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# Laser Performance of Er,Yb:YAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> Crystals with Different Erbium Concentrations

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**Abstract:** The effect of erbium concentration on the laser performance of Er,Yb:YAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> crystals was investigated. A maximal output power of 1.6 W in CW and 2.7 W in QCW regimes was obtained at 1522 nm.

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

## 1. Introduction

Erbium-doped laser materials are widely used for laser operation in the 1.5-1.6 μm spectral range with promising applications including eye-safe laser range finding, medicine, fiber-optic communication systems, and optical location. Phosphate glasses currently are the leading Er<sup>3+</sup>, Yb<sup>3+</sup> co-doped laser materials, because they combine very efficient energy transfer from Yb<sup>3+</sup> to Er<sup>3+</sup> ions (η≈90 %) with a long lifetime of erbium upper laser level <sup>4</sup>I<sub>13/2</sub> (7-8 ms) and short lifetime of the <sup>4</sup>I<sub>11/2</sub> energy level (2-3 μs), which prevents the depopulation of this level by means of excited-state absorption and up-conversion processes. However, phosphate glass has poor thermo-mechanical properties (a thermal conductivity of 0.85 W×m<sup>-1</sup>×K<sup>-1</sup>), that limits the average output power of Er,Yb:glass lasers due to the thermal effects [1].

The Er,Yb-codoped oxoborate crystals possess abovementioned spectroscopic characteristics and high thermo-mechanical properties for efficient laser operation. CW room-temperature laser operation was demonstrated for the following Er,Yb-codoped oxoborate crystals: GdCa<sub>4</sub>O(BO<sub>3</sub>)<sub>3</sub> [2], LaSc<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> [3], YCa<sub>4</sub>O(BO<sub>3</sub>)<sub>3</sub> [4]; while for Li<sub>6</sub>Y(BO<sub>3</sub>)<sub>3</sub> [5], Sr<sub>3</sub>Y<sub>2</sub>(BO<sub>3</sub>)<sub>4</sub> [6], Sr<sub>3</sub>Gd<sub>2</sub>(BO<sub>3</sub>)<sub>4</sub> [7], and LuAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> [8] quasi-continuous-wave regime of operation was realized. Comparatively recently, excellent laser performance of Er,Yb-codoped YAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> (YAB) and GdAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> crystals was demonstrated [9, 10]. Diode-pumped Er,Yb:YAB laser exhibited a slope efficiency as high as 35 % and output power up to 1 W at several wavelengths between 1522 and 1602 nm. However, the optimization of erbium concentration and determination of its influence on the laser performance for oxoborate crystals weren't performed.

In this work we present the investigation of the effect of erbium concentration on the laser performance of Er,Yb:YAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> crystals.

## 2. Spectroscopy

Er,Yb:YAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> single crystals with different erbium concentrations were grown by dipping seeded high-temperature solution growth at a cooling rate 0.2°C–5°C per day in the temperature range of 1060°C–1000°C using K<sub>2</sub>Mo<sub>3</sub>O<sub>10</sub>-based flux. As a result, Er,Yb:YAB crystals with high optical quality and the size up to 20×10×10 mm<sup>3</sup> have been obtained. The concentrations of the dopants were measured by microprobe analysis to be 0.83×10<sup>20</sup> cm<sup>-3</sup> (1.5at.%), 1.11×10<sup>20</sup> cm<sup>-3</sup> (2.0at.%), 1.66×10<sup>20</sup> cm<sup>-3</sup> (3.0at.%) and 2.22×10<sup>20</sup> cm<sup>-3</sup> (4.0at.%) for erbium and 6.0×10<sup>20</sup> cm<sup>-3</sup> (11at.%) for ytterbium ions.

The polarized absorption cross-section spectra of Er,Yb:YAB crystal around 980 nm at room-temperature recorded with a spectrophotometer Cary-5000 are depicted in Fig. 1. A strong absorption band corresponding to transition <sup>2</sup>F<sub>7/2</sub>→<sup>2</sup>F<sub>5/2</sub> of Yb<sup>3+</sup> ions is centered at 976 nm with a maximum absorption cross-section of about 2.75×10<sup>-20</sup> cm<sup>2</sup> and bandwidth of 17 nm (FWHM) in σ polarization.

The stimulated emission cross-section spectra calculated by the reciprocity method using the Stark energy level scheme of <sup>4</sup>I<sub>13/2</sub> and <sup>4</sup>I<sub>15/2</sub> manifolds are plotted in Fig. 2. A number of local maxima are observed in both σ and π polarizations [9].

## 3. Laser experiments

The laser experiments were performed in Z-shaped cavity. The plane-plane Er(Xat.%),Yb(11at.%):YAB (where X=1.5at.%; 2at.%; 3at.%; 4at.%) crystal 1.5 mm long antireflection coated for both pump and lasing wavelengths

was mounted on the copper thermoelectrically cooled heatsink. The temperature of the active element was kept at 18°C. As a pump source a 15 W fiber-coupled ( $\varnothing$  105  $\mu$ m, NA=0.12) laser diode emitting near 976 nm was used. A combination of two lenses ( $f_1=f_2=80$  mm) was used to focus pump beam into the gain medium. The cavity-mode diameter at the active element was close to the pump beam waist. The transmittance of output coupler was 5 % at the laser wavelength. The setup for laser experiments is presented in Fig. 3.

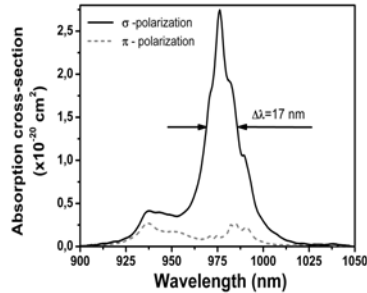


Fig. 1. Room-temperature polarized absorption spectra of Er,Yb:YAB crystal at 1  $\mu$ m

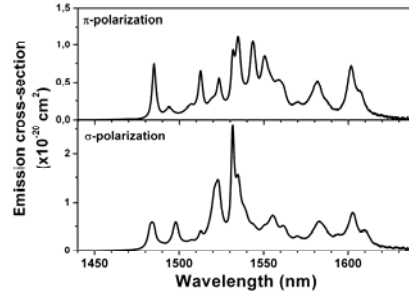


Fig. 2. Emission cross-section spectra of Er,Yb:YAB crystal near 1.5  $\mu$ m

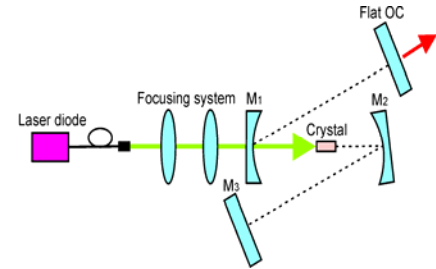


Fig. 3. The setup for laser experiments

Input-output characteristics of CW Er(1.5at.%),Yb(11at.%):YAB laser are plotted in Fig. 4. The laser threshold was measured to be about 1.5 W of absorbed pump power. The maximum CW output power of 1.2 W with slope efficiency near 26 % was obtained at 1522 nm at about 6.2 W of absorbed pump power. After further increasing of pump power, the rising of output laser power wasn't observed. It provides evidence for the influence of thermal load in the crystal on laser performance. To reduce the thermal load, laser experiments with quasi-CW (QCW) pumping were performed. By using a chopper with a duty cycle of 1:5 in the pumping channel, the maximal output peak power up to 2 W with slope efficiency of 35 % was obtained at the absorbed peak pump power of 7.3 W (Fig. 4).

For Er(2at.%),Yb(11at.%):YAB the maximum CW output power of 1.6 W at 1522 nm was demonstrated with slope efficiency of 32 % and 1.7 W laser threshold of absorbed pump power. While for QCW regime of operation laser emission was observed at 1543 nm with slope efficiency near 32% at low pump power, however, at an absorbed peak pump power of more than 5.5 W the emission wavelength switched to 1522 nm and the slope efficiency was increased drastically to 41 %. The maximal output peak power of 2.7 W was obtained in that case at an absorbed pump peak power of more than 9 W (Fig. 5).

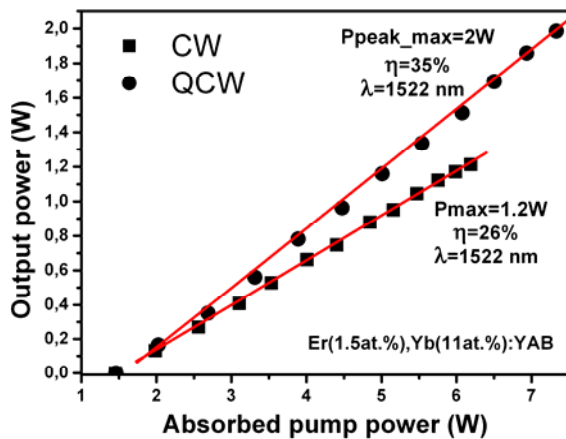


Fig. 4. Input-output characteristics of CW and QCW Er(1.5at.%),Yb(11at.%):YAB diode-pumped laser

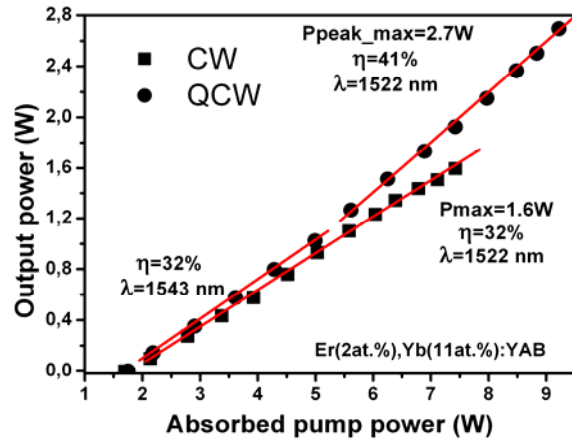


Fig. 5. Input-output characteristics of CW and QCW Er(2at.%),Yb(11at.%):YAB diode-pumped laser

Figure 6 shows input-output diagrams of CW and QCW Er(3at.%),Yb(11at.%):YAB diode-pumped laser. For CW operation the slope efficiency was reduced to 23 %. The maximal output power of 0.6 W in this case was limited by the damage of active element. To prevent destruction of the crystal further experiments were carried out with quasi-CW pumping. The maximal output peak power of 2.5 W with slope efficiency of 35 % was obtained at 1522 nm.

Laser experiments with Er(4at.%),Yb(11at.%):YAB were held in QCW regime of operation. The laser threshold was measured to be about 2.6 W of absorbed peak pump power. The maximum QCW output peak power of 2.2 W with slope efficiency near 40 % was obtained at 1531 nm at about 9 W of absorbed peak pump power (Fig. 7).

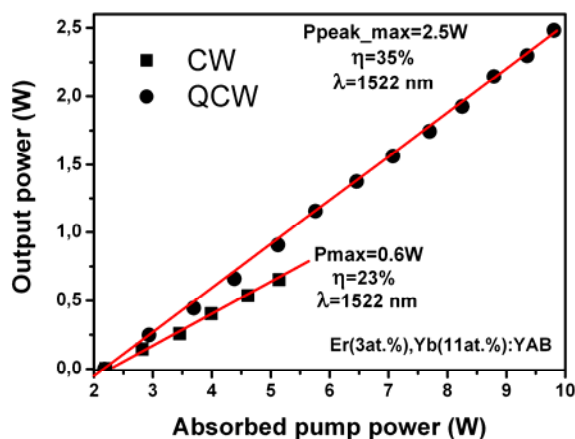


Fig. 6. Input-output characteristics of CW and QCW Er(3at.%),Yb(11at.%):YAB diode-pumped laser

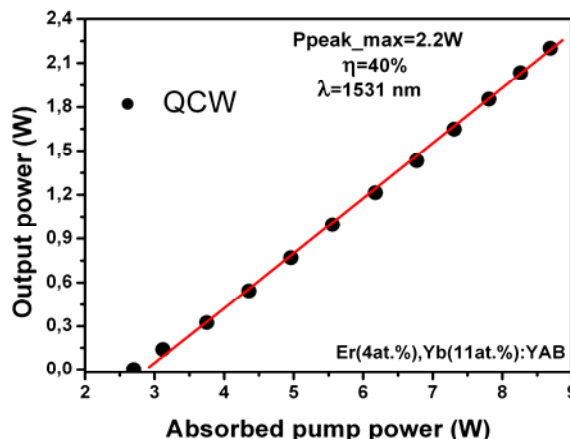


Fig. 7. Input-output characteristics of QCW Er(4at.%),Yb(11at.%):YAB diode-pumped laser

The spatial profile of the output beam was close to TEM<sub>00</sub> mode with  $M^2 < 1.2$  during all laser experiments. Laser characteristics of Er,Yb:YAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> crystals with different erbium concentration are plotted in Table 1.

Table 1. Laser performance of Er,Yb:YAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> crystals with different erbium concentration

Crystal	CW		QCW	
	$\eta$ , %	$P_{max}$ , W	$\eta$ , %	$P_{peak\ max}$ , W
Er(1.5at.%),Yb(11at.%):YAB	26	1.2	35	2
Er(2at.%),Yb(11at.%):YAB	32	1.6	41	2.7
Er(3at.%),Yb(11at.%):YAB	23	0.6	35	2.5
Er(4at.%),Yb(11at.%):YAB	-	-	40	2.2

In conclusion, the effect of high erbium concentration on the laser performance of Er,Yb:YAB crystals was investigated. It was demonstrated, that there is no degradation of QCW laser performance for erbium concentration up to 4.0at.%.

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