Efficient 1 W continuous-wave diode-pumped $Er,Yb:YAl_3(BO_3)_4$ laser

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We report the spectroscopy and high-power continuous-wave (CW) diode-pumped laser operation of $Er:Yb:YAl_3(BO_3)_4$ crystal. Absorption and stimulated emission spectra, emission lifetimes, and efficiency of energy transfer from Yb^{3+} to Er^{3+} ions were determined. A CW Er:Yb:YAB laser emitting at 1602, 1555, and 1531 nm with output power as high as 1 W and slope efficiency up to 35% was demonstrated. © 2007 Optical Society of America

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Efficient continuous-wave (CW) and *Q*-switched solid-state lasers emitting in the eye-safe 1.5 μm spectral region are very promising for many practical applications, including range finding, environmental sensing, aerial navigation, telecommunications, and medicine. Nowadays various Er:Yb codoped glasses (in particular, phosphate) are mostly used as gain media in this type of laser. Spectroscopic properties of Er,Yb glasses make them very efficient 1.5 μm laser materials: the short $^4I_{11/2}$ level lifetime minimizes excited state absorption and upconversion losses, whereas the high luminescence quantum yield from the $^4I_{13/2}$ level provides high laser efficiency. However, glasses suffer from low thermal and mechanical stability that limits the laser power to the level of a few hundred milliwatts due to the thermal lensing effects and optical damage of the active element. This is why the search for an efficient crystalline host for Er doping is of high interest.

CW room-temperature 1.5–1.6 μm lasing has been demonstrated for several Er-doped and Er,Yb-codoped crystals, including $Y_3Al_5O_{12}$ [1], Y_2SiO_5 [1], $Ca_2Al_2SiO_7$ [2], YVO_4 [3], $LaSc_3(BO_3)_4$ [4], and $KY(WO_4)_2$ [5], but typical output power was below 150 mW in combination with poor slope efficiency. To our knowledge, the most efficient diode-pumped laser action to date has been demonstrated in Yb,Er-activated oxoborates: 250 mW of cw output power with 26.8% efficiency for $YCa_4O(BO_3)_3$ [6] and 158 mWwith 14% efficiency for $GdCa_4O(BO_3)_3$ [7].

$YAl_3(BO_3)_4$ crystal is a well-known laser host for Yb and Nd ions [8,9]. For Er-doped YAB, only crystal growth [10], some spectroscopic properties [11,12], and quasi-CW lasing with average output power of about 40 mW were reported in [13]. In this Letter we report the spectroscopy and for the first time to our knowledge high-power CW laser operation of a diode-pumped $Er:Yb:YAl_3(BO_3)_4$ laser crystal.

Er,Yb:YAB crystals with size of 8 mm × 8 mm × 12 mm were obtained by dipping seeded high-temperature solution growth at a cooling rate of 0.2°C–5°C per day in the temperature range of 1060°C–1000°C using $K_2Mo_3O_{10}$-based flux [14]. The concentrations of the dopants were measured by microprobe analysis to be $6\times10^{20}\ \mathrm{cm}^{-3}$(11 at.%) for Yb^{3+} and $0.825\times10^{20}\ \mathrm{cm}^{-3}$(1.5 at.%) for Er^{3+}.

The polarized absorption spectra of Er,Yb:YAB crystal measured in the 900–1050 nm range at room temperature are shown in Fig. 1. The spectral resolution was 0.4 nm. The Yb $^2F_{7/2}\rightarrow{}^2F_{5/2}$ absorption band in σ polarization is comparatively broad (17 nm FWHM) with a maximum absorption cross section of about $2.75\times10^{-20}\ \mathrm{cm}^2$ at 976 nm. In π polarization it is considerably weaker (less than $0.3\times10^{-20}\ \mathrm{cm}^2$).

Figure 2 shows the accurate absorption spectra of Er,Yb:YAB crystal at 1.45–1.65 μm ($^4I_{15/2}\rightarrow{}^4I_{13/2}$ transition of Er). In this spectral range the peaks of the σ-polarized spectrum are generally higher than those of the π-polarized spectrum. The strongest peak with a cross section of $2.75\times10^{-20}\ \mathrm{cm}^2$ is located at 1531 nm.

For lifetime measurements Er(2 at.%):YAB crystal was excited by a Nd:YAG pulse-pumped optical parametric oscillator tuned to 976 nm. Excitation pulse duration was about 20 ns. The fluorescence decay was detected using a 0.3 m monochromator, pho-

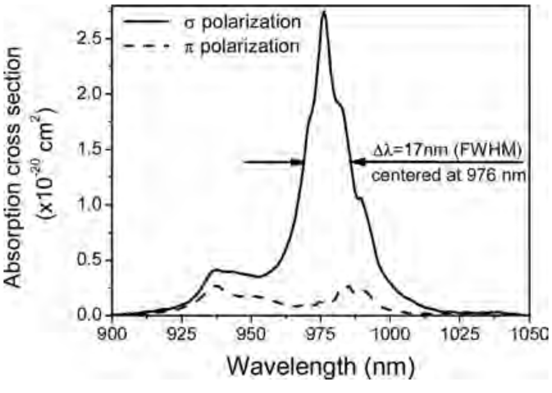

Fig. 1. Room-temperature polarized absorption spectra of Er,Yb:YAB crystal at 1 μm.

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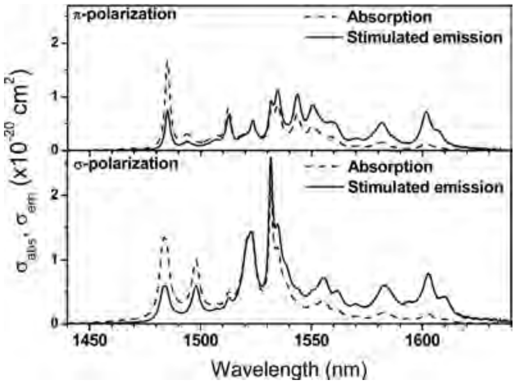

Fig. 2. Room-temperature polarized absorption (dashed curve) and emission (solid curve) spectra of Er,Yb:YAB crystal at 1.45–1.65 μm.

tomultiplier tube with temporal response of about 1 ns and a 500 MHz digital oscilloscope. The decay curve of 1.5 μm emission was single exponential, and the decay time was measured to be about 325 μs, which significantly differs from the value for the radiative lifetime calculated by You *et al.* using Judd–Offelt analysis (4.41 ms [12]). Thus the value for luminescence quantum yield for the Er^{3+} $^4I_{13/2}$ manifold in YAB is estimated to be about 7%. Such a low quantum efficiency is explained by the large phonon energy in YAB (>1400 cm^{-1} [15]) that leads to a high nonradiative $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition probability.

Er $^4I_{11/2}$ level lifetime is an important spectroscopic parameter strongly affecting lasing efficiency of Er,Yb-codoped systems. The short $^4I_{11/2}$ lifetime leads to low Er $^4I_{11/2} \rightarrow {}^4F_{7/2}$ upconversion and Er $\rightarrow$Yb backtransfer probabilities. This lifetime can be estimated by measuring the $^4I_{13/2}$ level rise time in Er single-doped crystal pumped to the $^4I_{11/2}$ level. We obtained a $^4I_{11/2}$ level lifetime of about 80 ns in Er:YAB, which is significantly shorter than in $Y_3Al_5O_{12}$ (100 μs, [1]), Y_2SiO_5 (16 μs, [1]), YVO_4 (28 μs, [3]), and phosphate glasses (2–3 μs, [16]).

Yb $^2F_{5/2}$-level luminescence decay was measured in Yb single-doped YAB as well as in Er,Yb codoped crystal using the same experimental configuration with the photomultiplier tube replaced by an InGaAs photodiode. To prevent radiation trapping (reabsorption) caused by significant overlap of the absorption and emission bands, a fine powder of crystals immersed in glycerin was used [17]. The lifetime of Yb^{3+} ion in Yb(7 at.%):YAB crystal was measured to be 480 μs, whereas in Er(1.5 at.%),Yb(11 at.%):YAB it shortens to 60 μs. The lifetime reduction is a consequence of efficient nonradiative resonant energy transfer from the Yb^{3+} to the Er^{3+} ions. The energy-transfer efficiency was estimated according to the formula $\eta = k/\tau^{-1} = \tau(1/\tau - 1/\tau_0)$ [18], where k is the energy transfer rate, τ is the Yb lifetime in Yb,Er codoped crystal, and τ_0 is the Yb lifetime in Yb single-doped crystal. For Er(1.5 at.%),Yb(11 at.%):YAB crystal the energy-transfer efficiency η was determined as 88%. The energy transfer in YAB is more efficient than in vanadates [3] and tungstates [5], but less efficient than in several borates [18,19], which denotes the necessity of further dopant concentration optimization.

The stimulated emission cross-section spectra were calculated by the reciprocity method using the measured absorption spectra and the data on Stark splitting of the upper and lower laser levels obtained by Földvári *et al.* [11]. Spectra are plotted in Fig. 2. The highest stimulated emission cross section of about 2.6×10^{-20} cm^2 is located at 1531 nm. From the σ-polarized gain cross-section curves (Fig. 3), calculated as $g(\lambda) = \beta\sigma_{em} - (1-\beta)\sigma_{abs}$ (β is the ratio of the number of excited ions to the total number of ions), one can conclude that laser emission at low inversion is expected at the wavelength of 1602 nm. For the inversion parameter β of 0.55 lasing should be possible within the range from 1520 to 1630 nm.

The laser experiments were performed in a three-mirror cavity (Fig. 4) consisting of a flat input mirror (M1), a 100 mm radius of curvature folding mirror (M2), and a flat output coupler (M3). The input mirror was deposited onto a surface of a 1.5 mm long c-cut Er(1.5 at.%),Yb(11 at.%):YAB crystal, whereas the second face of the crystal was antireflection coated at 1.4–1.6 μm. As a pump source a 7 W fiber-coupled (Ø = 105 μm, NA = 0.22) laser diode (LD) emitting near 976 nm was used. The pump beam was collimated and then focused by two antireflection-

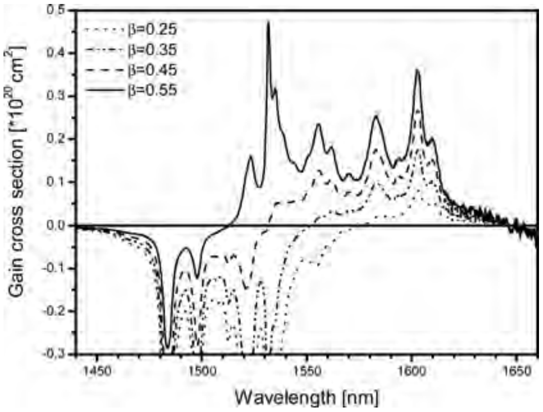

Fig. 3. σ-polarized gain coefficient curves for Er,Yb:YAB crystal at 1.45–1.65 μm for different values of the inversion parameter β.

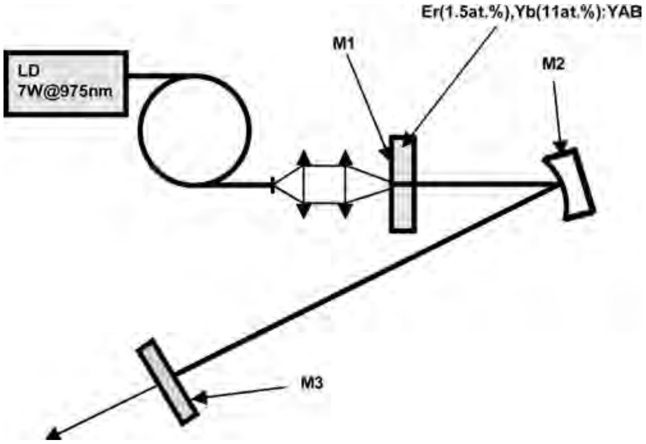

Fig. 4. Cavity setup for laser experiments.

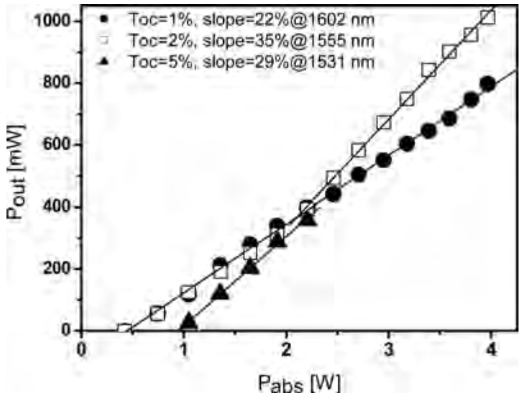

Fig. 5. Input–output characteristics of CW Er, Yb: YAB laser.

coated 80 mm focal length lenses into 110 μm spot inside the crystal. The cavity-mode diameter at the active element was close to the pump beam waist.

Figure 5 shows the input–output diagrams of CW Er, Yb: YAB laser. For output coupler transmittance of 1% the maximum output power of 795 mW with slope efficiency of 22% was obtained at 1602 nm. The laser threshold was about 400 mW of absorbed pump power. With 2% output coupler transmittance for absorbed pump power exceeding 2.5 W the emission wavelength switched from 1602 to 1555 nm, and slope efficiency increased up to 35%, resulting in maximum output power of 1 W. For 5% output coupler transmittance a maximum output power of 360 mW at 1531 nm was obtained with slope efficiency of 29% and laser threshold of about 1 W. The output power in this configuration was limited by the input mirror damage deposited on a crystal surface.

The wavelength switching similar to that observed in the Er, Yb: YAB laser was previously reported for Yb: $GdVO_4$ [20]. The intracavity passive losses depend on the output coupler transmittance and thermal effects inside the small pumped volume of the crystal. Changes in the losses during laser operation may lead to changing of the wavelength of maximum gain resulting in spectral shift of laser output. The exact origin of this behavior is a subject of further investigations.

In conclusion, a CW diode-pumped Er, Yb: YAB laser with output power of about 1 W and slope efficiency up to 35% was realized for the first time to our knowledge without any pump beam chopping. Lasing was obtained at the wavelengths of 1531, 1555, and 1602 nm.

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