiber with 10% reflectivity Bragg grating. Reflecting coefficient of the semi-transparent Bragg grating was chosen to be 10% with the aim to extract the maximum signal power [23]. The length of the active fiber was chosen to get the maximum power at 977 nm and reduce 1030 nm signal amplification. Unabsorbed pump power was removed from the laser system after 10% Bragg grating (Figure 2). Output fiber end was cleaved at an angle to avoid undesirable backward reflection.

Dependence of the output power at wavelength of 977 nm on pump power delivered from semiconductor diode is shown in Figure 3. Spectrum measured at maximal pump power is depicted in the inset of Figure 3. Lasing threshold was approximately 10 W. Difference between signal and noise level was estimated to be equal about 33 dB. Differential efficiency of generation was 25%. Thus 5.5 W of single-mode emission at wavelength of 977 nm was achieved on the output end of all-fiber laser and it was limited with the only available pump power.

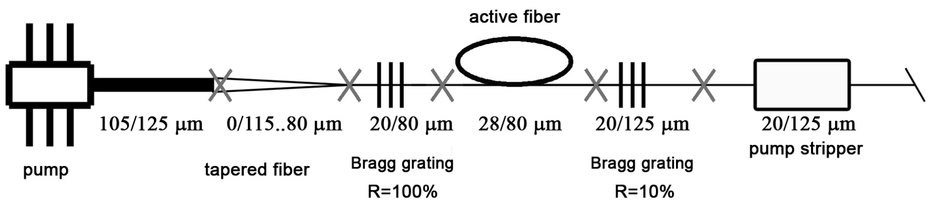

Figure 2. Laser scheme

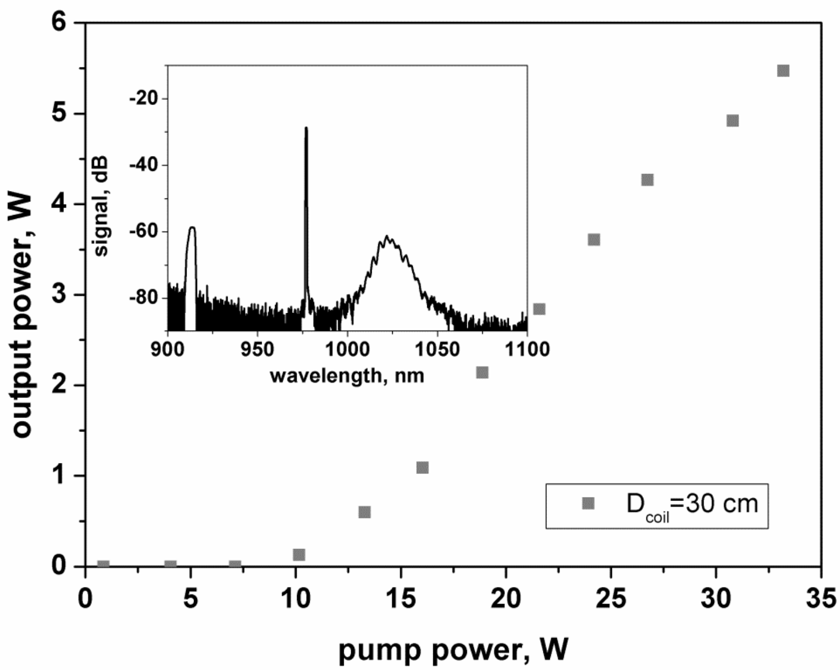

Figure 3. Dependence of output power at wavelength of 977 nm on pump power

3.2 Amplifier scheme

To clarify dependence of amplification efficiency on operating wavelength the simplest amplifier scheme was realized (Figure 4). Laser semiconductor diode pigtailed with single mode fiber was used as seed. Change of operating wavelength was done by replacement of the fiber Bragg grating (FBG) spliced to the diode on a home-made one (FBG with wavelength from 974 nm to 985 nm were available during experiment). An isolator optimized for 980 nm wavelength separated the seed and the amplifier stages. Multimode pump was injected into the amplifier stage with a help of 2+1→1 pump combiner. Two commercially available semiconductor diodes (pigtailed with 105/125 μm, NA0.22 fiber) with total output power of 50 W was used. A special double clad single-mode home-made fiber of 12/125 μm was used to minimize the mode mismatch between the fiber at the output of pump combiner (6 μm core diameter) and the 40/115x115 μm Yb-doped fiber. It is worse to note that cut-off of the fiber with core diameter of 40 μm was near 1.36 μm, but coiling fiber on a spool with diameter of 16 cm allowed us to achieve single-mode propagation regime due to high bend sensitivity of the high-order modes. Unabsorbed pump power was removed from the laser system by homemade pump stripper placed at the output of the active fiber. Measured dependence of amplification efficiency on operating wavelength is shown in Figure 5. It could be seen that high conversion efficiency was achieved in the wavelength range of 975.5-978.5 nm.

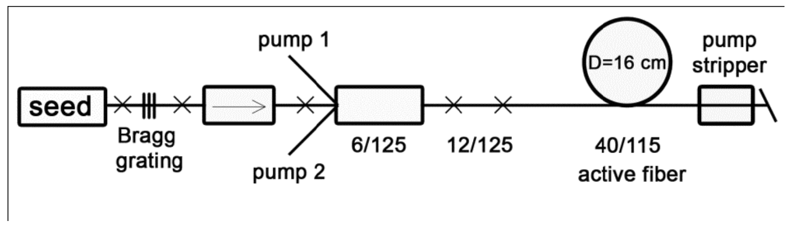

Figure 4. Scheme for measurement of amplification efficiency dependence on operating wavelength

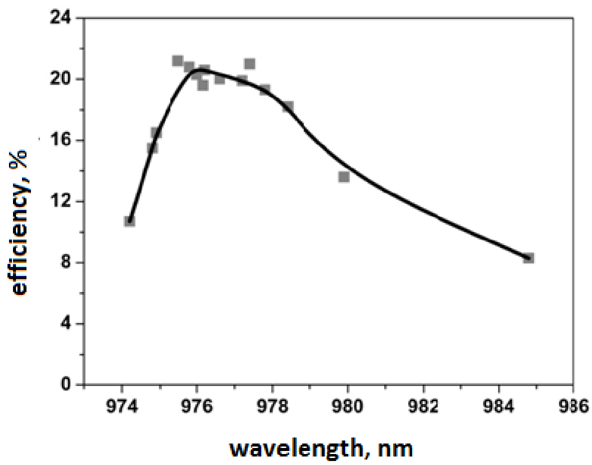

Figure 5. Dependence of amplification efficiency on operating wavelength

It should be noted that the fiber of 40/115x115 μm was extremely sensitive to microbendings that results in mode field distribution distortion. To achieve a high quality of the output beam, the end of the active fiber was spliced with a short part (about several centimeters) of a passive single-mode fiber (mode field diameter was about 19 μm). Output fiber end was also angled-cleaved. As a result 5.7 W of single-mode emission was obtained (Figure 6 and Figure 7). Difference between signal and noise level of the output signal was higher than 30 dB. Differential efficiency of generation was 15%. It is evident that decreasing of lasing efficiency was caused by mode field diameter mismatch between active fiber and the output passive fiber. No spectral modulation (corresponding to interference between fundamental and LP_{11} mode) was observed at the output of passive fiber.

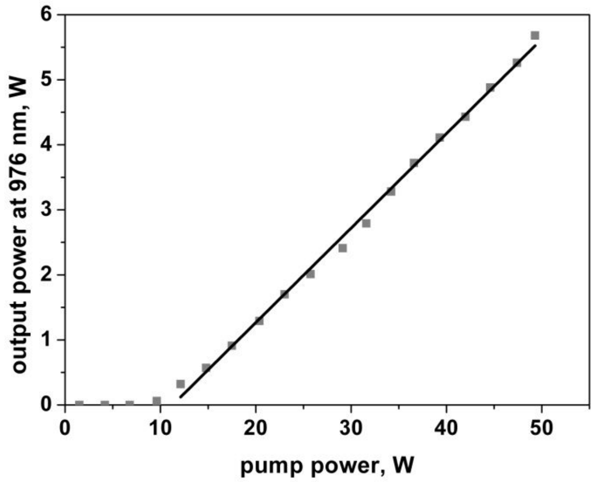

Figure 6. Dependence of output power at wavelength of 976 nm on pump power of seed source; inset – measured image of mode on the output end of fiber amplifier.

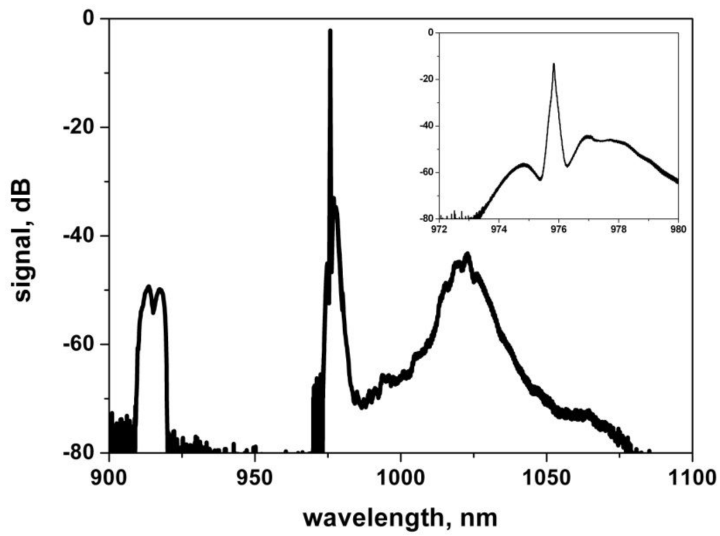

Figure 7. Spectrum of the amplifying signal at maximal available pump power (resolution of 0.1 nm), inset – zoomed signal spectrum (resolution of 0.02 nm)

4. CONCLUSION

In summary, special optical fiber construction for effective lasing at wavelength near 0.98 μm was developed. Fibers adapted for laser creation and the fiber appropriating for signal amplification were fabricated. On the basis of the optical fibers all-fiber single-mode laser scheme and amplifier scheme with output power higher than 5 W were realized. To the best of our knowledge the achieved output power at wavelength of near 0.98 μm is record high for all-fiber laser construction and the most important that the result was limited with the only available pump power. Absence of bulk elements in the laser and amplifier schemes allows integrating the sources in other fiber laser construction. Also it should be emphasize that the used laser and amplifier schemes were the simplest and it contained commercial available components predominantly.

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