All-fiber mode-locked laser at 977 nm

Svetlana S. Aleshkina[*a], Denis S. Lipatov[b], Vladimir V. Velmiskin[a], Tatiana A. Kochergina[a], Andrey Fedotov[c], Regina Gumenyuk[c], Leonid V. Kotov[d], Valery L. Temyanko[d], Mikhail M. Bubnov[a], Alexey N. Guryanov[b] and Mikhail E. Likhachev[a]

[a]Fiber Optics Research Center of the Russian Academy of Sciences, 38 Vavilov Street, Moscow, Russia, 119333; [b]Institute of High Purity Substances of the Russian Academy of Sciences, 49 Tropinin Street, Nizhny Novgorod, Russia, 603950; [c]Tampere University of Technology, *4* Kalevantie, Tampere, Finland, 33101; [d]College of Optical Sciences, University of Arizona,1630 E. University Blvd, AZ Tucson, USA,85721-0094

ABSTRACT

In this paper, we have developed Yb-doped fiber suitable for creation of all-fiber seed laser schemes operating near 977 nm. The fiber was based on a ring-doping design (cladding was partially doped with Yb-ions), which allowed us to fabricate a relatively small core and provide mode field diameter (MFD) of the active fiber comparable with standard fibers (to achieve small splicing losses with commercially available optical fibers) and, simultaneously, increase absorption from the cladding to keep a reasonably high lasing efficiency. So MFD_x of the fiber was 12 μm, MFD_y was 14 μm. Outer silica cladding of the active fiber was decreased to diameter of 80 μm and a special pump and signal combiner was used to inject pump and signal into the active fiber. Based on the developed Yb-doped fiber an all-fiber polarization maintaining mode-locked laser with central wavelength around 977 nm was demonstrated for the first time. SESAM was used as a saturable absorber. The laser was self-starting for pump powers above 4.6 W, with the output power of 3 mW. The autocorrelation was the best fitted with $sech^2$ profile and pulse duration was estimated to be as long as 9.5 ps. The fundamental cavity frequency corresponded to the pulse repetition rate of 33.532 MHz. Signal-to-noise ratio measured in the radio frequency range was more than 50 dB, the line width was below 1 kHz, which indicate ultimate stability of the fabricated mode-lock laser.

Keywords: Yb-doped laser, laser at 980 nm, mode-locking, fiber laser

1. INTRODUCTION

All-fiber laser systems operating in the spectral range near 977 nm is of great interest for many applications, such as high power single-mode pump sources for Er- and Yb-doped fiber amplifiers, frequency doubling (488 nm as alternative for Ar-laser) and quadrupling (244 nm as alternative for Kr-excimer laser). It is well known that Yb-ions in silica glass matrix have intensive emission band near 977 nm occurring according to three-level laser scheme [1, 2]. However the same value of absorption cross sections of Yb-ions at 977 nm indicates the need for a population inversion of more than 50% to ensure positive gain at this wavelength resulted in a high lasing threshold. Furthermore the main problem to achieve lasing near this wavelength is appearance of stimulated emission of Yb-ions with amplification maximum near 1030 nm happening due to four-level laser scheme. The ratio between absorption cross-section and cross-section of stimulated emission at wavelengths above 1000 nm is low and a reasonably small inversion of Yb^{3+} ions is sufficient to start lasing at 1000-1150 nm, while at least 50% inversion of Yb^{3+} ions is required to overcome the lasing threshold at 977 nm. Thus, to create Yb-doped laser sources at 977 nm, special optical fibers, as well as special laser schemes

* sv_alesh@fo.gpi.ru; phone +7 499 135-7449; fax +7 499 135-8139; fibopt.ru

[2-8], are required. This requirement becomes even more critical for master oscillator laser schemes, where there is a strong feedback. The signal generated in one round trip (in our case both at 977 nm and at wavelengths of longer than 1000 nm) acts as a seed source for the following amplification cycles. In the stable lasing regime if net loss in the resonator are low, the Yb^{3+} ions inversion might be small, which results in preferable condition for lasing at wavelength above 1000 nm. Thus presence of even weak seed signal in this spectral range is sufficient to disrupt the generation near 977 nm. At the same time emission cross sections of Yb-ions near 977 nm is much higher than at wavelengths longer than 1000 nm. By this reason shortening of the active fiber length and/or introducing of intracavity losses for wavelength above 1000 nm into the laser scheme allow to achieve stable lasing near 977 nm. The best condition for lasing near 977 nm is achieved when an active fiber is core pumped. However the limited output power of commercially available single-mode pump diodes makes such laser schemes less attractive as compared to clad-pumped schemes, where pump diodes with output power as high as tens or even hundreds of watts are available.

At the same time existing Yb-doped fiber designs for lasing at 977 nm have a large core diameter (typically more than 20 μm) and, as consequence, a high lasing threshold and a high splice loss with standard single-mode fibers (or even impossibility to spliced such fiber at all, for example, in the case of Photonic Crystal Fibers). Such fibers are not suitable for fabrication of an all-fiber pulsed seed sources operated near 977 nm. To date, the demonstrated clad-pumped fiber lasers at 977 nm contain a lot of bulk elements [9, 10]. Moreover, to the best of our knowledge, there were no sources delivering polarized emission among the seed lasers at 977 nm proposed to date, which reduces its practical significance. In a non-PM type of lasers, the losses can be adjusted by polarization controller [11]. This fact gives a certain level of flexibility and simplicity to the setup but sacrifices stability. In PM-type lasers, the polarization state is fixed. This provides stability, but the system is insensitive to the additional adjustment, and it applies higher requirements to the laser design.

In this paper, we have developed Yb-doped all-glass polarization maintaining (PM) optical fiber suitable for creation of all-fiber seed laser schemes operating near 977 nm. The fiber was based on a ring-doping design (cladding was partially doped with Yb-ions), which allowed us to fabricate a relatively small core and provide mode field diameter (MFD) of the active fiber comparable with standard fibers (to achieve small splicing losses with commercially available optical fibers) and, simultaneously, increase absorption from the cladding to keep a reasonably high lasing efficiency. Usage of the fiber in the master oscillator laser scheme with SESAM saturable absorber allowed us to create the first all-fiber PM mode-locked laser at 977 nm.

2. FIBER DESIGN AND ITS PROPERTIES

As it was mentioned, the generation of Yb-doped fiber lasers at wavelength of near 977 nm is a challenging task due to nearly equal emission and absorption cross sections at this wavelength (operation in a three-level laser scheme) and also due to the possibility of Yb-ions lasing at longer wavelengths, above 1000 nm (operation in a four-level laser scheme, which has much smaller lasing threshold). According to [12], increase of efficiency in cladding pumped Yb-doped fiber lasers operating near 977 nm can be achieved by a reduction of the ratio between the first inner cladding area and the Yb-doped area. It means that for efficient lasing at 980 nm, it is necessary to increase Yb-doped area or/and reduce inner cladding area where pump light propagates. Therefore, in the present work we used active fiber with a cladding diameter of 80 μm developed in [13]. The active fiber refractive index profile and image of the fiber facet are depicted in Figure 1. The outer fiber's diameter was smaller than diameter of conventional fibers but it was still matched commercially available fiber cleaving and splicing equipment. The fiber core was designed to have a large diameter of Yb-doped region (~20 μm) and reduced MFD: for x axis it was 12 μm, for y axis it was 14 μm. This feature resulted in a relatively low splice loss of 0.35 dB with standard step-index fiber with core diameter of 10 μm. Moreover, in comparison with proposed earlier active fiber designs for lasing near 977 nm, the 80 μm clad size provided relatively low generation thresholds at wavelengths near 977 nm, which is especially important for small-signal amplification. The use of the fiber in the small-signal amplifier scheme [13] showed that in the saturation regime the signal can be amplified with an efficiency of about 10% to hundreds of mW using a low-power pump diode (maximum Pout ~ 10 W).

To guarantee comparability of the active fiber NA and NA of the pump combiner, the Yb-doped fiber was coated with a reflective polymer with an NA of more than 0.45. Measured cladding absorption at wavelength of 915 nm was 3.4 dB/m. Borosilicate rods, integrated into the fiber construction, ensured its polarization properties. The extinction ratio, measured at a fiber length of 1 m, was as high as 23 dB.

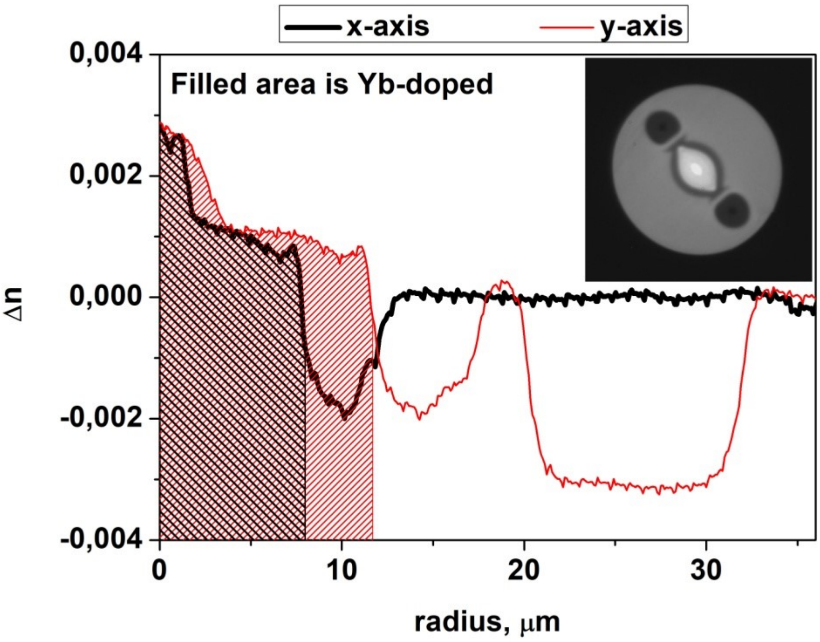

Figure 1. Measured refractive index profile of the active fiber and image of the fiber facet.

3. LASER SCHEME AND OUTPUT PARAMETERS OF THE LASER

The laser scheme manifested itself a ring cavity, the active element of which was the Yb-doped optical fiber with ring Yb-doping of the cladding [13] and with length of 16 cm (Figure 2). The co-propagating pump radiation was injected into the active fiber by a specialty developed pump and signal combiner (configuration 2 + 1 in 1), the signal core of which had a core size of 10 μm, a cladding size of 80 μm (losses for pump emission were 0.8 dB, the signal emission losses was 2.9 dB). The unabsorbed pump power was removed from the system by a home-made pump-stripper manufactured using a 10/125 μm optical fiber [14]. A circulator was included in the laser cavity to provide unidirectional propagation of signal radiation, as well as to feed emission to the SESAM semiconductor structure. To suppress lasing at wavelengths longer than 1000 nm, we additionally used a special cavity design that included high intra cavity losses and an additional filter to suppress a lasing in the wavelength region more than 1000 nm. The filter (WDM 980/1030 nm played its role in the cavity) helped to suppress an emission around 1030 nm, while high intra cavity losses (70% of the generated power was extracted from the laser cavity) helped to suppress lasing at shorter edge of this wavelength range (~1000 nm). Choosing of 70/30 coupler in 2x2 configuration allowed us to control ASE level over 1000 nm wavelength range, since it propagated in both directions. In order to eliminate the back reflection from the free end of the coupler, an isolator was used. All components of the scheme were polarization maintaining. The circulator was polarizing (light polarized along the fast axis was blocked in) and it allowed propagation of only one polarization state inside the laser cavity. All fibers and fiber components used in the scheme had a core diameter of 10 μm. The scheme did not contain any dispersion compensation components; the laser operated in the net normal dispersion regime.

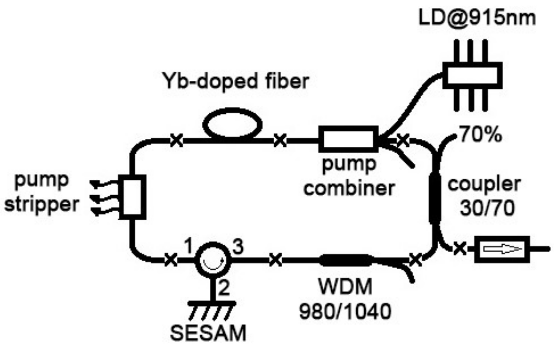

Figure 2. Laser scheme.

The laser was self-starting for pump powers above 4.6 W, with the output power of 3 mW and it worked for a long time without adjusting. The main reason of the low total efficiency of our laser was connected with a small fraction of the absorbed pump power and operation near 977 nm radiation lasing threshold (higher than 3 W). The autocorrelation was the best fitted with $sech^2$ profile and pulse duration was estimated to be about 9.5 ps (Figure 3). The spectrum of the generated pulses occupied almost all of the Yb-ions gain range near 977 nm, and it was the Yb-ions gain spectrum, which limited the spectral bandwidth of the generated pulses. The spectral bandwidth of the generated pulsed was 2.2 nm at the level of 10 dB (Figure 4a). A narrow spectral bandwidth might be one of the reasons why the pulses could not be compressed. The signal to noise ratio was about 30 dB (Figure 4b). The fundamental cavity frequency corresponded to the pulse repetition rate of 33.532 MHz. The stability of the produced mode-locked laser was very high as it follows from the spectrum of RF analyzer (Figure 5). Signal-to-noise ratio measured in the radio frequency range was more than 50 dB, the line width was below 1 kHz, which indicate ultimate stability of the fabricated mode-lock laser.

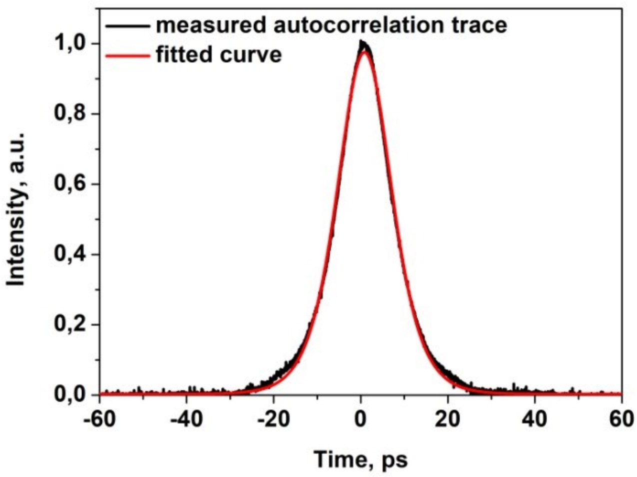

Figure 3. Autocorrelation trace and corresponding fitted by sec^2 function curve

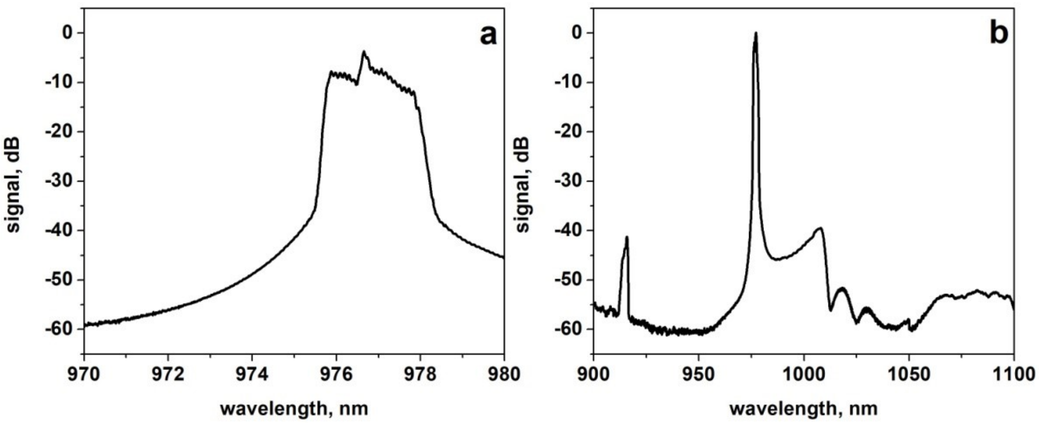

Figure 4. a - Pulse spectrum measured with resolution of 0.02 nm and b – total output spectrum measured with resolution of 0.5 nm

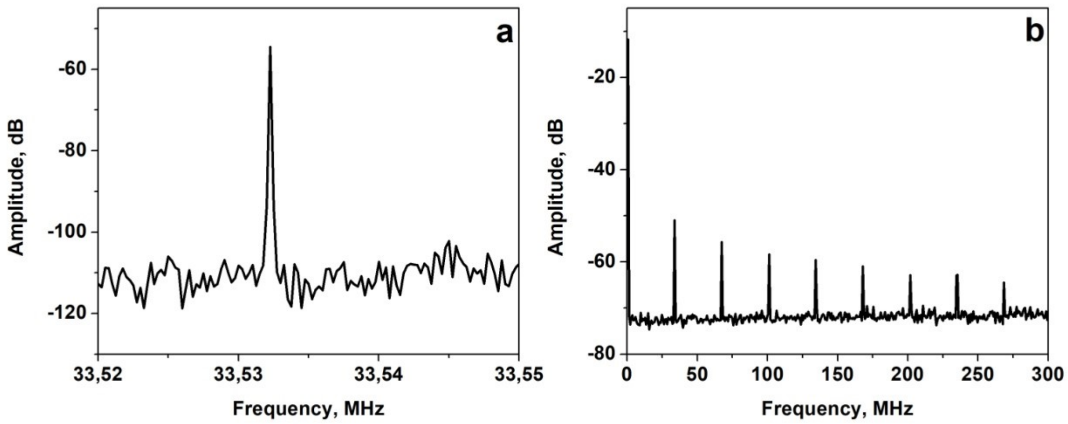

Figure 5. Measured RF-spectra of the generated pulses

4. DISCUSSION AND CONCLUSION

As far as we know in the present work we demonstrated the first polarization-maintaining all-fiber mode-locked laser operated at 977 nm wavelength range. All-silica-glass all-PM laser format guarantee simplicity and stability of the proposed laser configuration; the scheme was compact (all fibers could be bent) and reliable. As an active element of the laser we used clad pumped specially-designed Yb-ring-doped fiber compatible with standard optical fibers and fiber handling equipments (cleavers, fusion splicers) that made it possible to integrate the active fiber in the laser scheme with minimal losses for pump and signal emission. For scheme creation we used standard fusion splicer and cleaver. Pump power of only 4.6 W was enough to provide stable mode-lock laser generation. It is important to note that a unique property of the proposed laser scheme was the presence of an intracavity natural filter based on the gain spectrum of Yb-ions at 977 nm that limited the spectral width of the generated pulses. Furthermore, an additional factor contributing to the achievement of pulse generation at 977 nm was introduction of additional losses into the laser cavity. It helped us to suppress generation of unwanted amplified stimulated emission at 1030 nm from the one hand and to provide operation of the amplifier part of the laser in a small signal amplification regime from the other hand that kept inversion population on a high level along the Yb-doped fiber length and provided the high gain of the emission at 977 nm for a fixed active fiber length.

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REFERENCES

[1] Paschotta R., Nilsson J., Tropper A. C. and Hanna D. C., "Ytterbium-doped fiber amplifiers," in IEEE Journal of Quantum Electronics, vol. 33, no. 7, pp. 1049-1056 (1997)

[2] Boullet Johan, Zaouter Yoann, Desmarchelier Rudy, Cazaux Matthieu, Salin François, Saby Julien, Bello-Doua Ramatou, and Cormier Eric, "High power ytterbium-doped rod-type three-level photonic crystal fiber laser," Opt. Express 16, 17891-17902 (2008)

[3] F. Röser, C. Jauregui, J. Limpert, and A. Tünnermann, "94 W 980 nm high brightness Yb-doped fiber laser," Opt. Express 16, 17310-17318 (2008).

[4] Aleshkina S. S., Levchenko A. E., Medvedkov O. I., Bobkov K. K., Bubnov M. M., Lipatov D. S., Guryanov A. N., and Likhachev M. E., IEEE Photonics Technol. Lett. 30, 127 (2018)

[5] Li W., Matniyaz T., Gafsi S., Kalichevsky-Dong M. T., Hawkins T. W., Parsons J., Gu G., and Dong L., Opt. Express 27, 24972 (2019).

[6] M Leich et al, "Tapered large-core 976 nm Yb-doped fiber laser with 10 W output power", Laser Phys. Lett. 11 045102 (2014)

[7] Ylä-Jarkko K. H., Selvas R., Soh D. B. S., Sahu J. K., Codemard C. A., Nilsson J., Alam S. A., and Grudinin A. B., "A 3.5 w 977 nm cladding pumped jacketed air-clad ytterbium-doped fiber laser," in Advanced Solid-State Photonics, (Optical Society of America, 2003), p. 103.

[8] Soh D. B. S., Codemard C., Sahu J. K., Nilsson J., Philippov V., Alegria C., and Jeong Y., "A 4.3 w 977 nm ytterbium-doped jacketed-air-clad fiber amplifier," in Advanced Solid-State Photonics, (Optical Society of America, 2004), p. MA3. (2004)

[9] Lhermite J., Lecaplain C., Machinet G., Royon R., Hideur A., and Cormier E., "Mode-locked 0.5 µJ fiber laser at 976 nm," Opt. Lett. 36, 3819-3821 (2011);

[10] Lhermite J., Machinet G., Lecaplain C., Boullet J., Traynor N., Hideur A., and Cormier E., "High-energy femtosecond fiber laser at 976 nm," Opt. Lett. 35, 3459-3461 (2010)

[11] Ping-Xue Li et al, "980-nm all-fiber mode-locked Yb-doped phosphate fiber oscillator based on semiconductor saturable absorber mirror and its amplifier", *Chinese Phys. B* 25 084207 (2016)

[12] Nilsson J., Minelly J. D., Paschotta R., Tropper A. C., and Hanna D. C., "Ring-doped cladding-pumped single-mode three-level fiber laser," Opt. Lett., vol. 23, 355-357 (1998)

[13] Aleshkina S. S., Lipatov D. S., Kochergina T. A., Velmiskin V. V., Temyanko V. L., Kotov L. V., Bardina T. L., Bubnov M. M., Guryanov A. N., and Likhachev M. E., Quantum Electron. 49, 919 (2019)

[14] . Aleshkina S. S, Kochergina T. A., Bobkov K. K., Kotov L. V., Bubnov M. M., Park J., and Likhachev M. E., "High-power 125-µm-optical fiber cladding light stripper," in 2016 Conference on Lasers and Electro-Optics (CLEO), 1–2 (2016)