Infrared Physics and Technology 105 (2020) 103215

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Laser-diode dual-end-pumped electro-optic Q-switched slab Tm:YAP laser

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ARTICLE INFO

Keywords:
Tm:YAP laser
High repetition rate
RTP
Electro-optic Q-switch

ABSTRACT

A high-repetition-rate and double-end pumped electro-optic Q-switched Tm:$YAlO_3$ (Tm:YAP) laser is reported. The Tm:YAP slab crystal cut by c-axis is used as the laser gain medium, and the $RbTiOPO_4$(RTP) crystal is selected as the electro-optic Q-switched crystal. Choosing volume Bragg gratings (VBG) as the input mirror to narrow the output line width. When the pump power is 79.2 W, at a repetition rate of 10 kHz, maximum average-output-power of 21.96 W is achieved, with the pulse width of 20.64 ns and output energy of 2.20 mJ. The output peak power is 107.3 kW and the slope efficiency is 29.2%. The center wavelength is 1937.87 nm and the line width is 0.73 nm. The beam quality in the x direction is 1.48, and in the y direction is 1.50.

1. Introduction

The mid-infrared 1.9 μm laser is a safe light for human eyes and is in the weak absorption band of the atmosphere. Therefore, it has important values in the fields of atmospheric detection of CO_2, laser measurement of wind speed, etc [1]. 1.9 μm laser is easily absorbed by biological tissues, it can cause clotting and be used for eye and tooth surgery [2], It is also a high-efficiency pump source of 3–5 μm, 8–12 μm generated by OPO, and the far-infrared laser is a kind of ideal light source against a new generation of infrared guided missiles [3]. Compared with Tm laser pumping Q-switched Ho laser and then output laser as a pumping source of optical parametric oscillator (OPO), using Q-switched Tm:YAP laser directly as an OPO pumping source can greatly simplify the structure and improve the stability of the laser system.

Compared with Tm:YAG crystal ($\sigma = 2.2 \times 10^{-21}$ cm^2), Tm:YAP crystal has a larger emission cross-section ($\sigma = 5.5 \times 10^{-21}$ cm^2) and better mechanical thermal properties. At the same time, compared with Tm:YLF ($\sigma = 0.76 \times 10^{-21}$ cm^2), the influence of crystal relaxation oscillation can be avoided for Tm:YAP crystal under high repetition frequency operation. Especially, the proper upper level lifetime of Tm:YAP crystal ($\tau = 4.4$ ms) is more suitable for high repetition rate and high energy operation, while the upper level lifetime for Tm:YLF is 16.4 ms and for Tm:YAG is 13.9 ms [4,5].

High repetition rates operation short pulsed laser output can be achieved by Q-switching which mainly contains actively Q-switching and passively Q-switching.

Based on the development of materials science, such as Cr:ZnS/Cr:ZnSe, InGaAs/GaAs, graphene oxid, Black phosphorus nanotablets, and MoS_2 can be used to obtain the passively Q-switching. In 2015, Jerusalem technical collage reported the passively Q-switched Tm:YAP laser. The Tm:YAP crystal dimension was 3 mm × 3 mm × 10 mm. The Cr:ZnS was the saturable absorber. Repetition rates of 561 Hz was obtained with output power of 1.037 W, pulse width of 35.8 ns, single pulse energy of 1.85 mJ, peak power of 51.7 kW, central wavelength of 1935 nm, and slope efficiency of 37.2%. When the Cr:ZnS was replaced by Cr:ZnSe, repetition rates of 833 Hz was obtained, with output power of 1.29 W, pulse width of 42.2 ns, single pulse energy of 1.55 mJ, peak power of 36.7 kW, central wavelength of 1935 nm, and slope efficiency of 36.6%[6]. In 2016, Shandong University reported the passively Q-switched Tm:YAP laser. The Tm:YAP crystal dimension was 3 mm × 3 mm × 7 mm. BP was used as the saturable absorber. Repetition rates of 81 kHz was obtained, with output power of 3.1 W, pulse width of 181 ns, single pulse energy of 39.5 μJ, peak power of 218 W, central wavelength of 1969 nm-1979 nm, and slope efficiency of 48% [7]. In 2016, Shangdong Normal University reported a passively Q-switched Tm:YAP laser and the Tm:YAP crystal dimension was 3 mm × 3 mm × 5 mm. Graphene monolayer was taken as the saturable absorber. Repetition rates of 62.38 MHz was obtained, with output power of 256 mW, pulse width of 0.29 ps, single pulse energy of 41 nJ, peak power of 138 kW, central wavelength of 1988.5 nm [8]. In 2017, Army night vision and Electronic Sensor Council of Virginia reported the passively Q-switched Tm:YAP laser. The Tm:YAP crystal dimension was 1 mm × 4 mm × 7 mm. Cr:ZnS was the saturable absorber, with initial transmission of 95%. Repetition rates of 8.8 kHz was obtained, with output power of 4.4 W, pulse width of 72 ns, single pulse energy of 0.5 mJ, peak power of 6.9 kW, central wavelength of 1940 nm, and slope efficiency of 30%. When the initial transmission of

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https://doi.org/10.1016/j.infrared.2020.103215
Received 6 January 2020; Received in revised form 19 January 2020; Accepted 22 January 2020
Available online 25 January 2020
1350-4495/

Cr:ZnS was 80%, repetition rates of 3.86 kHz was obtained, with output power of 5.6 W, pulse width of 10.5 ns, single pulse energy of 1.45 mJ, peak power of 138 kW, central wavelength of 1890 nm, and slope efficiency of 31%[9]. In 2018, Fort Belvoir, Virginia, USA reported the passively Q-switched Tm:YAP laser. The Tm:YAP crystal dimension was 1 mm × 5 mm × 7 mm. Cr:ZnS was the saturable absorber, with initial transmission of 91%. Repetition rates of 6.2 kHz was obtained with output power of 4 W, pulse width of 22.24 ns, single pulse energy of 0.6 mJ, peak power of 29 kW, central wavelength of 1940 nm, and slope efficiency of 46% [10]. In 2018, Fujian institute of material structure reported a passively Q-switched Tm:YAP laser. The Tm:YAP crystal dimension was 3 mm × 3 mm × 5 mm. $MoSe_2$ was the saturable absorber. Repetition rates of 110 kHz, were was obtained with output power of 466.3 mW, pulse width of 360 ns, single pulse energy of 3.615 μJ, peak power of 11.7 W, and central wavelength of 1936.8 nm [11]. In 2018, Nanjing university reported a passively Q-switched Tm:YAP laser. The Tm:YAP crystal dimension was 3 mm × 3 mm × 8 mm. $MoSe_2$ was the saturable absorber. Repetition rates of 86 kHz was obtained, with output power of 466.3mW, pulse width of 488 ns, single pulse energy of 41.8 μJ, peak power of 85.9 W, central wavelength of 1993.1 nm, and slope efficiency of 46% [12].

Acousto-optic (AO) Q-switch is commonly used as one actively Q-switching mode. In 2004, Coherent technology company reported an AO Q-switched laser, with a repetition rates of 5 kHz, output power of 35 W, single pulse energy of 7 mJ, central wavelength of 1940 nm, slope efficiency of 29.1% [13]. In 2008, Zhe Jiang University reported an AO Q-switched Tm:YAP laser. The Tm:YAP crystal dimension was 3 mm × 3 mm × 7 mm. Repetition rates of 1 kHz was obtained with output power of 1.57 W, pulse width of 80 ns, single pulse energy of 1.57 mJ, peak power of 19.6 kW, central wavelength of 1990 nm and slope efficiency of 12.5% [14]. In 2008, Harbin Institute of Technology reported an AO Q-switched Tm:YAP laser. The Tm:YAP crystal dimension was 2.6 mm × 2.6 mm × 5 mm. Repetition rates of 5 kHz was obtained with output power of 3.9 W, pulse width of 81.58 ns, single pulse energy of 0.78 mJ, peak power of 9.56 kW, central wavelength of 1937 nm, and slope efficiency of 29.4% [15]. In 2010, they reported a LD double-ended pumped AO Q-switched laser. The Tm:YAP crystal dimension was 3 mm × 3 mm × 12 mm. Repetition rates of 10 kHz was obtained with output power of 12.5 W, pulse width of 126 ns, single pulse energy of 1.25 mJ, peak power of 9.92 kW, central wavelength of 1990 nm, and the slope efficiency of 25% [16]. In 2014, they reported an AO Q-switched Tm:YAP laser and the Tm:YAP crystal dimension was 3 mm × 3 mm × 16 mm. Repetition rates of 200 kHz was obtained with output power of 1.28 W, pulse width of 4.3 ns, single pulse energy of 6.4 μJ, peak power of 1.49 kW, central wavelength of 1989.8 nm, and slope efficiency of 3.2% [17]. In 2015, they reported an intracavity AO Q-switched Tm:YAP Raman laser. The Tm:YAP crystal dimension was 3 mm × 3 mm × 10 mm. Repetition rates of 1 kHz was obtained with output power of 880 mW, pulse width of 400 ns, single pulse energy of 0.88 mJ, peak power of 2.2 kW, central wavelength of 1940 nm, and slope efficiency of 5%[18]. Although the repetition rate can be high, the output power is low. While the high output power can be realized, the repetition rate is low.

The EO Q-switched is commonly used as the other actively Q-switching mode. EO Q-switched has the advantages of fast switching speed, narrow pulse width and high extinction ratio. It can get stable short pulses and easy to achieve precise synchronization control and stable output. In recent years, with the development of new types of electro-optic crystals (such as RTP) which suitable for middle infrared band, the EO Q-switched solid state lasers have been improved. In 2015, Harbin Institute of Technology reported that the electro-optical cavity-dumped Tm:YAP laser and the Tm:YAP crystal dimension was 1.5 mm × 6 mm × 40 mm. Repetition rates of 100 kHz was obtained with output power of 3.02 W, pulse width of 7.1 ns, single pulse energy of 0.03 mJ, peak power of 4.25 kW, central wavelength of 1996.9 nm, and slope efficiency of 5.2% [19].

Although passive Q-switching can obtain a narrow pulse laser output, its poor output stability and low pulse energy make it difficult to achieve accurate synchronous output. Compared with acousto-optic Q-switch, electro-optic Q-switch can change cavity loss rapidly and achieve more stable laser pulse. RTP crystal owns high damage threshold, low insertion loss, no deliquescent, high extinction ratio, especially, larger electro-optic coefficients ($\gamma_{c1} = 30.2pm/v$, $\gamma_{c2} = 30.2pm/v$) [20], which means the lower half-wave voltage when it is applied in 2 μm electro-optic Q-switched lasers. However, there's little reports on 2 μm lasers based on RTP crystal as the electro-optic Q-switch crystal.

This paper reports a LD double-end-pumped electro-optical Q-switched Tm:YAP laser. The c-axis-cut Tm:YAP crystal has a large emission cross-section near 1940 nm, and the dimension of the crystal is 2 mm × 6 mm × 15 mm. The pumping source is a laser-diode with a center wavelength of 795 nm. The RTP crystal is the electro-optic crystal. At the repetition rate of 10 kHz, average output power of 21.96 W is obtained with a center wavelength of 1937.87 nm and line width of 0.73 nm, which satisfies the absorption peak of the Ho laser crystal. To our knowledge, this is the highest average output power for EO Q-switched Tm:YAP laser. High-repetition rate and high-power output also satisfy the requirements of pumping source for nonlinear frequency conversion crystals such as $AgGaSe_2$ and $AgGa_{1-x}In_xSe_2$ [21,22].

2. Experimental setup

The experimental setup of laser-diodes (LDs) double-end pumped

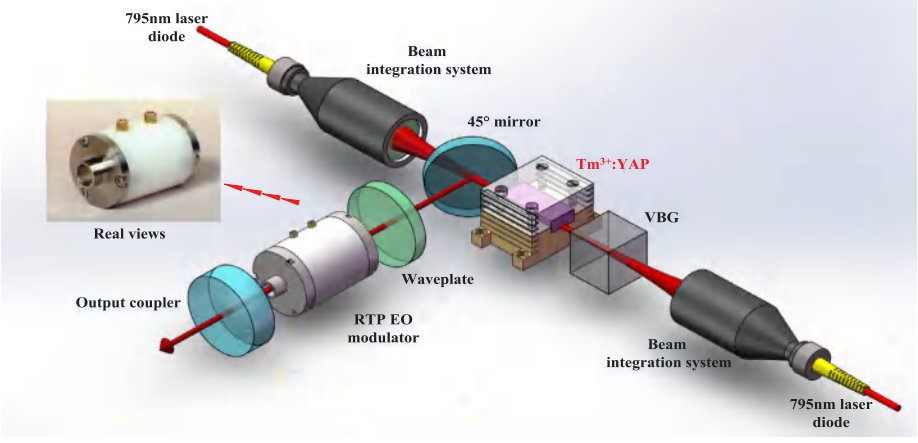

Fig. 1. The structure of electro-optical Q-switch Tm:YAP laser.

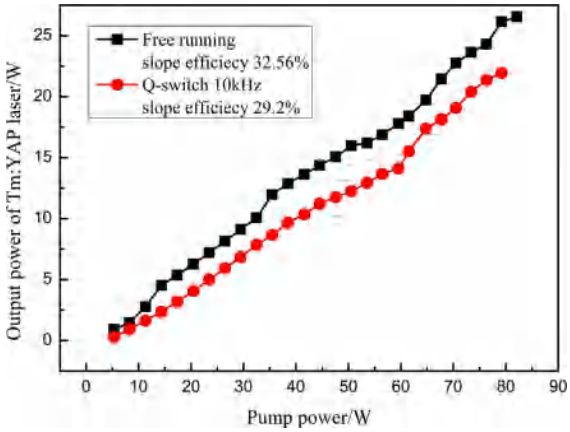

Fig. 2. The output power under free running and Q-switched operation.

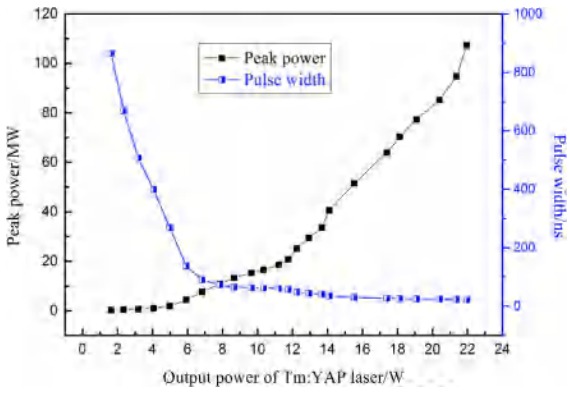

Fig. 3. The Peak power and pulse width versus output power at 10 kHz.

electro-optic Q-switched Tm:YAP laser is shown in Fig. 1. Two fiber-coupled LDs with fiber core diameter of 400 μm and numerical aperture of 0.22 are used as the pumping sources. The maximum power and center wavelength for both LDs are 60 W and 795 nm. By using beam integration system, the pump lights injected into the crystal are controlled to be 800 μm. The dimensions and the doping concentration of c-cut Tm:YAP crystal is $2 \times 6 \times 15$ mm^3 and 2.5at.%. Both ends of the crystal are coated with high transmission at 795 nm ($T > 99.9\%$) and anti-reflection at 1.94 μm ($R < 0.5\%$). The crystal is wrapped with indium foil and put into the micro-channel heat sink, of which the temperature is maintained at 289 K by a water cooler with temperature

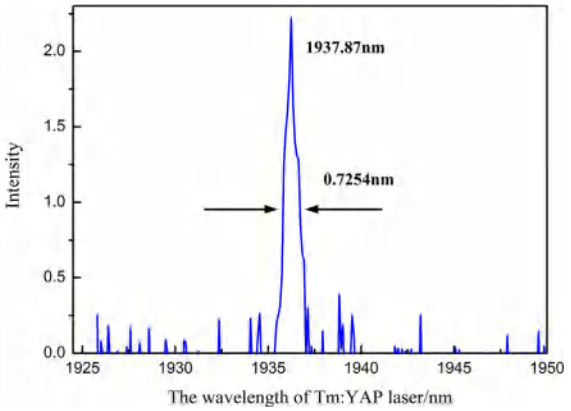

Fig. 5. Output wavelength of EO Q-switched Tm:YAP laser.

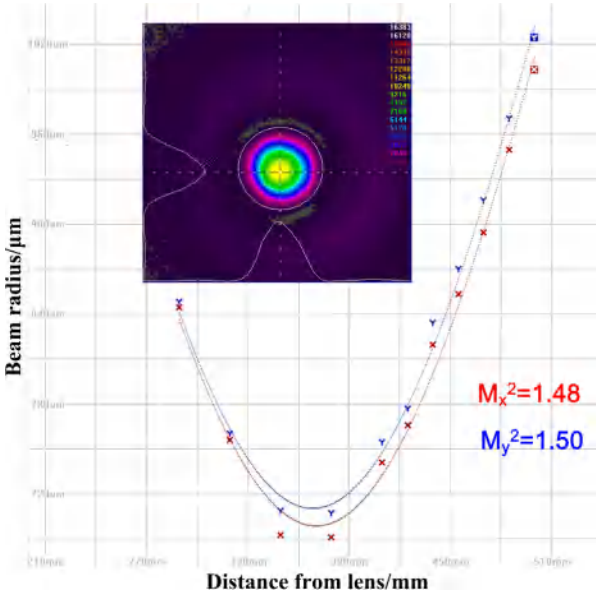

Fig. 6. Beam quality factor of electro-optic modulator Tm:YAP laser measured at an output average power of 21.96 W.

control accuracy of ± 0.1 °C (SH150-1000, produced by lab tech Ltd). "L" -type resonator with a length of 150 mm is used. An volume bragg gratings (VBG) with dimensions and transmitted band of $6 \times 6 \times 6$ mm^3 and 0.3 nm is chosen as the input mirror. Two faces of

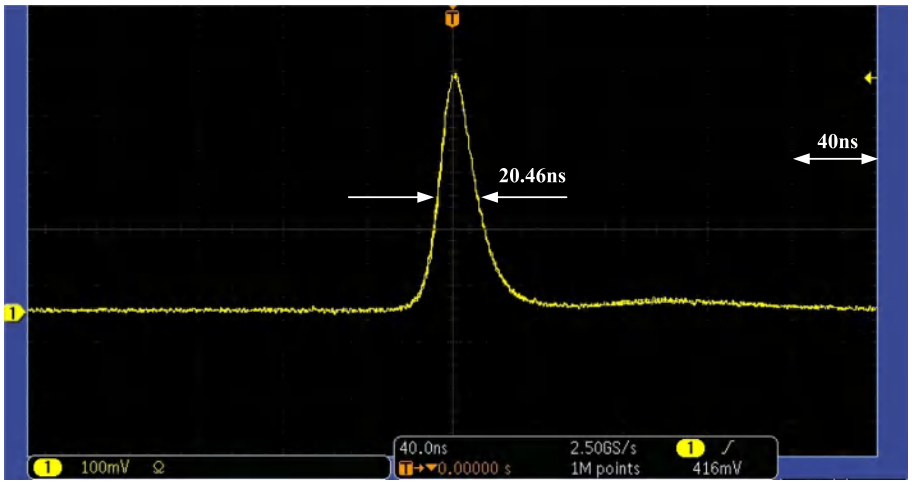

Fig. 4. The narrowest pulse width with pulse Tm:YAP laser.

the VBG are coated with anti-reflection of 795 nm (R < 0.5%) and high-reflection of 1940 nm (R > 99.5%). A 45° mirror with anti-reflection of 795 nm (R < 0.5%) and high-reflection of 1940 nm (R > 99.5%) is used as another input mirror. A concave mirror with transmission of 10% at 1940 nm and radius of curvature of 150 mm is used as the output mirror. An electro-optic Q-switch (Series 1147-3-2000, produced by Fastpulse Technology, INC.) with two RTP crystals,each of the RTP crystals dimensions is 2 mm × 2 mm × 12 mm and the effective aperture diameter of 2 mm and high-transmission at 1940 nm (T > 99%) and a quarter wave plate are inserted in the resonator to produce Q-switched operation.

3. Experimental results and analysis

The output power under free-running is shown in Fig. 2. As the voltage was fixed at 0 V, when the pump power is 82.1 W, the output power of Tm:YAP laser is 26.57 W and the slope efficiency is 32.56%. As the voltage was fixed at 1100 V, the phase delay for 1940 nm was obtained to be 0.5π. At pulse repetition rate of 10 kHz, maximum output average power of 21.96 W and slope efficiency of 29.2% is achieved for Tm:YAP laser at pump power of 79.2 W. To our knowledge, it is the best result of Q-switched Tm:YAP laser.

The peak power and pulse width versus output power at a repetition rate of 10 kHz is shown in Fig. 3. As the output power increases, the output peak power of Q-switched Tm:YAP laser increases. And the pulse width narrows gradually.

At the pumping power of 79.2 W, the output average power is 21.96 W. The Q-switched pulses were detected by a high-speed silicon photodiode (PCT-3TE-12, Vigo Inc.) and shown by a digital oscilloscope (DPO3054, Tektronix Inc.). The narrowest pulse width is 20.46 ns at output average power is 21.96 W. The single pulse energy is 2.2 mJ. And the peak power is calculated to be 107.3 kW. Fig. 4 shows the narrowest pulse width at repetition rate of 10 kHz.

The output wavelength of EO Q-switched laser was measured by a spectrograph (AQ6375, Co.Yookogawa Inc.). The spectrometer resolution is 1 pm. At repetition rate of 10 kHz and the maximum output average power of 21.96 W, the center wavelength was measured to be 1937.87 nm, and the line width was only 0.73 nm (see Fig. 5), which due to the contribution of the volume Bragg gratings (VBG). The output laser is suitable for being directly a pumping source of OPO of 3–5 μm and 8–12 μm because of its stable center wavelength and narrower line width.

The beam quality analyzer (Pyrocam-III Co. Spiricon) was used to analyze the beam quality of the electro-optic Q-switched Tm:YAP laser at a repetition rate of 10 kHz and an output power of 21.96 W. The beam quality in the x-direction was 1.48, and the beam in the y-direction was 1.50, as shown in Fig. 6.

4. Conclusion

In this paper, we studied LD double-end pumped electro-optical Q-switched Tm:YAP laser. As the repetition rate was 10 kHz, the maximum output average power was 21.96 W. The single-pulse energy was 2.2 mJ and the peak power was 107.3 kW. The center wavelength was 1937.87 nm and the line width was 0.73 nm. The beam quality in the x direction was 1.48, and 1.50 in the y direction. The characteristics of the EO Q-switched laser mentioned in this paper are more suitable as a pump source for Ho lasers and nonlinear frequency conversion for 3–5 μm, 8–12 μm laser.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work is supported by Natural Science Foundation of China (Grant no. 11974060).

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