All-fiber mode-locked laser at 0.98 μm

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ABSTRACT

A double-clad Yb-doped PM-fiber for small signal amplifiers near 0.976 μm was developed. The fiber was designed to have a relatively small mode field diameter compatible with standard step-index single-mode optical fibers. Another feature of the fiber was a small threshold for 0.976 μm signal amplification, which was achieved by a creation of a thin inner cladding (80 μm diameter). Utilization of the realized fiber allowed us to construct an all-fiber picoseconds mode-locked laser at 0.98 μm for the first time to the best of our knowledge.

Keywords: ring-doping, optical fibers, fiber lasers, ytterbium

1. INTRODUCTION

Currently, Yb-doped fiber lasers emitting in the spectral range of near 0.976 μm have attracted huge interest due to prospects of their practical application (in the medicine, replacement of argon and excimer krypton laser by frequency doubling and quadrupling). At the same time fabrication of single-mode fiber laser systems emitting near 0.976 μm is a challenging task. The main obstacle is devoted to appearance of amplified spontaneous emission (ASE) of Yb^{3+}-ions near 1.03 μm. To suppress this effect a relatively short Yb-doped fiber should be used, which results in a high amount of unabsorbed pump power. Core pumping is the most efficient in this case, but laser parameters are limited by the available power of single-mode pump sources near 0.915μm (~300 mW). So in recent years a lot of attention was paid to development of specialty Yb-doped fiber designs for generation near 0.976 μm compatible with cladding pumping [1-7]. A high core to cladding diameters ratio is typically utilized to increase pump absorption and reduce unabsorbed pump power [1-6]. Recently significant progress was achieved by design of photonics bandgap fibers with enhances leakage loss near 1.03 μm, but the price was the increase of the net fiber length up to 12 m [7]. However, all above mentioned fibers had a large core diameter (25-100 μm) which cannot be spliced to standard single-mode fibers (maximum core diameter is 10 μm) with low losses. A large first cladding (125-300 μm in diameter) resulted in a high threshold for achieving positive gain near 0.976 μm (needed pump power was tens of Watts). Moreover, most of these fiber designs required bulk optics for pump and signal coupling. As a result, these fibers hardly can be used for fabrication of seed sources and preamplifiers operating near 0.976 μm, where all-fiber design (to increase reliability) and a low lasing threshold are on high demand.

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In the present work we designed and realized a special Yb-doped fiber with ring-doping, which was optimized to achieve increased amplification efficiency at 0.98 μm, low amplification threshold and low fusion splicing losses with commercially available single-mode fibers. This fiber was used for fabrication of all-fiber small signal amplifier at 0.98 μm and for realization of all-fiber mode-locked seed laser at 0.98 μm.

2. ACTIVE FIBER DESIGN

The fiber was designed as an active medium for clad pumped laser/amplifier schemes operated at 0.98 μm. In this case the most important fiber parameter providing high pump to signal conversion efficiency is the overlap integral between Yb-doped and pumped area. The point is that for a fixed Yb^{3+} ions concentration the maximum active fiber length is limited by the appearance of amplified spontaneous emission (ASE) of Yb-ions in the region of near 1.03 μm. Shorten of fiber length for suppression of ASE near 1.03 μm results in a high part of unabsorbed pump power. Increase of cladding pump absorption rate for a fixed Yb-ions concentration can be achieved by increase of ratio between Yb-doped area and fiber first cladding area. In the most ordinary case, the doping region is identified with the core region and enlargement of pump absorption rate from the cladding can be achieved by core diameter scaling. However fusion splicing losses grow with increase of active fiber core diameter, which neglect increase in pump-to-signal conversion efficiency. In addition, an increase of the fiber core size can lead to deterioration of output beam quality (M^2) due to non-single mode propagation regime (propagation of several transverse modes inside the active fiber core) and also due to the amplification of cladding modes with non-zero mode field intensity in the Yb-doped region.

In our modeling a ring-doping technique [8] was used to increase cladding absorption, maintain single-mode propagation and keep splicing losses. The fiber preform was fabricated by MCVD technology. The fiber design consisted of Yb-doped core and Yb-doped cladding. It allowed us to achieve a relatively small mode field diameter (MFD) (which results in low splicing losses with a standard single mode fiber with the core diameter of 10 μm) and, simultaneously, to increase the absorption from the cladding (to keep a reasonably high lasing efficiency). Due to the fact that Yb-doped lasers at 0.98 μm suffer from photodarking, as core matrix we have utilized insensitive to this effect P_2O_5-Al_2O_3-SiO_2 glass [9] with excess of phosphorus oxide [11]. However introduction of phosphorus oxide excess (not associated with aluminum oxide) makes a positive contribution to the refractivity of the glass medium that in our case resulted in that the realized refractive index of the Yb-doped region was above the un-doped silica glass level. So the developed refractive index profile design was modified: the core was composed of two Yb-doped regions. The central one had an increased refractive index that promoted tightening of the fundamental mode field. And the second one promoted increased pump absorption. The Yb oxide concentration was 0.16 mol. %. Two B-doped rods were injected into the fiber preform in order to provide polarization sensitivity. The fiber was drawn in a reflective polymer coating providing NA~ 0.45. Measured refractive index profile and image of the fiber end are depicted in Figure 1. The measured MFD of the fundamental mode along the x and y axes were 12 μm and 14 μm, respectively, which ensured reasonably low splicing losses (0.35 dB) of the fabricated fiber and standard single-mode step-index optical fibers with core diameter of 10 μm. To increase the pump absorption and reduce the lasing threshold for 0.976 μm the outer cladding diameter of the fiber was reduced down to the minimum diameter compatible with standard fusion splicers (80 μm). The cladding absorption near 915 nm was 3.4 dB/m, polarization extinction ratio at the output of few meters fiber exceeded 20 dB. Mode composition of the fiber core was studied by the scanning beam method at a wavelength of 1.06 μm. The shift of the exciting beam relative to the fiber core axis led to reducing of the fundamental mode field intensity without high-order modes excitation, which indicated that the fiber is single-mode at a wavelength of about 1.06 μm. The measurement of mode composition at wavelength of 0.976 um was impossible due to the intense Yb^{3+}-ions absorption in this spectral region and the subsequent generation of spontaneous luminescence in the region of 1.03 μm.

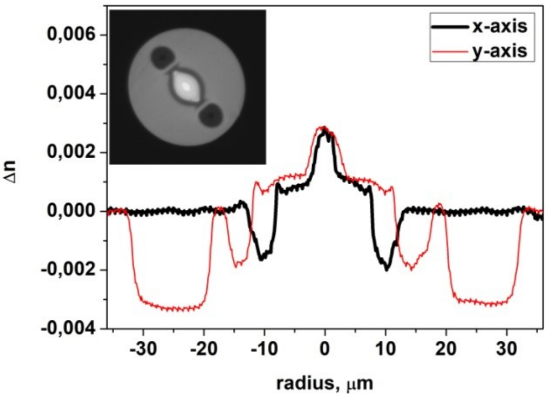

Figure 1. a: Figure 1. a - Measured refractive index profile of the realized fiber and image of the fiber facet (inset)

3. SMALL SIGNAL AMPLIFIER

An all-fiber master oscillator power amplifier at 0.976 μm was built based on the realized fiber (Figure 2). As a seed source a semiconductor diode pigtailed with an optical fiber was used. Wavelength stabilization was carried out due to home-made fiber Bragg grating. The seed laser power injected into the active fiber was estimated due to the signal at the free end of the coupler. To prevent seed master oscillator damage by backward ASE at 0.98 μm, an isolator was placed in front of the amplifier part of the scheme. A commercially available multimode semiconductor diode at 0.915 μm with a maximum output power of 27 W was used as a pump source. Pump was coupled into the developed Yb-doped fiber with a help of a specialty designed pump combiner (configuration of 2+1 to 1), the signal fiber of which had a silica cladding diameter of 80 μm and a core diameter of 10 μm (the optical losses at the pump wavelength were 0.8 dB; the losses at the signal wavelength were 2.9 dB). The specially developed home-made pump stripper (with core diameter of 10 μm and clad diameter of 125 μm) [12] was applied in the scheme to remove unabsorbed pump power. Further, the output fiber of pump stripper was spliced with a fiber having an identical diameter and aperture of the core, but covered with a high-index polymer coating, which made it possible to evacuate the remaining pump radiation from the cladding. The output end of the fiber was angle cleaved to suppress the reflection from the fiber end. The optimal length of the Yb-doped fiber was 37 cm. The signal-to-noise ratio in this case was as high as 30 dB and grew with a further decrease in the active fiber length. The highest pump-to-signal conversion efficiency of 9.7% was achieved near 0.977 μm (Figure 3a). The lasing threshold did not exceed 3 W (Figure 3b), which is significantly less than that of the cladding pumped amplifiers for this spectral range reported previously [1,2,4,8].

First of all we studied dependence of the signal-to-noise ratio on the input signal power (the ratio of the amplified signal power to the integrated luminescence power near 0.98 μm). To provide the identical input signal conditions (the same splicing and bending losses), an input signal attenuator was integrated into the scheme. It allowed us to change the input signal power from 10 μW to 50 mW. As an example, Figure 4 shows the dependence of the added signal power at a wavelength of 0.977 μm, the generated ASE power at 0.98 μm and ASE power at 1.03 μm on the input signal power. The dependence corresponds to the signal wavelength, which provides the highest signal-to-noise ratio, because at this wavelength the signal has maximum gain. It can be seen from Figure 4, that at input signal power of about 1 mW, signal-to-noise ratio is more than 20 dB, which is sufficient for most of applications. In the experiment we did not take into account the ASE at 1.03 μm because of the possibility of efficient cleaning of the signal spectra by commercially available fiber filters. The spectral dependence of the signal-to-noise ratio, measured for a narrow-band source at the input signal power of 1 mW, is shown in Figure 5a. The study of the gain spectra at the lower input seed power (at the level of 10 μW) showed the possibility of 40 dB amplification of the signal. It is worth noting that in this case, a high signal to noise ratio can be achieved using spectral filters (it is the most effective in the case of amplification of single-frequency or narrow-band signal). Figure 5b shows the measured dependence of the small signal (with a power of 10 μW) gain on the signal wavelength. It can be seen that signal amplification of more than 25 dB can be realized in the spectral range from 0.974 μm to 0.980 μm.

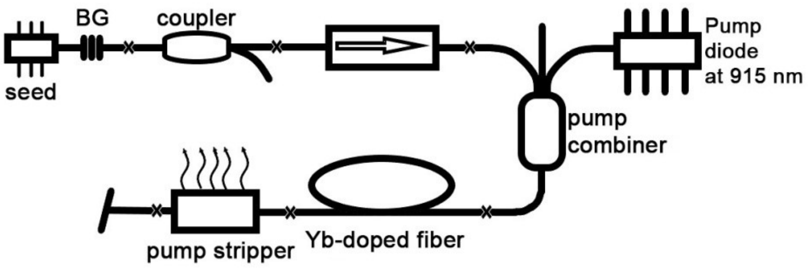

Figure 2. Amplifier scheme

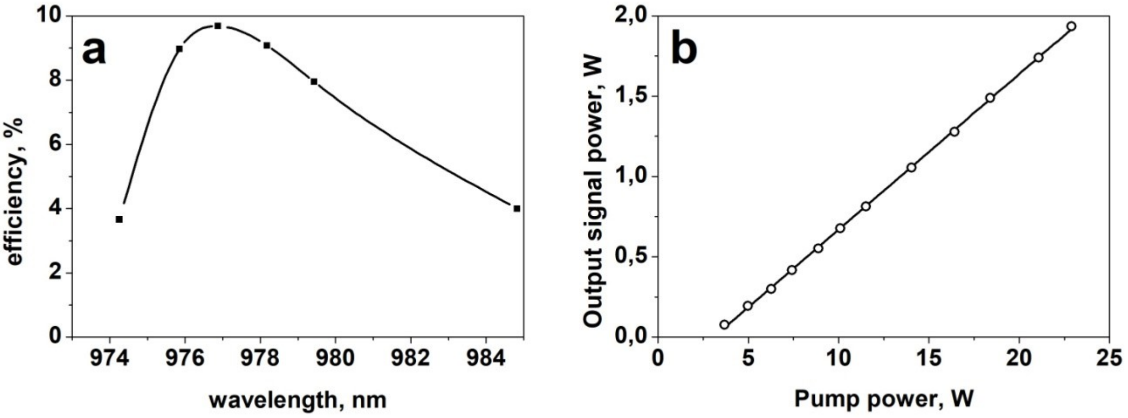

Figure 3. Spectral dependence of a slope pump to signal efficiency (a) and amplification of the signal at 0.977 μm

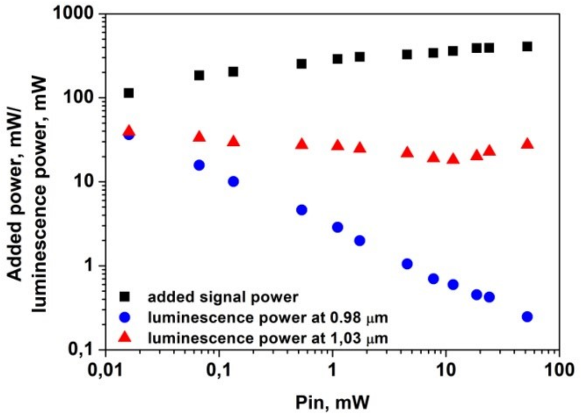

Figure 4. Added signal power and ASE power at 0.98 μm and 1.03 μm on seed power.

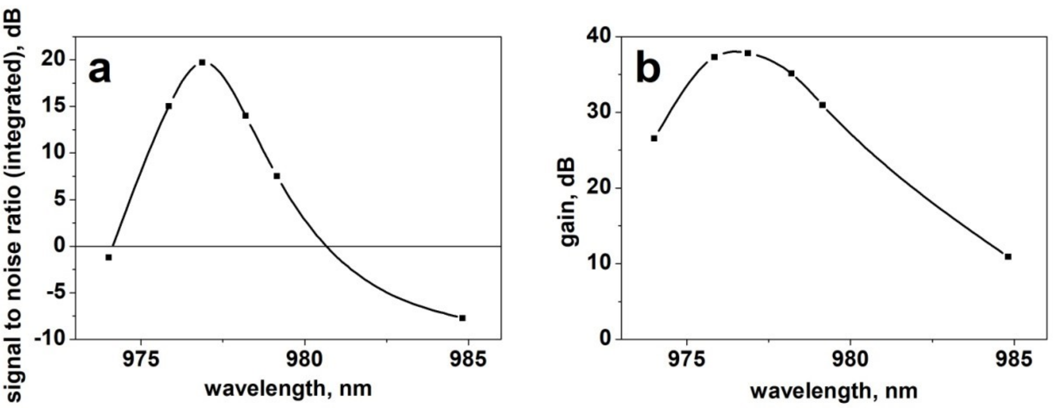

Figure 5. Signal to noise ratio at the input signal power of 1 mW (a) and spectral gain dependence at 10 μW of signal power

4. ALL-FIBER MODE-LOCKED LASER

An all-fiber mode-locked laser scheme was created using the similar amplifier scheme (Figure 6a). All components of the scheme except the passive fiber (where NPE take place) were polarization-maintaining. Fast axis was blocked in a circulator to allow lasing at only slow polarization. All fibers had core diameter of about 10 μm; dispersion of it was normal. A commercially available multimode semiconductor diode with the output power of 10 W, emitting at wavelength of 915 nm, was used as a pump source. The unabsorbed pump power was evacuated as in the previous experiment by a home-made fiber pump stripper [12] (core and cladding diameter of the fiber was 10 and 125 μm, respectively). Due to the relatively low round trip loss in the laser scheme the amplifier operated in a small-gain regime that reduced inversion and made possible lasing near 1.03 μm even when fiber length was below optimal reported above. Complete suppression of ASE near 1.03 μm was achieved by shortening the active fiber length down to 16 cm and by adding of 980/1040 fiber filter in the scheme.

The laser threshold for CW operation was ~3.2 W. The pulse operation was self-starting for pump powers above 4.6 W, with the output power of 3.25 mW. Figure 6b and 6c illustrates autocorrelation trace and the corresponding spectrum for the mode-locked pulse train. The autocorrelation was the best fitted with sech^2 profile and pulse duration was estimated to be as long as 9.5 ps. The pulse repetition rate was 33.4 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.

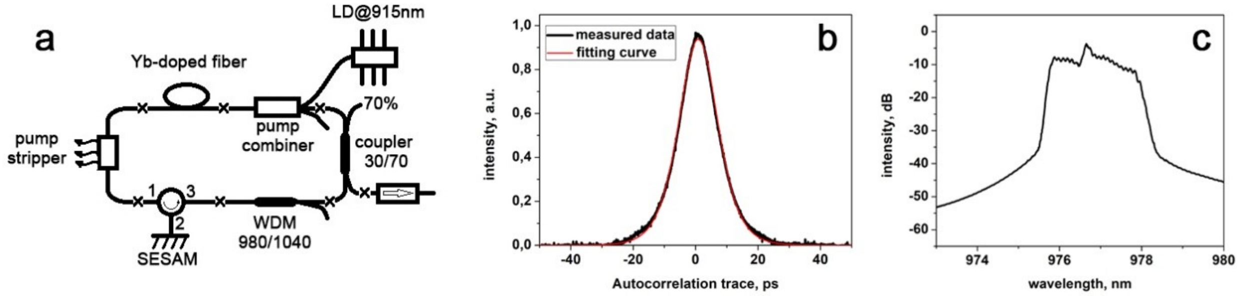

Figure 6. a – Laser scheme; b – autocorrelation trace, c – corresponding spectrum

5. CONCLUSION

In the present work, we developed the design of an optical fiber for all-fiber small signal amplifier and master oscillators at 0.98 μm creation based on additional doping of the fiber cladding. Polarization maintaining optical fiber was implemented. One of the main features of the fiber design is the low fusion splicing losses with standard single-mode fibers with a core diameter of 10 µm. An all-fiber amplifier with the gain threshold of about 3 W and the slope efficiency of 9.7% (measured in saturation regime) was realized. It was shown that the developed amplifier was suitable for small signal amplification. Amplification of the seed signal with power of about 1 mW to 20 dB resulted in the ratio of the amplified signal to the integrated ASE power at 0.976 µm exceeded 20 dB. A 40 dB gain of an ultra-small signal with a power of ~ 10 µW was demonstrated. The realized optical fiber was tested in the scheme of all-fiber mode-locked laser based on a SESAM. Pulses with duration of 9.5 psec and spectrum bandwidth covering the whole Yb-gain range at 0.98 µm were achieved. To the best of our knowledge we have demonstrated for the first time an all-fiber mode-lock laser operating near 0.976 µm.

ACKNOWLEGEMENTS

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