# Continuous-wave Laser on Er,Yb-Codoped Pentaborate Crystal

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## Abstract

We report, for the first time to our knowledge, a diode-pumped continuous-wave microchip Er,Yb:$YMgB_5O_{10}$ laser. The purpose of this work was to study the growth technique, spectroscopic properties and continuous-wave laser performance of $Er^{3+}$,$Yb^{3+}$:$YMgB_5O_{10}$ novel crystal.

Absorption and luminescence spectra as well as kinetics of luminescence decay were studied. Ytterbium-erbium energy transfer efficiency was determined. The output characteristics (output power, slope efficiency, laser wavelength) of $Er^{3+}$,$Yb^{3+}$:$YMgB_5O_{10}$ laser were determined.

Two intensive absorption bands with peaks centered at 937 nm and 976 nm were observed in the absorption spectra at the wavelength near 1 μm. The maximum value of absorption cross-section was determined to be $1.5 \cdot 10^{-20}$ $cm^2$ at 976 nm for polarization $E//N_g$. A number of narrow lines were observed in the absorption spectra in the 1425–1575 nm spectral range (transition $^4I_{15/2} \rightarrow {}^4I_{13/2}$ of erbium ions). The lifetime of the upper laser level $^4I_{13/2}$ of $Er^{3+}$ ions was determined to be 390 ± 20 μs. The ytterbium-erbium energy transfer efficiency for $YMgB_5O_{10}$ crystal with 2 at.% of $Er^{3+}$ and 11 at.% for $Yb^{3+}$ was close to 84 %. The maximal continuous-wave output power of 0.2 W with slope efficiency of 8 % regarding to absorbed pump power was realized at the wavelength of 1570 nm. With the improvement of cavity parameters the output laser performance of the Er,Yb:$YMgB_5O_{10}$ crystal can be further enhanced.

Taking into account high thermal conductivity of ≈ 6.2 $W \cdot m^{-1} \cdot K^{-1}$, the Er,Yb:$YMgB_5O_{10}$ crystal can be considered as a good gain medium for 1.5 μm lasers for applications in laser rangefinder and LIDAR systems.

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

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# Непрерывный лазер на кристалле пентабората, соактивированного ионами эрбия и иттербия

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Впервые сообщается о непрерывном лазере на кристалле Er,Yb:$YMgB_5O_{10}$ с диодной накачкой. Изучены условия синтеза кристаллов, спектры поглощения и люминесценции, кинетики затухания люминесценции. Определена эффективность переноса энергии от ионов иттербия к ионам эрбия. Определены выходные характеристики (выходная мощность, дифференциальный КПД, длина волны генерации) лазера на основе кристалла $Er^{3+}$,$Yb^{3+}$:$YMgB_5O_{10}$.

В спектрах поглощения в области 1 мкм наблюдаются две интенсивные полосы поглощения с пиками на длинах волн 937 нм и 976 нм. Максимальное поперечное сечение поглощения достигает $1.5 \cdot 10^{-20}$ см$^2$ на длине волны 976 нм для поляризации $E//N_g$. В спектре поглощения в спектральной области 1425–1575 нм наблюдается набор узких полос поглощения. Измеренное время жизни верхнего уровня $^4I_{13/2}$ ионов $Er^{3+}$ составило 390 ± 20 мкс. Эффективность переноса энергии от ионов иттербия к ионам эрбия для кристалла Er(2 ат.%),Yb(11 ат.%):$YMgB_5O_{10}$ достигала 84 %. Максимальная выходная мощность лазерной генерации на длине волны 1570 нм составила 0,2 Вт при дифференциальном КПД 8 %.

Благодаря высокой теплопроводности ($\approx 6.2$ Вт·м$^{-1}$·К$^{-1}$) кристалла Er,Yb:$YMgB_5O_{10}$, он может быть с успехом использован в качестве активной среды для лазеров дальномерных систем и ЛИДАРов.

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

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## Introduction

Nowadays eye-safe lasers emitting in 1.5–1.6 μm spectral range find application in LIDAR systems for robots, self-driving cars, etc. due to its eye-safety and high transparency of the atmosphere. Currently, many sources are emitting in this spectral range, but solid-state lasers on $Er^{3+}$ and $Yb^{3+}$-codoped crystals are of greatest interest. Phosphate glasses currently are the leading $Er^{3+}$, $Yb^{3+}$-codoped laser materials, because they combine very efficient energy transfer from $Yb^{3+}$ to $Er^{3+}$ ions ($\eta \approx 90$ %) with a long lifetime of the erbium upper laser level $^4I_{13/2}$ (7–8 ms) and short lifetime of the $^4I_{11/2}$ energy level (2–3 μs), which prevents the depopulation of this level because of excited-state absorption and upconversion processes [1]. However, phosphate glass has poor thermomechanical properties (a thermal conductivity of 0.85 $W \cdot m^{-1} \cdot K^{-1}$) [2], which limits the average output power of Er,Yb:glass lasers because of the thermal effects. A maximal continuous-wave (CW) output power did not exceed 353 mW with a slope efficiency of 26 % [3]. For this reason, the search for new crystalline hosts for Er,Yb-codoping is ongoing.

Due to their spectroscopic characteristics and high thermal conductivity, Er,Yb-codoped borate crystals are most widely used crystalline laser media for lasers operating in the 1.5–1.6 μm spectral range. To date, effective laser operation has been obtained by using various erbium, ytterbium codoped borate crystals [4–9]. By using of Er,Yb:$GdAl_3(BO_3)_4$ crystal the maximal output power in continuous-wave mode exceeded 1.5 W with the slope efficiency of about 35 % [9]. Recently, one more borate crystal $YMgB_5O_{10}$ (YMBO) has been regarded as a potential laser host material owing to large thermal conductivity ($6.2 \pm 0.3$ $W \cdot m^{-1} \cdot K^{-1}$) and good optical properties [10]. Moreover, in comparison with huntite-type borates, YMBO bulk crystals of large enough with good optical quality can be obtained reproducibly by optimizing the crystal growth conditions.

In this paper the laser related spectroscopy and, for the first time to our knowledge, continuous-wave laser performance of Er,Yb:$YMgB_5O_{10}$ crystal are presented.

## Experimental details

### *Crystal growth*

Er,Yb:YMBO (Er = 2.0 at.%, Yb = 11 at.%) single crystals were obtained by high-temperature solution growth on dipped seeds (SGDS) from $K_2Mo_3O_{10}$ flux melt. The ratio of the raw materials was Er,Yb:$YMgB_5O_{10}$: $K_2Mo_3O_{10}$ = 80:20 wt.%. The growth technique follows Ref. [10]. The chemicals used (at least 99.996 % and 99.99 % purity for rare earth and other materials, respectively) were $R_2O_3$ (R = Y, Yb, Er), MgO and $B_2O_3$, but $K_2Mo_3O_{10}$ was previously sintered from $K_2MoO_4$ (99.0 %) and $H_2MoO_4$ (99.5 %) at 650 °C for 24 h by a scheme:

$$K_2MoO_4 + 2H_2MoO_4 \rightarrow K_2Mo_3O_{10} + 2H_2O\uparrow. \quad (1)$$

The starting charge was placed into a platinum crucible of 250 ml in volume and heated to a maximum temperature which is normally 100–150 °C above the expected saturation point. After the solution homogenization within 10–20 hours, the saturation temperature ($T_{sat}$) was accurately determined by dipping a trial YMBO crystal in the solution, and it was kept at constant temperature by observing growth/dissolution of the crystal face at different temperatures. The $T_{sat}$ were found from the experimental data on changes both in weight and micro-relief of the probe seeds after soaking in fluxed melts from 10 min to several hours, depending on an expected deviation from their equilibrium state. The obtained value of $T_{sat}$ was about ≈ 950 °C for the solute concentration being investigated. As a result visually macrodefect-free Er,Yb:YMBO single crystal was grown. The dimensions of the crystal obtained were typically 20×15×10 mm (Figure 1).

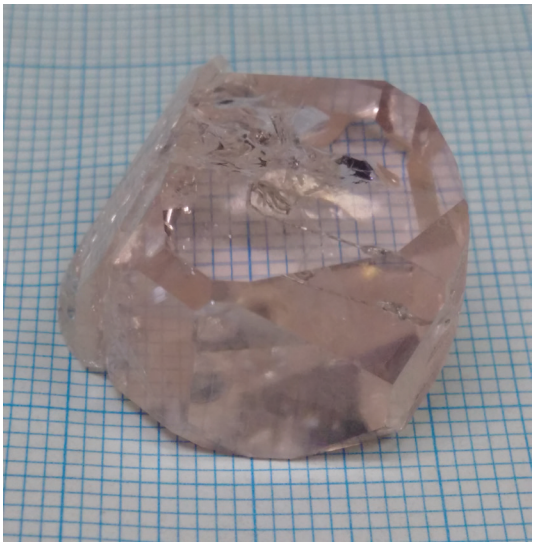

**Figure 1** – The Er,Yb:YMBO crystal grown by the SGDS method

### *Investigation of spectroscopic characteristics*

In our study polarized absorption spectra of Er,Yb:YMBO crystal at room temperature were registered by a Varian CARY-5000 spectrophotometer in the spectral ranges 875–1025 nm and 1425–1575 nm. The spectral bandwidth was 0.5 nm. Two polished plates with dimensions of 5×7×2 $mm^3$ oriented along three principal optical indicatrix axes $N_g$, $N_m$ and $N_p$ were used. The concentration of doping ions in the crystal was determined by means of a Tescan VEGA II LMU scanning electron microscope with Oxford INCA Energy 350 energy dispersive x-ray analyzer to be $1.4 \cdot 10^{20}$ $cm^{-3}$ of $Er^{3+}$ and $9.8 \cdot 10^{20}$ $cm^{-3}$ $Yb^{3+}$.

The lifetime measurements were performed using an optical parametric oscillator based on a β-$Ba_2B_2O_4$ crystal and pumped by the third harmonic of a Q-switched Nd:YAG laser. The fluorescence from the sample was collected on the entrance slit of a monochromator and registered by an InGaAs photodiode coupled with a 500 MHz digital oscilloscope. It is well known that radiation trapping strongly influences the fluorescence dynamics of ytterbium ions because of the significant overlap of the absorption and emission bands. To prevent reabsorption the measurements of $Yb^{3+}$ luminescence kinetics were performed using a fine powder of the crystals immersed in glycerin [11].

The energy transfer efficiency was determined by estimation of the $^2F_{5/2}$ level lifetime shortening in Er,Yb-codoped crystals and Yb-single doped crystal according to the formula (2) [12]:

$$\eta = \tau(1/\tau - 1/\tau_0), \quad (2)$$

where τ is the ytterbium $^2F_{5/2}$ level lifetime in Er,Yb-codoped crystal; $\tau_0$ is the ytterbium $^2F_{5/2}$ level lifetime in Yb single-doped crystal.

Luminescence spectra were registered at room temperature using an experimental setup that ensured synchronous detection of the optical signal. The excitation source was a semiconductor laser diode emitting at the wavelength near 976 nm. The luminescence was detected by an InGaAs photodetector. Its signal was processed by a lock-in amplifier. The output signal of the amplifier was digitized using an analog-to-digital converter and stored on a computer.

### *Setup for continuous-wave laser experiments*

A plane–plane $N_p$-cut Er,Yb:YMBO crystal with a length of 2 mm was used as an active medium. The polished facets of the crystal were antireflection-coated for both pump (900–1100 nm) and laser (1500–1650 nm) wavelengths. The active element was wrapped in indium foil for good thermal contact and mounted between two copper slabs with the hole in the center to permit passing of pump and laser beams. The temperature of an active element was kept at 20 °C. As a pump source a 976 nm fiber coupled laser diode (Ø105 μm, NA = 0.22) was used. The plano-plano cavity with geometrical cavity length not exceeding 5 mm was adopted. The one-lens focusing system focused the pump beam into a 120-μm spot inside the laser crystal with the confocal parameter of 2.3 mm. Three output couplers with different transmittances at the laser wavelengths were used during laser experiments. The laser setup is shown in Figure 2.

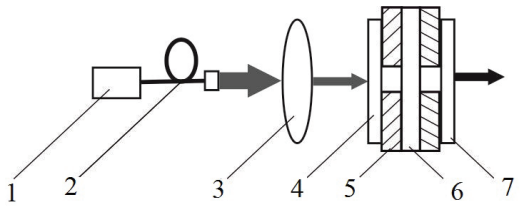


**Figure 2** – The experimental setup of a continuous wave diode-pumped Er,Yb:YMBO laser: 1 – laser diode; 2 – fiber; 3 – focusing system; 4 – input mirror; 5 – copper heatsink; 6 – active element; 7 – output coupler

## Results and discussion

### *Spectroscopy*

The room-temperature polarized absorption cross-section spectra of the Er,Yb:YMBO crystal in the spectral range of 875–1025 nm (transitions of $^2F_{7/2} \rightarrow {}^2F_{5/2}$ of $Yb^{3+}$ ions and $^4I_{15/2} \rightarrow {}^4I_{11/2}$ of $Er^{3+}$ ions) are shown in Figure 3. Two intensive absorption lines with peaks centered at 937 nm and 976 nm are observed. These peaks coincide with the emission wavelengths of commercial available InGaAs laser diodes. The maximum value of absorption cross-section was determined to be $1.5 \cdot 10^{-20}$ $cm^2$ at 976 nm with the bandwidth (FWHM) of about 3.5 nm for polarization $E//N_g$ axis. Thus, the pump beam polarization corresponded to the $N_g$ axis of the crystal will be preferable for laser experiments.

Figure 4 shows the room-temperature polarized absorption spectra of Er,Yb:YMBO crystal in the 1425–1575 nm spectral range (transition $^4I_{15/2} \rightarrow {}^4I_{13/2}$ of erbium ions). A number of narrow lines are observed for three polarizations. The maximum value of absorption cross-section was determined to be $1.6 \cdot 10^{-20}$ $cm^2$ at 1482 nm for polarization $E//N_m$ axis.

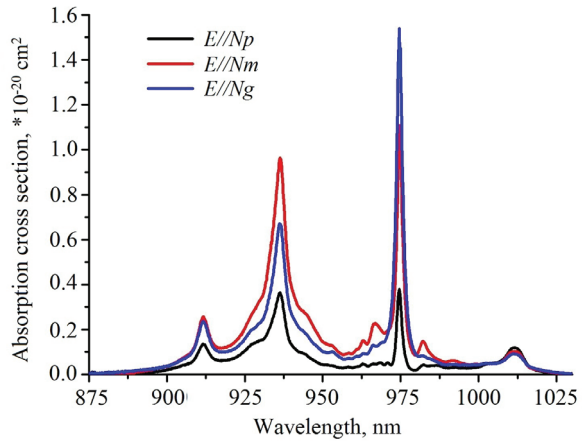


**Figure 3** – Polarised absorption cross-section spectra of Er,Yb:YMBO crystal at near 1 μm

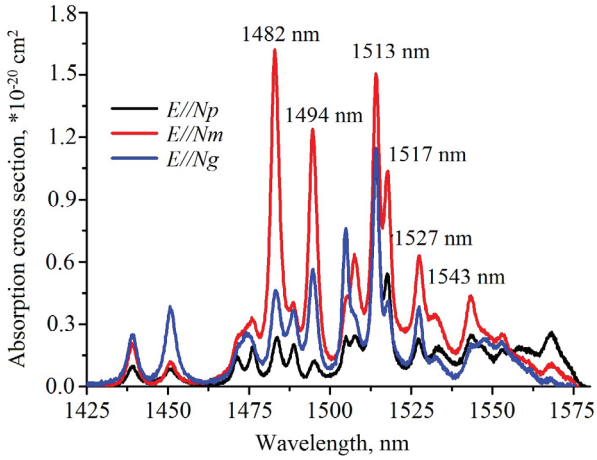


**Figure 4** – Polarised absorption cross-section spectra of Er,Yb:YMBO crystal at near 1.5 μm

The measured decay curve of 1.5 μm emission was single exponential (Figure 5), and the luminescence decay time of the $^4I_{13/2}$ level was obtained to be about 390 ± 20 μs.

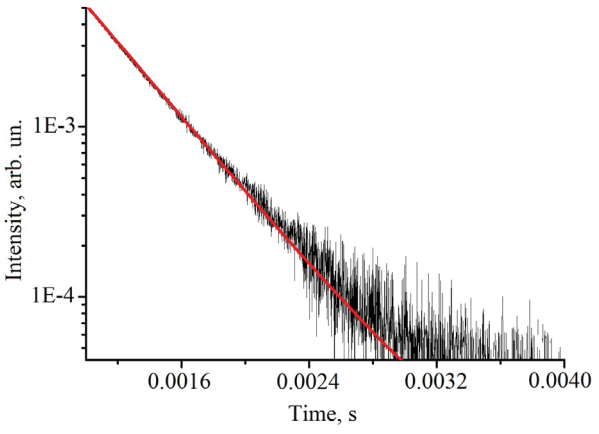


**Figure 5** – Kinetics of luminescence decay of Er,Yb:YMBO in the region of about 1.5 μm

The dependence of obtained lifetimes of $^2F_{5/2}$ energy level on different weight content of Yb(1 at.%):YMBO crystalline powders in glycerin suspension is presented in Figure 6. The fluorescence lifetime decreased with the decreasing of powder concentration in suspension. Starting from a certain powder content, the lifetime remained constant despite further dilution, which indicates negligible reabsorption influence. The $^2F_{5/2}$ energy level lifetime of ytterbium ions was measured to be 580 ± 10 μs.

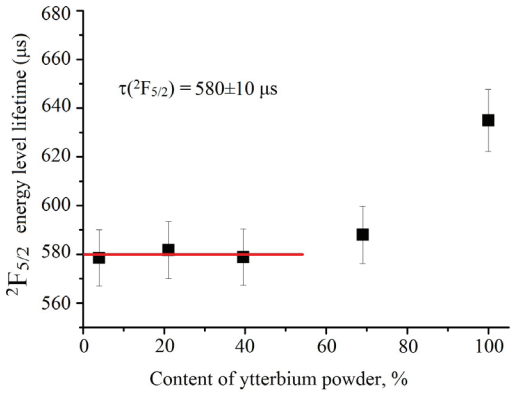


**Figure 6** – The $^2F_{5/2}$ energy level lifetimes of Yb(1 at.%):YMBO crystal

The $^2F_{5/2}$ energy level lifetime of $Yb^{3+}$ was measured to be 95 ± 5 μs in Er(2 at.%),Yb(11 at.%):YMBO. By using formula (2) the energy transfer efficiency from ytterbium to erbium ions was calculated to be about 84 %. It should be mentioned that the energy transfer efficiency in Er,Yb:YMBO is similar to those in Er,Yb:YAB and Er,Yb:GdAB crystals [8, 9].

The polarised luminescence spectra of the Er,Yb:YMBO crystal (Figure 7) measured at room temperature are characterized by a structured bands in the spectral range 1450–1650 nm.

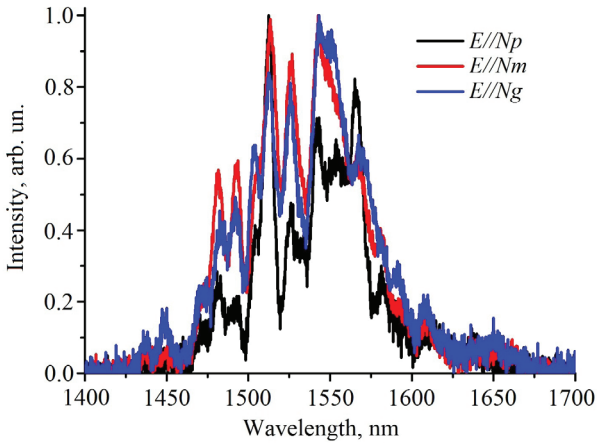


**Figure 7** – Polarised luminescence spectrum of the Er,Yb:YMBO crystal

### *Laser characteristics of* Er,Yb:YMBO *crystal*

Input-output characteristics of continuous-wave diode-pumped microchip Er,Yb:YMBO laser are plotted in Figure 8. The best laser performance was demonstrated with the 2 % output coupler transmittance. The laser threshold was measured to be about 2 W of absorbed pump power. The maximum CW output power of 200 mW with the slope efficiency near 8 % was obtained at 1570 nm at about 4.7 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 our mind, with the improvement of cavity parameters the output laser performance of the Er,Yb:$YMgB_5O_{10}$ crystal can be further enhanced.

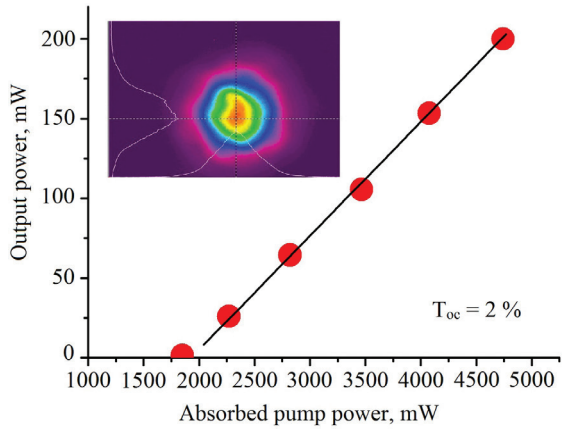


**Figure 8** – The laser performance of Er,Yb:YMBO crystal in continuous-wave mode

The laser radiation was linearly polarized ($E//N_m$). The laser wavelength was measured to be 1570 nm. The spatial profile of the output beam measured at 4.5 W of absorbed pump power is presented in the inset in Figure 8.

## Conclusion

In conclusion, a continuous-wave diode-pumped Er,Yb:YMBO laser with output power of 200 mW and slope efficiency of 8 % at near 1570 nm was realized for the first time to our knowledge. Absorption and luminescence spectra, emission lifetimes, and efficiencies of energy transfer from $Yb^{3+}$ to $Er^{3+}$ ions were determined.

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