High repetition rate Tm:Ho:LuLiF master-oscillator and Tm-doped fiber power-amplifier system

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A high repetition rate Tm:Ho:LuLiF master-oscillator and polarization-maintaining (PM) Tm-doped fiber power-amplifier system is presented. A 11.3-kHz, 0.4-nm line width, 0.89-W Tm:Ho:LuLiF seed laser is developed. Using a two-stage PM Tm-doped fiber power amplifier system, 32.4-W output power is obtained with 0.4-nm line width at a central wavelength of 2058.5 nm, corresponding to 0.66-W seed laser. The laser spectrum and pulse profile are measured.

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High repetition rate, narrow line width, linearly polarized 2-μm lasers attract growing interest due to their advantages of several kilohertz pulse repetition rates, high peak power, narrow spectral line width, ample absorption lines in atmosphere, and good beam quality. Their applications include lidars for measuring wind and CO_2, nonlinear frequency conversion, biomedical application, eye-safe transmitter, and optical communication in space[1−7].

In the past several years, multi-stage fiber amplifiers optimized for 1- and 1.5-μm lasers have demonstrated the ability to deliver several hundred watts of output power with narrow line width, linearly polarized output, and single mode beam quality. The recent advances in high power Tm-doped fibers operating efficiency with 790-nm cladding pumping have generated power levels of up to 1 kW; a 600-W single-mode, single-frequency continous wave (CW) Tm fiber laser amplifier has been reported[8]. Among the laser materials for generating 2-μm laser emission, Tm-doped fibers can produce higher efficiency with a compact structure and simple thermal management. More importantly, Tm-doped silica fibers have been proven useful in pulse generation and amplification in the 2-μm spectral band. However, only a few pulsed Tm-doped fiber lasers in 2 μm have been developed. In 2008, Creeden *et al.* reported more than 20 W of average output power at 1.995 μm from a pulsed Tm-doped fiber amplifier (TDFA) system operating at 100 kHz with 20-ns pulses[9]. In 2009, they developed a power-scaled TDFA chain and ZGP mid-IR optical parametrical oscillator (OPO) system at a 100-kHz repetition rate; the seed was amplified more than 25 dB to the average output power of 21 W with 30-ns non-polarized pulses[10].

In this letter, we demonstrate a linearly polarized Q-switched Tm:Ho:LuLiF master oscillator and polarization-maintaining (PM) Tm-doped fiber power amplifier system.

The experimental setup consists of a seed source as the master-oscillator and two stages of PM Tm-fiber as the power amplifier, as shown in Fig. 1. The master oscillator is a self-made 2058.4-nm laser with a line width of 0.4 nm and a line polarized Q-switched Tm:Ho:LuLiF laser with one piece of quartz etalon to tune the wavelength from 2050 to 2067 nm; it works at a 11.3-kHz repetition rate. The pre-amplifier stage contains a 50-W 792-nm laser diode, which is provided by the Nlight Photonics Company, with a numerical aperture (NA) of 0.22 and a core diameter of 400 μm. The device also includes a 2.8-m-long 25/400-μm 0.09/0.46 NA PM Tm-doped double-clad fiber. The pre-amplifier module is conduction-cooled and tunable from 10 mW to 5 W. The power-amplifier is based on a large mode area PM Tm-doped fiber for high power operation. The gain medium is an 8-m-long 25/400-μm 0.09/0.46-NA PM Tm-doped double-clad fiber. A maximum pulsed output power of 32.4 W is obtained, corresponding to an 11.3-kHz repetition rate, 115-ns (full-width and half-maximum) pulse width, and 0.4-nm line width. The laser works at a 2058.5-nm central wavelength. Each stage uses two isolators to prevent back reflection light.

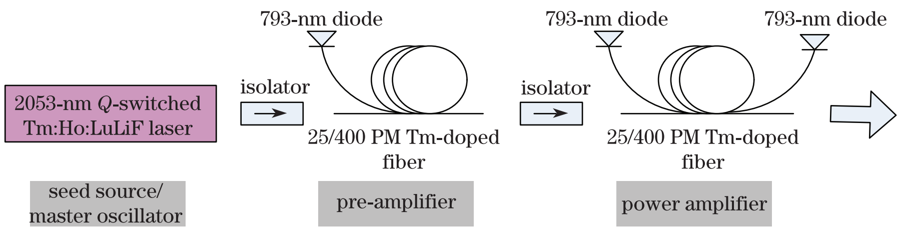

Fig. 1. Illustration of a narrow line width PM Tm:fiber amplifier MOPA module.

The resonator used in the seed source has a plano-concave geometry with an end-pumped configuration. Figure 2 shows the schematic of the seed source. A fiber-coupled laser diode (LD) module is used as the pump source working at 792 nm; it is collimated and focused on Tm:Ho:LuLiF crystal by a 1:1 image coupler lens. The rear mirror is a flat mirror coated with high reflectivity of 2053 nm and anti-reflectivity of 792 nm, whereas the output resonator mirror is a curved mirror with a 100-mm radius of curvature coated with 95% reflectivity at 2053 nm. The cavity length is about 94 mm. An a-cut Tm:Ho:LuLiF crystal with doping concentration of 5% Tm and 0.5% Ho ions is used as the gain medium. The dimensions are 2.5×2.5×6 (mm). Both surfaces of the crystal are coated with anti-reflectivity at 792 and 2053 nm. The crystal is cooled at 10 °C to ensure good thermal conduction and high efficiency. The acousto-optical (AO) Q-switch used here is a QS027-10M-NL5, Gooch & Housego, and the modulation frequency is set to 11.3 kHz. An uncoated 1.5-mm etalon is used. By tuning the angle, a 2050–2067-nm wavelength laser can be obtained.

The seed source can yield the maximum output power of 1.147 W under the pump power of 5 W, as shown in Fig. 3. The lasing threshold is 830 mW. Without the insertion of the etalon, a linear fit to the data shows a slope efficiency (η) of 25.86% in the Q-switched mode. In contrast, with the insertion of the etalon, the slope efficiency drops to 21.94%, and the output power drops to 890 mW. Considering the loss of coupler lens and rear mirror loss, especially the unabsorbed 792-nm laser power, the efficiency would be higher than that. The temporal pulse at a pump power of 4.25 W is shown in Fig. 4. The pulse width is about 126 ns, which is measured by an InGaAs detector (G8422-03, Hamamatsu Photonics) connected to Lecroy Wavejet 324 oscilloscopes. The wavelength of Tm:Ho:LuLiF laser is measured by an optical spectrum analyzer (AQ6375, Yokogawa Electric Corporation). Its spectrum with the insertion of the etalon is shown in Fig. 5. The line width is 0.4 nm at a 2058.4-nm central wavelength.

The output of the master oscillator is collimated using a pair of aspheric lens and passes through two free-space

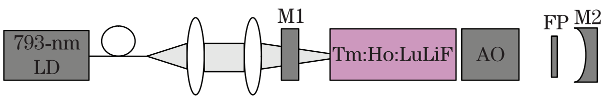

Fig. 2. Schematic diagram of the seed source. M: mirror, FP: Fabry-Perot.

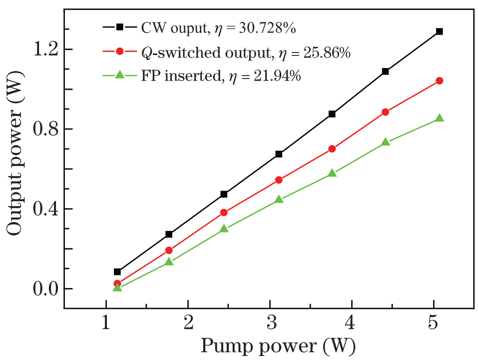

Fig. 3. Seed source output power versus incident pump power.

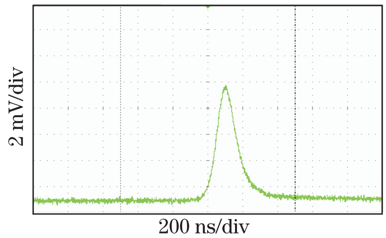

Fig. 4. Temporal pulse profile of the seed source laser.

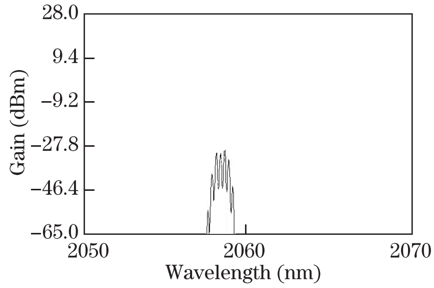

Fig. 5. Spectrum of the seed source laser.

optical isolator (OFR, IO-4-2050-HP). The isolator is polarization dependent; 20% of the power generated by the oscillator is lost. Using another aspheric lens and a half-wave plate, 660 mW of 2058.4-nm laser is launched into the 25/400-μm Tm:fiber pre-amplifier. Using the fiber, 430-mW seed laser remains. The laser line width becomes 0.2 nm because of the high-order mode filter in the fiber core. The pre-amplifier is pumped by a fiber coupled with a 50-W 792-nm diode array. The performance of the TDFA is shown in Figs. 6 and 7. The maximum output power can reach 5.15 W without amplified spontaneous emission (ASE), and the pulse width is narrower than that of the seed laser, which is about 118 ns. Higher pump power can cause higher laser output power, but the spectrum will become worse, and a 1.95-μm ASE laser will occur. The spectrum at a 5-W output power is shown in Fig. 8; the line width is 0.2 nm.

The pre-amplifier laser is collimated by an aspheric lens, and two optical isolators (OFR, IO-4-2050-HP) are used to prevent the back-scattering of laser from the power amplifier. A half-wave plate is used to match the pre-amplifier laser and the power amplifier's polarization direction. The pump diodes are two water-cooled 100-W 792-nm modules containing beam-shaped diode laser bars (Apollo Instruments Inc.). The beam size is 20×16

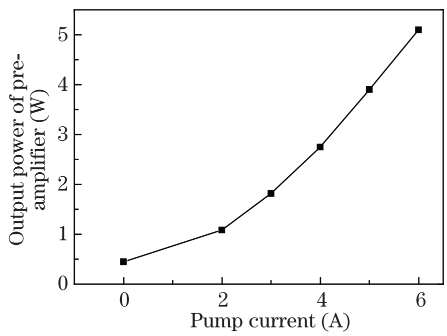

Fig. 6. Pre-amplifier's output power versus incident pump current.

(mm) and the divergences are both 4 mrad at two directions, respectively. A different pump style is explored; its power characteristics are shown in Fig. 9. When the fiber is single-end pumped, about 17-W maximum output power is obtained. Using dual-end pumping, the maximum output power up to 32.4 W is obtained; the peak power is up to 24.9 kW. The temporal pulse profile and the spectrum of the dual-end pump are shown in Figs. 10 and 11. The pulse width is 115 ns, and the line width is about 0.4 nm. The pulse train is shown in Fig. 12. The repetition rate is 11.3 kHz.

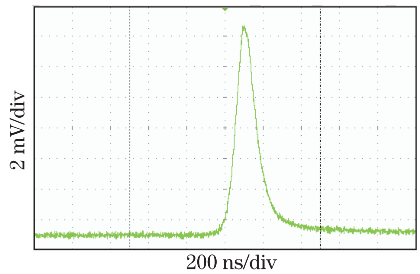

Fig. 7. Temporal pulse profile of the pre-amplifier at 5-W output power.

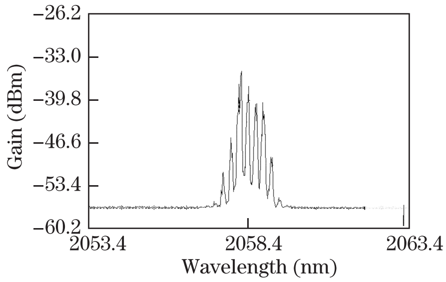

Fig. 8. Spectrum of the pre-amplifier at 5-W output power.

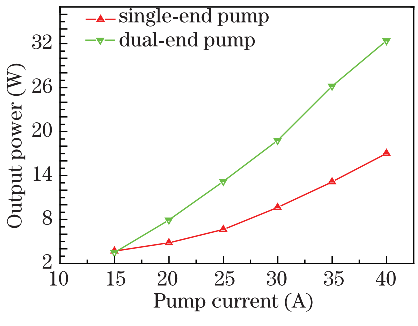

Fig. 9. Output power of the power amplifier versus incident pump current.

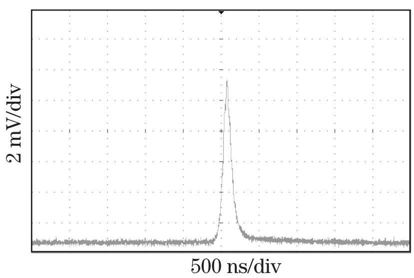

Fig. 10. Temporal pulse profile at 32.4-W output power.

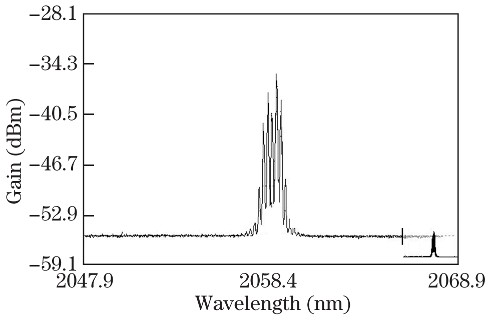

Fig. 11. Spectrum at 32.4-W output power amplifier.

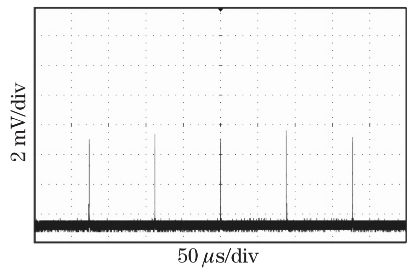

Fig. 12. Output pulse train of the system.

In conclusion, a 0.4-nm line width, linearly polarized Q-switched Tm:Ho:LuLiF master oscillator and PM Tm-doped fiber power amplifier (MOPA) system is developed. The seed laser is a Q-switched 11.3-kHz Tm:Ho:LuLiF laser with 0.4-nm line width at 2058.4 nm. The seed laser is amplified by two-stage TDFAs. The average output power increases from 0.66 to 32.4 W, whereas the pulse width decreases from 126 to 115 ns. The spectrum is maintained at 0.4 nm line width. The scaling ability of this MOPA system is unfolded. This system can be used as a pump source of a ZGP OPO system.

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