

High Power Diode-Pumped Erbium Laser Emitting at Near 1.5 μm

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Abstract

Solid-state lasers emitting in the 1.5–1.6 μm spectral range are very promising for eye-safe laser range finding, ophthalmology, fiber-optic communication systems, and optical location. The aim of this work is the investigation of spectroscopic and laser properties of gain medium based on borate crystal for abovementioned lasers.

Spectroscopic and laser properties of Er,Yb:YAl₃(BO₃)₄ crystals with different concentrations of dopants were investigated. Polarized absorption and emission cross-section spectra were determined. The ytterbium-erbium energy transfer efficiency was estimated. The maximal energy transfer efficiency up to 97 % was obtained for Er(4 at.%),Yb(11 at.%):YAl₃(BO₃)₄ crystal.

The laser operation of heavily doped crystals with erbium concentration up to 4 at.% ($2.2 \cdot 10^{20} \text{ cm}^{-3}$) was realized. By using of Er(2 at.%),Yb(11 at.%):YAl₃(BO₃)₄ crystal a maximal continuous-wave (CW) output power of 1.6 W was obtained at 1522 nm with slope efficiency of 32 %. By using of Er(4 at.%),Yb(11 at.%):YAl₃(BO₃)₄ crystal a maximal peak output power up to 2.2 W with slope efficiency of 40 % was realized in quasi-continuous-wave regime of operation. The spatial profile of the output beam was close to TEM₀₀ mode with $M^2 < 1.2$ during all laser experiments.

Based on the obtained results, it can be concluded that Er,Yb:YAl₃(BO₃)₄ crystals are promising active media for lasers emitting in the spectral range of 1.5–1.6 μm for the usage in laser rangefinder and laser-induced breakdown spectroscopy systems, and LIDARs.

Keywords: erbium, ytterbium, borate crystals, diode-pumped, continuous-wave laser operation.

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Эрбиевый лазер, излучающий в области 1.5 мкм, с высокой выходной мощностью

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Твердотельные лазеры, излучающие в спектральной области 1.5–1.6 мкм, находят широкое применение в дальнометрии, офтальмологии, волоконно-оптических системах и оптической локации. Целью данной работы являлось исследование спектроскопических и генерационных свойств активной среды на основе кристалла бората для указанных лазеров.

Проведено исследование спектроскопических и генерационных свойств кристаллов Er, Yb:YAl₃(BO₃)₄ с различным содержанием ионов-активаторов. В результате определены спектры поперечных сечений поглощения и стимулированного испускания в поляризованном свете. Проведена оценка эффективности переноса энергии от ионов иттербия на ионы эрбия. Максимальная эффективность переноса энергии достигала 97 % для кристалла Er(4 at.%), Yb(11 at.%):YAl₃(BO₃)₄.

Реализована лазерная генерация для кристаллов с высоким содержанием ионов эрбия до 4 ат.% ($2.2 \cdot 10^{20} \text{ см}^{-3}$). При использовании кристалла Er(2 at.%), Yb(11 at.%):YAl₃(BO₃)₄ получен непрерывный режим генерации с максимальной выходной мощностью до 1,6 Вт на длине волны 1522 нм при дифференциальной эффективности 32 %. В квазинепрерывном режиме генерации для кристалла Er(4 at.%), Yb(11 at.%):YAl₃(BO₃)₄ максимальная пиковая мощность достигала 2,2 Вт при дифференциальной эффективности по поглощённой мощности накачки 40 %. Профиль распределения интенсивности в поперечном сечении лазерного пучка хорошо аппроксимировался функцией Гаусса рассчитанное значение параметра распространения лазерного пучка M^2 не превышало 1,2, что соответствует TEM_{00} моде резонатора.

На основе полученных результатов, можно сделать вывод, что данные кристаллы являются перспективными активными средами, для лазеров, излучающих в спектральном диапазоне 1.5–1.6 мкм, для применения в составе систем лазерной дальнометрии, лазерно-искровой эмиссионной спектроскопии и лидаров.

Ключевые слова: эрбий, иттербий, бораты, диодная накачка, непрерывная лазерная генерация.

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Introduction

Laser radiation at 1.5–1.6 μm is located in the eye-safe wavelength range and sensitive region of Ge and InGaAs photodiodes. Other advantages of this radiation are high transparency in atmosphere and fused-silica waveguides. All this makes efficient solid-state laser sources emitting in this spectral range very attractive for compact laser range finding, optical location and fiber-optic communication systems.

The $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition of erbium ions is a simple and reliable method for obtaining 1.5–1.6 μm laser operation. However, erbium ions suffer from low pump absorption at the wavelength of commercially available laser diodes near 980 nm. This fact obliges to use additional co-doping with ytterbium ions that strongly absorb pump radiation and transfer it to the erbium ions. For efficient operation of such Er-Yb co-doped lasers two main spectroscopic conditions should be satisfied. The first is short lifetime of the $^4I_{11/2}$ energy level that prevents up-conversion processes and depopulation of this level by means of energy back transfer. The second condition is high enough $^4I_{13/2}$ level lifetime to keep quite low laser threshold. These conditions are well satisfied in Er,Yb-glasses, but the glasses suffer from poor thermo-mechanical properties (thermal conductivity of $0.85 \text{ W} \times \text{m}^{-1} \times \text{K}^{-1}$) [1], which limits the CW output power by a few hundred milliwatts. A maximal CW output power for Er,Yb-glasses didn't exceed 353 mW with slope efficiency of 26 % [2].

The borate crystals co-doped with erbium and ytterbium ions satisfy abovementioned spectroscopic characteristics and possess high thermo-mechanical properties (thermal conductivity of Er,Yb:YAl₃(BO₃)₄ is $7.7 \text{ W} \times \text{m}^{-1} \times \text{K}^{-1}$ and $6 \text{ W} \times \text{m}^{-1} \times \text{K}^{-1}$ along a and c axes, respectively) for efficient laser operation [3]. Room-temperature laser operation was demonstrated for following Er,Yb-codoped borate crystals: GdCa₄O(BO₃)₃ [4], LaSc₃(BO₃)₄ [5], YCa₄O(BO₃) [6], GdAl₃(BO₃)₄ [7, 8], LuAl₃(BO₃)₄ [9]. Efficient high power laser performance of diode-pumped Er,Yb:YAl₃(BO₃)₄ (YAB) crystals was demonstrated recently [10–12]. The maximal output power up to 1 W with slope efficiency of 35 % at several wavelengths between 1522 and 1602 nm was obtained using crystal with dopant concentrations of 1.5 at.% ($0.8 \cdot 10^{20} \text{ cm}^{-3}$) for erbium and 11 at.% ($6.0 \cdot 10^{20} \text{ cm}^{-3}$) for ytterbium ions, respectively [10]. However, the optimization

of erbium concentration and determination of its influence on the laser performance for oxoborate crystals weren't performed. Here we present the investigation of the effect of erbium concentration on the laser performance of Er,Yb:YAl₃(BO₃)₄ crystals and as a result efficient laser operation at near 1.5 μm .

Crystal growth and spectroscopic properties

Er,Yb:YAl₃(BO₃)₄ single crystals with different erbium concentrations were grown by dipping seeded high-temperature solution growth at a cooling rate 0.2 °C–0.5 °C per day in the temperature range of 1060 °C–1000 °C using K₂Mo₃O₁₀-based flux [13]. As a result, Er,Yb:YAB crystals with high optical quality and the size up to 20×10×10 mm have been obtained. The concentrations of the dopants were measured by microprobe analysis to be $0.8 \cdot 10^{20} \text{ cm}^{-3}$ (1.5 at.%), $1.1 \cdot 10^{20} \text{ cm}^{-3}$ (2.0 at.%), $1.7 \cdot 10^{20} \text{ cm}^{-3}$ (3.0 at.%) and $2.2 \cdot 10^{20} \text{ cm}^{-3}$ (4.0 at.%) for erbium and $6.0 \cdot 10^{20} \text{ cm}^{-3}$ (11 at.%) for ytterbium ions.

The polarized absorption cross-section spectra of Er,Yb:YAB crystal around 980 nm at room-temperature are depicted in Figure 1. The $^2F_{7/2} \rightarrow ^2F_{5/2}$ absorption band is centered at 976 nm with a maximum absorption cross-section of about $2.75 \times 10^{-20} \text{ cm}^2$ and bandwidth of 17 nm (FWHM) in σ polarization.

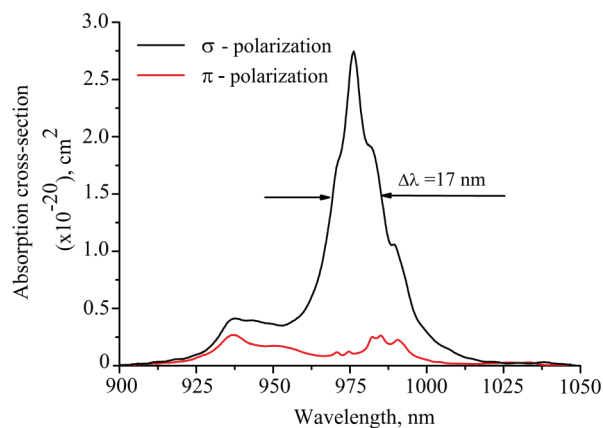


Figure 1 – Room-temperature polarized absorption spectra of Er,Yb:YAB crystal at 1 μm

The stimulated emission cross-section spectra calculated by the reciprocity method using the Stark energy level scheme of $^4I_{13/2}$ and $^4I_{15/2}$ manifolds [3] are plotted in Figure 2. A number of local maxima are observed in both σ and π polarizations.

The energy transfer efficiency was measured by the estimation of $^2F_{5/2}$ level lifetime shortening

in Er,Yb-codoped and Yb-single doped crystals according to the formula [6]:

$$\eta = k/\tau^{-1} = \tau(1/\tau - 1/\tau_0),$$

where k is the energy transfer rate, τ is the ytterbium ${}^2F_{5/2}$ level lifetime in Er,Yb-codoped crystal, and τ_0 is the ytterbium ${}^2F_{5/2}$ level lifetime in Yb single-doped crystal.

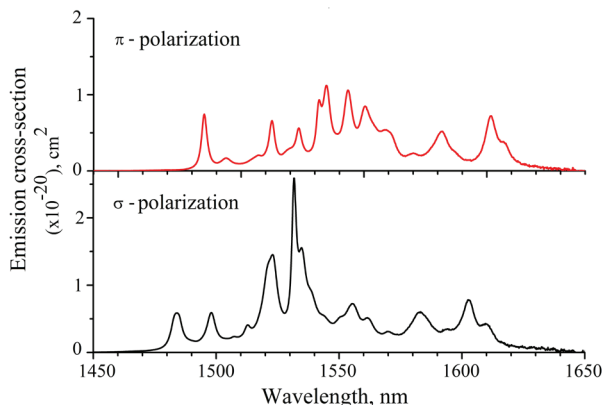


Figure 2 – Emission cross-section spectra of Er,Yb:YAB crystal near 1.5 μm

The values of energy transfer efficiencies in Er,Yb:YAB crystals with different erbium and constant ytterbium concentrations are shown in Table 1. The energy transfer efficiency amplifies with the increasing of erbium concentration up to the value of 97 % for Er(4 at.%),Yb(11 at.%):YAB crystal.

Table 1

The energy transfer efficiencies in Er,Yb:YAB crystals

Crystal	Er ³⁺ ions, at. %	Yb ³⁺ ions, at. %	² F _{5/2} , μs (Yb single-doped)	² F _{5/2} , μs (Yb,Er co-doped)	Energy transfer efficiency, %
	1.5			60	88
YAB	2.0	11.0	480	30	94
	3.0			20	96
	4.0			17	97

Laser experiments

The laser experiments were performed in Z-shaped cavity. The details of active elements used during laser experiments are plotted in Table 2.

The temperature of mounted on the thermoelectrically cooled copper heatsink active

elements was kept at 18 °C. As a pump source a 15 W fiber-coupled (Ø 105 μm, NA = 0.22) laser diode emitting near 976 nm was used. Pump beam was collimated by a 80 mm focal length doublet and then focused into 100 μm spot inside Er,Yb:YAB crystal with another 80 mm length doublet. The cavity-mode diameter at the active element was close to the pump beam waist. The output couplers with the transmittance of 1 %, 2 %, 5 % and 10 % were used during laser experiments. The setup for laser experiments is presented in Figure 3.

Table 2

The details of active elements

Crystal	Er ³⁺ ions, at. %	Yb ³⁺ ions, at. %	Width, mm	Orientation
	1.5			c-cut
YAB	2.0	11.0	1.5	c-cut
	3.0			c-cut
	4.0			a-cut

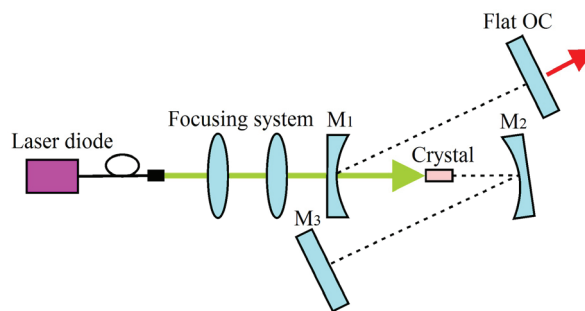


Figure 3 – Setup for laser experiments

The laser experiments were started with Er(1.5 at.%),Yb(11 at.%):YAB crystal, which was studied in our previous investigations [10, 14]. The best laser performance was demonstrated with 5 % output coupler transmittance. Input-output characteristics of continuous-wave laser are plotted in Figure 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 (Figure 4).

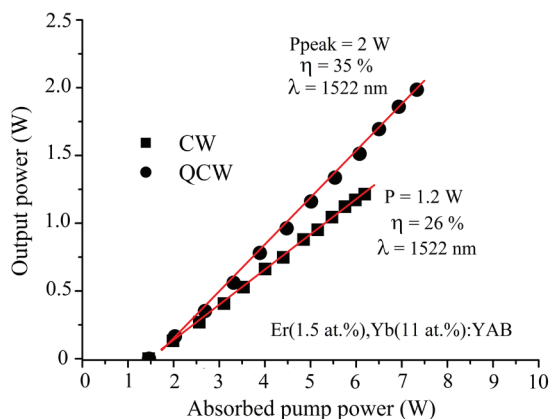


Figure 4 – Input-output characteristics of CW and QCW Er(1.5 at.%), Yb(11 at.%):YAB diode-pumped laser

For Er(2 at.%), Yb(11 at.%):YAB the CW laser emission with a slope efficiency of near 27 % was observed at 1543 nm and 1.7 W laser threshold of absorbed pump power; however at an absorbed pump power of more than 4 W the emission wavelength switched to 1522 nm and the slope efficiency was increased to 32 %. The maximal output power of 1.6 W was obtained in that case. The similar situation with switching of emission wavelength was observed for QCW regime of operation at an absorbed pump peak power of more than 5.5 W. The maximal output peak power of 2.7 W with slope efficiency up to 41 % was obtained at an absorbed pump peak power of more than 9 W (Figure 5). The wavelength switching can be explained by the laser wavelength dependence on the inversion density (or intracavity losses). The intracavity losses depend on the output coupler transmittance and thermal effects inside the pumped volume of the crystal. Changes in the losses during laser operation may lead to changing of the wavelengths [7, 15].

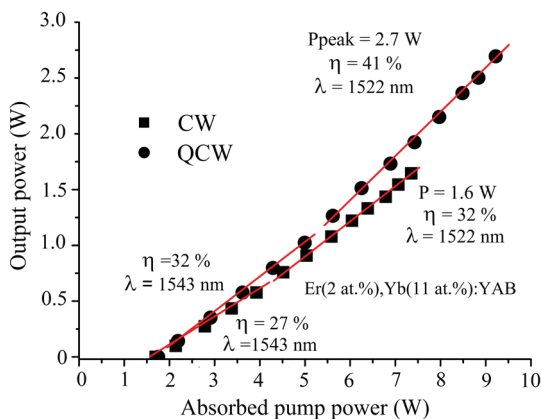


Figure 5 – Input-output characteristics of CW and QCW Er(2 at.%), Yb(11 at.%):YAB diode-pumped laser

Figure 6 shows input-output diagrams of CW and QCW Er(3 at.%), Yb(11 at.%):YAB diode-pumped laser. For CW operation the slope efficiency was reduced to 23 %. The maximal output power of 0.5 W in this case was limited by the damage of active element. To our mind, this damage can be caused by the residual internal stress for highly erbium doped crystals. 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.

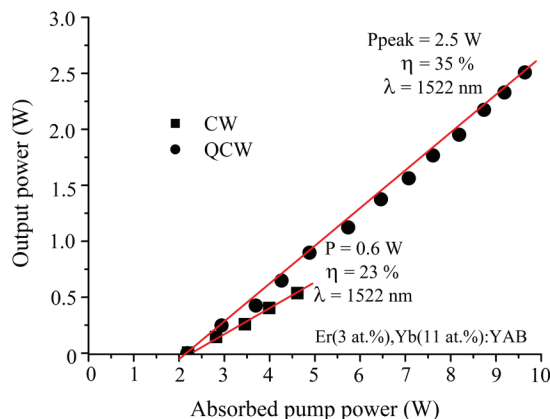


Figure 6 – Input-output characteristics of CW and QCW Er(3 at.%), Yb(11 at.%):YAB diode-pumped laser

Laser experiments in QCW regime of operation were held with available a-cut Er(4 at.%), Yb(11 at.%):YAB crystal. In case of usage c-cut and a-cut crystals the lasers demonstrate close slope efficiencies at the slightly different wavelengths (1522 and 1531 nm), respectively [10, 14]. 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 (Figure 7).

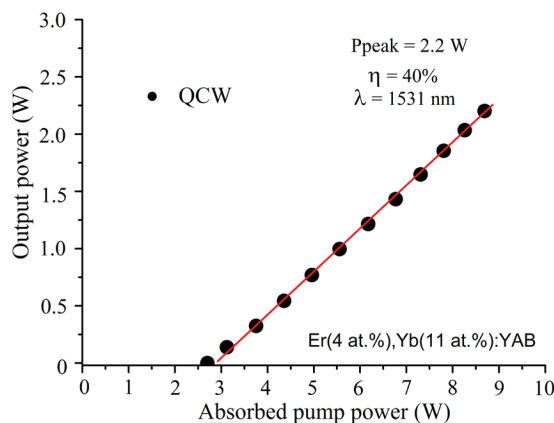


Figure 7 – Input-output characteristics of QCW Er(4 at.%), Yb(11 at.%):YAB diode-pumped laser

Laser characteristics of Er,Yb:YAl₃(BO₃)₄ crystals with different erbium concentrations are plotted in Table 3. The highest slope efficiency was demonstrated with the output coupler transmittance of 5 % for crystals with different erbium concentrations. The increasing of the laser threshold values up to

2.6 W for crystal with the erbium concentration of 4 at.% was observed. This fact is explained by the increasing of reabsorption losses because of quasi-three level scheme of laser operation. The spatial profile of the output beam was close to TEM₀₀ mode with $M^2 < 1.2$ during all laser experiments.

Table 3

Laser performance of Er,Yb:YAB crystal with different erbium concentrations

Crystal	Er ³⁺ ions, at. %	Yb ³⁺ ions, at. %	CW		QCW			
			P _{abs} , W	η, %	P _{max} , W	P _{abs} , W	η, %	P _{max} , W
YAB	1.5	11.0	1.4	26	1.2	1.4	35	2
	2.0		1.7	32	1.6	1.7	41	2.7
	3.0		2.2	23	0.6	2.2	35	2.5
	4.0		–	–	–	2.6	40	2.2

Conclusion

In conclusion, the effect of high erbium concentration on the laser performance of Er,Yb:YAB crystals was investigated. The results demonstrate that there is no degradation of QCW laser performance for erbium concentration up to $2.2 \cdot 10^{20} \text{ cm}^{-3}$ (4.0 at.%). It is rather different in comparison with Er,Yb-glasses where decreasing of laser slope efficiency begins from the erbium concentration of $1.0 \cdot 10^{20} \text{ cm}^{-3}$ [4]. Maximal CW output power of 1.6 W with slope efficiency of 32 % and QCW peak output power of 2.7 W with slope efficiency of 41 % was obtained for Er(2 at.%),Yb(11 at.%):YAB crystals. The obtained result shows the prosperity of Er,Yb:YAB crystal usage as an active medium of eye-safe 1.5–1.6 μm lasers for rangefinding applications.

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