High-powered millijoule pulse energy Tm^{3+}-doped fiber amplifier at 2.05 μm

Renlai Zhou (周仁来)*, **Youlun Ju (鞠有伦)**, **Yunjun Zhang (张云军)**, **and Yuezhu Wang (王月珠)**

National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150080, China

**Corresponding author: zrlhit@126.com*

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A high-powered millijoule pulse energy Tm^{3+}-doped fiber amplifier seeded with a Q-switched operation of Tm (4 at.-%), Ho (0.4 at.-%):YVO_4 laser is reported. The output characteristics of the amplified laser are studied at the coupled powers of 0.266, 1.24, and 2.65 W. Maximum output power up to 15.7 W is at 10-kHz repetition rate. Nonlinear effects are not observed from the emitting spectrum and the full-width at half-maximum (FWHM) of the pulse duration is reduced from 40.1 to 25.9 ns at 1.57-mJ pulse energy. The beam quality factor $M_x^2 = 1.9\pm0.03$, $M_y^2 = 2.1\pm0.02$ at the output power of 14.5 W is measured using the traveling knife-edge method.

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High-powered, short-pulse, high-repetition rate laser sources emitting in the 1.9–2.1-μm region have potential applications, in such as lidar for atmospheric pollution monitoring, remote sensing, range finders, wind shear detection[1−3], and medical applications[4−7]. These laser sources can also be used to pump $ZnGeP_2$ crystal optical parametric oscillator (OPOs) to generate the high peak power, high pulse repetition frequency 3–5-μm laser sources, which are key components in advanced security and defense systems. Q-switched 1.9–2.1-μm lasers output can be obtained directly from Tm^{3+}-doped, Ho^{3+}-doped, or Tm^{3+}, Ho^{3+} co-doped crystal (or ceramic) pumped by high-powered laser diode due to their inherent stability, efficiency, and robustness[8−10]. However, pulsed 2-μm laser output have not been successfully obtained at high power levels due to thermal lens effect or thermal damage of the laser crystal. Therefore, more complex laser geometries have to be applied to compensate for thermally induced distortions that seriously reduce the efficiency of the laser.

The generation of 2-μm laser nanosecond pulses in a fiber can follow two approaches. One is to Q-switch a Tm^{3+}-doped fiber laser[11−13], which has the advantage of direct and efficient generation of pulses in a single stage with the desired parameters. However, in conventional Q-switched fiber laser, the laser pulse duration is in the range of >100 ns. This is attributed mainly to the direct proportionality between the generated pulse duration and the cavity length, which is typically in the range of several meters or even longer. In addition, due to the long cavities inherently connected to fiber lasers, the repetition rates of Q-switched fiber sources are often limited to a few kHz. The other is the amplification of a low-energy seed source with a defined and flexible pulse duration (even sub-nanosecond pulses are possible) and repetition rate[14,15]. Limpert *et al.* have demonstrated the fiber-based amplification of a Q-switched Nd:YAG thin-disk laser, and obtained a maximum output power of up to 100 W in repetitions ranging from 3 to 50 kHz[16]. In particular, bend-loss-induced mode filtering has allowed pulsed fiber lasers and amplifiers to be scaled to mJ pulse energies and MW peak powers while maintaining diffraction-limited beam quality[17]. Hence, this method permits the use of multimode fibers with large core diameters capable of generating higher pulse energies and peak powers through the use of the strong increase in bend loss with mode order. On the other hand, a Q-switched bulk laser with a simple scheme, which provides moderate power 2-μm laser nanosecond pulses with stable, controlled characteristics, including fixed duration, pulse energy, peak power, beam quality, and polarization state, can be employed as a seed laser.

In this letter, we report on a high-powered millijoule pulse energy amplified radiation system at 2.054 μm at the repetition rate of 10 kHz. The maximum output power was 15.7 W when the incident pump power was 80.8 W and the minimum pulse duration was 25.9 ns. The emitting spectrum was measured at different pulse energies, and no obvious nonlinear effects were observed in the spectrum of the amplified pulse. The beam quality factor $M_x^2 = 1.9\pm0.03$, $M_y^2 = 2.1\pm0.02$ was measured using the traveling knife-edge method.

Experimental setup of the pulse fiber amplifier is shown in Fig. 1. An acousto-optical (AO) Q-switched operation of Tm (4 at.-%), Ho (0.4 at.-%):YVO_4 laser pumped by an 808-nm diode laser was employed as a nanosecond seed source. The laser delivered a maximum power of 8.5 W at the repetition rate of 10 kHz and a pulse duration of 32.5 ns. The emitting spectrum was measured at different output powers, which contained two wavelengths of 2,041 and 2,054 nm. To select a single wavelength, a 0.1-mm Fabry-Perot etalon was used in the experiment. A Faraday optical isolator was used to prevent counter propagation of the laser beam which may destroy the operation of the seed laser. An aspheric lens (f = 5 mm) was used to couple the seed laser into the Tm-doped gain fiber.

A 3-m-long low numerical aperture (NA), large mode area, double-clad Tm^{3+}-doped silica fiber was used in the experiment. The fiber had a core diameter of 25 μm (NA=0.1) and a thulium doping concentration of ∼ 2.2 wt.-%. The octagonal pure-silica inner cladding was coated with a low-index polymer and had a 400-μm diameter and a NA of 0.46. The large core of the fiber was

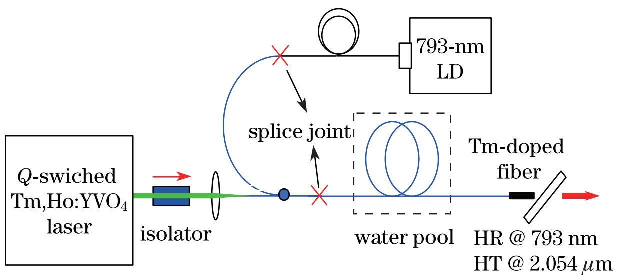

Fig. 1. Experimental setup of the Tm^{3+}-doped fiber amplifier.

used to reduce laser power density, which allowed a higher power scalability to be obtained in pulsed operation. The fiber amplifier was pumped by a 180-W laser diode at 793 nm (2.5-nm bandwidth) with a 200-μm pigtail fiber coupling output. The pigtail fiber was spliced directly to a branch of the master-oscillator fiber power amplifier system. Due to the quasi-three-level nature of the Tm^{3+}-doped fiber, cooling the fiber was critical for achieving high conversion efficiencies. The laser output end was clipped between copper sinks and then cooled by water. The central part of the Tm^{3+}-doped fiber was wrapped on a 12-cm diameter copper cylinder, which was cooled by circulating water with a temperature of 18 °C. A high reflection for pump light and high transmission for amplified light dichroic mirror was placed with an angle of 45° to separate the pump light and the amplified light.

To amplify the seed laser, it is necessary to couple the seed laser into the fiber core. The power meter used in the experiment was a thermal power meter (Coherent, PM30) placed at the output end of the Tm^{3+}-doped fiber to monitor the coupled seed power. Figure 2 shows the average output power and pulse energy of the amplifier with different coupled seed laser powers at the repetition rate of 10 kHz. The maximum output powers were 10.7 W (1.07 mJ), 12.9 W (1.29 mJ), and 15.7 W (1.57 mJ) at the coupled seed laser powers of 0.266, 1.24, and 2.65 W, respectively. The output signal power increased linearly with the launched pump power, and the changing of slope efficiency was not obvious at different coupled powers. The slope efficiency was too low for a typical Tm^{3+}-doped fiber laser or amplifier, as shown in Fig. 2. This result can be explained by the fact

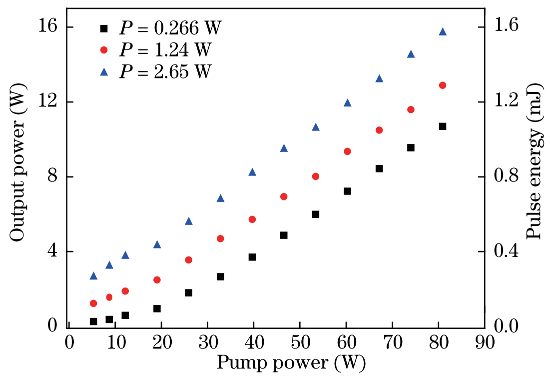

Fig. 2. Amplified laser output power and pulse energy at the coupled powers of 0.266, 1.24, and 2.65 W versus incident 793-nm pump power.

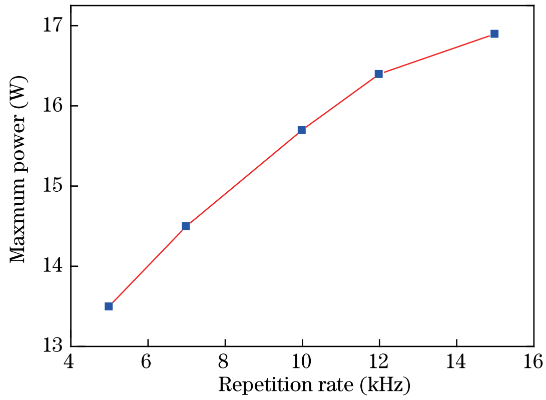

Fig. 3. Amplifier average output power as a function of pulse repetition rates.

that lower seed power was coupled into the fiber core, and most of the seed power was emitted through the fiber clad. Figure 3 shows the amplifier average output power with 2.65-W coupled seed laser powers at different repetition rates. As the repetition rate increased, the maximum achieved average output power increased near linearly. We did not find any facet damage at the maximum power. Therefore, more output signal power can be realized if we increase the pump power.

The emitting spectra at output signal pulse powers of 4.32, 10.6, and 14.5 W were recorded with a monochrometer (300-mm focal length, 600-lines/mm grating blazed at 2.0 μm) and plotted against the seed source spectrum at the repetition rate of 10 kHz. The lasing radiation was monitored by an InGaAs detector with a SR830 lock in the amplifier for signal extraction. Figure 4 shows the amplified output laser spectra. The output laser wavelength was centered at 2.054 μm, and the full-width at half-maximum (FWHM) of the spectra was less than 5 nm. Nonlinear effects such as stimulated Raman scattering and four-wave mixing were not observed. However, the FWHM of the spectra were broadened along with increasing output power, and we believe the main reason for this is self-phase modulation.

The amplified laser pulse was detected using an InGaAs photodiode and recorded by a 350-MHz digital oscilloscope (Wavejet332, Lecroy). Figure 5 shows the pulses of seed source and amplified laser at 10-kHz repetition rate. When the output amplified pulse energy reached 1.57 mJ, the FWHM of pulse duration was

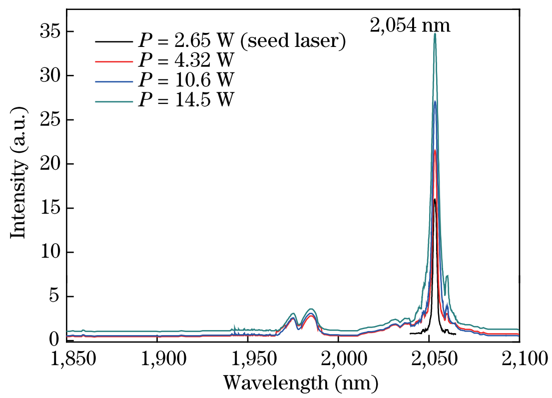

Fig. 4. (Color online)Emitting spectra of the seed and amplified lasers.

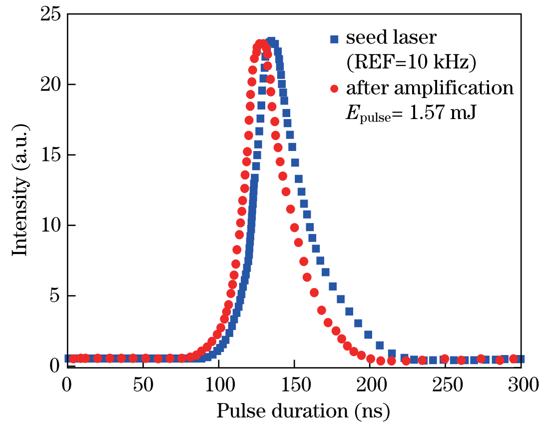

Fig. 5. Photodiode signal of the nanosecond seed laser and amplified pulses (E_{pulse}=1.57 mJ).

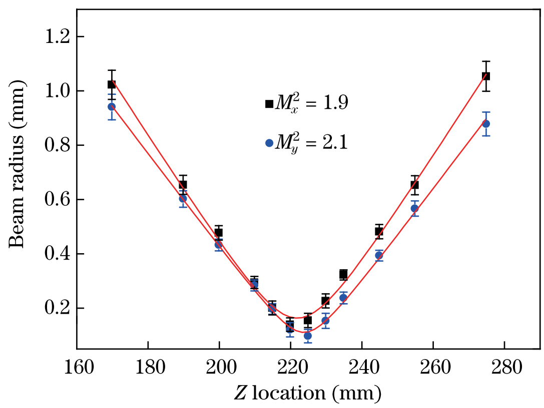

Fig. 6. Beam radius for the amplified laser as a function of the distance from the focusing lens at the output power of 14.5 W.

reduced from 40.1 to 25.9 ns, corresponding to a peak power of 60.6 kW. The pulse shortening factor increased with a decrease of the repetition rate corresponding to a higher energy density in the pulse.

The beam radius for the amplified laser at the output power of 14.5 W was also measured using the 90/10 knife-edge method. A lens (f = 150 mm) was located 200 mm away from the output-coupling mirror. We then measured the beam radius from the X and Y directions. Figure 6 shows the measured beam radius at different positions after the lens. By fitting the Gaussian beam standard expression to these data, we estimated the beam quality to be $M_x^2 = 1.9 \pm 0.03$, $M_y^2 = 2.1 \pm 0.02$.

In conclusion, we demonstrate a pulse Tm^{3+}-doped fiber amplifier through combiner pump. The maximum output power reaches 15.7 W when the incident pump power is 80.8 W, and the minimum pulse duration reaches 25.9 ns at 10-kHz repetition rate. The emitting spectrum is measured at different pulse energies and nonlinear effects are not obvious. The FWHM of pulse duration decreases from 40.1 to 25.9 ns at 1.57-mJ pulse energy. The beam quality factor $M_x^2 = 1.9 \pm 0.03$, $M_y^2 = 2.1 \pm 0.02$ at the output power of 14.5 W is measured using the traveling knife-edge method. To our knowledge, this high-powered, short pulse, high repetition rate laser source can be used directly to pump $ZnGeP_2$ crystal OPO to generate 3–5-μm light source.

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