

# In-band pumped room-temperature Er:KY(WO<sub>4</sub>)<sub>2</sub> laser emitting around 1.6 μm

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## Abstract

We present efficient continuous-wave operation of an Er:KY(WO<sub>4</sub>)<sub>2</sub> crystal under in-band pumping by a compact diode-pumped Er, Yb:GdAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> laser. Maximum slope efficiency of 27% and output power of 35 mW at 1609.5 nm were obtained with beam propagation factor  $M^2 < 1.2$ . Absorption and stimulated emission cross-section spectra, as well as the radiative lifetime of the <sup>4</sup>I<sub>13/2</sub> energy level, were determined.

(Some figures may appear in colour only in the online journal)

## 1. Introduction

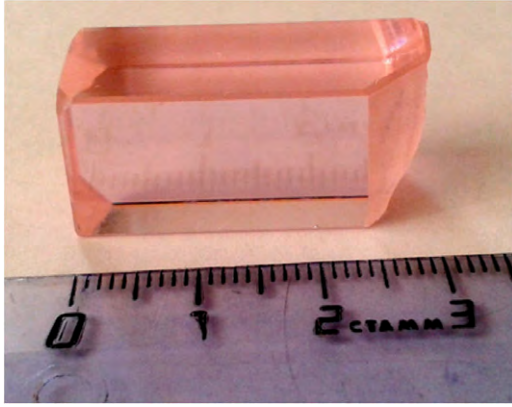
Erbium lasers emitting in the eye-safe spectral range around 1.6 μm are attractive for applications in laser range finding, ophthalmology, fiber-optic communication systems and optical location.

Continuous-wave (CW) room-temperature laser operation was demonstrated for several Er-, Yb-codoped crystals: garnets [1], vanadates [2], oxoborates [3–6] and tungstates [7, 8]. Here the ytterbium absorption band at 0.9–1.0 μm was used for pumping and energy transfer to Er ions was utilized. However, the intrinsic slope efficiency of lasers based on these materials is limited to 60% due to the large quantum defect. The most efficient diode-pumped laser action to the best of our knowledge has been demonstrated for Er, Yb:YAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> crystal [6]. The slope efficiency of 35% with output power up to 1 W was obtained. Lasers based on Er, Yb:KY(WO<sub>4</sub>)<sub>2</sub> crystal have also been realized. However, the low energy transfer efficiency of tungstate crystals limited the maximum slope efficiency to only several percent either with Ti:sapphire [7] or laser diode pumping [8]. Additional co-doping with Ce<sup>3+</sup> was used in order to increase the slope

efficiency of tungstate lasers to 17% in a quasi-CW regime [9, 10].

Direct in-band pumping of Er-doped materials in the <sup>4</sup>I<sub>13/2</sub> energy level with radiation at 1.5–1.6 μm wavelength significantly reduces the quantum defect and thermal load. It enables us to significantly increase the slope efficiency of the lasers. CW room-temperature laser action with in-band pumping was demonstrated for Er-doped bulk garnets [11, 12], vanadates [13, 14], sesquioxides [15] and fluorides [16] as well as fibers [17, 18]. However, due to significant up-conversion losses the erbium concentration in the media was limited to low values that oblige us to use crystals of several centimeters in length. This fact imposes restrictions on the quality of the pump beam. Among tungstate crystals quasi-CW laser action on structurally disordered Er-doped NaY(WO<sub>4</sub>)<sub>2</sub> was reported at room temperature [19]. A wide-band InGaAsP/InP laser diode emitting at 1.5 μm was used as a pump source. The slope efficiency of 33% with output power of 1.05 W at the wavelength of 1609 nm was reported.

In this paper, we present, for the first time to the best of our knowledge, efficient CW laser operation of



**Figure 1.** Er-doped  $\text{KY}(\text{WO}_4)_2$  single crystal grown by the TSSG method.

an Er:KY(WO<sub>4</sub>)<sub>2</sub> crystal in-band pumped by a compact diode-pumped Er, Yb:GdAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> laser [20].

## 2. Experimental details

KY(WO<sub>4</sub>)<sub>2</sub> (KYW) is a monoclinic crystal with  $C2/c$  space group. The parameters of the unit cell are  $a = 10.64 \text{ \AA}$ ,  $b = 10.35 \text{ \AA}$ ,  $c = 7.54 \text{ \AA}$ ,  $\beta = 130.5(2)^\circ$  and the weight density is  $6.5 \text{ g cm}^{-3}$  [21]. Er:KYW single crystals were grown by the top-seeded solution growth (TSSG) method (see figure 1).

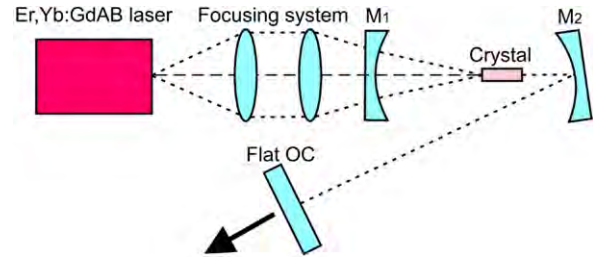
For investigation of the spectroscopic properties the sample with an Er<sup>3+</sup> concentration of 0.5 at.% was used. Polarized absorption spectra at room temperature were measured with a spectrophotometer, Varian CARY 5000. The spectral bandwidth was 0.4 nm. The lifetime measurements were performed using an optical parametric oscillator emitting near 1530 nm based on a  $\beta$ -Ba<sub>2</sub>B<sub>2</sub>O<sub>4</sub> 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 0.3 m monochromator and registered by an InGaAs photodiode coupled with a 500 MHz digital oscilloscope.

A plane–plane  $N_p$ -cut Er(2 at.%):KYW crystal with a length of 14.5 mm was used as an active medium. The facets of the crystal were antireflection-coated for both pump and laser wavelengths. The crystal was mounted on the copper heatsink without any additional cooling. A diode-pumped Er, Yb:GdAl<sub>3</sub>(BO<sub>3</sub>)<sub>4</sub> laser with output power up to 650 mW at 1531 nm was used as a pump source. The laser output was linearly polarized with close to Gaussian intensity profile ( $M^2 < 1.2$ ). The combination of two lenses ( $f_1 = 25 \text{ mm}$ ,  $f_2 = 60 \text{ mm}$ ) was used to focus the pump beam in the gain medium into a spot of  $35 \text{ \mu m}$  radius ( $1/e^2$  intensity). The pump beam polarization corresponded to the  $N_m$  optical axis of the crystal. The laser experiments were performed in a three-mirror cavity which is presented in figure 2.

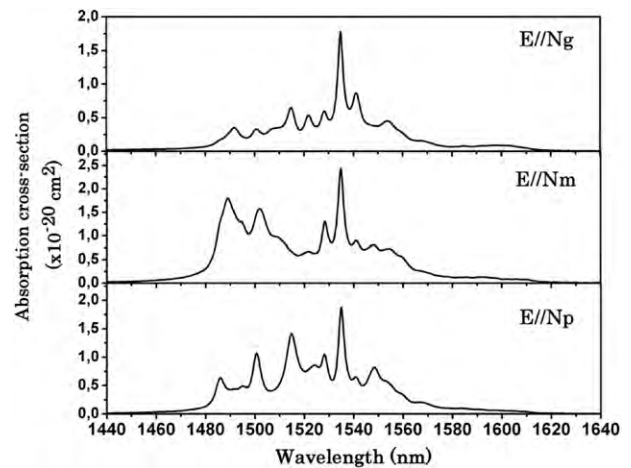
## 3. Results and discussion

### 3.1. Spectroscopy

The absorption cross-section spectra of the Er:KYW crystal in the spectral range of 1440–1640 nm (transition



**Figure 2.** Cavity setup for laser experiments.

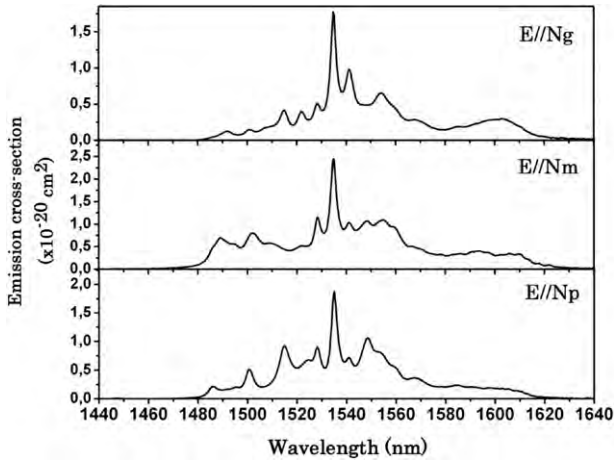


**Figure 3.** Room-temperature polarized absorption cross-section spectra of Er:KYW crystal.

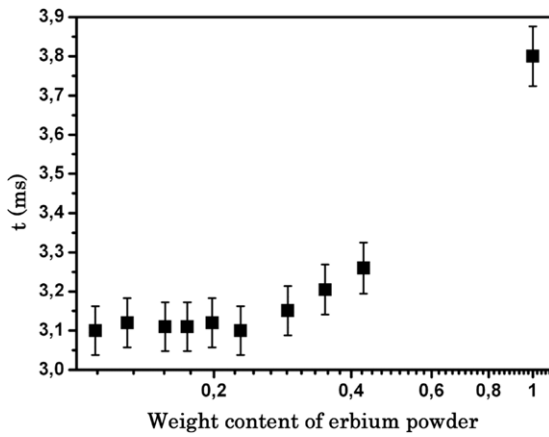
$^4I_{15/2} \rightarrow ^4I_{13/2}$  of erbium ions) are presented in figure 3. The highest absorption can be observed at 1534 nm for light polarization  $\mathbf{E} \parallel N_m$ , where the maximum cross-section is  $2.4 \times 10^{-20} \text{ cm}^2$ . This wavelength corresponds to emission spectra of the InGaAsP/InP laser diode, which gives us the opportunity to consider the Er:KYW crystal as a promising laser medium under in-band pumping.

The stimulated emission cross-section spectra were calculated by the reciprocity method [22], using the energy level scheme of  $^4I_{13/2}$  and  $^4I_{15/2}$  manifolds reported in [23]. The spectra are shown in figure 4 and are similar to the results of [23]. One can see a broad and smooth emission in the spectral range of 1570–1630 nm that can be utilized in mode-locked operation.

It is well known that radiation trapping strongly influences the fluorescence dynamics of Er<sup>3+</sup> ions in crystals and glasses because of the significant overlap of the absorption and emission bands. The high refractive index of Er:KYW ( $n_g = 2.05$ ;  $n_m = 2.01$ ;  $n_p = 1.97$ ) increases the probability of reabsorption even in optically thin samples because of the total internal reflection [24]. In our experiments we used a fine powder of Er(0.5 at.%):KYW crystal immersed in glycerin. 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 lifetime of the  $^4I_{13/2}$  level was



**Figure 4.** Polarized emission cross-section spectra of Er:KYW crystal.



**Figure 5.** Fluorescence lifetime of the Er(0.5 at. %):KYW crystalline powder immersed in glycerin.

determined to be 3.1 ms (see figure 5), which is slightly different from the results of [7, 23].

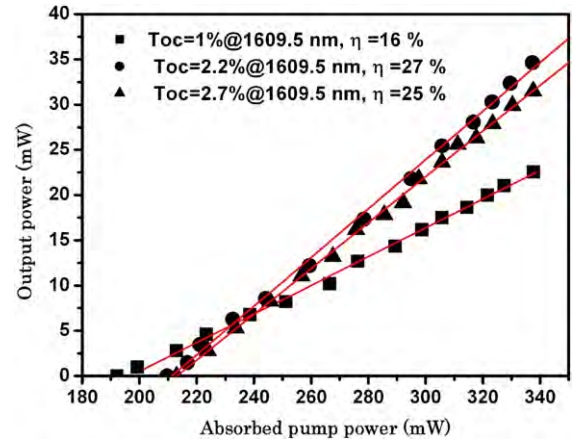
The radiative lifetime of the  $^4I_{13/2}$  erbium level was calculated by the use of the integral reciprocity method [25]:

$$\tau_{\text{rad}} = \frac{3}{8\pi n^2 c} \frac{Z_2}{Z_1} \frac{1}{\sum_{\beta} \int \sigma_{\text{abs}}^{\beta}(\lambda) \lambda^{-4} \exp(-hc/(kT\lambda)) d\lambda} \times \exp(-hc/(kT\lambda_0)) \quad (1)$$

where  $n$  is the average refractive index of a crystal,  $c$  is the velocity of light,  $\beta$  denotes the polarization state,  $h$  and  $k$  are the Planck and Boltzmann constants, respectively,  $T$  is the host crystal temperature and  $\sigma_{\text{abs}}$  is the ground-state absorption cross-section;  $Z_1$  and  $Z_2$  are partition functions of the lower and upper multiplets, defined as

$$Z_m = \sum_k g_k^m \exp(-E_k^m/(kT)) \quad (2)$$

where  $m = 1, 2$ ;  $g_k^m$  is the degeneration of the sublevel having the number  $k$  and the energy  $E_k^m$  measured from the lower sublevel of the corresponding multiplet;  $\lambda_0$  is the wavelength corresponding to the energy  $E_{ZL}$  and  $E_{ZL}$  is the energy



**Figure 6.** Input–output characteristics of CW in-band pumped Er:KYW laser.

distance between the lower sublevels of the multiplets for the ground and excited electronic states.

The radiative lifetime of the  $^4I_{13/2}$  level was calculated to be 3.06 ms and it is in excellent agreement with the value obtained from the experiment. The luminescence quantum yield was estimated to be close to 1.

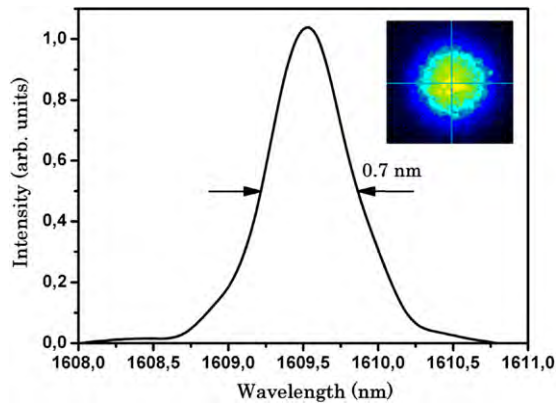
### 3.2. Laser performance

Figure 6 shows input–output characteristics of the CW in-band pumped Er:KYW laser. The absorbed pump power was calculated from the measured absorption coefficient at the laser threshold. The maximum slope efficiency of 27% with output power up to 35 mW was obtained for an output coupler transmittance of 2.2%. The laser radiation was linearly polarized along the  $N_m$  optical axis of the crystal. For 1% output coupler transmittance the slope efficiency reduced to 16% and output power was 23 mW. The laser threshold was 190 mW of absorbed pump power. A slope efficiency of 25% and maximum output power of 31 mW were obtained for 2.7% output coupler transmittance. The laser wavelength was measured to be 1609.5 nm and did not depend on the output coupling (see figure 7). The spatial profile of the output beam was close to Gaussian with  $M^2 < 1.2$  (see the inset in figure 7). To find a correspondence between laser and spectral properties of the Er:KYW crystal gain coefficient spectra were calculated.

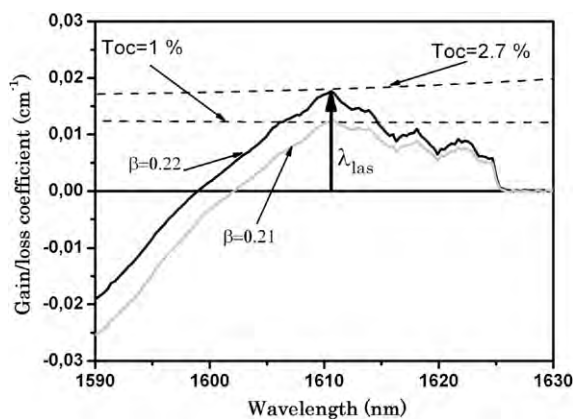
The gain coefficient  $g(\lambda)$  was calculated for different values of inversion parameters  $\beta$ :

$$g(\lambda) = N(\beta \cdot \sigma_{\text{se}}(\lambda) - (1 - \beta) \cdot \sigma_{\text{abs}}(\lambda)), \quad (3)$$

where the inversion parameter  $\beta = N_{\text{ex}}/N$  shows the ratio of the volumetric density of excited Er ions  $N_{\text{ex}}$  to the total Er ions concentration  $N$ ,  $\sigma_{\text{se}}$  is the stimulated emission cross section and  $\sigma_{\text{abs}}$  is the absorption cross section. Figure 8 shows the gain coefficient spectra for polarization  $\mathbf{E} \parallel N_m$  with  $\beta = 0.21$  and 0.22 as well as the loss coefficient spectra estimated for output couplers with 1% and 2.7% transmittance. It can be clearly seen that the laser wavelength



**Figure 7.** Laser spectrum of the in-band pumped Er:KYW laser. Inset: intensity profile of the laser output.



**Figure 8.** Gain coefficients (solid lines) calculated for  $\beta = 0.21$  and  $0.22$ ; loss coefficients (dashed lines) estimated for output coupler transmittance of 1% and 2.7%.

should not be shifted when the output coupler transmittance increases from 1 to 2.7%.

During the laser experiments strong green fluorescence caused by the up-conversion to the level  $^4S_{3/2}$  was observed. To our mind, reducing the erbium concentration will contribute to a decrease of energy transfer up-conversion and will result in an increase of the laser slope efficiency and output power.

#### 4. Conclusions

In conclusion, a CW in-band pumped room-temperature Er:KY(WO<sub>4</sub>)<sub>2</sub> laser was demonstrated for the first time to the best of our knowledge. Maximum slope efficiency of 27% and output power of 35 mW at 1609.5 nm were obtained with beam propagation factor  $M^2 < 1.2$ .

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