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CW laser performance of Yb and Er,Yb doped tungstates

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Abstract. Room temperature cw laser action of Yb^{3+}-doped $KY(WO_4)_2$ and $KGd(WO_4)_2$ crystals at 1.025 μm and Er, Yb : $KY(WO_4)_2$ at 1.54 μm has been demonstrated under pumping by both Ti-sapphire laser and InGaAs laser diodes. A slope efficiency of Yb-lasers up to 78% has been obtained.

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Yb-doped materials attract interest as promising active media for 1 μm all-solid-state infrared lasers pumped by InGaAs diode lasers. Trivalent ytterbium has important advantages in comparison with the widely used Nd^{3+} laser ion, such as 3 or 4 times longer emission lifetime in similar hosts with enhanced storage capacity and reduced quantum defect between absorption and emission. The smaller Stokes shift reduces heating and increases the laser efficiency. The lack of relevant higher-lying excited states due to the two-level electronic structure of Yb^{3+} eliminates ESA and upconversion processes as possible sources of losses in Yb-lasers. The laser performance of Yb^{3+} ion has been reported recently in YAG [1], apatite crystals [2, 3], fluorophosphate glasses [4] and $BaCaBO_3F$ [5]. High-output power from Yb : YAG thin-disc lasers have been demonstrated by using a specific pump arrangement [6]. In the present paper, cw laser action is demonstrated in two Yb^{3+}-doped crystalline hosts $KY(WO_4)_2$ (KYW) and $KGd(WO_4)_2$ (KGW) under Ti-sapphire and diode laser pumping to our knowledge for the first time. These tungstates were shown to be good hosts for other rare-earth laser ions [7].

Yb^{3+} ion serves also as a good sensitizer for Er^{3+} in the Er- and Yb-codoped glasses for 1.5 μm lasers [8]. Recently, room temperature cw laser action around 1.6 μm was demonstrated in Er,Yb-doped YAG and Y_2SiO_5 under pumping by Ti-sapphire laser [9] and by InGaAs laser diodes [10]. Although these crystals exhibit better thermomechanical properties and an efficient Yb–Er energy transfer, the laser efficiency of glasses is higher. Thus, the search for new 1.5 μm diode-pumped laser crystals is further important. Here we report, for the first time to our knowledge, room-temperature cw operation of Er, Yb : $KY(WO_4)_2$ near 1.54 μm under both Ti-sapphire and diode-laser pumping.

Rare-earth potassium tungstates have a monoclinic C2/c (C^6_{2h}) structure [11]. The parameters of the unit cell are $a = 8.095$ Å, $b = 10.43$ Å, $c = 7.588$ Å and $\beta = 94°$ for $KGd(WO_4)_2$ and $a = 8.05$ Å, $b = 10.35$ Å, $c = 7.54$ Å and $\beta = 94°$ for $KY(WO_4)_2$. Yb^{3+} (and Er^{3+}) substitutes the Y^{3+} (or Gd^{3+}) at a site with C_2 point symmetry. The single crystals were grown by a modified Czochralski method. The crystals KGW and KYW doped with 5 at% of Yb^{3+} were used for laser experiments at the wavelengths near 1 μm and KYW codoped with 0.5 at% of Er^{3+} and 5 at% of Yb^{3+} was used for 1.5 μm laser measurements. The laser crystals were not antireflection-coated.

The polarized absorption and emission spectra of Yb^{3+} : KYW at room temperature are shown in Figs. 1 and 2, respectively. The luminescence decay time was measured to be 0.85 ms at 295 K in Yb^{3+} : KYW. Yb^{3+} in KGW exhibits very similar spectroscopic characteristics. Using the reciprocity method [12], the peak-stimulated emission cross section at 1025 nm was estimated to be 3×10^{-20} cm^2 for $E \| a$ polarization. For the laser experiments with cw Ti-sapphire laser pumping, the 1 mm thick crystals were placed at the center of a 10 cm nearly concentric laser cavity. The pump beam was focused into the sample through the high-reflective (1000–1100 nm) mirror with a 5 cm focal length lens. Output couplers with transmission between 3% and 8% were used. The output power was measured with a thermopile detector. The input–output characteristics of the Yb-lasers for pumping at 981.2 nm ($E \| a$) are shown in Fig. 3. The laser output was polarized parallel to the a-axis of the crystal and was observed at 1025 nm wavelength with approximately 8 nm spectral width (FWHM). The laser threshold was about 35 mW of absorbed pump power in Yb : KGW and 70 mW in Yb : KYW. Slope efficiencies as high as 78% for Yb : KYW and 72% for Yb : KGW with respect to absorbed pump power (Fig. 3) were achieved.

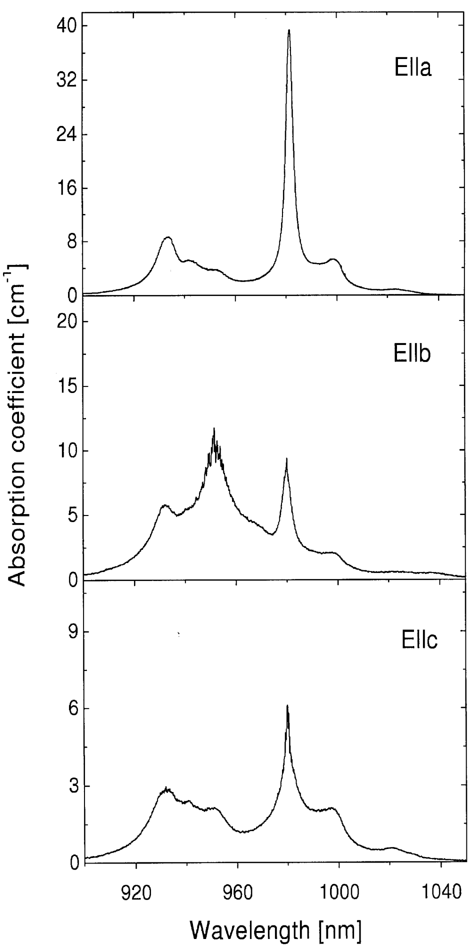

Fig. 1. Polarized absorption spectra of Yb : KY$(WO_4)_2$ recorded at room temperature

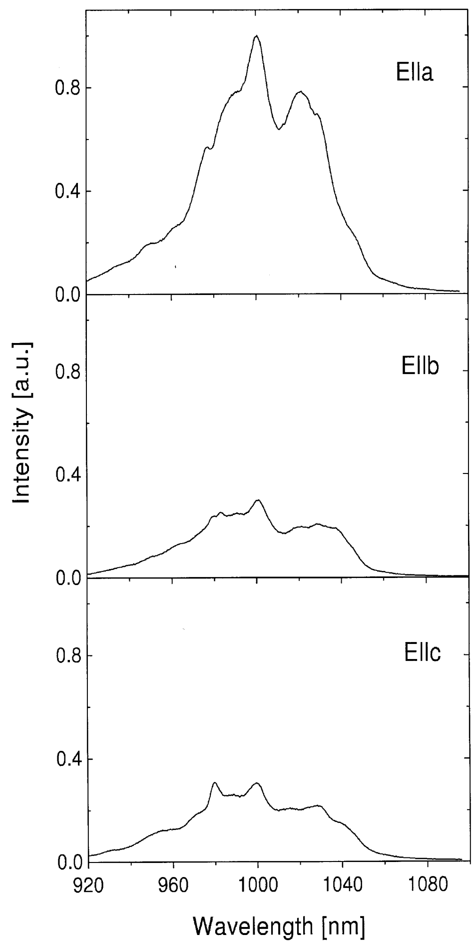

Fig. 2. Room-temperature emission spectra of Yb : KY$(WO_4)_2$

The absorbed pump power was measured during lasing by using special spectral filters placed in front of the detector, which enable to measure the rest of pump radiation and the Yb-laser output separately. A 0.5 W output power was achieved from Yb : KGW-laser at 940 mW of incident pump power. The results of laser experiments are summarized in Table 1.

The slope efficiency of Yb-doped KYW and KGW can probably be improved by using antireflection coatings at the crystal surfaces for laser wavelength in order to reduce the intracavity losses and by optimizing the output coupler transmission, pump wavelength and crystal length.

For the laser experiments under diode pumping, a nearly hemispherical cavity geometry was used with a 50 mm radius of curvature output mirror. The emission of two 1 W InGaAs diodes operating around 965 nm was used simultaneously to pump the sample by using a polarizing beam combiner. The pump beams were focused into the crystal with a 25 mm focal length lens. The best lasing was obtained when the 5 mm long Yb(5%) : KYW crystal was excited with pump beam polarizations along the *a*- and *b*-axis of the crystal. The output at

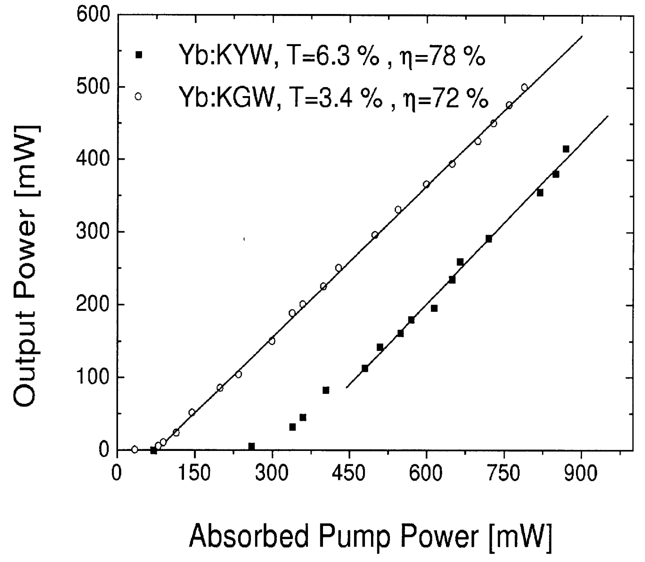

Fig. 3. Input–output data for Ti-sapphire laser-pumped Yb : KYW and Yb : KGW

Table 1. Summary of laser results

Crystal	Length [mm]	Threshold [mW]	Laser wave-length [μm]	Slope efficiency [%]	Output coupling [%]
Ti-sapphire pumping					
$Yb^{3+}:KY(WO_4)_2$	1.0	70	1.025	78	6.3
$Yb^{3+}:KGd(WO_4)_2$	1.0	35	1.025	72	3.4
$Er^{3+}, Yb^{3+}:KY(WO_4)_2$	5.0	380	1.54	1.0	1
Diode pumping					
$Yb^{3+}:KY(WO_4)_2$	5.0	450	1.025	10	3

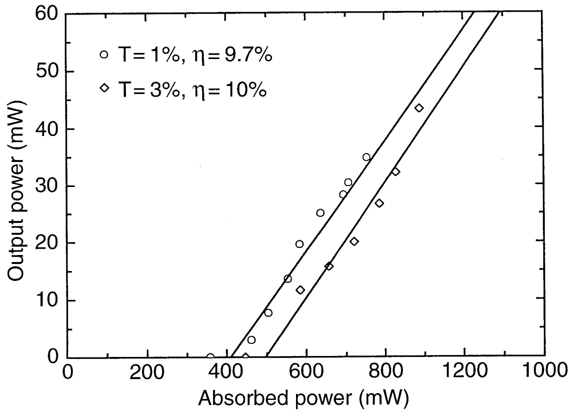

Fig. 4. Input–output data for diode pumped Yb (5%) : $KY(WO_4)_2$, $d = 5$ mm

1025 nm was polarized parallel to the *a*-axis. The input–output diagram for the diode-pumped Yb : KYW-laser is shown in Fig. 4. The laser threshold was measured to be 360 mW of absorbed pump power with 1% output coupling. A slope efficiency of approximately 10% and a maximum output power of 43 mW were obtained with 3% transmission of the output mirror.

The difference in the laser characteristics of the Yb-laser at diode pumping in comparison with pumping by the Ti-sapphire laser is due to the low absorption of the crystal at the wavelength of the diode-laser emission (965 nm). We had to use comparatively long laser crystals (5 mm), thus, the reabsorption losses due to the quasi-three-level scheme of the Yb-laser were high. Furthermore, the overlap between pump beam and cavity mode was worse. We think that the use of InGaAs diodes emitting at 980 nm will enhance the Yb : KYW laser efficiency.

Polarized absorption and emission spectra of Er (0.5%),Yb (5%) : $KY(WO_4)_2$ at room temperature are shown in Figs. 5 and 6, respectively. The lifetime of the $^4I_{13/2}$ level of Er^{3+} was determined from the fluorescence decay measurements to be 5 ms. The lifetime of the $^2F_{5/2}$ level of the Yb^{3+} is reduced from 0.85 ms in the crystal without Er^{3+} to 0.35 ms in the codoped crystal due to Yb–Er energy transfer. The risetime of the Er^{3+} emission at 1.5 μm was measured to be also approximately 0.35–0.4 ms. From the fluorescence intensity measurements the efficiency of the energy transfer from

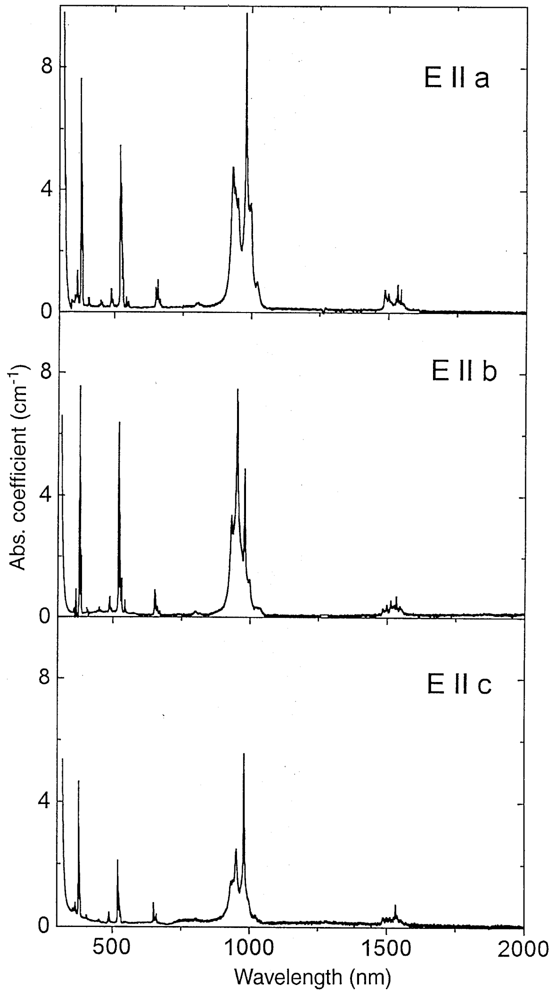

Fig. 5. Polarized absorption spectra of Er (0.5%), Yb (5%): $KY(WO_4)_2$ at room temperature

Yb to Er was estimated to be about 50%. This agrees roughly with the observed lifetime reduction. Strong absorption of the Yb^{3+} in the range 900–1000 nm can be used for diode-laser pumping of the Er^{3+}.

The 1.5 μm Er-laser experiments under Ti-sapphire pumping were performed with the same nearly concentric laser cavity configuration as used for the Ti-sapphire-pumped Yb-laser. The Er, Yb : KYW crystal of 0.5 mm in length was pumped at 930 nm wavelength ($E\|a$, $k\|b$). With

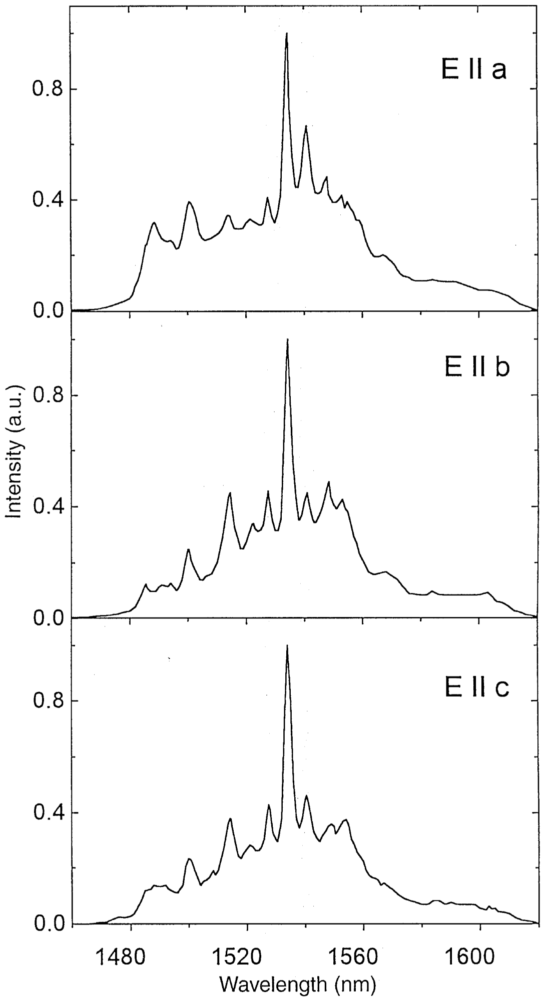

Fig. 6. Emission spectra of Er (0.5%), Yb (5%) : KY(WO$_4$)$_2$ near 1.5 µm

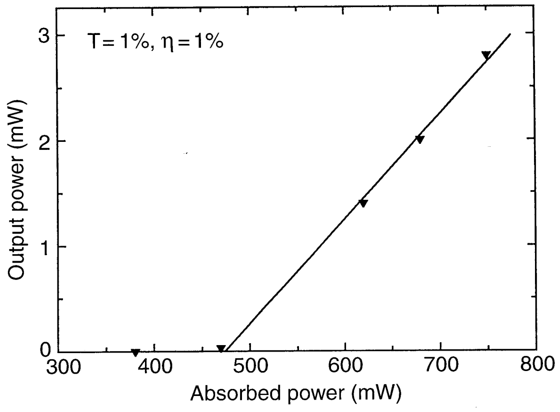

Fig. 7. Efficiency data for Er (0.5%), Yb (5%) : KY(WO$_4$)$_2$ (d = 2.5 mm) under Ti-sapphire laser pumping

a high-reflecting output mirror, the threshold of lasing at the wavelength of 1580 nm ($E_{\text{out}} \| a$) was reached at 205 mW of absorbed pump power. The maximum output power of 2.8 mW and a slope efficiency of about 1% was obtained at 1540 nm wavelength of the Er,Yb : KYW-laser with an 1% output coupler (Fig. 7). Laser operation of Er, Yb : KYW was also achieved by pumping with two InGaAs diodes (965 nm) using the polarizing beam combiner and the hemispherical cavity configuration of the diode-pumped Yb-lasers. A 0.25 m Spex monochromator, Ge-detector and oscilloscope were used to detect and to analyze the laser emission. Laser operation has been obtained with a high-reflective output mirror at about 1 W of incident pump power polarized parallel to the a- and b-axis. The output power was less than 1 mW.

The low efficiency of the 1.5 µm Er, Yb : KYW-laser can be due to strong upconversion losses, since a strong green emission from the $^4S_{3/2}$ level of Er^{3+} was observed from the pumped volume in the crystal.

In conclusion, the laser characterization of Yb^{3+}-doped KYW and KGW was performed. A stimulated emission cross section of 3×10^{-20} cm^2 ($E \| a$) was estimated for Yb^{3+} at 1025 nm. Room-temperature cw laser operation is demonstrated in these crystals by pumping with a Ti-sapphire laser and InGaAs laser diodes. An output power of 0.5 W and slope efficiencies near 78% have been obtained in the case of Ti : sapphire pumping. Strong absorption coefficients near 981 nm (up to 40 cm^{-1}) and broad spectral width of laser radiation make Yb-doped tungstates promising for microchip and ultrashort pulse lasers with tunability of wavelength. In comparison with the Yb : YAG laser, the Yb-doped tungstates have a number of advantages, such as higher absorption coefficient, smaller quantum defect between absorption and emission, higher emission cross section and therefore these materials are suitable for high-power thin-disc lasers [6].

CW lasing at room temperature in Er, Yb : KYW at 1.54 µm was obtained under Ti-sapphire and diode-laser pumping. The efficiencies of the 1.54 µm lasers are very small, most probably due to upconversion losses.

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