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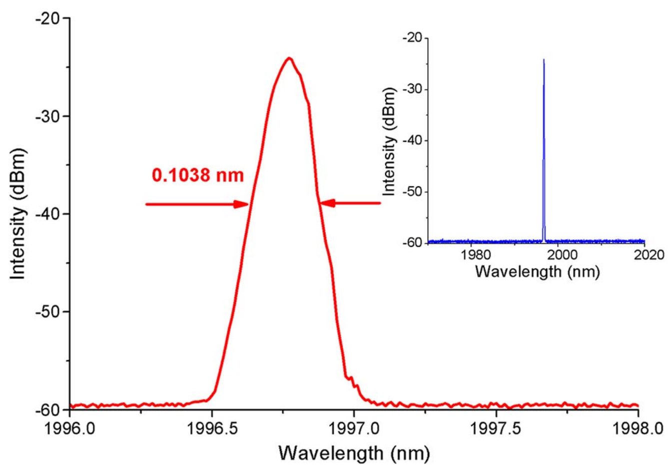

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2.4-W Narrow-Linewidth Q-Switched Tm^{3+}-Doped Double-Clad Fiber Laser

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Abstract: A narrow-linewidth 793-nm diode-pumped Tm^{3+}-doped double-clad silica fiber laser operated at 2 μm and actively Q-switched with an acousto-optic modulator is reported. Using a fiber Bragg grating as an output coupler, approximately 0.1-nm linewidth at 1996.8-nm pulses is derived at 80-kHz repetition rate. The maximum average output power is above 2 W for 11.6-W absorbed pump power. Less than 150-ns pulse is obtained at the repetition rate of 30 kHz. The laser is a promising seed laser for amplification in a master oscillator power amplifier system.

Index Terms: Tm^{3+}-doped fiber laser, narrow linewidth, actively Q-switched.

1. Introduction

Tm^{3+}-doped fiber lasers operating in eye-safe wavelength around 2 μm have attracted increasing interest in recent years. These lasers can be used in a wide range of applications, such as optical spectroscopy, lidar systems, laser surgery, and nonlinear frequency conversion [1]–[3]. Rare-earth-doped fiber lasers benefiting from simple thermal management can provide high-power levels while still maintaining good beam quality. Several theoretical and experimental studies on Tm^{3+}-doped fiber laser have been reported [4]–[6]. Exceeding 1-kW continues-wave (CW) Tm^{3+}-doped fiber laser has been approached with the advent of mature coupling technique, large mode-area gain fiber, and high-power 790-nm pumping laser diode that has a theoretical 200% quantum efficiency by taking advantage of a highly efficient cross-relaxation process [7], [8]. However, many applications require pulsed 2-μm laser beam not only with short pulse duration but also with narrow linewidth.

Pulsed Tm^{3+}-doped fiber lasers can be generated via gain switching [9], mode locking [10], [11], or Q-switching [12]–[17]. The spectrum linewidths in Q-switched fiber lasers are reportedly much greater than 1 nm [12], [13], [15]–[17]. Only a few studies have focused on narrowing the output spectrum linewidth in Q-switched fiber lasers. One effective approach to spectrally narrow a fiber laser is to use volume Bragg gratings (VBGs). Less than 0.2-nm width at 2052-nm Q-switched fiber laser pulses with 200-ns duration have been developed by using a VBG in a 4-m-long Tm^{3+}-doped polarization-maintaining silica large-mode area fiber [18]. The fiber Bragg grating (FBG) is an important fiber-optic device used for spectral filtering, wavelength tuning, and sensing in optoelectronics and lasers. It is also a promising component for spectral narrowing. Several CW lasers with narrow linewidth have been demonstrated using FBGs in all-fiber configurations [19], [20].

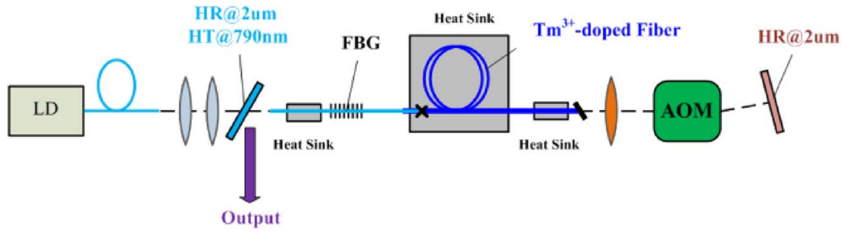

Fig. 1. Schematic of the experimental setup.

In this letter, a narrow-linewidth Q-switched 793-nm LD-pumped Tm^{3+}-doped fiber laser with an acousto-optic modulator (AOM) is presented. Using an FBG as output coupler, approximately 0.1-nm linewidth at 1996.8-nm pulses is derived. The maximum average output power is 2.4 W at 80-kHz repetition rate, corresponding to a slope efficiency of 33%. The pulsewidth under maximum average output at 30 kHz is less than 150 ns. The laser performance under different absorbed pump powers and repetition rates is also demonstrated.

2. Experimental Setup

Fig. 1 shows the schematic of the experimental setup. The diameter of the 793-nm LD pigtail is 250 μm. Two aspheric lenses are used to couple the pump light into the fiber. A 45° dichroic mirror with 99% reflectivity around 2 μm and 97% transmissivity at 793 nm is employed to transmit the pump light and extract the 2 μm laser beam. The FBG is inscribed onto a multimode double-clad fiber with a core diameter of 25 μm and an inner-cladding diameter of 250 μm. It has a reflectivity of 8% at 1996.8 nm with a bandwidth of 0.7 nm. To generate short pulses and ensure sufficient gain, we use a 70-cm highly doped double-clad Tm^{3+}-doped silica fiber with a 9.5-dB/m absorption coefficient at 793 nm. The fiber has a core diameter of 25 μm and numerical aperture (NA) of 0.09, giving a V-value of 3.53 at 2 μm. The inner clad is octagonal-shaped with a flat to flat diameter of 250 μm and NA of 0.46. The active fiber and recoated splicing point are wrapped with a bending diameter of 20 cm on a water-cooled metallic heat sink for efficient heat cooling. The input and output ends are also fixed into metallic heat sinks. The laser beam emitted from the other end of the fiber is collimated by an antireflection-coated aspheric lens, send into an antireflection-coated AOM with a deflection efficiency of 80% in first-order configuration. The laser cavity is formed between the FBG and a feedback mirror that has a 99% reflectivity around 2 μm. The fiber end facing the AOM is angle-cleaved to suppress Fresnel back reflections. The whole cavity length of the fiber laser is approximately 150 cm, and the pump coupling efficiency of the system is approximately 85%.

3. Experimental Results and Discussion

The laser output power is measured with a power meter (Coherent PM10). The laser spectrum is determined with a spectral analyzer (Yokogawa AQ6375) with a spectral resolution of 0.05 nm. The pulse characteristics are detected with an InGaAs detector (G8422-03, Hamamatsu Photonics) combined with a 1-GHz oscilloscope (Tektronix MDO4104-3).

Fig. 2 shows the average output power at different repetition rates. It can be seen that, when the repetition rate decreases from 80 kHz to 30 kHz, the output power only slightly decreases. This result indicates that the acousto-optic modulation frequency does not significantly affect the laser output power. The laser threshold is approximately 4.6 W. The maximum output power at 80 kHz is 2.4 W when the absorbed pump power is about 11.5 W, thereby resulting in a slope efficiency of 33%.

Fig. 3 shows the pulsewidth under different absorbed pump powers and repetition rates. The pulsewidth decreases when the absorbed pump power increases or the repetition rate decreases. Approximately 125-ns pulse is obtained at the repetition rate of 30 kHz, with average output power of 2.25 W. The pulse train and pulse shape recorded under this repetition rate are shown in Fig. 4.

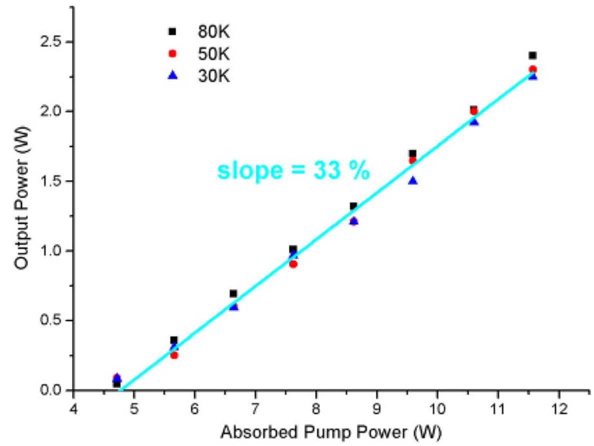

Fig. 2. Average output power at different repetition rates.

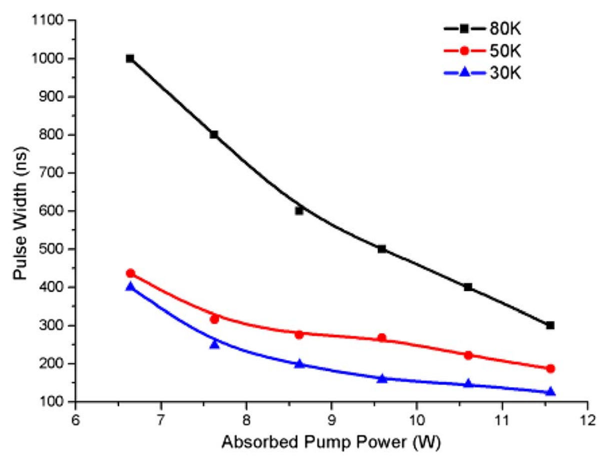

Fig. 3. Pulsewidth under different absorbed pump powers.

The root-mean-square intensity stability of the pulse train is 90%. The pulse shape shows a few multiple peaks, which result from the mode beating in the fiber laser [21].

Notably, when the laser output is at a high level, a low switching frequency (such as 20 kHz) destabilizes the laser pulsing. At this time, more than one pulse appears in one switching period, typically consisting of one main pulse and another one or two subpulses. The time interval between the main pulses and the subpulses remains almost the same when the switching frequency changes. Further research indicates that the subpulses disappear as the cavity opening time decreases. This phenomenon may be due to the relaxation oscillation resulting from the prolonged cavity opening time. Shortening the cavity opening time can destroy the periodicity of the subpulses and finally eliminate them. However, laser pulses with repetition rate lower than 30 kHz cannot be obtained because of the radio frequency closing time limit of the AOM driver in our experiment.

The spectrum of the maximum output power at 80 kHz is shown in Fig. 5. The inset shows the spectrum in a larger region with a resolution of 0.05 nm. The central wavelength is 1996.8 nm with a full width at half-maximum (FWHM) of 0.1038 nm. Fig. 6 gives the spectrum of maximum output power at different repetition rate. The FWHMs of the spectrum are 0.1391 nm and 0.1614 nm when the repetition rate is 50 kHz and 30 kHz. Although the spectrum shows a slight broaden as the repetition decreases, it still remains a single line, which means that the ASE has been effectively suppressed in the laser.

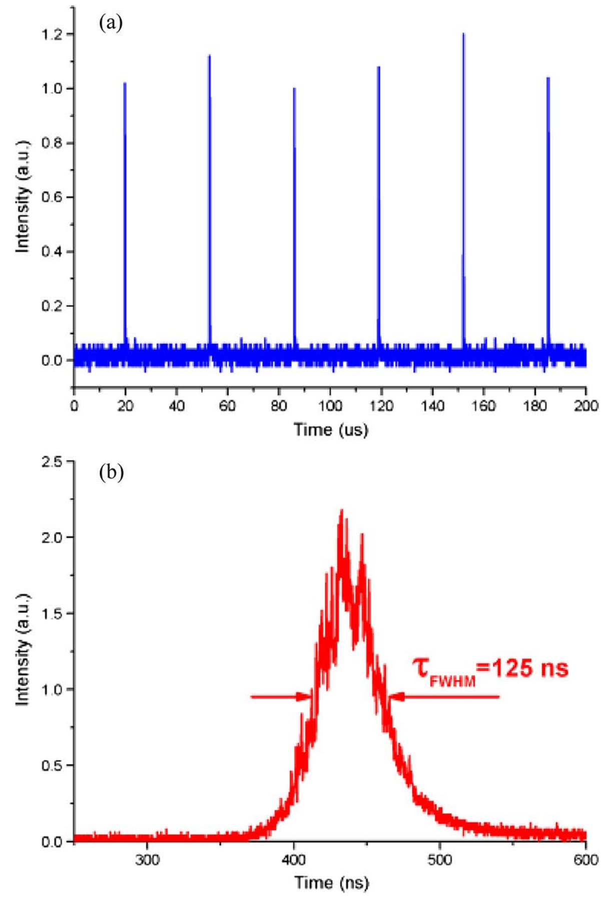

Fig. 4. Pulse train (a) and pulse shape (b) at 30 kHz.

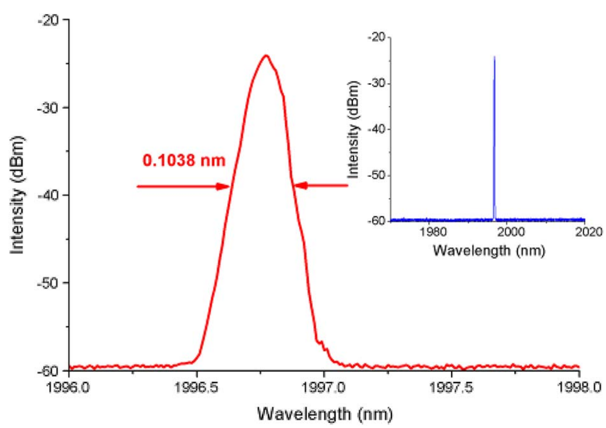

Fig. 5. Spectrum of maximum output power at 80 kHz.

The stability of the laser spectrum strongly depends on the angle of the feedback mirror, especially at high pumping power. When the absorbed pump power is above 12 W, the output spectrum cannot maintain a single line. This behavior is expected because of the multimode FBG reflection characteristics and broad gain bandwidth of Tm^{3+}-doped fibers [22]. In addition, the

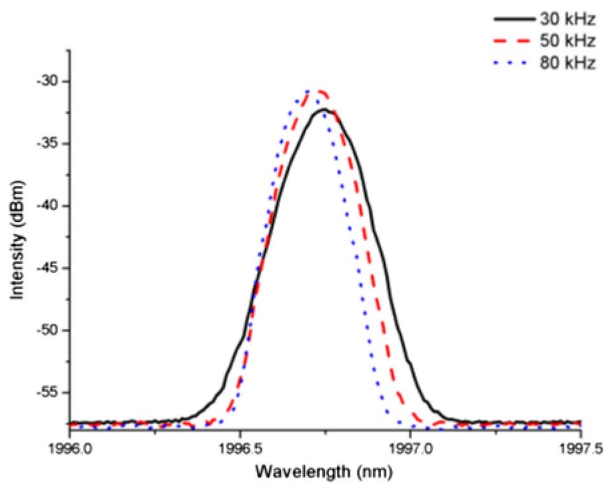

Fig. 6. Spectrum of maximum output power at different repetition rate.

reflectivity of the FBG is slightly low, which results in the inability to provide adequate feedback to suppress other spectral lines.

4. Conclusion

We have presented a 0.1-nm linewidth Q-switched 793-nm LD-pumped Tm^{3+}-doped fiber laser. A stable 2-μm pulsed laser beam with above 2-W average power is achieved at the repetition rate of 80 kHz. Less than 150-ns pulse has been obtained at the repetition rate of 30 kHz. This laser system is a promising seed laser for amplification in a master oscillator power-amplifier system. Further studies may focus on improving the stability of the output spectrum using a single-mode FBG with higher reflectivity.

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