Performance of a monolithic Tm:YLF micro laser

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We report a monolithic Tm:YLF micro laser in this Letter. In order to improve the relaxation oscillation of the laser, both ends of the crystal are coated, making the Tm:YLF crystal itself a resonant cavity. The micro laser is pumped by a 792 nm laser diode operated in the continuous wave (CW) mode. We obtain maximum output powers of 7.78 and 10.4 W at the total incident power of 43.6 W with focus lenses of 37.5 and 40 mm, respectively, corresponding to the slope efficiencies of 25.6% and 40.0% and the optical–optical conversion efficiencies of 17.8% and 23.8%. It is clear that the amplitude of the relaxation oscillation is smaller and the beam quality is better with the focus length of 37.5 mm; however, the laser with the focus length of 40 mm produces a higher output power and a more stable wavelength centering at 1878.44 nm.

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Tm^{3+}-doped solid-state lasers operating in the 1.8–2 μm spectral range are of great use in numerous applications, such as ladar, medical operation, remote sensing, and micromachining[1–5]. Research has shown that 2 μm Ho^{3+}-doped laser pulses pumped by Tm^{3+}-doped lasers[6,7] can act as the ideal pump source for the optical parametric oscillators and optical parametric amplifications in the generation of mid-infrared lasers[8,9]. Tm:YLF crystals are one of the most promising Tm^{3+}-doped materials because of their negative temperature coefficient of the refractive index; strong natural birefringence, providing a linear polarization generation; and a wide emission range, which finely matches the absorption band of the Ho:YAG crystal[10,11]. However, in the study of Tm^{3+}-doped solid-state lasers, their inherent instability is a common problem[12] that is mainly aroused by the relaxation oscillation generated by the interaction between the intra-cavity radiation and the active media. Many factors involving the mechanical vibration of the optical elements, instability of the pump power, and thermal instability of the active media along with the combination of the long lifetime of the upper laser level and relatively low laser gain of the Tm^{3+}-doped crystal result in the intrinsic intensity instabilities of this class of lasers[13]. These instabilities can cause damage to the films of optical elements and destabilize the operation of the whole laser setup[14].

Due to the importance of eliminating the instability existing in the Tm^{3+}-doped laser, plenty of work has been done to find out how the relaxation oscillation is generated and how to erase it. In 1998, Elder and Payne reported the instabilities of a diode-pumped Tm:YAP laser[15]. In 2006, Razdobreev and Shestakov demonstrated the self-pulsing of a monolithic Tm:YAP micro laser and tried to explain the excited absorption at the lasing wavelength[16]. In 2015, Wu *et al.* pointed out that self-pulsing of Tm-doped lasers should not only be ascribed to excited-state absorption, but also to the nonlinear dynamical chaos[17].

In this Letter, we investigate the performance of a monolithic Tm:YLF micro laser by coating both ends of the crystal. We tried to improve the relaxation oscillation of the laser by making the Tm:YLF crystal itself a resonant cavity for the first time, to our knowledge. The Tm:YLF micro laser is pumped by a fiber-coupled laser diode (LD) emitting at 792 nm and operated in the continuous wave (CW) mode. By changing the focus lens, we obtain output powers of 7.78 and 10.4 W at the total incident power of 43.6 W with focus lengths of 37.5 and 40 mm, respectively, corresponding to the slope efficiencies of 25.6% and 40.0% and the optical–optical conversion efficiencies of 17.8% and 23.8%. We saw that the amplitude of the relaxation oscillation is smaller and the beam quality is better with the focus length of 37.5 mm; however, the laser with the focus length of 40 mm produces a higher output power and a more stable wavelength centering at 1878.44 nm.

We drew a schematic diagram of the experimental setup, as shown in Fig. 1. The Tm:YLF crystal was 3 mm × 3 mm × 12 mm in size and 3.5 at. % Tm^{3+}-doped. A Tm:YLF crystal wrapped with indium foil was installed on a copper heat sink cooled by circulating water to keep the crystal temperature at 17°C. The pump side of the crystal was high transmission (HT) coated at 792 nm and 22% transmission coated at 1.9 μm, and the other side of the Tm:YLF crystal was HT coated at 792 nm and high reflectivity (HR) coated at 1.9 μm. Therefore, the Tm:YLF crystal itself is a resonant cavity, making the pump end of the crystal act as the output coupler. The laser was pumped by a fiber-coupled 792 nm LD and collimated and focused into the center of the crystal by the focus lenses f1 and f2. The core diameter of the fiber is 0.4 mm, and the numerical aperture of pump laser is

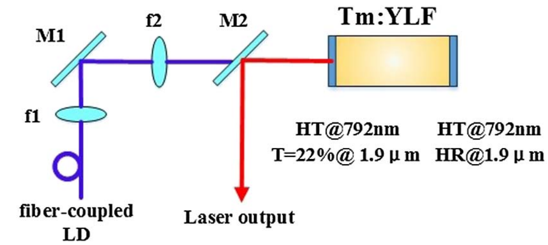

Fig. 1. Experimental setup for the Tm:YLF micro laser.

0.16. The focus lens f1 with the focus length of 15 mm works as the collimating lens in the setup. By changing f2 with focus lengths of 37.5 and 40 mm, we could minimize the amplitude of the relaxation oscillation and acquire other characteristics of the laser. M1 is a flat mirror that is HR coated at 792 nm, and M2 is a 45° dichroic mirror that is HT coated at 792 nm and HR coated at 1.9 μm. What should be noticed was that the length between f2 and M2 was adjusted with different focus lenses so the spot of the pump laser was the smallest one in the center of the Tm:YLF crystal.

Since the laser setup we demonstrated is a monolithic micro one, all the optical elements are fixed on a small plate. Due to the limited distance between M1 and M2, we can only alter the position and the focusing length of the f2 in a confined range in order to focus the light collimated by f1 into the center of the Tm:YLF crystal by means of f2. Considering all the reasons cited above, we have to utilize a limited number of lenses instead of a series of lenses, though with a series of lenses, we might be able to find an optimum condition for the best laser. In the Letter, lenses with focusing lengths of 37.5 and 40.0 mm are utilized.

The cross-relaxation between the $^3H_4$ and $^3F_4$ levels of Tm:YLF absorbs one pump photon and produces two excitation ions in the upper laser level $^3F_4$, as shown in Fig. 2; this is caused by the interaction between Tm^{3+} ions. This makes the laser achieve a quantum efficiency approaching two. The excitation energy is also lost due to the absorption from the excited state to higher levels or due to up-conversion (during the interaction of two excited Tm^{3+} ions)[18].

Relaxation oscillation can be understood as follows: when the population inversion is above the threshold, the crystal starts to emit the laser and consume the inverted particle, triggering the decrease of the population inversion and the decline of the output power. As the population inversion is below the threshold with no emitting light, the number of the inverted particles begins to accumulate, and then the above process repeats.

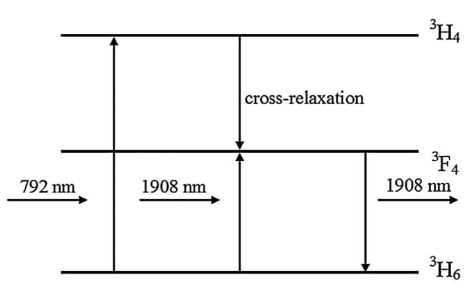

Fig. 2. Energy level diagram of the Tm:YLF crystal.

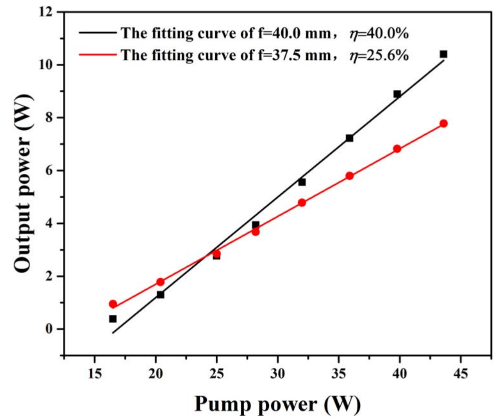

Fig. 3. Output powers of the lasers with focus lengths of 40 and 37.5 mm versus the pump power.

The output power of the Tm:YLF micro laser in the CW mode as a function of the incident pump power is shown in Fig. 3, which was measured by a Coherent PM30 power meter. We obtained the maximum output powers of 7.78 and 10.4 W at the total incident power of 43.6 W with the focus lengths of 37.5 and 40 mm, respectively, corresponding to slope efficiencies of 25.6% and 40.0%, which indicated an optical-optical conversion efficiency of 17.8% and 23.8%. It is shown in Fig. 4 that optical-optical conversion efficiency augments as the incident pump power increases. The reason that the slope efficiency and the optical–optical conversion efficiency with the focus length of 40 mm are larger than those with the focus length of 37.5 mm is that the former radius of the pump light in the crystal is a better match with the radius of the oscillating light inside the resonant cavity.

The relaxation oscillation of the laser was recorded by an oscilloscope, and we define the amplitude of the relaxation oscillation as the division of the variance and the average of the relaxation oscillation, which is given by

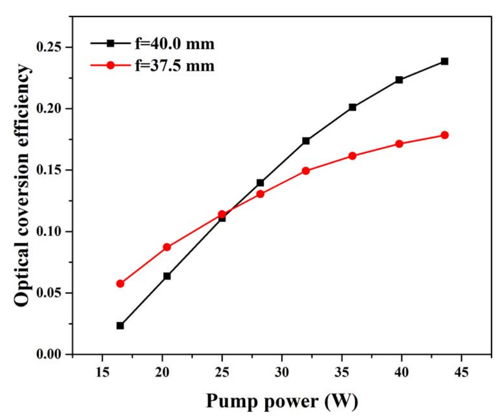

Fig. 4. Optical–optical conversion efficiency of the lasers with focus length sof 40 and 37.5 mm versus the pump power.

$$\text{Amplitude} = \frac{\sqrt{\frac{\sum_i^n (y_i - \bar{y})^2}{n-1}}}{\bar{y}}, \tag{1}$$

where y is the value of the data point of the recorded relaxation oscillation, and n is the total number of the data points. With this definition, we can get the amplitudes of the relaxation oscillations at different incident powers. The average amplitudes of the relaxation oscillations were 0.07 and 0.03, and the minimum amplitudes were 0.03 and 0.017 with focus lengths of 37.5 and 40 mm, respectively, which were smaller than that of many works done before. As shown in Fig. 5, the relaxation oscillation of the laser with the shorter focus length in Fig. 5(a) was far more stable than the laser with a longer one in Fig. 5(b). So, we can conclude that such a structure of the Tm:YLF micro laser is able to improve the inherent instability of a Tm^{3+}-doped laser. We can see that the amplitude of the relaxation oscillation with the short focus length is 0.0169, which is smaller than that of 0.0804 with a long focus length at the incident pump power of 43.6 W from Fig. 5. Such improvement derives from the short structure of the resonant cavity and the absence of the cavity vibration.

The laser spectrum was recorded by a spectrum analyzer (BRISTOL INSTRUMENTS 721) at different incident pump powers. From Fig. 6, we can see that the wavelength of the laser is 1879.1 nm and barely changes at different pump powers with the focus length of 40 mm. In contrast, with the focus lens of 37.5 mm, the laser peaks at two wavelengths, 1878.8 and 1887.0 mm, at a lower incident power and the laser centering at 1907.3 nm becomes stable when the pump power grows. It is not hard to comprehend from Fig. 6 that there was a gain competition effect existing in the crystal. So, we can make a rough explanation of the spectrum recorded that because of the gain competition effect, when using a focus lens with a longer focus length or pumping at a lower power, the laser with a wavelength of 1880 nm dominates, and when pumping at a higher power, the laser mainly emits approximately at 1908 nm.

Figure 7 shows the measured beam radius under the maximum CW output power of 2.9 W at various distances from the lens with $f = 100$ mm. The transverse output beam profile was measured by using a 90/10 knife-edge technique. We measured the beam radius at the incident

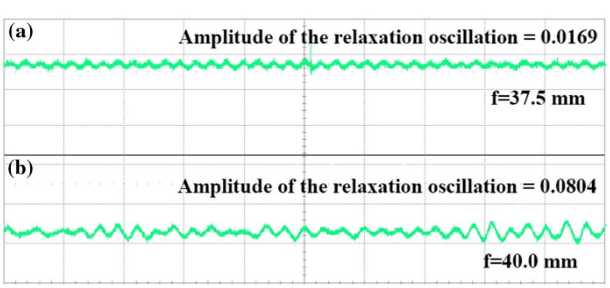

Fig. 5. Relaxation oscillation of the lasers with focus lengths of 40 and 37.5 mm at the pump power of 43.6 W.

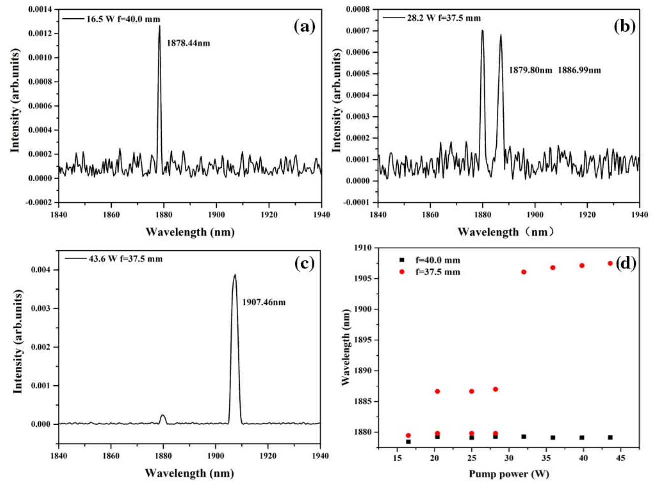

Fig. 6. Wavelengths of the lasers with focus lengths of 40 and 37.5 mm as a function of the incident pump power.

pump power of 25 W and at the maximum pump power of 43.6 W with the focus lens of 37.5 mm in order to check whether the beam quality changed as the pump power increased or not. As shown in Fig. 7, the beam quality factor M2 at the incident pump power of 25 W was calculated to be 5.91, which was 7.8 at the incident pump power of 43.6 W. It is not hard to see that the beam quality got worse as the pump power augmented.

As can be seen through the passage, we place the emphasis mainly on the improvement of the amplitude of the relaxation oscillation by coating both ends of the crystal and making it a resonant crystal, and we devote little effort to analyzing the change of the frequency of the relaxation oscillation. Although the improvement of both the amplitude and the frequency of the relaxation oscillation of the Tm:YLF micro laser operating as the pump source can stabilize the output characteristics of the Ho-doped laser, we nonetheless believe that the stabilization of the amplitude plays a more important role and thus we focus mainly on this factor. While there are no specific records of the frequency of the relaxation oscillation, we find that the frequency of the micro laser during the experiment is higher than that of the normal one with a rough contrast at the same pump power, which is ascribed to the much smaller size of the cavity. Under a pump power of 43.6 W, the frequency of the relaxation

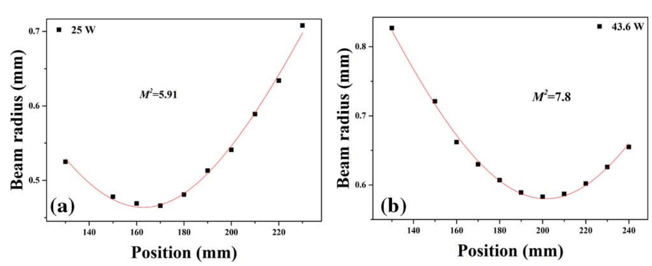

Fig. 7. Beam radius of the lasers with the focus length of 37.5 mm at the incident pump powers of (a) 25 and (b) 43.6 W.

oscillation is about 154 kHz, which is much higher than that of the normal cavity structure[19], and the frequency of the Ho-doped laser, which is approximately dozens of kilohertz, can lower the impact of the instability of the Tm:YLF laser.

In conclusion, we report the performance of a monolithic Tm:YLF micro laser and the work that we do to improve its relaxation oscillation by coating both ends of the crystal and making the Tm:YLF crystal itself a resonant cavity. The Tm:YLF micro laser is pumped by a fiber-coupled LD emitting at 790 nm. By changing the focus lens, we obtain output powers of 7.78 and 10.4 W at the total incident power of 43.6 W with the focus lengths of 37.5 and 40 mm, respectively, corresponding to slope efficiencies of 25.6% and 40.0% and optical–optical conversion efficiencies of 17.8% and 23.8%. When making a comparison between the performance of the lasers with the focus lengths of 37.5 and 40 mm, we can calculate that the amplitude of the relaxation oscillation is smaller and the beam quality is better with the focus length of 37.5 mm; however, the laser with the focus length of 40 mm produces a higher output power and a more stable wavelength centering at 1878.44 nm.

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