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Compact self-Q-switched laser near 2 μm

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ABSTRACT

A diode pumped Tm^{3+} doped YAlO$_3$ (Tm:YAP) self-Q-switched near 2 μm laser was studied with a compact linear cavity. Stable self-Q-switched laser pulses were obtained at the central wavelength of 1988 nm with the maximum average output power of 1.68 W, corresponding to the slope efficiency of 31.7%. The pulse repetition rate and single pulse energy were 65.16 kHz and 25.7 μJ, respectively. To the best of our knowledge, this is the first demonstration of a diode pumped all-solid-state self-Q-switched laser at the 2 μm region.

1. Introduction

In recent years, pulsed solid-state lasers emitting in 2 μm eye-safe region have attracted a lot attentions due to their wide applications in medicine, ranging, laser LIDAR, environmental atmosphere monitoring and so on. Additionally, they can also be used as pump source for pumping optical parametric oscillators (OPOs) and solid-state lasers in middle-infrared region [1–5]. Generally, Q-switching methods provide simple ways to obtain nano- or microsecond pulses at 2 μm. During Q-switched operation, resonator losses can be switched by using active or passive modulation schemes. Active Q-switching at 2 μm is obtained using electro-optic (EO) or acousto-optic (AO) devices to provide the required optical shutters [6,7]. Passive Q-switching at 2 μm is initiated by saturable absorbers made of various semiconductor-based and carbon-based materials or crystals doped with such ions as Cr^{2+} etc. [8–16]. However, in active Q-switched lasers, laser architectures containing such elements suffer from higher cost, lack of compactness, and increased complexity. In passively Q-switched lasers, we need use a saturable absorber in cavity, which increases the intracavity losses. At the same time the optical damage threshold of the absorber limits the passively Q-switched pulse energy. Another mechanism for the generation of nanosecond to microsecond pulses is self-Q-switching. It was first reported in ruby lasers by Freund [17]. It is far simpler and lower cost in comparison with other Q-switching methods. In this technique, no special modulation elements are required inside the laser cavity to initiate and sustain the pulsing mechanism. The laser cavity simply consists of an optical resonator, a suitable gain medium, and a pump source. These characteristics make self-Q-switching become a potential method for obtaining the pulse laser. Recently, the diode pumped all-solid-state self-Q-switched laser has been demonstrated only at 1 μm region [18–20], but not at 2 μm region.

The Tm:YAP single crystal is attractive as active material for 2 μm lasers mainly due to its natural birefringence combined with good thermal and mechanical properties similar to those of the YAG crystal [21]. In addition, the emission cross section of thulium in the YAP crystal (5.5×10^{-21} cm^2) is twice as high as that in the YAG crystal (2.2×10^{-21} cm^2) [22]. So, Tm:YAP crystal is suitable for laser diode pumped and is a promising material for laser. There is increasing interest in Q-switched Tm:YAP lasers because high-energy Q-switched pulses are expected in such lasers due to an upper-level lifetime of as high as 4 ms. In 2004, Sullivan et al. demonstrated a AO Q-switched Tm:YAP laser with a maximum repetition rate of 30 kHz [7]. In 2010, B. Q. Yao et al. demonstrate the first use of InGaAs/GaAs as a saturable absorber in the passive Q-switching of a diode pumped Tm:YAP laser [8]. Recently, our research group first demonstrated the Tm:YAP

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passively Q-switched laser based on the carbon nanotube saturable absorber [9]. However, the self-Q-switched Tm:YAP laser has never been reported.

In this paper, a compact diode pumped self-Q-switched laser at the 2 μm region was demonstrated for the first time. With a simple flat-concave resonator, the maximum output power of the Tm:YAP self-Q-switched laser was 1.68 W with the slope efficiency of 31.7% under the absorbed pump power of 7.04 W. The maximum self-Q-switch pulse energy of 25.7 μJ was obtained at a repetition rate of 65.16 kHz. The minimum pulse width was measured to be about 1.64 μs. Several aspects of the self-Q-switched lasers, including the output characteristics, the variation of laser pulse width, and repetition rate with the absorbed pump power, were first investigated here in some detail. The experimental results show that Tm:YAP was a promising laser material for all-solid-state self-Q-switched pulsed lasers.

2. Experiment setup

The experimental arrangement is shown in Fig. 1. The pump source was a fiber coupled diode 795 nm continuous wave (CW) laser with a core diameter of 400 μm, a maximum output power of 30 W and numerical aperture of 0.22. The pump beam was focused into the Tm:YAP crystal by a coupling system whose focal length was 50 mm, and the focused pump spot radius was about 160 μm. The laser crystal was a piece of $3 \times 3 \times 5\ \mathrm{mm}^3$ Tm:YAP (b-cut) and the gain medium had a Tm^{3+} doping concentration of 5 at%. The crystal had antireflection coating at the pump and laser wavelengths on both its surfaces. The crystal was wrapped in a piece of indium, foiled and mounted in a copper block to keep the cooling by the water with temperature control stability of ±0.1 °C. The water temperature was maintained at 18 °C. This active cooling ensured stable output power and helped to preserve the laser crystal from thermal fracture. The absorption of the diode pump by the crystal was ~77.4%. The resonator consisted of one dichroic input coupler M1 (HT@795 nm and HR@1.9-2.1 μm), and a concave output coupler (OC) M2 with the curvature radius of 100 mm and transmission of 2% and 5%. In order to realize the laser operation in TEM_{00} mode and result in high conversion efficiency, the length of resonator was configured to keep the mode matching in crystal between the pump beam and the fundamental resonant mode. The laser pulse signal was recorded by a 1 GHz digital oscilloscope (Tektronix DPO 4104) and a fast photodiode detector (ET-5000) with a rising time of 250 ps. The average output power was measured by a laser power meter (30A-SH-V1, made in Israel).

3. Results and discussion

Two output couples (OC) were used in our experiment, with transmission of 2% and 5%, respectively. The average output power as a function of the absorbed pump powers are shown in Fig. 2. The solid blue marks in Fig. 2 shown the average output power for the transmission of 2%. The laser pump threshold power was about 1.41 W. The maximum average output of 1.03 W under absorbed pump power of 7.04 W, given a slope efficiency of 18.4%. For the 5% transmission output mirror, at the same absorbed pump power of 7.04 W, the maximum average output of 1.68 W was obtained with the slope efficiency of 31.7%, corresponding to the laser threshold power of 1.74 W.

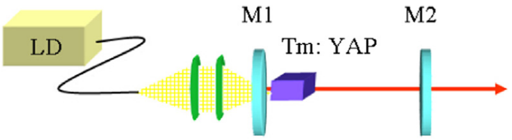

Fig. 1. Schematic of experimental setup of the diode-end-pumped Tm:YAP self-Q-switched laser.

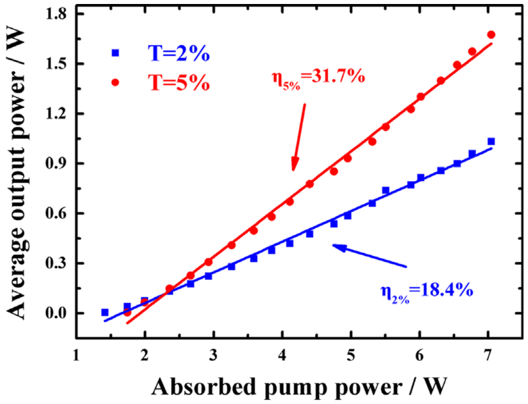

Fig. 2. Average output power as a function of the absorbed pump power.

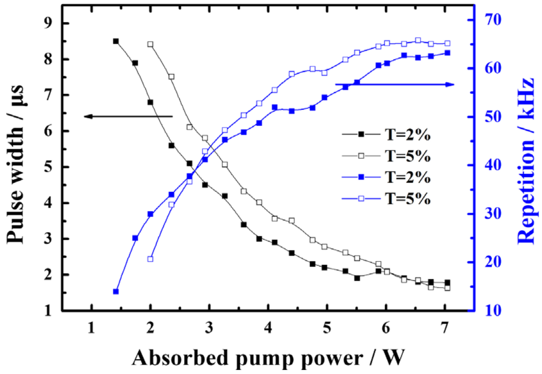

Fig. 3. Pulse width and repetition rate as a function of absorbed pump power.

The pulse width and the repetition rate of the self-Q-switched operation as the function of the absorbed pump power are shown in Fig. 3. It can be seen that the repetition increases, and the pulse width decreases rapidly with the augments of absorbed pump power. For the 2% OC, when the absorbed pump power increased from 1.41 to 7.04 W, the pulse duration decreased monotonically from 8.5 to 1.79 μs while the pulse repetition rate increased from 14 to 63.19 kHz, corresponding to 3.57–16.3 μJ of the single pulse energy. For the 5% OC, as the absorbed pump power ranged from 1.74 to 7.04 W, the pulse duration decreased monotonically from 8.42 to 1.64 μs while the pulse repetition rate increased from 20.68 kHz to 65.16 kHz, corresponding to 2.42–25.7 μJ of the single pulse energy. The maximum repetition rate of 65.16 kHz and the minimum pulse width of 1.64 μs were achieved under the absorbed pump power of 7.04 W. The self-Q-switched pulse spectrum was measured by an optical spectrum analyzer (AvaSpec-NIR256–2.2-RM). Fig. 4 shows the self-Q-switched spectrums under the absorbed pump power of 7.04 W. We can see that for the different output couplers, the central wavelengths were similar, which were around 1988 nm with a broad FWHM of 22 nm.

This phenomenon was also realized in many lasers including ruby [23], Nd:YAG [24], Cr:LiSAF [25], Cr:LiCAF [19,26], Alexandrite [20] and Tm-doped fiber [27–29] lasers. The physics behind self-Q-switching is not very well understood, and might be different for different gain media. For Cr^{3+}-doped gain media such as Cr:LiCAF, Cr:LiSAF and ruby, the self-Q-switching effect is attributed to a nonlinear loss mechanism created by a time-dependent lens occurring inside the gain medium and originating from refractive index changes induced by the population inversion. For Tm-doped fiber such as Tm^{3+}-doped silica fiber, the self-Q-switching

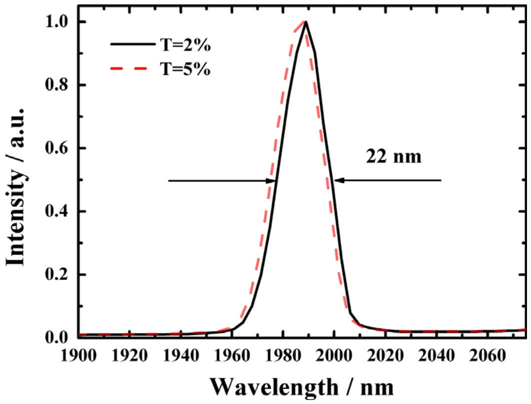

Fig. 4. Optical spectrum of diode-pumped Tm:YAP laser under the absorbed pump power of 7.04 W.

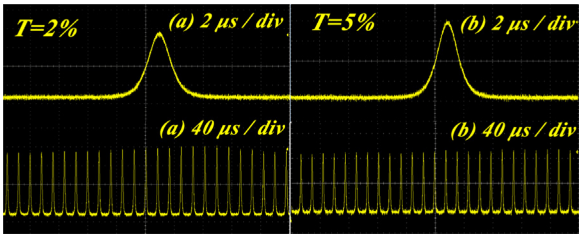

Fig. 5. Typical pulse profile of the self-Q-switched Tm:YAP laser. (a) The initial transmissions of output coupler $T=2\%$. (b)The initial transmissions of output coupler $T=5\%$.

Table 1
The experimental results obtained at the absorbed pump power of 7.04 W.

Output coupler transmission T	2%	5%
Average output power (W)	1.03	1.68
Pulse repetition rate (kHz)	63.19	65.16
Pulse width (μs)	1.79	1.64
Peak power (W)	9.11	15.64
Pulse energy (μJ)	16.3	25.7

behavior is attributed to the reabsorption of the laser photons in the unpumped part of the fiber [30]. In our experiment, the self-Q-switching effect maybe is attributed to a nonlinear loss mechanism created by a time-dependent lens occurring inside the gain medium and originating from refractive index changes induced by the thermal lensing. The further detailed studies are required to fully understand the underlying physics of self-Q-switching.

Fig. 5 gives a recorded typical oscilloscope pulse train, with time jitter less than 10%. As it is seen, the short pulse duration and high repetition were obtained by using a higher initial transmission of output coupler. Experimental results for different transmissions of OC are summarized in Table 1. The experimental result was obtained at the absorbed pump power of 7.04 W. In order to protect the laser crystal from damage, we did not increase the pump power any more. In our experiment, the pulse duration was wider than [7–9]. But the self-Q-switching is far simpler and lower cost in comparison with other Q-switching methods. The laser cavity simply consists of an optical resonator, a suitable gain medium, and a pump source. The narrower pulse duration and the higher pulse energies will be obtained in the next work.

4. Conclusions

In conclusions, we have reported a compact diode-pumped self-Q-switched Tm:YAP laser at 1988 nm for the first time. Under the absorbed pump power of 7.04 W, the shortest pulse width of 1.64 μs was obtained with a corresponding maximum average output power of 1.68 W and the slope efficiency 31.7%. At around 65.16 kHz repetition rate, the energy of a single self-Q-switched pulse was estimated to be about 25.7 μJ and the peak power was 15.64 W. Our experimental results show that Tm:YAP was a excellent self-Q-switched crystal for compact and efficient all-solid-state lasers.

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