Stable kilo-hertz electro-optically Q-switched Tm,Ho:YAP laser at room temperature

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1. Introduction

Solid-state lasers emitting in 2 μm eye-safe region have attracted a lot of attention due to their wide applications, such as LIDAR, laser ranging, medicine, environmental atmosphere monitor and so on [1–4]. Furthermore, pulsed 2 μm lasers with short duration, high pulse energy, and high peak power are effective pump sources for optical parametric oscillators (OPOs) generating in 3–12 μm spectral regions [5–8]. Active Q-switching techniques such as acoustic-optic (AO) Q-switching have been widely employed in 2 μm pulsed lasers, however, its long transition time and low diffraction efficiency limit its applications in high pulse energy lasers. On the other hand, EO Q-switch plays an irreplaceable role in high pulse energy and short pulse durations due to its high efficiency, fast switching speed, high stability, and feasible controllability. To date, nonlinear crystals including RTP, LGS, and LN have been successfully employed for EO Q-switches for 2 μm lasers [9–14]. Based on RTP EO Q-switch, Goidring et al. obtained pulses with duration of 57 ns and pulse energy of 2.4 mJ under a PRR of 1 kHz from a diode-pumped EO Q-switched Tm:YAG laser [9]. Nieuwenhuis et al. demonstrated a RTP EO Q-switch in a lamp pumped Cr, Tm:YAG laser, and 100 ns pulses with a PRR of 5 Hz, corresponding to a pulse energy of 42 μJ were generated [10]. However, RTP crystals are biaxial, so it is necessary to compensate the natural birefringence in making electro-optical devices by using two mutually orthogonal crystals, which makes the device complicated. Utilizing LGS as EO Q-switch, Wang et al. depicted a lamp pumped EO Q-switched Cr, Tm, Ho:YAG laser, and pulses as short as 35 ns with a pulse energy as high as 520 μJ were obtained at a PRR of 3 Hz [11]. But LGS crystals have a low electro-optical coefficient (2.68 pm/V), which will lead to a large half voltage. LN crystals possess a lower half-wave voltage, broader spectral transparence region (0.4–5 μm) compared with LGS crystals and can be made into electro-optical devices by using only one crystal which is easier than RTP crystals. The excellent properties make LN crystals attractive for use in EO Q-switches at 2 μm. By using LN based EO Q-switch, Barnes et al. reported a flash pumped EO Q-switched Ho:YAG laser, and 30 ns pulses with a PRR of 5 Hz and a single pulse energy of 80 μJ were obtained [14]. However, the obtained EO Q-switching PRR is as low as several Hz, limiting its applications.

EO Q-switching technique utilizes the control of polarization inside the cavity to realize the pulse formation, thus gain medium with polarized emission characteristics is favorable for EO Q-switching operation. Biaxial crystal YAP (short for YAlO3) possesses natural birefringence, which makes it less sensitive to thermally induced birefringence [15], thus is very suitable for
generating pulsed lasers with the aid of EO Q-switching. On the other hand, Tm sensitized Ho laser shows vital properties, including “two for one” efficiency via cross relaxation between adjacent Tm$^{3+}$ ions, broad absorption band around 800 nm where commercial GaAs/AlGaAs laser diodes are available. With Tm$^{3+}$ and Ho$^{3+}$ ions co-doped in host YAP, the Tm$_2$Ho$_y$YAP crystal possesses not only polarized emission characteristics, but long fluorescence lifetime of about 5 ms [15], which is much helpful for high energy pulses generation. By using Tm$_2$Ho$_y$YAP crystal as gain media, Yao et al. reported a diode pumped AO Q-switched c-cut Tm$_2$Ho$_y$YAP laser at 77 K, from which pulses with duration of 40 ns and pulse energy of 3.3 mJ were obtained under a PRR of 1 kHz [16]. Before long, Li et al. demonstrated an AO Q-switched b-cut Tm$_2$Ho$_y$YAP laser at 77 K, and a maximum single pulse energy of 0.46 mJ with pulse duration of 100 ns was achieved at a PRR of 2.5 kHz [17]. However, the pulsed Tm$_2$Ho$_y$YAP laser based on AO Q-switching worked at low temperature, which limits its application. Furthermore, we did not find any report on EO Q-switched Tm$_2$Ho$_y$YAP laser at room temperature until now.

Here we demonstrate a diode-pumped b-cut Tm$_2$Ho$_y$YAP pulsed laser at room temperature with a self-made EOM, which was made of z-cut LN crystal operating in transverse-field configuration and had an extinction ratio of 324:1. The EO Q-switched Tm$_2$Ho$_y$YAP laser characteristics were investigated in details, and a minimum output power of 50 W. The emission wavelength red-shifted from 788.8 nm to 789.8 nm with different injected currents. By measuring the output spectra of the diode laser for pumping under different injection currents, the absorption peak around 790 nm of the Tm$_2$Ho$_y$YAP crystal versus incident pump power. The pulse to pulse amplitude instability of 4.6% indicated a very stable EO Q-switching operation.

2. Experimental setup

The experimental setup of diode-pumped EO Q-switched Tm$_2$Ho$_y$YAP laser is schematically shown in Fig. 1. The pump source was a fiber-coupled diode laser emitting at 790 nm with a maximum output power of 50 W. The fiber core diameter was 100 μm. A 1:1 imaging module was used to focus the pump light into the Tm$_2$Ho$_y$YAP crystal with a pump spot diameter of 100 μm. The employed 5 at% Tm$^{3+}$ and 0.3 at% Ho$^{3+}$ doped, $4 \times 4 \times 8$ mm$^3$ b-cut Tm$_2$Ho$_y$YAP crystal was grown by the Czochralski technique. Both surfaces of the b-cut Tm$_2$Ho$_y$YAP crystal were antireflection coated from 750 to 850 nm (reflectivity < 2%) and 1930–2230 nm (reflectivity < 0.8%). The b-cut Tm$_2$Ho$_y$YAP crystal was wrapped in indium foil and mounted in a copper block cooled at 13.5 °C with water. The employed resonant cavity was formed by four mirrors with a total length of 31 cm. $M_1$ and $M_2$ were concave mirrors (R=75 mm for $M_1$ and R=50 mm for $M_2$) with high reflectivity coated (reflectivity > 99.9%) from 1800 to 2100 nm and antireflection coated from 750 to 850 nm (reflectivity < 2%). $M_3$ was a flat mirror also with high reflectivity coated (reflectivity > 99.9%) from 1800 to 2100 nm. The output coupler (OC) was a flat mirror with transmission of T=2%. The employed EOM was homemade by a z-cut LN crystal with size of 9 $\times$ 9 $\times$ 25 mm$^3$. A 5/4 voltage of 3 kV was applied through a gold electrode attached on the LN crystal to ensure the even distribution of electric field. The extinction ratio of the LN crystal based EOM was measured to be 324:1.

3. Experimental results and discussions

First, we measured the absorptance of the b-cut Tm$_2$Ho$_y$YAP crystal under different incident pump powers, which is shown in Fig. 2. It was obvious that the absorptance was only 47.5% for the incident pump power of 1.7 W, while increased with the augment of the incident pump powers, and reached 81% at the highest incident pump power in our experimental range, which was mainly due to the wavelength fluctuations of the diode lasers under different injected currents. By measuring the output spectra of the diode laser for pumping under different injection currents, the emission wavelength red-shifted from 788.8 nm to 789.8 nm with the augment of the injection currents as shown in Fig. 2, which meant that the higher the injected current was, the closer to one absorption peak around 790 nm of the b-cut Tm$_2$Ho$_y$YAP crystal.

Fig. 2. Emission wavelength of the diode laser and absorptance of the Tm$_2$Ho$_y$YAP crystal versus incident pump power.

The long-term output power stability versus time. It was observed that the absorptance was only 47.5% for the incident pump power of 1.7 W, while increased with the augment of the incident pump powers, and reached 81% at the highest incident pump power in our experimental range, which was mainly due to the wavelength fluctuations of the diode lasers under different injected currents. By measuring the output spectra of the diode laser for pumping under different injection currents, the emission wavelength red-shifted from 788.8 nm to 789.8 nm with the augment of the injection currents as shown in Fig. 2, which meant that the higher the injected current was, the closer to one absorption peak around 790 nm of the b-cut Tm$_2$Ho$_y$YAP crystal.

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powers were measured by using a laser power meter (MAX500AD, Coherent Inc., USA). As shown in Fig. 3, the average output powers increased almost linearly versus absorbed pump powers, the threshold absorbed pump power was 1.29 W. A maximum output power of 1.014 W was obtained at the absorbed pump power of 7.4 W, corresponding to a slope efficiency of 16.9%. When operating in Q-switching regime, the PRRs of 200 Hz, 500 Hz, 800 Hz, and 1 kHz were chosen in order to investigate the average output power characteristics from the EO Q-switched Tm,Ho:YAP laser versus absorbed pump powers. The laser pulse trains were recorded by a digital oscilloscope (1 GHz bandwidth; Tektronix DPO 7102, USA) and a fast InGaAs photodetector with a rise time of \( t_p = 35 \text{ ps} \) (ET-5000, EOT, USA). The average output powers versus absorbed pump powers were measured at the different PRRs of EOM. The threshold absorbed pump power were 2.36 W, 1.35 W, 1.35 W and 1.29 W for different PRRs of 200 Hz, 500 Hz, 800 Hz and 1 kHz, respectively. At the absorbed pump power of 7.4 W, the corresponding maximum output powers of 330 mW, 515 mW, 534 mW and 546 mW, respectively. With linearly fitted the measured output powers versus absorbed pump powers, the corresponding slope efficiencies of 6.0%, 8.3%, 8.7% and 9.0% were obtained with respect to the absorbed pump powers, respectively, as shown in Fig. 2. At the maximum output power of 546 mW with a corresponding PRR of 1 kHz, the output power was recorded for one hour, and a long-term power instability of 0.66% was observed as shown in the inset of Fig. 3.

By dividing the average output powers by corresponding PRRs, the single pulse energies were calculated as shown in Fig. 4, from which we can see that the single pulse energies increased with the augment of absorbed pump powers. At the maximum absorbed

![Fig. 4. Single pulse energies versus absorbed pump powers at different PRRs.](image1)

![Fig. 5. Pulse durations versus absorbed pump powers at different PRRs.](image2)

![Fig. 6. Pulse peak powers versus absorbed pump powers at different PRRs.](image3)
A pump power of 7.4 W, maximum pulse energies of 1.65 mJ, 1.03 mJ, 0.668 mJ and 0.546 mJ were achieved under the PRRs of 200 Hz, 500 Hz, 800 Hz and 1 kHz, respectively. Considering the upper lifetime of about 5 ms in Tm,Ho:YAP crystal [15], the optimal operation PRR for EO Q-switched Tm,Ho:YAP laser would be 200 Hz, where the energy storage capacity of the Tm,Ho:YAP crystal could be fully utilized.

The pulse durations were recorded versus the absorbed pump powers at different PRRs as shown in Fig. 5. The minimum pulse durations of 107.4 ns, 127.9 ns, 135.1 ns, and 145.8 ns were obtained for the PRRs of 200 Hz, 500 Hz, 800 Hz and 1 kHz, respectively, corresponding to the calculated peak powers of 15.36 kW, 8.05 kW, 4.9 kW and 3.74 kW as shown in Fig. 6.

The pulse characteristics of energies and durations versus PRRs were investigated with the absorbed pump power fixed at the maximum value of 7.4 W, as shown in Fig. 7. With the PRR changed from 200 Hz to 1 kHz, the single pulse energy decreased from 1.65 mJ to 0.546 mJ, while the pulse duration increased from 107.4 ns to 145.8 ns as shown in Fig. 7. The maximum single pulse energy of 1.65 mJ was generated at 200 Hz mainly attributed to the upper-level lifetime of about 5 ms for Tm,Ho:YAP crystal. According to the pulse energies and durations, the peak powers were calculated and depicted versus the PRRs as shown in Fig. 8, from which we found that the pulse peak powers decreased almost linearly when the PRR was set above 200 Hz, and a maximum peak power of 15.36 kW was obtained under a PRR of 200 Hz, corresponding well to the upper lifetime of about 5 ms in Tm,Ho:YAP crystal.

The temporal pulse profiles of EO Q-switched Tm,Ho:YAP lasers at the PRR of 200 Hz for generating the highest pulse energy and the maximum PRR of 1 kHz are shown in Fig. 9, from which we can see the secondary pulses came out at the PRR of 1 kHz due to the piezoelectric ring effect of LN crystal under high PRRs, thus we did not increase the PRR further. For the pulses with duration of 107.4 ns and 145.8 ns generated at respective PRRs of 200 Hz and 1 kHz, the pulse to pulse amplitude instability were measured to be 4.6% and 5.83% in one hour. The observed degradation of pulse to pulse stability at the PRR of 1 kHz was also attributed to the piezoelectric ring effect of LN crystal.

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We employed a laser spectrometer (APE WaveScan, APE Inc.) with a resolution bandwidth of 0.4 nm to record the output spectra. The output wavelength was located at 2128.4 nm with a FWHM of 4.42 nm as shown in Fig. 10 (a). And we also measured the output beam quality at the highest output power under a PRR of 1 kHz by using the 90.0/10.0 scanning-knife edge method [19], and the measured data is shown in Fig. 10 (b). The M² factors were best-fitted to be 1.78 in the tangential direction and 1.57 in the sagittal direction, respectively.

4. Conclusion

In this letter, we demonstrated a diode-pumped LiNbO₃ EO Q-switched b-cut Tm,Ho:YAP laser at room temperature. At the absorbed pump power of 7.4 W, the shortest pulse duration of 107.4 ns and maximum single pulse energy of 1.65 mJ were achieved at a PRR of 200 Hz. With the PRR increased to 1 kHz, the maximum output power of 546 mW with an output beam quality M² factor less than 1.78 was achieved. The pulse to pulse ampli-

tude instabilities of 4.6% and 5.83% at 200 Hz and 1 kHz were mainly attributed to the piezoelectric ring effect of LN crystal. The results demonstrated the excellent potential of EO Q-switched Tm,Ho:YAP laser for generating pulses at 2 μm with high stability and pulse energy. However, the obtained pulse durations were still beyond 100 ns due to the long cavity configuration, so shorter pulses are expected to be obtained with more compact cavity employed.

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References


