Passively Q-switched 1.5-1.6 μm $Er:Yb:LuAl_3(BO_3)_4$ laser with $Co^{2+}:Mg_{0.4}Al_{2.4}O_4$ saturable absorber

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Abstract: Using a $Co^{2+}:Mg_{0.4}Al_{2.4}O_4$ spinel crystal as saturable absorber, efficient passively Q-switched pulse laser operating at 1.5-1.6 μm was realized in an $Er:Yb:LuAl_3(BO_3)_4$ crystal end-pumped by a 970 nm diode laser. At absorbed pump power of 15.7 W, 1540 nm laser with 28.6 μJ energy, 40 ns duration and 22 kHz repetition rate, and 1520 nm laser with 9.9 μJ energy, 37 ns duration and 63 kHz repetition rate were obtained in a plano-concave cavity, respectively. For a plano-plano cavity, corresponding values of 1520 nm laser were 16.3 μJ, 14 ns and 41 kHz, respectively, and the maximum output peak power was about 1.16 kW.

OCIS codes: (140.3500) Lasers, erbium; (140.3380) Laser materials; (140.3540) Lasers, Q-switched.

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1. Introduction

Eye-safe 1.5-1.6 μm pulse lasers emitted from a compact source are of potential interest in some areas, such as sensing of gases and contamination in air, medicine, laser-range-finding, and lidar [1, 2]. Passive Q-switching of Er-Yb solid-state laser is an attractive technique developed for these applications, because it makes1.5-1.6 μm pulse laser device with kilowatt-level peak power and nanosecond duration compact and low-cost [2, 3].

For Er-Yb codoped crystals, few investigations of passively Q-switched 1.5-1.6 μm laser operation have been reported till now [4, 5]. With a $Co^{2+}:MgAl_2O_4$ crystal as saturable absorber, 1540 nm pulse laser with energy of about 2.8 μJ and duration of 5-6 ns, and 1604 nm pulse laser with energy of 4.3 μJ and duration of 150 ns have been realized in $Er:Yb:GdCa_4O(BO_3)_3$ and $Er:Yb:YVO_4$ crystals, respectively [4, 5]. The obtained maximum output peak powers are only about 0.5 kW and 0.03 kW, respectively. Among Er-Yb codoped crystals, $Er:Yb:YAl_3(BO_3)_4$ (Er:Yb:YAB) crystal has been considered as the best 1.5-1.6 μm laser crystal for continuous-wave (cw) 970 nm diode pumping [6]. 1.5-1.6 μm cw laser with output power of 1 W and slope efficiency of 35%, and passively mode-locked 1530 nm pulse laser with duration of 4.8 ps and average output power of 280 mW have been realized in Er:Yb:YAB crystal [7, 8], which show that the crystal has better laser performance than that of the commercially available Er:Yb:phosphate glasses. Therefore, as a member of the same family, $Er:Yb:LuAl_3(BO_3)_4$ (Er:Yb:LuAB) crystal should also be an interesting and valuable 1.5-1.6 μm laser crystal [9].

Similar to the $Co^{2+}:MgAl_2O_4$ crystal, Co^{2+}-doped alumina-rich $Mg_{0.4}Al_{2.4}O_4$ spinel crystal is a novel saturable absorber for Q-switching of 1.5-1.6 μm lasers [10]. Its ground-state absorption cross-section at 1535 nm is about 2.54×10^{-19} cm^2. Using a $Co^{2+}:Mg_{0.4}Al_{2.4}O_4$ crystal as saturable absorber, 1535 nm pulse laser with energy of 4.8 μJ and duration of 3.5 ns has been realized in Er:Yb:glass [10]. In this work, using an Er:Yb:LuAB crystal as gain medium and a $Co^{2+}:Mg_{0.4}Al_{2.4}O_4$ as saturable absorber, efficient passively Q-switched 1.5-1.6 μm pulse laser with kilowatt-level peak power and ten-odd nanosecond duration is demonstrated when the gain medium is end-pumped by a 970 nm diode laser.

2. Laser experimental arrangement

End-pumped linear resonators were adopted in the experiment and the schematic of experimental setups are depicted in Fig. 1. A 0.7-mm-thick and *c*-cut Er(1.1 at.%):Yb(24.1 at.%):LuAB crystal chip was used as gain medium. A 970 nm fiber-coupled diode laser (800 μm diameter core) from Coherent Inc. was used as pump source. After passing a simple telescopic lens system (TLS), the pump beam was focused to a spot with waist radius of about 220 μm in the crystal chip. The uncoated crystal chip was attached on an aluminum slab with heat-conducting adhesive and there is a hole in the center of the slab to permit the passing of the pump and fundamental laser beams. For making the laser more compact, no other device was used to control the temperature of the chip, which was only cooled by the natural air. In order to reduce the influence of pump-induced thermal load on laser performance and avoid the fracture of the chip at high pump power, the diode laser was operated in quasi-cw mode. Pump pulse width was 2 ms and pulse period was 100 ms. Because the duty cycle of the used diode laser was 2%, average power mentioned hereinafter was the measured average power multiplied by fifty. About 85% of the incident pump power was absorbed by the crystal chip. A 1-mm-thick $Co^{2+}:Mg_{0.4}Al_{2.4}O_4$ crystal with Co^{2+} concentration of 0.02 at.% was used as saturable absorber and placed as close as possible to the Er:Yb:LuAB crystal. The saturable absorber wafer was antireflection coated and had an initial transmission of about 97% around 1530 nm. The flat

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input mirror (IM) of the laser resonator had 90% transmission at 970 nm and 99.8% reflectivity around 1530 nm. For the plano-concave cavity, two output mirrors (OMs) with a fixed 30 mm radius of curvature (RoC) and different transmissions (1.5% and 2.4%) around 1530 nm were used. In order to reduce the cavity loss, the length of the plano-concave cavity was set close to the RoC of OMs. For the plano-plano cavity, one flat OM with transmission of 4.6% around 1530 nm was used. The cavity length was kept at about 7 mm. Spectrum of the passively Q-switched Er:Yb:LuAB laser was recorded with a monochromator (Triax550, Jobin-Yvon) associated with a TE-cooled Ge detector (DSS-G025T, Jobin-Yvon). Pulse profile was measured by a 2 GHz InGaAs photodiode connected to a digital oscilloscope with bandwidths of 1 GHz (DSO6102A, Agilent).

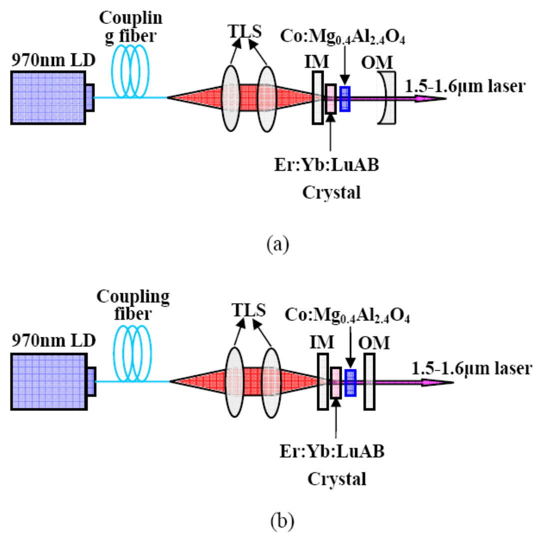

Fig. 1. Experimental setups of the quasi-cw 970 nm diode-pumped passively Q-switched Er:Yb:LuAB lasers at 1.5–1.6 μm: (a) plano-concave cavity; (b) plano-plano cavity.

3. Results and discussion

For a cavity with a fixed OM, spectra of the passively Q-switched Er:Yb:LuAB laser were similar at various pump powers in this work. Then, only those recorded at the maximum absorbed pump power of 15.7 W are shown in Fig. 2 for the sake of brevity. It can be seen that laser wavelengths were about 1540 and 1520 nm for the OMs with transmissions of 1.5% and 2.4%, respectively. The variation of output wavelength of the Er:Yb:LuAB laser with the transmission of OM is caused by the gain characteristic of the quasi-three-level laser and has already been reported in previous investigations of Er-Yb solid-state lasers [6, 7, 9, 11]. The higher cavity loss caused by the higher OM transmission implies that larger population inversion of Er^{3+} ions, i.e. higher gain in the cavity, is required for achieving laser oscillation. The α-polarized gain spectra of the Er:Yb:LuAB crystal depicted in Ref [9]. have indicated that the gain cross section at 1520 nm increases more rapidly than that at 1540 nm with the population inversion. Therefore, when the gain of the Q-switched pulse laser is higher than a certain level, the gain cross section at 1520 nm of the Er:Yb:LuAB crystal may be larger than that at 1540 nm.

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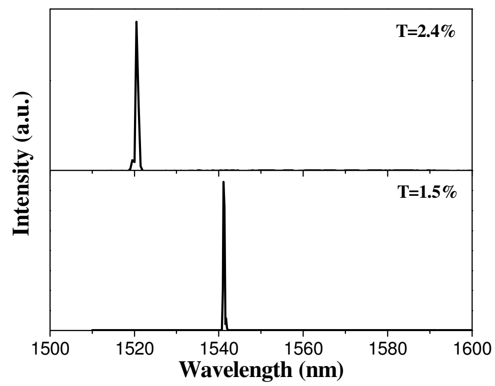

Fig. 2. Spectra of the passively Q-switched Er:Yb:LuAB laser at absorbed pump power of 15.7 W in plano-concave cavities.

Figure 3 shows average output power of the passively Q-switched Er:Yb:LuAB laser as a function of absorbed pump power in the plano-concave cavities. At absorbed pump power of 15.7 W, 1540 nm pulse laser with the maximum average output power of 0.63 W and slope efficiency of 8.1%, and 1520 nm pulse laser with the maximum average output power of 0.62 W and slope efficiency of 9.2% were achieved for the OMs with transmissions of 1.5% and 2.4%, respectively. The absorbed pump thresholds of the 1540 and 1520 nm lasers were about 8.0 and 9.0 W, respectively.

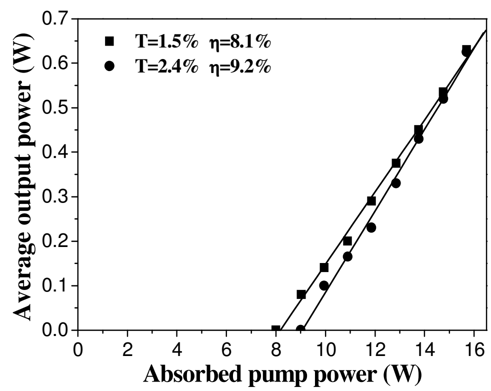

Fig. 3. Average output power of the passively Q-switched Er:Yb:LuAB laser as a function of absorbed pump power at 970 nm in plano-concave cavities.

Figures 4 and 5 show the pulse profiles of the passively Q-switched Er:Yb:LuAB laser at absorbed pump power of 15.7 W in the two plano-concave cavities with different OM transmissions. For the transmission of 1.5%, pulse repetition rate is about 22 kHz and pulse duration is about 40 ns. The pulse-to-pulse amplitude fluctuation and interpulse time jittering are about 12% and 9%, respectively. When the transmission increases to 2.4%, pulse repetition rate rapidly increases to about 63 kHz and pulse duration is about 37 ns. The pulse-to-pulse amplitude fluctuation and interpulse time jittering are about 15% and 10%, respectively. Theoretically, for cw pumped passively Q-switched laser with quasi-three-level nature, the pulse repetition rate f can be expressed as [12, 13]:

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$$f = \frac{1}{\tau_a \ln\left(\dfrac{1-\delta\psi}{1-\psi}\right)}, \tag{1}$$

in which

$$\psi = \frac{\ln\left(\dfrac{1}{R}\right) + \ln\left(\dfrac{1}{T_0^2}\right) + L + L'}{2\sigma n_{cw} l}, \tag{2}$$

where τ_a is the fluorescence lifetime of the upper laser level of gain medium, δ is the fraction of the population inversion left over at the start of the next pulse for the repetitively Q-switched laser and takes on the values between 0 and 1, σ is stimulated emission cross section at laser wavelength of gain medium, n_{cw} is the cw population inversion density and proportional to the cw pump power, l is the length of gain medium, R, T_0, and L are the reflectivity of OM, initial transmission of saturable absorber, and the round-trip dissipative optical loss, respectively. $L^{'}$ is the reabsorption loss of quasi-three-level laser. It can be deduced from above equations that pulse repetition rate increases with the decrement of OM transmission and reabsorption loss, and the increment of stimulated emission cross section at laser wavelength. As mentioned above, for the higher OM transmission, larger population inversion of Er^{3+} ions, which indicates the smaller reabsorption loss, is required for achieving laser oscillation. At the same time, the α-polarized stimulated emission cross section at 1520 nm is larger than that at 1540 nm for Er:Yb:LuAB crystal [9]. When the OM transmission increases from 1.5% to 2.4%, laser wavelength is shifted from 1540 nm to 1520 nm and then the influence of the reduction of reabsorption loss and the increment of emission cross section on pulse repetition rate may be stronger than that of the increment of OM transmission. Therefore, the pulse repetition rate obtained at 1520 nm laser is higher than that at 1540 nm. Slight difference of pulse duration between these lasers may be originated from the small change of cavity length, as well as different OM transmissions and initial transmissions of saturable absorber at two laser wavelengths [12].

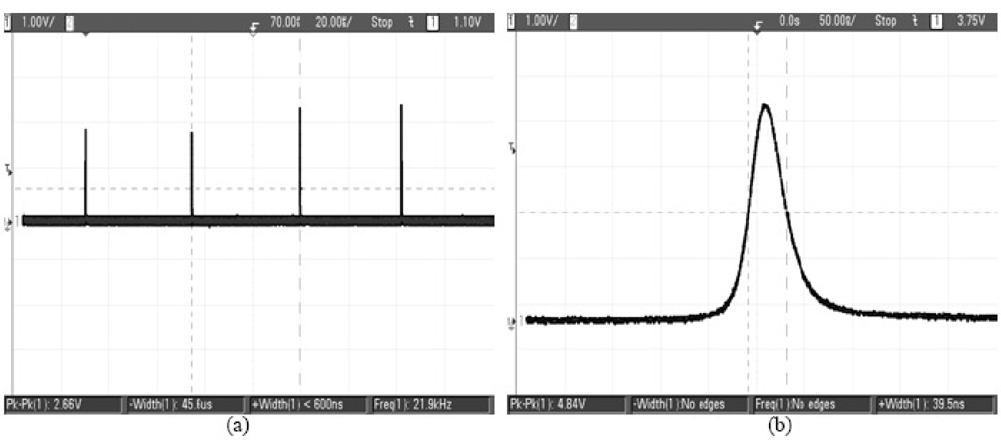

Fig. 4. Pulse train (a) and oscilloscope trace (b) of the passively Q-switched Er:Yb:LuAB laser at absorbed pump power of 15.7 W in a plano-concave cavity when the transmission of the output mirror was 1.5%. Pulse repetition rate and duration are about 22 kHz and 40 ns, respectively.

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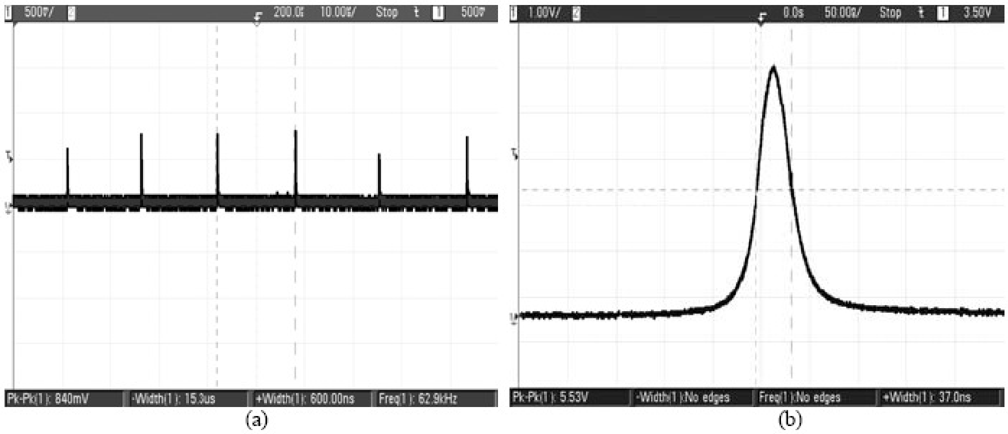

Fig. 5. Pulse train (a) and oscilloscope trace (b) of the passively Q-switched Er:Yb:LuAB laser at absorbed pump power of 15.7 W in a plano-concave cavity when the transmission of the output mirror was 2.4%. Pulse repetition rate and duration are about 63 kHz and 37 ns, respectively.

Figure 6 shows pulse repetition rate of the passively Q-switched Er:Yb:LuAB laser as a function of absorbed pump power in the plano-concave cavities. For the OM transmissions of 1.5% and 2.4%, pulse repetition rates increase from 8 to 22 kHz and from 15 to 63 kHz, respectively, when absorbed pump power is changed from 10 to 15.7 W. Furthermore, pulse durations of both lasers are almost kept invariant at various pump powers [12]. At absorbed pump power of 15.7 W, pulse energy and peak power of the 1540 nm laser were estimated to be about 28.6 μJ and 0.72 kW, respectively, for the OM transmission of 1.5%. For the OM transmission of 2.4%, the corresponding values of the 1520 nm laser decreased to be about 9.9 μJ and 0.27 kW, respectively.

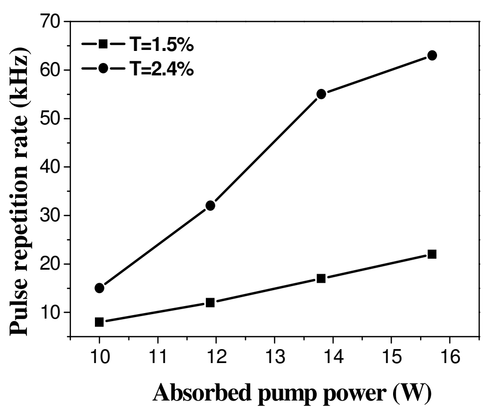

Fig. 6. Pulse repetition rate of the passively Q-switched Er:Yb:LuAB laser as a function of absorbed pump power at 970 nm in plano-concave cavities.

Because laser pulse with higher peak power and shorter pulse duration can be obtained in a shorter resonator [12], the passively Q-switched Er:Yb:LuAB laser in a plano-plano cavity with 7 mm length was also investigated. Figure 7 shows average output power of the laser as a function of absorbed pump power at 970 nm. At absorbed pump power of 15.7 W, the maximum average output power and slope efficiency were 0.65 W and 10.5%, respectively, for the OM transmission of 4.6%. The absorbed pump threshold was about 9.5 W. Spectra were

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similar at various pump powers and laser wavelength was centered at 1520 nm, as shown in the inset of Fig. 7.

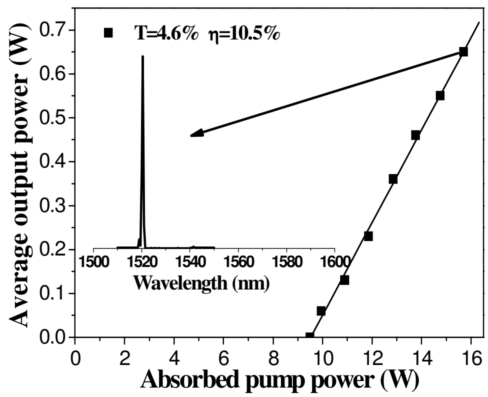

Fig. 7. Average output power of the passively Q-switched Er:Yb:LuAB laser as a function of absorbed pump power at 970 nm in a plano-plano cavity. The inset shows the spectrum at absorbed pump power of 15.7 W.

Pulse profile of the passively Q-switched Er:Yb:LuAB laser at absorbed pump power of 15.7 W in the plano-plano cavity is shown in Fig. 8. Pulse repetition rate is about 41 kHz and pulse duration is about 14 ns. When the OM transmission increases from 2.4% to 4.6%, laser wavelength is kept at 1520 nm and the influence of the increment of OM transmission on pulse repetition rate may be stronger than that of the reduction of reabsorption loss. Therefore, the pulse repetition rate obtained in the plano-plano cavity with OM transmission of 4.6% is lower than that n the plano-concave cavity with OM transmission of 2.4%. The pulse-to-pulse amplitude fluctuation and interpulse time jittering are about 13% and 7%, respectively. When absorbed pump power was reduced to 10 W, pulse repetition rate decreased to about 10 kHz and pulse duration was still kept at about 14 ns. The maximum pulse energy and output peak power of 1520 nm in the plano-plano cavity were estimated to be about 16.3 μJ and 1.16 kW, respectively. The obtained energy and peak power in this work are higher than those realized in the diode-pumped passively Q-switched Er:Yb:$GdCa_4O(BO_3)_3$ (about 2.8 μJ and 0.5 kW) and Er:Yb:YVO_4 (about 4.3 μJ and 0.03 kW) lasers [4, 5]. When the resonator is further shortened in the future, the pulse duration can become shorter and the output peak power of the passively Q-switched Er:Yb:LuAB laser can be enhanced.

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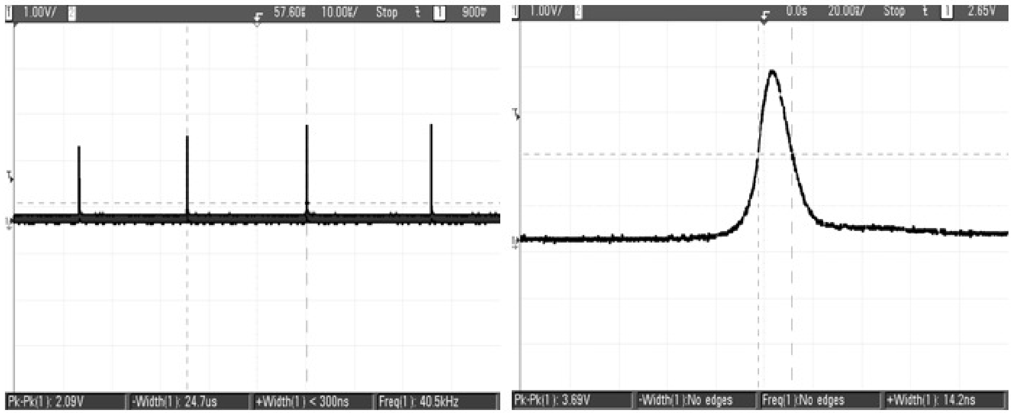

(a) (b)

Fig. 8. Pulse train (a) and oscilloscope trace (b) of the passively Q-switched Er:Yb:LuAB laser at absorbed pump power of 15.7 W in a plano-plano cavity. Pulse repetition rate and duration are about 41 kHz and 14 ns, respectively.

4. Conclusion

End-pumped by a 970 nm diode laser with 2% duty cycle, efficient passively Q-switched Er:Yb:LuAB pulse laser at 1.5-1.6 μm was realized when a Co^{2+}:$Mg_{0.4}Al_{2.4}O_4$ spinel crystal was used as saturable absorber. When the absorbed pump power was 15.7 W and the OM transmission increased from 1.5% to 2.4% in plano-concave cavities, wavelength of output laser was blue-shifted from 1540 to 1520 nm and pulse repetition rate was rapidly changed from 22 to 63 kHz, while pulse duration was kept at about 40 ns. For a plano-plano cavity, 1520 nm pulse laser with 16.3 μJ energy, 14 ns duration, 41 kHz repetition rate, and 1.16 kW peak power was obtained at absorbed pump power of 15.7 W.

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