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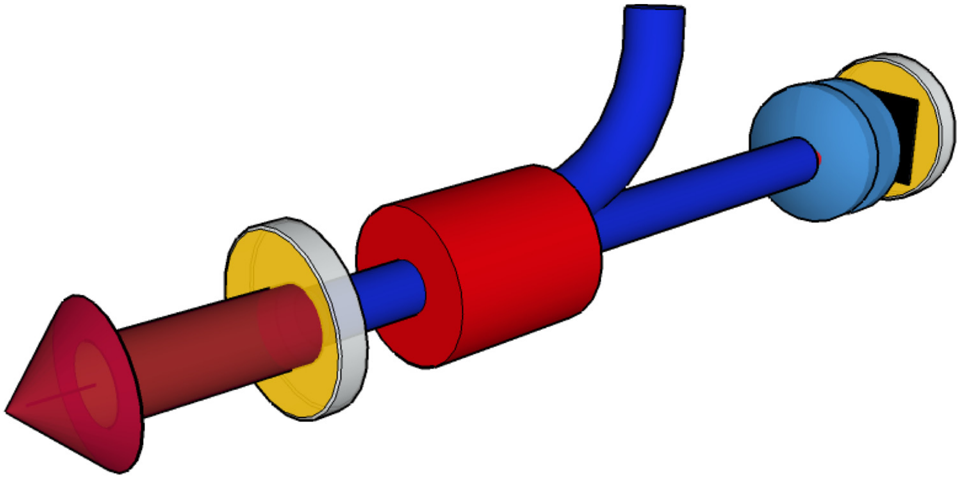

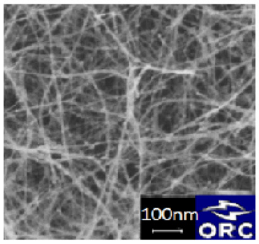

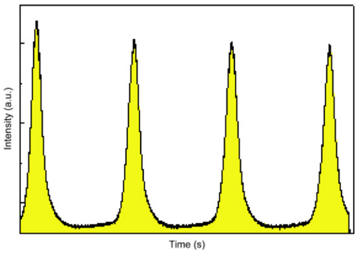

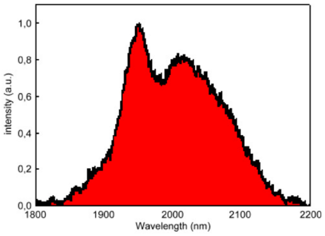

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High-Repetition-Rate Q-Switched Holmium Fiber Laser

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Abstract: Pulses of 118 nJ at the repetition rate of 170 kHz and central wavelength of 2097 nm have been produced by holmium fiber laser Q-switched by carbon nanotube saturable absorber. Efficient operation of holmium fiber with fairly high-doping level has been demonstrated by using refined preform fabrication, which allowed for short-length cavity laser. The results demonstrate the practical potential of holmium fibers for Q-switched lasers with high-repetition rate operating above 2 μm wavelength.

Index Terms: Fiber lasers, Q-switched lasers, carbon nanotubes and confined systems.

1. Introduction

Q-switched fiber lasers operating around the 2-μm band could be highly practical sources for numerous applications where nanosecond-range, high-energy pulses are required, e.g., remote sensing, material processing, micromachining, laser surgery, and optical parametric oscillators [1]. Compared with the other types of Q-switch sources, fiber lasers have an advantage of better heat dissipation due to larger surface area, environmental stability, and more compact and robust designs. The pulse repetition rate of fiber lasers is usually of the order of tens of kilohertz limited by the cavity, which is typically a few meters long. On the other hand, high-repetition rate of more than 100 kHz is particularly desirable in medicine, LIDARs, and high-resolution photoacoustic microscopy [2]. It should be noted that although an active Q-switching provides better control of pulse parameters, the passive techniques offer more compact and cost-effective design.

Q-switched fiber lasers have been recently demonstrated with pulse repetition rates in a range of 300 kHz–1.4 MHz at 1 μm [3], [4] and ~200 kHz at 1.5 μm [5], [6]. Tailoring the operation to longer wavelengths limited by the transparency band of silica fiber is routinely achieved with thulium and holmium rare-earth materials, exhibiting efficient pump to signal conversion [7]. The holmium-doped could operate above 2.1 μm, which is beyond the reach of thulium fibers [8]–[13]. The extended wavelength tailoring toward longer wavelengths attainable with holmium fiber is essential for some applications. Particularly, 2.11–2.4 μm spectral range matches the high transparency window of the atmosphere, and therefore, the light sources operating at these wavelengths can be used for free-space optical communications and infrared astronomy [14]. 2.1-μm lasers are valuable for medical applications because they allow precise surgery with the minimum penetration length inside the organic tissue [1], [15].

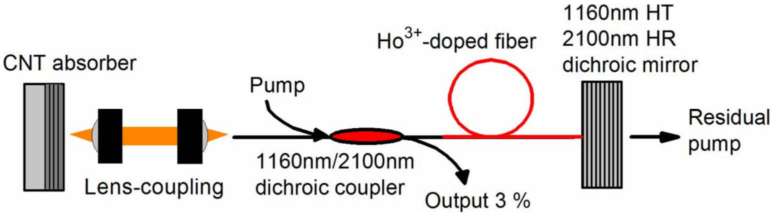

Fig. 1. Schematic of Q-switched holmium fiber laser with lens-coupled CNT absorber mirror.

Tm-doped Q-switched fiber lasers have been demonstrated with the repetition rate up to 530 kHz [8]–[11]. The self-pulsed operation has been reported using long cavity with a few meters of heavily Ho-doped fiber exploiting the same fiber as a gain and absorbing media [16]–[19]. Such chaotic self-pulsing regime, however, exhibits low efficiency, is capable of producing rather long pulses, and has poor temporal stability with undetermined repetition rate. The short-length fiber cavity allows reduction of the overall background absorption which is high in silica at the 2.XX-μm wavelength range and eventually to increase laser efficiency, decrease pulse duration, and increase the repetition rate [20]. Using high-gain efficiently pumped fiber and exploiting saturable absorbers specially designed for Q-switched operation would greatly improve performance and move these lasers toward a practical area.

In this paper, we report the highly doped holmium fiber laser Q-switched with CNT absorber. A-27-cm-long cavity comprises 9 cm of holmium fiber pumped with a 1156-nm semiconductor disk laser. 320-ns pulses have been obtained with the repetition rate of 170 kHz, pulse energy of 118 nJ, and the central wavelength of 2097 nm.

2. Experimental

Since the Q-switched pulse repetition rate is one of the objectives of this study, the efforts were made to reduce the cavity length. It should be mentioned that the repetition rate of passively Q-switched lasers is controlled by cavity loss and length and absorbed pump power [7]. A thin-film CNT absorber placed on a high reflective mirror and a dielectric mirror terminates the fiber laser cavity, as shown in Fig. 1. The latter has a 99.9% reflectivity at 2100 nm and a high transmission at the pump wavelength and allows the removal of an unabsorbed pump from the cavity. The pump was launched through an 1160/2100-nm dichroic pump coupler that is also used as a 3% output port. The 9-cm length of holmium-doped fiber was found to provide the best performance. The total cavity length of 27 cm also includes a free space section of 10 cm and 8 cm added by a passive fiber and coupler.

The pump light was provided by a 1.16-μm continuous wave semiconductor disk laser (SDL) that produced up to 3 W of output power with the beam quality factor M^2 of 1.13 that allows 70% of power to be launched into a single-mode fiber [21], [22]. A 1.16-μm pumping wavelength matches closely the wavelength of Ho^{3+} peak absorption [12].

The active fiber heavily doped with Ho^{3+} and codoped with Al_2O_3 was made with MCVD technology using a solution doping method. Holmium concentration is of 3×10^{20} cm^{-3}. The core-cladding refractive index difference is 6×10^{-3}, and the second cutoff wavelength was 2 μm. The peak absorption at 1.15 μm in the gain fiber was measured to be 150 dB/m. The spectrum of amplified spontaneous emission of the Ho-doped fiber is plotted in Fig. 2.

A carbon nanotube absorber was implemented to facilitate passive Q-switching [5], [23]. Single-wall carbon nanotubes (SWCNTs) were prepared with a thermal decomposition of ferrocene vapor in a carbon monoxide atmosphere. SWCNT film was then placed on a highly reflective golden mirror, as can be seen in Fig. 3.

The pressure of 1000 Pa was applied to bond the film to the mirror. The details of CNT fabrication and characterization can be found in [23]. The modulation depth, saturation fluence, and nonbleachable loss measured at 1.56 μm of a CNT absorber were 6%, 320 μJ/cm^2, and 4%, respectively. It is expected

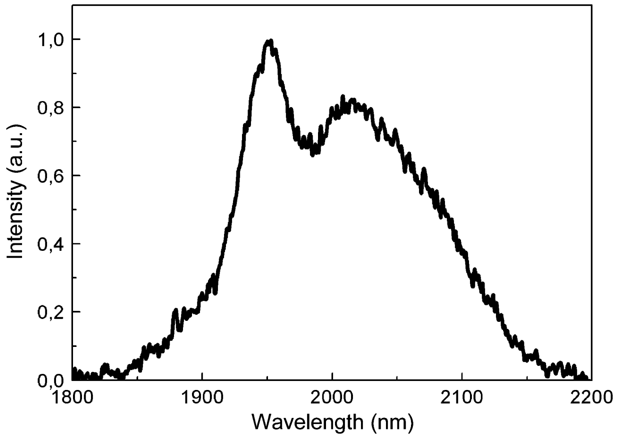

Fig. 2. Amplified spontaneous emission of the Ho-doped fiber pumped at 1.16 μm.

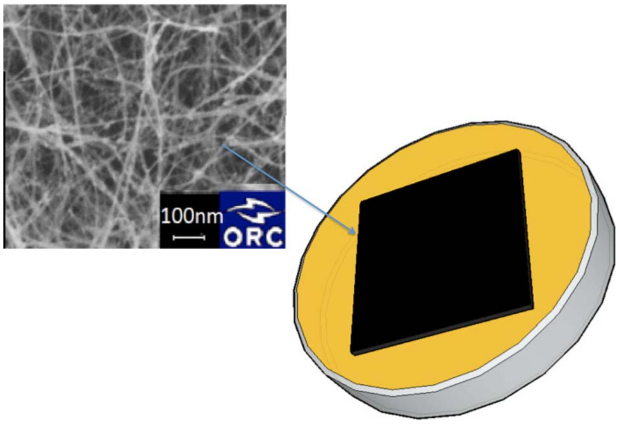

Fig. 3. CNT film SEM picture revealing 1–3 nm diameters of the nanotubes and the schematic of the film placed on a high reflective golden mirror.

that relatively fast recovery time of CNT absorbers imposes some losses to Q-switched pulses [20]. Therefore, using slow absorbers, e.g., purposely designed SESAMs, may result in further improvement of performance.

3. Results

The lasing threshold was measured to be 970 mW. Q-switched pulses were obtained at 1.55 W of pump with 20 mW of average output power and 320 ns pulse duration at the repetition rate of $\sim$170 kHz. Corresponding pulse energy is 118 nJ. The output pulse spectrum and oscilloscope trace are shown in Fig. 4. The central wavelength of the pulse spectrum is 2097 nm. Pulsed operation was self-starting, and no signs of degradation related to a CNT absorber were observed.

Laser output performance versus the pump power is demonstrated in Fig. 5. The significant improvement of pulse characteristics with the pump power indicates that laser performance can be further enhanced with higher pumping rate. It should be noted that using highly doped fiber requires an accurate optimization of the gain fiber length. Particularly, shorter length reduces the power characteristics, while an excessive length decreases the repetition rate and causes temporal instabilities.

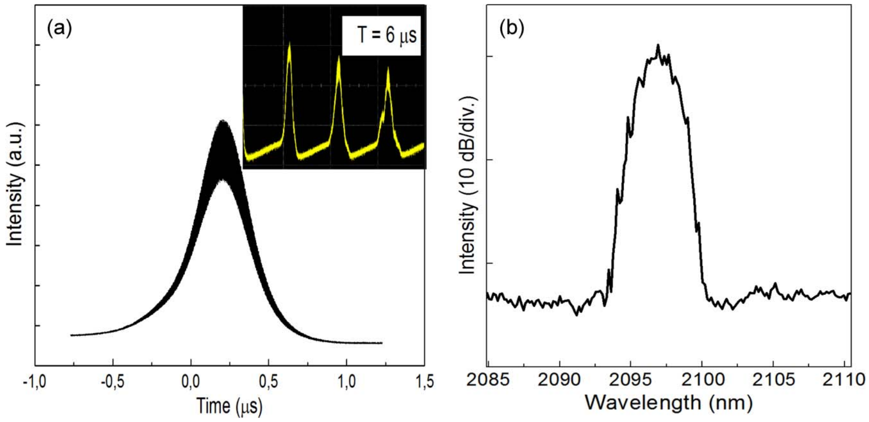

Fig. 4. (a) Scope trace of the Q-switched pulse; corresponding pulse train is shown on the insert. Scope traces were taken with a 2.5-GHz photodetector. (b) Pulse optical spectrum.

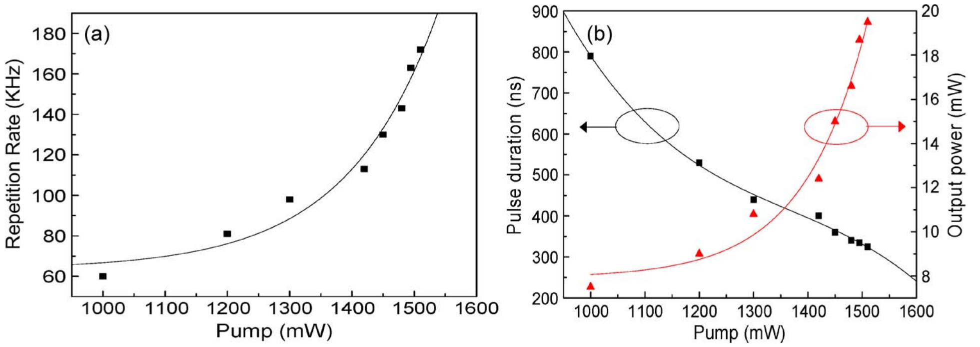

Fig. 5. Q-switched pulse characteristics versus pump power (a) Repetition rate. (b) Pulse duration and the average power.

4. Conclusion

In conclusion, we have reported a Q-switched Ho^{3+}-doped fiber laser producing 118-nJ pulses with the repetition rate of 170 kHz and the wavelength of 2097 nm. Laser performance demonstrates power scalable behavior, which suggests that pulse characteristics could be further improved using a more powerful pumping source. The results demonstrate the promising potential of holmium fiber lasers for applications that require pulsed mid-infrared light sources.

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