Highly efficient dual-wavelength acousto-optically Q-switched Tm,La:CaF_2 laser

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A highly efficient milli-joule-level Q-switched Tm,La:CaF_2 laser is experimentally demonstrated. By employing an acousto-optic modulator, the diode-pumped pulsed lasers are stably operated at repetition rates ranging from 500 Hz to 10 kHz. Dual-wavelength operation of 1881.7 nm and 1888.5 nm is achieved with slope efficiency of 64.7%. Up to 1.89 mJ of pulse energy is obtained at a pulse width of 100 ns, corresponding to a peak power of 18.88 kW. These results verified that the Tm,La:CaF_2 crystal could be a promising candidate for achieving highly efficient and high-energy pulsed lasers.

Keywords: 2 μm thulium laser; acousto-optical Q-switching; Tm,La:CaF_2 crystal; dual-wavelength; high energy; high efficiency.

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1. Introduction

A Tm^{3+}-ions ($^3F_4 \rightarrow {}^3H_6$)-doped solid-state laser could provide wide laser spectra with a range from 1.8 to 2 μm. Eye-safe high-energy pulse laser emitting at 1.8–2 μm located at the atmosphere window and strong absorption peak of water molecules allows access to a mass of applications in remote sensing exploration, space optical communication, material processing, surgical treatment, and laser radar systems[1–3]. They were also used as pump source for achieving long-wave mid-infrared lasers[4]. In particular, the dual-wavelength high-energy pulse laser provides wide application prospects in the generation of terahertz waves by difference frequency, differential radar system, biomedicine, etc.[5–8].

Q-switching, including active Q-switching and passive Q-switching, is an important technology for producing high-energy short-pulse lasers. Benefiting from the emergence of various saturable absorbers (SAs), passively Q-switched lasers have been widely built in compact and inexpensive configurations[9–11], while, its operation stability and pulse parameters are limited by the inherent properties of SAs. Active Q-switching is a competitive technique in generating stable and high-energy pulses[12]. In practice, the actively Q-switched laser operation based on an electro-optical (EO) modulator requires high external voltage[13,14]. Compared with EO Q-switching, the acousto-optically (AO) Q-switched laser is simpler and cheaper.

Generally, Tm^{3+}-doped media can be pumped directly by the commercial AlGaAs laser diode (LD) operating around 790 nm, which can make the laser system more compact, economical, and efficient[15]. Moreover, the cross-relaxation cooperative mechanism of Tm^{3+} ions could improve quantum efficiency. It is worth noting that Tm^{3+}-doped laser materials usually possess a long upper-level lifetime, which is suitable for achieving high-energy pulsed lasers. The available Tm^{3+}-doped gain media suitable for actively Q-switched lasers have been extensively studied[16–18]. Calcium fluoride (CaF_2) crystals have been widely used as laser host materials because of low photon energy, wide transmission range, and large size growth[19–21]. Theoretically, clusters will be formed even at low doping concentration when Tm^{3+} ions are introduced into CaF_2 crystals[22]. Miraculously and interestingly, the distance between Tm^{3+} ions is greatly reduced by the presence of clusters, enhancing the cross-relaxation between neighbor ions and resulting in improved laser efficiency[23]. Tm,La:CaF_2 was proved to be an efficient laser material by Zhang *et al.* in 2018, and they reported a maximum output power of 4.269 W and a slope efficiency of 67.8% under continuous-wave (CW) operation[24]. The laser upper-level lifetime of Tm,La:CaF_2 is 7.6 ms, which promotes energy storage and facilitates the realization of high-energy pulsed laser output. Using passive Q-switching, we achieved 11.65 μJ of pulse energy in 2019[25]. The potential of Tm,La:CaF_2 crystals for generating high-energy pulses is yet to be exploited.

In this Letter, a highly efficient AO Q-switched Tm,La:CaF_2 laser is successfully constructed for the first time, to the best of our knowledge. The performance of the pulsed laser is systematically investigated at modulation frequencies of 500 Hz, 1 kHz, 5 kHz, and 10 kHz. At the absorbed pump power of 2.02 W, the average output power reaches 944 mW, with a slope efficiency of 64.7%. Pulses with 100 ns pulse width at 500 Hz are operated, corresponding to pulse energy of 1.89 mJ and peak power of 18.9 kW.

2. Experimental Setup

The schematic diagram of the AO Q-switched Tm,La:CaF_2 laser is shown in Fig. 1. The pump source is a fiber-coupled LD (792 nm, NA of 0.22, core diameter of 105 μm). The pump beam was focused into the crystal through a 1:2 collimation system. The gain medium is a 3% Tm^{3+}, 2% La^{3+}:CaF_2 crystal (doping concentration in atomic fraction, length of 5.9 mm, cross section of 3 mm × 3 mm), with an absorption efficiency of 43% for pump light. Grown by the temperature gradient technique[24], the sample is anti-reflection (AR)-coated at 792 nm and 1780–1980 nm. To effectively reduce heat accumulation, the sample is wrapped in indium foil and mounted on a copper heat sink connected to 12°C circulating water. The input mirror (IM) ($R = \infty$) and fold mirror (M2) ($R = 200$ mm) are AR-coated at 780–810 nm and high-reflection (HR)-coated at 1900–2000 nm. The output coupler (OC) is a plane mirror with a transmission of 10% at 1900–2000 nm. The arms of the three-mirror resonator are designed to be 110 mm and 220 mm long, allowing the oscillating spot radius on crystal to be about 110 μm, matching well with the pump light. The AO modulator (AOM, QS027-4M-AP1) used in this experiment was purchased from Gooch & Housego commercial company in the UK. Fabricated by fused quartz, the active aperture of the AOM is 4 mm with an interaction length of 46 mm. To reduce insertion loss, both surfaces of the fused quartz are AR-coated for laser radiation. The modulator is placed on a copper heat sink connected to 12°C circulating water to prevent thermal damage.

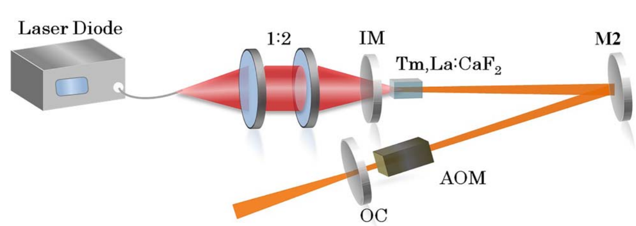

Fig. 1. Schematic diagram of AO Q-switched Tm,La:CaF_2 laser. AOM, acousto-optic modulator.

3. Results and Discussions

Firstly, the output power performance of the CW Tm,La:CaF_2 laser without AOM was studied, using a power meter (Laserpoint, Italy, A-40-D25-BBF). The output power was 973 mW at absorbed pump power of 2.02 W, with a slope efficiency of 66.2%, as shown in Fig. 2. To study high-energy laser output of the Tm,La:CaF_2 crystal, the AOM was introduced. The pulses achieved stable operations when the modulation frequencies of AOM were set from 500 Hz to 10 kHz. At 500 Hz, the maximum average output power was 944 mW with slope efficiency of up to 64.7% at an absorbed pump power of 2.02 W. At an absorbed pump power of 1.94 W, the average output power was 855 mW and 886 mW at the repetition rate of 1 kHz and 5 kHz, respectively. When the repetition rate increased to 10 kHz, 841 mW output power was achieved at the maximum absorbed pump power of 1.86 W. Stable pulse operation cannot be achieved when the frequency is greater than 10 kHz in this work. As we know, the higher the modulation frequency, the less time for energy accumulation. Especially, at relatively low pump power, the inverse population in the gain medium cannot be effectively accumulated in a finite time, resulting in the failure of pulse establishment.

It is worth noting that the average output power as well as the slope efficiency of AO Q-switched laser is very close to that of a CW laser without AOM, indicating that the insertion loss of AOM is small. The successful control of insertion loss can be attributed to the fact that both sides of the AO crystal are coated with highly efficient anti-reflective films for the emitted laser wavelength. Benefitting from good control of insertion loss, the AO Q-switched laser is oscillating at a nearly fundamental transverse electromagnetic mode (TEM_{00}). The far-field three-dimensional spatial form of the AO Q-switched laser beam was recorded at the maximum output power with a detection camera (NS2-Pyro/9/5-PRO, Photon), as presented in the insert image of Fig. 2.

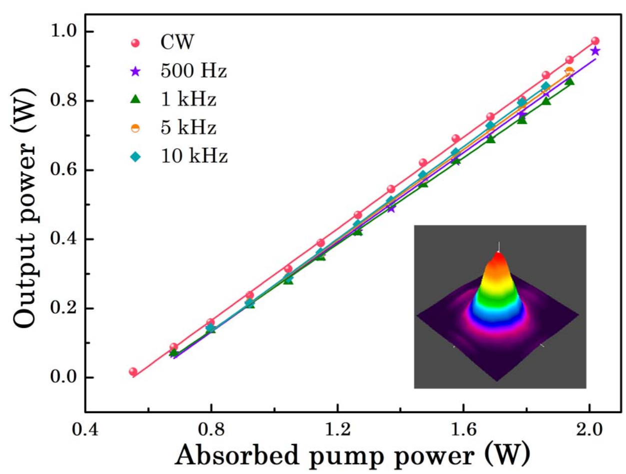

Fig. 2. Output power of CW and AO Q-switched laser. Insert, far-field three-dimensional intensity distribution of AO Q-switched laser at the maximum output power.

The laser spectra were observed continuously from low power onwards as the pumping power increased. The spectral analyzer (MS3504i, made in Belarus) used in this work has a resolution of 0.3 nm. Figure 3 shows the CW laser spectrum and the AO *Q*-switched laser spectrum at 500 Hz at the absorbed pump power of 2.02 W. The central wavelength for the CW regime was 1882.5 nm. The AO *Q*-switched laser operated at dual-wavelength with central wavelengths of 1881.7 nm and 1888.5 nm. The disordered structure of the Tm,La:CaF_2 crystal broadens the gain spectrum, which is conducive to the generation of dual-wavelength lasers in the natural state without any tuning means applied[26].

The pulse laser performance was recorded in detail. Figure 4 shows the relationship between pulse durations of AO *Q*-switched lasers at different modulation frequencies. With the increase of absorbed pump power, the pulse width decreases gradually. Under the same absorbed pump power, when the modulation frequency of the AOM increases from 500 Hz to 10 kHz, the pulse width becomes wider. This phenomenon could be attributed to the increase of repetition rate, which enlarged the time of pulse establishment. The shortest pulse width of 100 ns was obtained at modulation frequency of 500 Hz. The trend of the curve shows that the pulse width theoretically decreases further when the pump power continues to increase, especially at repetition frequencies of 5 kHz and 10 kHz. However, when we continued to increase the pump power in our experiment, although the output power continued to increase, the pulse sequence became unstable, with pulse widths sometimes narrowing to a few tens of nanoseconds and sometimes exceeding 100 ns, which we considered unstable laser operation and did not continue to record and demonstrate. Considering the phenomenon where the AO crystal module heats up rapidly when the pump power is further increased, we analyze that the main reason why the pulse becomes unstable is the severe thermal effect of the AO crystal caused by the current limited cooling conditions in our laboratory.

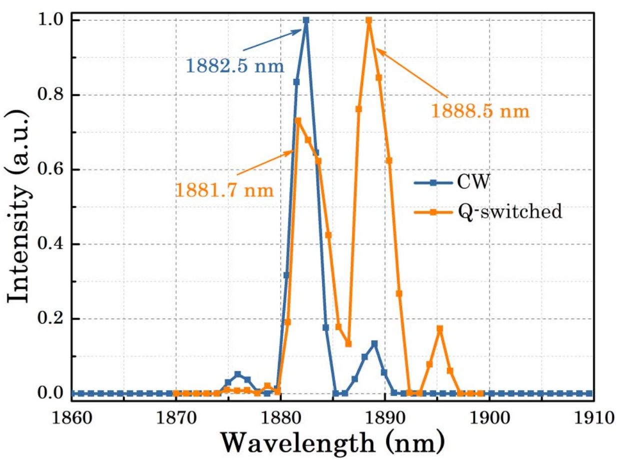

Fig. 3. CW and *Q*-switched laser emission spectra.

The single pulse energy and peak power of the AO *Q*-switched Tm,La:CaF_2 laser were calculated and presented in Figs. 5 and 6. The single pulse energy and peak power enlarged along with the increase of absorbed pump power, but no saturation trend was observed. Moreover, at the same absorbed pump power, the single pulse energy decreases with the increase of AO modulation frequency, because the increase of repetition rate shortens the energy accumulation time of laser gain medium. The maximum pulse energy of 1.89 mJ was obtained at 500 Hz, corresponding to peak power of 18.88 kW. To protect the crystal and the AOM, the pump power was not continuously increased in the experiment.

The AO actively *Q*-switched pulse trains were monitored by a high-speed detector (EOT, ET-5000) with a rise time of 28 ps and displayed on a digital oscilloscope (Tektronix DPO4104) with a bandwidth of 1 GHz. During the whole experiment, the AO *Q*-switched laser maintained a steady operation state. Figure 7 displays the temporal traces of the *Q*-switched laser at time scales of 100 ns/div and 10 ms/div under the maximum absorbed pump power and the modulation frequency of 500 Hz.

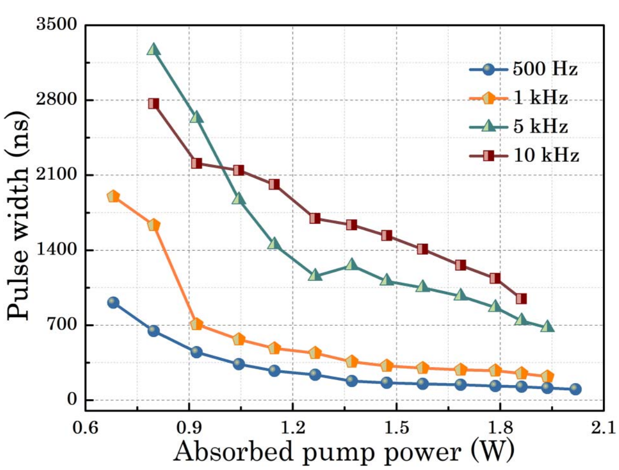

Fig. 4. Curves of pulse width versus absorbed pump power.

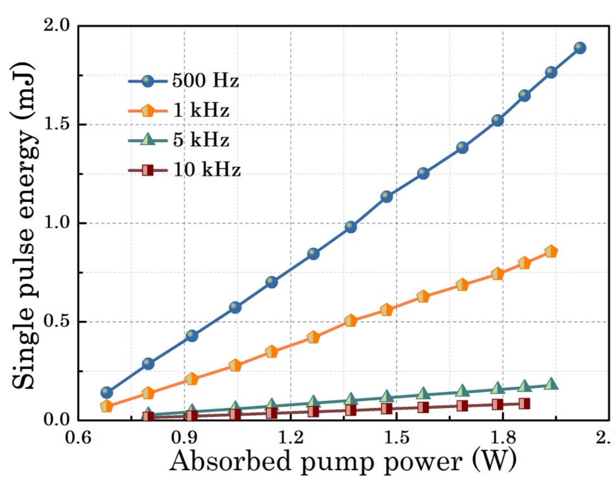

Fig. 5. Curves of single pulse energy versus absorbed pump power.

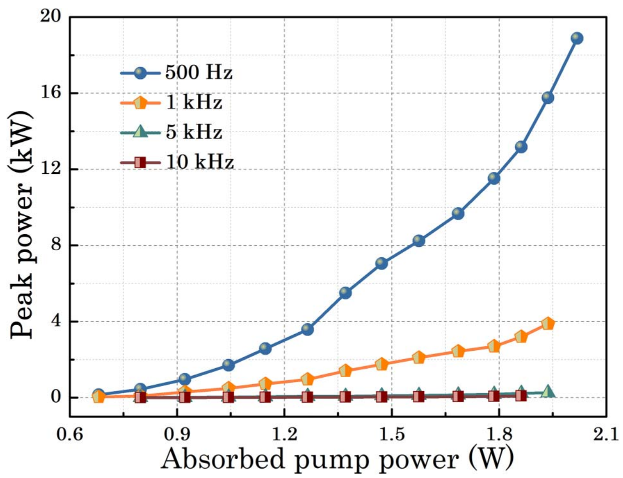

Fig. 6. Curves of peak power versus absorbed pump power.

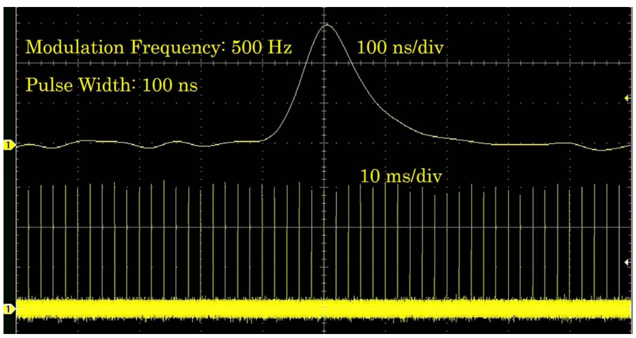

Fig. 7. Temporal traces of Q-switched laser at time scales of 100 ns/div and 10 ms/div.

The pulse trains had a good stability in a long time span and good pulse shape in a short time span. This also proves that the AO Q-switched laser works stably.

Table 1 summarizes the output characteristics of the AO Q-switched Tm^{3+}-doped lasers that have been reported. Obviously, Tm,La:CaF_2, with disordered structure, has a natural advantage in producing dual-wavelength lasers because of its broad fluorescence spectrum. Conspicuously, our work yields the highest slope efficiency in the case of diode-pumped AO Q-switched Tm^{3+}-doped solid-state lasers, to the best of our knowledge. The high efficiency can be attributed to the following three factors. First, the high laser efficiency benefits from the gain medium of Tm,La:CaF_2 crystal with excellent performance[20–24]. In addition, a proper resonant cavity design to ensure mode matching at the crystal and the successful control of insertion loss of the AO crystal are also key factors for the high efficiency.

Furthermore, milli-joule-level pulse energy of 1.89 mJ is achieved at the absorbed pump power of 2.02 W in our work and comparable to 1.97 mJ obtained from the Tm-doped yttrium lithium fluoride (Tm:YLF) laser at the absorbed pump power of 9.2 W[31]. In terms of pulse energy and peak power, Wen *et al.*[30] obtained excellent performance in the Tm-doped yttrium aluminum perovskite (Tm:YAP) laser with slope efficiency of 29.4% when the input pump power was up to 79.2 W. Considering the fact that the slope efficiency is up to 64.7% and the curves show no tendency towards saturation in Figs. 4–6, it is reasonable to believe that the Tm, La:CaF_2 laser will deliver more remarkable performance at higher pump power under improved thermal management conditions.

4. Conclusions

In conclusion, a highly efficient dual-wavelength actively Q-switched laser was successfully realized. By employing the AOM, a milli-joule-level Q-switched Tm,La:CaF_2 laser is experimentally investigated. The AO Q-switched Tm,La:CaF_2 laser operated stably at the modulation frequency of 500 Hz,

Table 1. Summaries of AO Q-Switched Tm^{3+}-Doped Solid-State Lasers[a].

Crystal	λ (nm)	τ (ns)	E_p (mJ)	P_p (kW)	η (%)	Ref.
Tm:$GdVO_4$	1912	48	0.4	8.3	–	[18]
Tm:YAG	2013	54	0.003	0.055	–	[27]
Tm:LSO	2040.1	345	0.26	0.75	12.3	[28]
Tm:SSO	1968	308	0.128	0.416	–	[17]
Tm,Y:CaF_2	1912	280	0.335	1.19	18.1	[29]
Tm:YAP	1988	38	16.36	430	29.4[b]	[30]
Tm:YLF	1879	37	1.97	53.2	36[c]	[31]
Tm,La:CaF_2	1881.7 + 1888.5	100	1.89	18.9	64.7	Our work

[a]λ, wavelength; τ, pulse width; E_p, pulse energy; P_p, peak power; η, slope efficiency.

[b]At input pump power of 79.2 W.

[c]At absorbed pump power of 9.2 W.

1 kHz, 5 kHz, and 10 kHz. At absorbed pump power of 2.02 W, the average output power of 944 mW was obtained with slope efficiency of up to 64.7%. The *Q*-switched laser emitting at 1881.7 nm and 1888.5 nm with 100 ns pulse width at 500 Hz was achieved. Pulse energy of 1.89 mJ and peak power of 18.88 kW were delivered. These results show that the Tm,La: CaF_2 crystal is a rising star in highly efficient high-energy operation in the ~2 μm band.

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