СЕКЦИЯ 3. ФИЗИЧЕСКИЕ, ФИЗИКО-МАТЕМАТИЧЕСКИЕ, МАТЕРИАЛОВЕДЧЕСКИЕ И ТЕХНОЛОГИЧЕСКИЕ ОСНОВЫ ПРИБОРОСТРОЕНИЯ

UDC 621.375.826

SPECTROSCOPY AND EFFICIENT LASER OPERATION OF $Er,Yb:GdAl_3(BO_3)_4$ CRYSTAL AT 1.5-1.6 μm

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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. Phosphate glasses currently are the leading Er^{3+},Yb^{3+} co-doped laser materials, because they combine very efficient energy transfer from Yb^{3+} to Er^{3+} ions ($\eta \approx 90$ %) with a long lifetime of 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 by means of excited-state absorption and up-conversion processes. However, phosphate glass has poor thermo-mechanical properties (thermal conductivity of 0.85 $W \times m^{-1} \times K^{-1}$), that limits the average output power of Er,Yb:glass lasers due to the thermal effects. A maximal CW output power didn't exceed 353 mW with slope efficiency of 26 % [1]. For this reason, the search of new crystalline host for Er,Yb-codoping is actual.

The Er,Yb-codoped oxoborate crystals possess abovementioned spectroscopic characteristics and high thermo-mechanical properties for efficient laser operation, that determines high interest in investigation spectroscopic and laser properties of this hosts. Comparatively recently, excellent laser performance of $Er,Yb:YAl_3(BO_3)_4$ (YAB) crystal has been demonstrated. Diode-pumped Er,Yb:YAB laser exhibited a slope efficiency as high as 35 % and output power of 0.8-1 W at several wavelengths between 1531 and 1602 nm [2].

In this work we present the spectroscopy and, for the first time to our knowledge, a high efficient diode-pumped CW laser operation of $Er,Yb:GdAl_3(BO_3)_4$ (GdAB) crystal.

Er,Yb:GdAB single crystals were grown by dipping seeded high-temperature solution growth. The concentrations of the dopants were measured by microprobe analysis to be 1 at. % for Er^{3+} and 8 at. % for Yb^{3+}.

The polarized absorption spectra of Er,Yb:GdAB crystal around 980 nm at room-temperature recorded with a spectrophotometer Cary-5000 are shown in Fig. 1. A strong absorption band corresponding to transition $^2F_{7/2} \rightarrow ^2F_{5/2}$ of Yb^{3+} ions is centered at 976 nm with a maximum absorption cross-section of about 3.6×10^{-20} cm^2 and bandwidth of 18 nm (FWHM) in σ polarization. Due to a comparatively broad absorption band thermal control of the pump laser diode is not necessary.

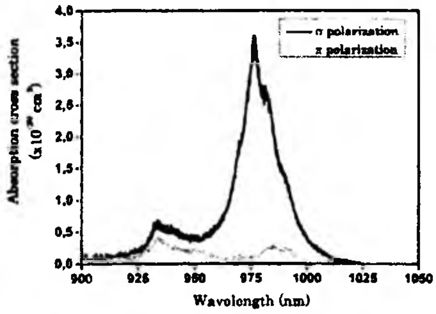

Fig. 1. Room-temperature polarized absorption spectra of Er,Yb:GdAB crystal at 1 μm

Figure 2 shows room-temperature polarized absorption spectra of Er,Yb:GdAB in the 1450-1650 nm spectral range (transition $^4I_{15/2} \rightarrow ^4I_{13/2}$ of erbium ions). A number of local maxima are observed in both σ and π polarizations.

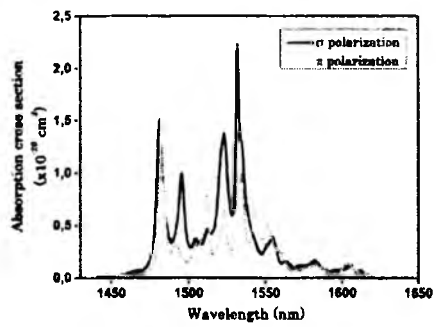

Fig. 2. Room-temperature polarized absorption spectra of Er,Yb:GdAB crystal at 1.5 μm

For lifetime measurements optical parametric oscillator LOTIS LT-2214OPO pumped by Nd:YAG laser with pulse duration of 20 ns was used as an excitation source. The fluorescence decay was registered by InGaAs photodiode and a 500 MHz digital oscilloscope.

The decay curve of 1.5 μm emission was single exponential and luminescence decay time of $^4I_{13/2}$ level was measured to be of about 350 μs. The measured lifetime is significantly shorter than radiative lifetime calculated from the Judd–Offelt analysis (3.72 ms [3]). Thus the luminescence quantum efficiency for the $^4I_{13/2}$ level of Er,Yb:GdAB was estimated to be of about 10%. Such low quantum efficiency is similar to

Er,Yb:YAB (8 % [2]) and explained by the large phonon energy in oxoborate crystals.

The $^2F_{5/2}$ level lifetimes of Yb^{3+} were measured both in Yb-single doped crystal and in Er,Yb:codoped GdAB. To prevent reabsorption caused by significant overlap of the absorption and emission bands all measurements were performed with fine powder of the crystals immersed in glycerin. The lifetime of ytterbium ion in Yb(0.8 at.%):GdAB was measured to be 450 μs. The energy transfer efficiency was measured by the estimation of shortening the $^2F_{5/2}$ level lifetime in Er,Yb-codoped crystals and Yb-single doped crystal. For Er(1 at. %),Yb(8 at. %):GdAB the energy transfer efficiency was determined as 83 %. The energy transfer efficiency in GdAB are similar to that in Er,Yb:YAB and Er,Yb:glass and higher than in vanadates and tungstates.

The stimulated emission cross-section spectra calculated by the integral reciprocity method using the radiative lifetime obtained from Judd-Offelt analysis [3] are shown in Fig.3. The highest stimulated emission cross section of about 2.1×10^{-20} cm^2 is located at 1531 nm.

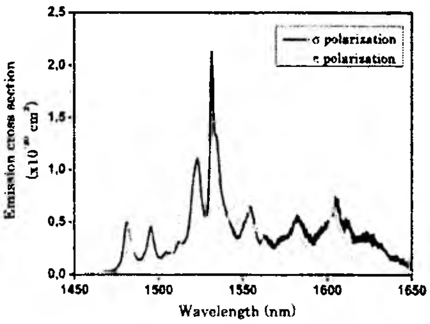

Fig. 3. Emission spectra of Er,Yb:GdAB crystal at 1.45-1.65 μm

The laser experiments were performed in Z-shaped cavity. The plane-plane a-cut Er(1 at. %),Yb(8 at. %):GdAB 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 17°C. As a pump source a 7 W fiber-coupled (Ø 105 μm, NA=0.22) laser diode emitting near 976 nm was used. A combination of two lenses (f_1=100 mm, f_2=80 mm) was used to focus pump beam into the gain medium, and pump beam spot radius was measured to be 45 μm ($1/e^2$ intensity). The cavity setup for laser experiments is presented in Fig. 4.

Input-output characteristics CW Er,Yb:GdAB diode-pumped laser are plotted in Fig. 5. For the output coupler transmittance of 1 % at 1602 nm (2% at 1531nm) the CW π-polarized output at 1602 nm with slope efficiency near 15 % was obtained at absorbed pump power up to 3.4 W and after further increasing of pump power the emission wavelength switched to 1531 nm (σ polarization) with similar slope efficiency. For the output coupler transmittance of 2 % at 1602 nm (4% at 1531nm) the CW π-polarized laser emission with slope efficiency near 19 % was observed at 1602 nm, however at absorbed pump power more than 3 W the emission wavelength again switched to 1531 nm (σ polarization) and slope efficiency was increased drastically to 35 %. The maximal output power of 745 mW was obtained in that case at absorbed pump power of 4W. The maximal output powers of 780 mW with slope efficiency 26 % and 670 mW with slope efficiency 23 % at 1531 nm (σ polarization) were obtained for output coupler transmittance of 5.5 % and 8 %, respectively, without switching between polarizations and wavelengths. The laser threshold was measured to be about 1 W for 5.5% output coupling.

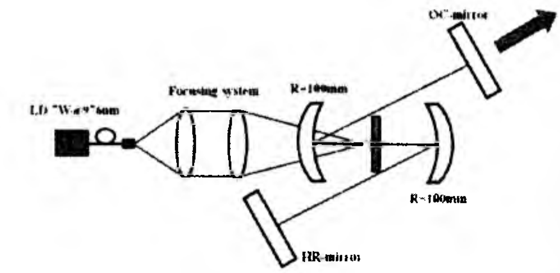

Fig. 4. Cavity setup for laser experiments

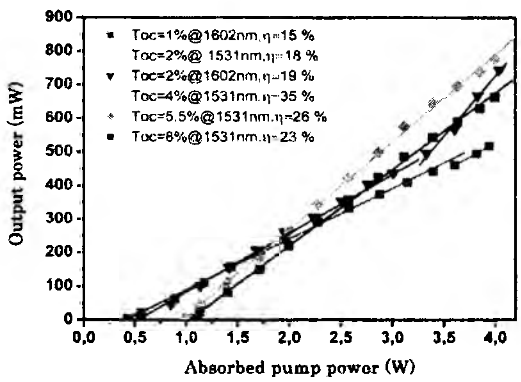

Fig. 5. Input-output characteristics of CW Er,Yb:GdAB diode-pumped laser

In conclusion, a CW diode-pumped Er,Yb:GdAB laser with output power of about 780 mW and slope efficiency as high as 26 % at 1531 nm was realized for the first time to our knowledge.

1. Diode-pumped continious-wave laser around 1.54 μm using Yb,Er - doped silico-boro-phosphate glass / T. Danger, G. Huber, B.I. Denker, B.I. Galagan, S.E. Sverchkov, in CLEO-98 Conference Technical Digest, Paper CTuM71.
2. Efficient 1 W continuous-wave diode-pumped Er,Yb:$YAl_3(BO_3)_4$ laser / N.A. Tolstik, S.V. Kurilchik, V.E. Kisel, N.V. Kuleshov, V.V. Maltsev, O.V. Pilipenko, E.V. Koporulina, and

N.I. Leonyuk // Optics Letters. - 2007. –Vol. 32, №22. – P.3233-3235.

3. Spectroscopic properties and laser performance of Er^{3+} and Yb^{3+} co-doped $GdAl_3(BO_3)_4$ crystal / Y. Chen. Y. Lin, X. Gong, Z. Luo, and Y. Huang // IEEE J. Quantum Electron. – 2007. – Vol. 43, №10. – P. 950-956.

UDC 621.373.826

EFFICIENT IN-BAND PUMPED $Er:KY(WO_4)_2$ LASER

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Applications of erbium lasers emitting in the eye-safe spectral range around 1.6 µm include laser range finding, ophthalmology, fiber-optic communication systems, and optical location. Continuous-wave (CW) room-temperature laser operation was demonstrated for several Er,Yb-codoped crystals: garnets, vanadates, oxoborates, and tungstates. However, the intrinsic slope efficiency is limited to be about 60 % due to the large quantum defect. $Er,Yb:KY(WO_4)_2$ lasers emitting in the spectral range around 1.6 µm have already been realized by pumping near 1 µm. Using CW Ti:sapphire laser at 930 nm as a pump source a slope efficiency of 1 % and an output power of 2.8 mW were obtained at the wavelength of 1540 nm [1]. The diode-pumped at 980 nm laser operation was obtained with maximum output power of 54 mW and slope efficiency up to 1.6 % [2].

In-band pumping in the spectral range 1.5-1.6 µm ($^4I_{15/2}$-$^4I_{13/2}$ transition) of Er^{3+} reduces the quantum defect and thermal load of the crystal and enables to increase strongly laser efficiency and output power in comparison with pumping of Er,Yb-codoped crystals near 1 µm. However, due to significant upconversion losses the maximal erbium concentrations are limited. Thus, owing to poor absorption near 1.5 µm of erbium comparatively long crystals with several centimeters in length have to be used. This fact imposes restrictions on the quality of pump beam.

In this work we present the spectroscopy and, for the first time to our knowledge, efficient continuous wave operation of $Er:KY(WO_4)_2$ crystal under in-band pumping by a compact diode-pumped $Er,Yb:GdAl_3(BO_3)_4$ laser.

Absorption spectra of Er^{3+} in KYW at room-temperature recorded with a spectrophotometer Cary-5000 in the spectral range 1440-1640 nm (transition $^4I_{15/2}\rightarrow{}^4I_{13/2}$ of erbium ions) are presented in Fig. 1 and show essential differences of absorption properties for polarizations of light along the three principal crystallooptic axes N_g, N_m, and N_p. The absorption cross-section is higher for light polarization $E//N_m$ with the maximum of 2.4×10^{-20} cm^2 at 1534 nm. This wavelength corresponds to emission wavelengths of InGaAsP/InP laser diode sources, that gives opportunity to consider Er:KYW crystal to be prospective laser material for laser diode in-band pumping.

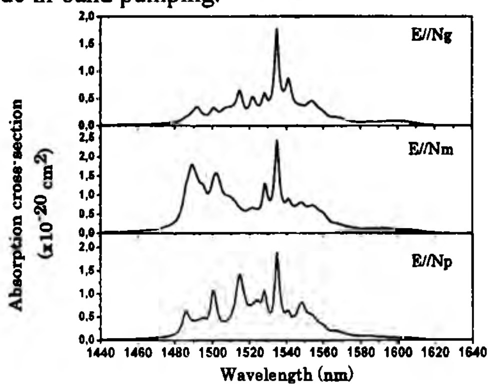

Fig. 1. Room-temperature polarized absorption cross-section spectra of Er:KYW crystal in the spectral range 1440-1640 nm

The stimulated emission cross-section spectra calculated by the reciprocity method using the energy position of the Stark levels of $^4I_{13/2}$ and $^4I_{15/2}$ manifolds are shown in Fig. 2. There is a broad emission features in the spectral range 1570-1630 nm that evidences of opportunity to realize mode-locked femtosecond in-band pumped Er:KYW laser.

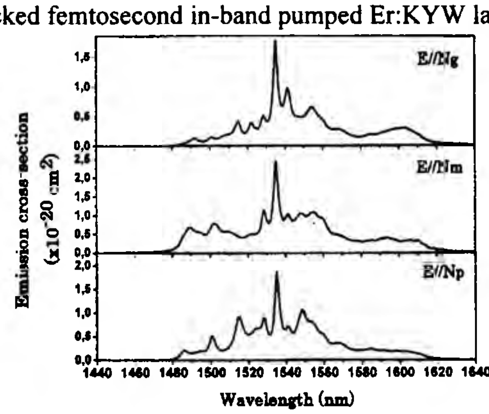

Fig. 2. Polarized emission cross-section spectra of Er:KYW crystal in the spectral 1440-1640 nm

For lifetime measurements optical parametric oscillator emitted at about 1530 nm on the basis of