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Eye-safe 1.55 μm passively *Q*-switched $Er,Yb:GdAl_3(BO_3)_4$ diode-pumped laser

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We report for the first time, to the best of our knowledge, on a diode-pumped passively *Q*-switched $Er,Yb:GdAl_3(BO_3)_4$ laser. By using a $Co^{2+}:MgAl_2O_4$ crystal as a saturable absorber, *Q*-switched laser pulses with a duration of 12 ns and a maximum energy of 18.7 μJ at a repetition rate of 32 kHz corresponding to an average output power of 0.6 W were obtained at 1550 nm under continuous-wave pumping. In the burst mode of operation, *Q*-switched laser pulses with the highest energy up to 44 μJ were realized with a pulse repetition rate of 6.5 kHz.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3500) Lasers, erbium; (160.5690) Rare-earth-doped materials.

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Erbium lasers emitting in the 1.5–1.6 μm spectral range are currently of great interest for applications in eye-safe laser rangefinders, optical location, and laser-induced breakdown spectroscopy (LIBS) systems [1]. In most cases, these applications require compact and low-cost sources of laser pulses with high average output power.

Passive *Q*-switching is one of the most simple and reliable methods to achieve the abovementioned requirements. Passively *Q*-switched diode-pumped Er,Yb:glass lasers were realized by using semiconductor saturable-absorption mirrors [2], as well as Co^{2+}-doped $LaMgAl_{11}O_{19}$ [3], ZnSe [4], and $MgAl_2O_4$ (MALO) [5,6] crystals. However, due to poor thermomechanical properties of phosphate glass hosts (a thermal conductivity of $0.85\ W \times m^{-1} \times K^{-1}$ [7]), high average output power in *Q*-switched mode cannot be achieved. With the Co:MALO crystal as a saturable absorber, Er,Yb:glass laser with a pulse energy of 22.4 μJ was demonstrated; however, the repetition rate did not exceed 1 kHz that corresponds to about 22 mW of *Q*-switched average output power [6]. For this reason, the search for new crystalline hosts for Er,Yb codoping is ongoing.

Er,Yb-codoped oxoborate crystals possess good spectroscopic characteristics and appropriate thermomechanical properties for efficient laser operation [8]. A passively *Q*-switched regime of operation was demonstrated by the usage of $Er,Yb:GdCa_4O(BO_3)_3$ [9], $Er,Yb:YAl_3(BO_3)_4$ (YAB) [10,11], $Er,Yb:LuAl_3(BO_3)_4$ (LuAB) [12], and $Er,Yb:Sr_3Lu_2(BO_3)_4$ [13] crystals. A pulse energy of 5.25 μJ at a repetition rate of 60 kHz corresponding to an average output power of 315 mW was realized for $Er,Yb:YAl_3(BO_3)_4$ crystal [10]. By using $Er,Yb:LuAl_3(BO_3)_4$ crystal, *Q*-switched pulses with a maximum energy of 6.1 μJ and an average output power of up to 420 mW were demonstrated; however, an additional sapphire heat diffuser was used in this case [12].

Recently, we investigated growth, spectroscopic, and laser properties of an Er,Yb-codoped gadolinium–aluminium orthoborate ($Er,Yb:GdAl_3(BO_3)_4$) laser crystal [14,15]. The crystal was grown by dipping seeded high-temperature solution growth at a cooling rate of 0.2°C–0.5°C per day in the temperature range of 1060°C–1000°C using $K_2Mo_3O_{10}$-based flux. Compared with isostructural Er,Yb:YAB and Er,Yb:LuAB crystals, $Er,Yb:GdAl_3(BO_3)_4$ (GdAB) crystal is characterized by a larger absorption cross section around 976 nm and a longer lifetime of the $^4I_{13/2}$ level with similar emission cross sections [16,17]. It has a strong absorption band with a maximum absorption cross section of about $3.6 \times 10^{-20}\ cm^2$ at 976 nm, high stimulated emission cross sections in the spectral range of 1500–1600 nm with a maximum peak of about $2.1 \times 10^{-20}\ cm^2$, a long enough $^4I_{13/2}$ level lifetime of 350 μs, and efficient energy transfer (>80%) from Yb^{3+} to Er^{3+} ions [14]. By using Er(1 at. %), Yb(8 at. %):GdAB crystal, a continuous-wave (CW) regime of operation with a maximum output power of 780 mW and a slope efficiency of 26% was obtained [15]. In this Letter, we present for the first time, to the best of our knowledge, a passively *Q*-switched Er,Yb:GdAB laser with high average output power.

Three high-optical-quality Er,Yb:GdAB single crystals with different doping concentrations and sizes up to 20 mm × 10 mm × 10 mm were grown for the current laser experiments. The concentrations of the dopants were measured by microprobe analysis. The details of active elements used for CW laser experiments are plotted in Table 1.

Initially, the CW laser experiments were carried out with a Z-shaped cavity. The experimental setup is shown in Fig. 1. The temperature of active element (AE) was kept at 14°C

Table 1. Details of Active Elements

Er^{3+} Ions, at. %	Yb^{3+} Ions, at. %	Thickness, mm	Orientation
1.0	8.0		
1.8	15.0	1.5	c–cut
2.1	17.0		

by means of copper slab with the hole in the center to permit passing of pump and laser beams and thermoelectrical cooling of the elements with a water-cooled heatsink. The active elements were antireflection coated for both pump and lasing wavelengths. As a pump source, a fiber-coupled (∅105 μm, NA = 0.22) laser diode emitting output power of 12 W in the CW regime and 20 W in quasi-continuous-wave (QCW) near 976 nm was used. The pump beam was focused into a 120 μm spot inside the Er,Yb:GdAB crystal. The cavity-mode diameter for the TEM_{00} transverse mode at the active element was close to the pump beam waist. A set of output couplers with different transmissions from 1.5% to 6% was used during continuous-wave laser experiments.

The highest output power as well as slope efficiency were obtained for the Er(1.8 at. %),Yb(15.0 at. %):GdAB crystal. Input–output characteristics are plotted in Fig. 2. The maximal CW output power of 1.7 W at an absorbed pump power of 8.9 W with slope efficiency of 36% was obtained at 1550 nm for the output coupler (OC) with transmission of 4% at laser wavelength. After a further increase of pump power, bending of the output laser characteristics was observed. This provides evidence for the influence of thermal load in the crystal on laser performance. To reduce the thermal load, laser experiments with QCW pumping were performed. By using a chopper with a duty cycle of 1:5 in the pumping channel, the output peak power up to 3.5 W was obtained at 1550 nm when the absorbed peak pump power was measured to be 13 W (Fig. 2).

The detailed results demonstrated by Er(1.0 at. %), Yb(8.0 at. %):GdAB and Er(2.1 at. %),Yb(17.0 at. %): GdAB lasers are listed in Table 2.

The wavelength shift to 1522 nm was observed for Er(1.0 at. %),Yb(8.0 at. %):GdAB crystal while using an OC with transmissions of 4.5% and 5.5%. This fact can be attributed to the three-level scheme of Er^{3+} laser operation. In this case, the laser wavelength depends on the inversion density (or intracavity losses) [15]. Laser experiments with Er(2.1 at. %),Yb(17 at. %):GdAB were held only in the QCW regime of operation because the active element was damaged during continuous-wave pumping. This damage can be caused

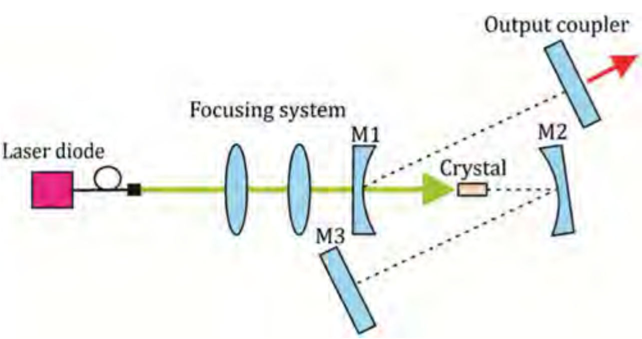

Fig. 1. Experimental setup for the CW laser experiments.

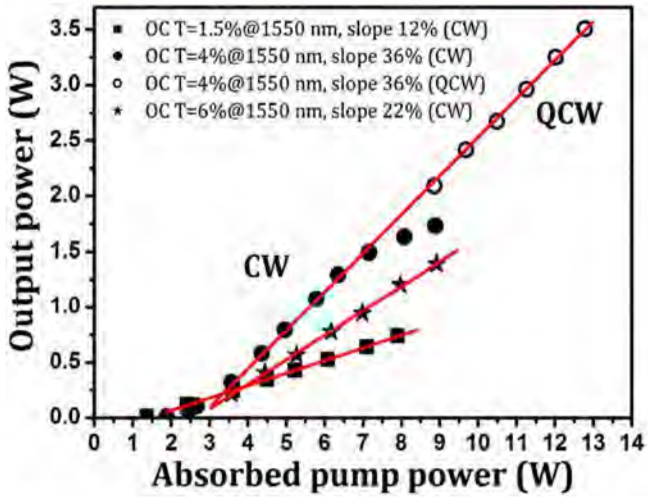

Fig. 2. Input–output characteristics of CW and QCW Er(1.8 at. %),Yb(15 at. %):GdAB diode-pumped lasers.

by the internal stress for highly erbium-doped crystals. The absence of wavelength shift for highly erbium-doped crystals (1.8 at. % and 2.1 at. %) can be associated with the increase of internal reabsorption losses inside the gain medium.

Q-switched laser experiments were started with the Z-shaped cavity described above. As an active element, Er(1.8 at. %),Yb(15 at. %):GdAB crystal was chosen. A 0.75 mm thick Co^{2+}:$MgAl_2O_4$ saturable absorber (SA) antireflection coated for both pump and lasing wavelengths with an initial transmission of 98.5% at 1550 nm was used [18,19]. The stable passively *Q*-switched regime of operation was obtained, however, pulse duration was more than 120 ns.

To shorten pulse duration, the plano–plano cavity with substantially reduced length was adopted. The coatings ($R > 99.5\%$ at 1550 nm and $T = 97\%$ at 976 nm) were deposited onto the outer side of the SA, while the inner side was antireflection coated for both pump and lasing wavelengths. The physical cavity length was about 7 mm, which was limited by the design of the active element cooling system. Two output couplers with transmissions of 6% and 9% at 1550 nm were used. The experimental setup is presented in Fig. 3.

At first, *Q*-switched laser experiments with a continuous-wave pumping beam focused into a 120 μm spot size were performed. Laser pulses with energy of 18.7 μJ and duration of 12 ns were obtained at a repetition rate of 32 kHz at 1550 nm for the output coupler with transmission of 6% when the absorbed pump power was 5.9 W (Fig. 4). The pulse energy as well as repetition rate decreased to 12 μJ and 26 kHz, respectively, when an OC with transmission of 9% was used at the similar absorbed pump power. Without the saturable absorber in the cavity and with an OC transmission of 6%, the continuous-wave output power was measured to be 880 mW at 5.9 W of the absorbed pump power that was close to the results obtained in a Z-shaped cavity. Thus, the conversion efficiency from the CW to *Q*-switched regime of operation reached up to 66% with 6% output coupling.

To reduce the thermal load and avoid damage of the crystal at higher pump powers, the QCW mode of pumping with a pump pulse width of 5 ms and a duty-cycle of 2% was applied. By using an OC with a transmission of 6%, the pulse

Table 2. Laser Performance of Er(1.0 at. %),Yb(8.0 at. %):GdAB and Er(2.1 at. %),Yb(17.0 at. %):GdAB Crystals

			CW Pumping			QCW Pumping		
Er^{3+} Ions, at. %	Yb^{3+} Ions, at. %	T_{oc}, %	P_{max}, W	η, %	λ, nm	P_{max}, W	η, %	λ, nm
1.0	8.0	1.5	0.8	14	1550	1.2	14	1550
		4.5	1.45	26	1522	1.9	26	1522
		5.5	1.37	24	1522	1.5	24	1522
2.1	17.0	1.5	–	–	–	0.97	10	1550
		4.0	–	–	–	1.93	20	
		6.0	–	–	–	2.0	24	

parameters were the same as in the case of CW pumping, but the maximum repetition rate was limited by the laser-induced damage threshold (LIDT) of AR coatings deposited on the saturable absorber. To reduce the intracavity energy density and prevent damage to the coatings, an OC with a higher transmission of 9% at laser wavelength was used. The pulse energy and repetition rate in the frame of each burst of Q-switched laser pulses were estimated to be 15 μJ and 100 kHz at 1550 nm at about 12.2 W of absorbed pump power for 9% OC (Fig. 5). The maximum pulse repetition rate hereafter was limited by LIDT of AR coatings of the saturable absorber.

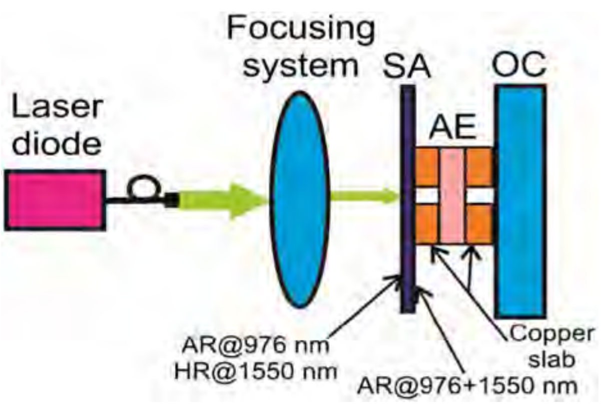

Fig. 3. Experimental setup for Q-switched laser experiments.

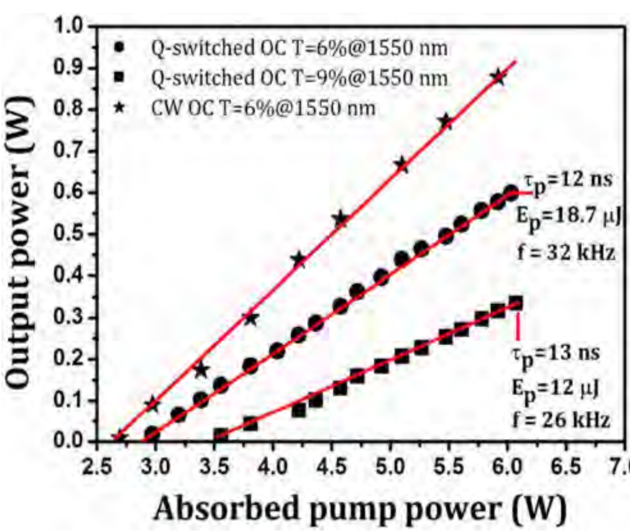

Fig. 4. Average output power versus absorbed pump power of the Q-switched Er,Yb:GdAB laser with CW pumping.

The pulse duration was measured to be 12 ns. The spatial profile of the output beam was TEM_{00} mode with $M^2 < 1.2$.

The Q-switched laser experiments were also carried out with larger pump beam waists of 200 and 300 μm. The detailed results are listed in Table 3.

The experiments were performed just with the QCW mode of pumping because of active element damage before achieving the laser threshold while CW pumping was used. The highest pulse energy of 44 μJ and peak power of 4 kW were obtained at 1550 nm with pump beam waist of 300 μm for an OC transmission of 6% with maximal repetition rate up to 6.5 kHz at absorbed pump power of 15 W. There were up to 30 pulses in the frame of one pump pulse that corresponds to total energy up to 1.3 mJ. The laser pulses with energy of 30 μJ at a

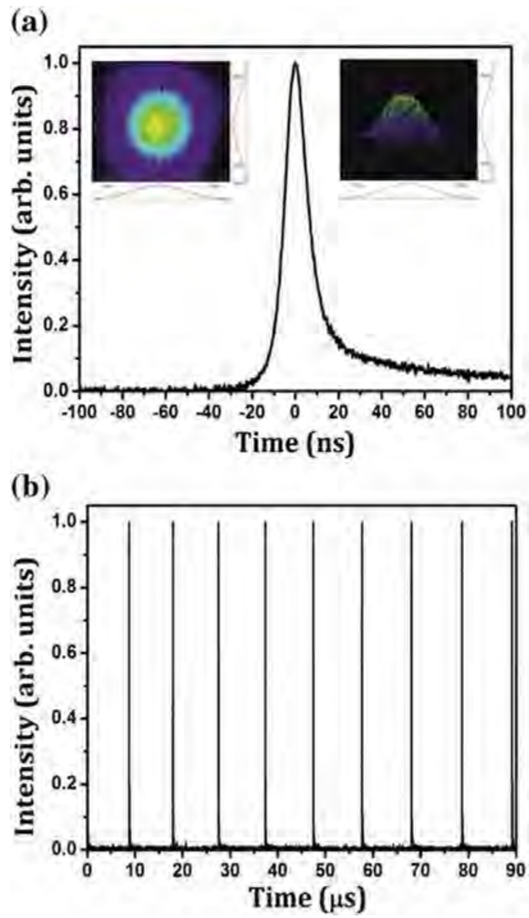

Fig. 5. (a) Single pulse and (b) pulse train records of the passively Q-switched Er,Yb:GdAB laser. The insets in (a) show the intensity profile of the output beam.

Table 3. Laser Characteristics of a *Q*-Switched Er,Yb:GdAB Laser with QCW Pumping

2ω, μm	T_{oc}, %	P_{abs}, W	E_p, μJ	τ_p, ns	f, kHz
200	6	11.3	30	11–12	35
	9	13.0	24		20
300	6	15.0	44		6.5
	9	17.5	29		5

repetition rate of 35 kHz were realized with a pump beam waist of 200 μm. The pulse duration was the same as in the case of pump beam waist of 120 μm that agreed well with passive *Q*-switching theory [20,21]. Further reduction of pulse duration as well an increase in peak power can be achieved by using a true microchip laser configuration with shorter cavity length and by optimization of OC and SA parameters [10].

In conclusion, a high-output-power diode-pumped Er, $Yb:GdAl_3(BO_3)_4$ laser was demonstrated. A maximum CW output power of 1.7 W as well as a QCW peak output power of 3.5 W with a slope efficiency of 36% were obtained for Er(1.8at. %),Yb(15at. %):GdAB crystal. A passively *Q*-switched Er, $Yb:GdAl_3(BO_3)_4$ laser was realized for the first time, to the best of our knowledge. Laser pulses with energy of 18.7 μJ and duration of 12 ns were obtained at a repetition rate of 32 kHz at 1550 nm under the continuous-wave pumping. In burst mode of operation, the highest pulse energy of 44 μJ and peak power of 4 kW were demonstrated at a pulse repetition rate up to 6.5 kHz.

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