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Laser oscillation of Er^{3+}:YVO_4 and Er^{3+}, Yb^{3+}:YVO_4 crystals in the spectral range around 1.6 μm

I. Sokólska[1,*], **E. Heumann**[1], **S. Kück**[1], **T. Łukasiewicz**[2]

[1] Institut für Laser-Physik, Universität Hamburg, Jungiusstrasse 9a, 20355 Hamburg, Germany
(Fax: +49-40/42838-6281, E-mail: sokolska@physnet.uni-hamburg.de)
[2] Institute of Electronic Materials Technology, ITME, Wólczyńska str. 133, 01-919 Warsaw, Poland

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Abstract. Laser oscillation around 1.6 μm was realised at room temperature for low-doped Er:YVO_4 crystals (0.5 at % and 1 at %) as well as for Er(1 at %), Yb(5 at %):YVO_4 crystal in continuous-wave mode. The maximum slope of the input–output curve was about 19% (vs. absorbed power) for Er(0.5 at %):YVO_4. The laser oscillation was discretely tunable in the spectral range between 1531 and 1604 nm.

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For many years Er^{3+}-doped materials have been widely investigated from the point of view of possible laser applications, especially in spectral ranges around 1.6 μm and 2.7 μm (e.g. [1] and [2] and references therein, respectively). The transition around 1.6 μm ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) is used for eye-safe lasers for medicine, telecommunication, remote sensing and light detecting and ranging (LIDAR). For wide applications of Er-laser materials, laser diodes operating in the range of about 975 nm should be used as a pump source ($^4I_{15/2} \rightarrow {}^4I_{11/2}$ transition of Er^{3+}). Suitable erbium-doped materials for 1.6 μm laser transition should be characterised first of all by a high phonon energy which enables fast depopulation of the pump level $^4I_{11/2}$ via nonradiative decay in order to prevent the significant excited-state absorption from this level and to populate efficiently the upper laser level $^4I_{13/2}$. The second important condition is that the excited-state absorption (ESA) $^4I_{13/2} \rightarrow {}^4I_{9/2}$ transition should not spectrally overlap with the range of stimulated emission around 1.6 μm. Additionally, a significant splitting of the ground-state multiplet is advantageous to achieve a quasi-4-level system. The above conditions are mostly fulfilled by Er^{3+}-doped glasses, which are so far the most efficient lasers at this transition. However, glasses suffer from poor thermal and mechanical stability, thus Er^{3+}-doped crystalline matrices are still intensively investigated in order to find suitable ones for this transition. Although Er^{3+} laser oscillation around 1.6 μm was reported for some of the most common laser hosts (e.g. YAG and YGG [3], YLF [4], $LaSc_3(BO_3)_4$ [5]), the performance of these lasers was rather bad.

The YVO_4 crystal host has very good thermal, mechanical and optical properties. In recent years it has found commercial application in high-power continuous-wave (cw) Nd^{3+} lasers with intracavity frequency-doubling (e.g. high-power Millenia series lasers from Spectra Physics or Verdi series from Coherent). Recently, basic spectroscopic investigations of Er^{3+}:YVO_4 crystals were carried out [6–9]. On the basis of spectroscopic results and also theoretical simulations [10] it was suggested that these crystals are promising for achieving an efficient laser in the 1.6 μm range because of the high emission cross-section, the short lifetime of the $^4I_{11/2}$ pump level (27 μs, [7]) and the negligible excited-state absorption on the possible laser wavelengths [9]. However, to our knowledge no laser oscillation around 1.6 μm has yet been reported for these crystals.

1 Experimental results and discussion

We investigated Er^{3+}:YVO_4 crystals grown by the Czochralski method with nominal dopant concentrations of 0.5 at %, 1 at % and 4 at % corresponding to 1.05×10^{20}, 2.1×10^{20} and 8.4×10^{20} ions/cm^3, respectively, and an Er^{3+}(1 at %), Yb^{3+}(5 at %):YVO_4 crystal. As a pump source, a Ti:sapphire laser (3900S Spectra Physics) operating at about 975 nm was used (matching the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ transition of Er^{3+} see Fig. 1). The polarisation-dependent absorption cross-sections for the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ transition are presented in Fig. 2a,b. The excitation around 975 nm results in an Er^{3+} emission around 1.6 μm due to the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition as well as a green up-converted emission ($^4S_{3/2} \rightarrow {}^4I_{15/2}$ transition). From the emission spectra recorded at room temperature around 1.55 μm for both polarisations, we estimated the emission cross-sections for this transition using the following

*Corresponding author.
Correspondence to: Institute of Low Temperature and Structure Research, Polish Academy of Sciences, P.O. Box 1410, Wroclaw, Poland
(E-mail: i.sokolska@int.pan.wroc.pl)

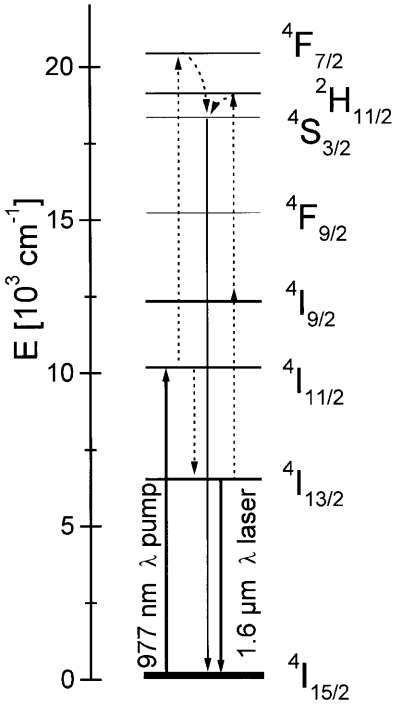

Fig. 1. Energy level diagram of Er^{3+} in YVO_4 crystal

Füchtbauer–Ladenburg formula (1)

$$\sigma_{em}(\lambda) = \frac{\lambda^5 \cdot I(\lambda)}{8\pi n^2 \tau_{rad} \int \lambda I(\lambda) d\lambda} , \qquad (1)$$

where $I(\lambda)$ is the intensity of corrected emission spectrum, τ_{rad} is the radiative lifetime of the $^4I_{13/2}$ multiplet, c is the velocity of light and n is the refractive index. The radiative lifetime obtained from Judd–Ofelt analysis is practically the same as experimentally obtained and is equal to about 2.35 ms [7], $n = 2.01$. As seen from Fig. 3, the peak values of emission cross-section obtained for Er^{3+}:YVO_4 by this method for the spectral range 1550–1600 nm are between $(5-10)\times10^{-21}$ cm^2 for both polarisations. These values are comparable or even a little larger than those for some other crystals, e.g. the peak emission cross sections around 1550 nm are 3.1×10^{-21} cm^2 for $YAlO_3$:Er [1], 3.3×10^{-21} cm^2 for YSO:Er [11], 4.5×10^{-21} cm^2 for YAG:Er [1], 5.5×10^{-21} cm^2 for YLF:Er [5, 12]), 5.9×10^{-21} cm^2 for $LaGaO_3$:Er^{3+} [13]. From the gain coefficient curves (Fig. 4) calculated as $g = N[P\sigma_{em} - (1-P)\sigma_{abs}]$, ($N$ is the concentration, P is the inversion coefficient), one can suppose that already for low inversion coefficient (P ≅ 0.2), laser oscillation should be possible within the range from 1530 to about 1610 nm.

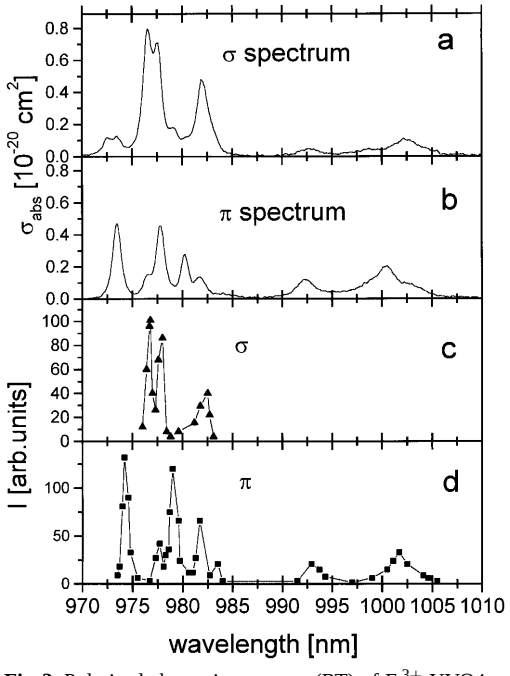

Fig. 2. Polarised absorption spectra (RT) of Er^{3+}:YVO4 crystal in the spectral range of the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ transition (*layers a* and *b*) and excitation curves of the laser oscillation realised at 1604 nm for Er^{3+}(0.5 at %):YVO_4 and Er^{3+}(1 at %):YVO_4 crystals (*layers c* and *d*, respectively)

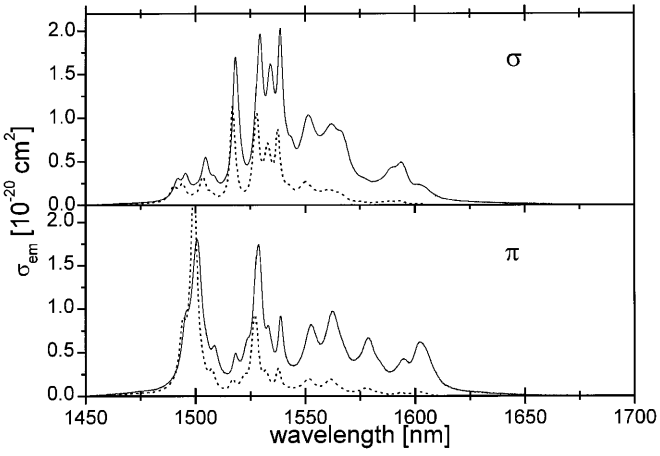

Fig. 3. Spectral dependencies of absorption cross-sections due to the $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition of Er^{3+} in YVO_4 crystal (dotted lines) and emission cross-sections ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) calculated from the Füchtbauer–Ladenburg formula (solid lines) for σ and π polarisation (*top* and *bottom layer*, respectively)

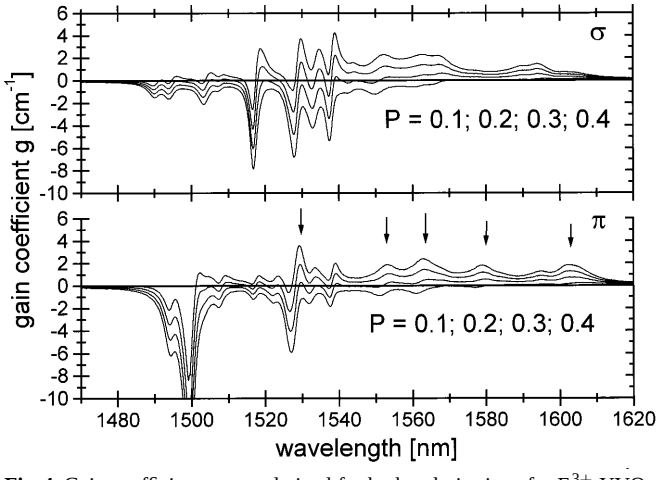

Fig. 4. Gain coefficient curves derived for both polarisations for Er^{3+}:YVO_4 in the spectral range of the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ laser transition for four values of the inversion parameter P (larger gain values for larger P). *Arrows* denote the wavelengths for which laser oscillation was realised

In our laser experiments we realised continuous wave (cw) laser oscillation for Er^{3+}(0.5 at %):YVO_4 and Er^{3+}(1 at %):YVO_4 and as well as for Er^{3+}(1 at %), Yb (5 at %):YVO_4 crystals. The pump beam from the Ti:sapphire laser was focused with a 5-cm lens into the uncoated crystals of about 3 mm, 1.3 mm and 1 mm thickness, respectively. The polarisation of the pump light was adjusted to the maximum absorbance of the crystal (i.e. the best laser output power) by a rotable $\lambda/2$ plate in combination with the Glan-prism. The resonator was nearly concentric with mirrors of 50-mm or 100-mm radius of curvature. The output mirror was highly reflective on the pump wavelength ($\sim$ 975 nm) in order to increase the power absorbed in the crystal by double-pass pumping. The transmittance of the output mirror for the laser wavelength ($\sim$ 1.6 μm) was about 1%. An optical diode has been used to prevent feedback of the pump radiation into the Ti:sapphire laser. In this configuration the free-running laser wavelength was 1604 nm. For the Er^{3+}(0.5 at %):YVO_4 crystal cooled with a Peltier element ($T \sim 0$ °C) we have obtained slightly above 100 mW output power for an incident power of about 1.7 W. The output power obtained without cooling is about 20% lower. The slope of the output power curve is about 6.7% versus incident power (Fig. 5). We estimated that about 35% of the incident power is absorbed in the Er(0.5 at %):YVO_4 crystal in the resonator. Thus, the slope of the input–output curve plotted versus absorbed power is about 19% (Fig. 5, top axis). The threshold of the laser oscillation for this crystal was below 170 mW of incident power (corresponding to about 60 mW of absorbed power). For 1% Er-doped crystal the maximum laser output power at 1604 nm was about 140 mW (without Peltier cooling) for an incident power of 1.8 W. The slope efficiency (vs. incident power) for this crystal is about 8%, that is slightly higher than for the lower-doped crystal. However, as the fraction of the absorbed power is much larger for this crystal (approximately 70%), the estimated slope efficiency vs. absorbed power is only about 13%. The reasons for the lower efficiency are most probably higher reabsorption losses and higher rates of energy transfer processes depopulating the upper laser level (($^4I_{13/2}$, $^4I_{13/2}$) → ($^4I_{15/2}$, $^4I_{9/2}$)). It is a typical problem by Er-doped lasers for this wavelength that low Er^{3+} concentration results in low absorption efficiency and thus population of the upper laser level, whereas higher dopant concentration results in the lower laser efficiency due to enhanced cross-relaxation processes. Therefore, a usual way to keep the Er^{3+} concentration low but achieve a higher absorption efficiency is to codope Er^{3+}-doped materials with Yb^{3+}, which can be efficiently pumped around 975 nm. However, in this case the requirement for increasing the Er-laser performance is an efficient energy transfer of the excitation energy from Yb^{3+} to Er^{3+} without introducing significant new loss processes. In our preliminary experiments the laser performance of Er(1%), Yb(5%):YVO_4 crystal was significantly worse than that of the Er(1%):YVO_4 crystal. The maximum output power obtained at 1604 nm was only about 40 mW for about 1.8 W of incident power. However, as our experiments were performed for one Er, Yb:YVO_4 crystal only, we can not state at the moment whether the reason for that is crystal quality, setup arrangement (polarisation dependencies, choice of output mirror) or physical phenomena generally valid for this system (reabsorption, back-transfer, enhanced cross-relaxation processes). The spectroscopy and energy transfer processes in an Er, Yb:YVO_4 system have not yet been studied in detail. They should be further investigated to determine their effect on the performance of the Er^{3+} laser and to find the optimum concentration of both dopants.

The tuning experiments were performed with a birefringent filter placed into the resonator. The birefringent filter was oriented in a way allowing π-polarised laser oscillation, because the gain coefficients around 1.6 μm are slightly higher for this polarisation. We obtained laser oscillation at 1531 nm, 1553 nm, 1564 nm, 1580 nm and 1604 nm (see arrows in Fig. 4). Continuous tunability was not observed at the pump power available.

For the laser oscillation at 1604 nm the excitation characteristics were taken out and are presented in Fig. 1c,d for Er:YVO_4 and in Fig. 6 for Er, Yb:YVO_4. As can be seen from Fig. 1c,d, laser emission can be excited in both polarisations. In the case of the low-doped Er(0.5 at %):YVO_4 crystal, the larger laser output power is obtained by pumping

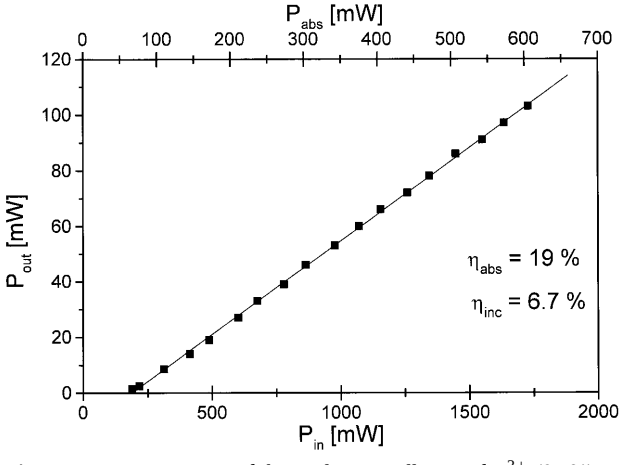

Fig. 5. Input–output curve of the cw laser oscillation of Er^{3+} (0.5%):YVO_4 crystal ($\lambda_{laser} = 1604$ nm, heat sink temperature $T \sim 0$°C, output mirror transmission ~1%). The slope of the curve is 6.7% versus incident power and approximately 19% versus absorbed power (*top axis*)

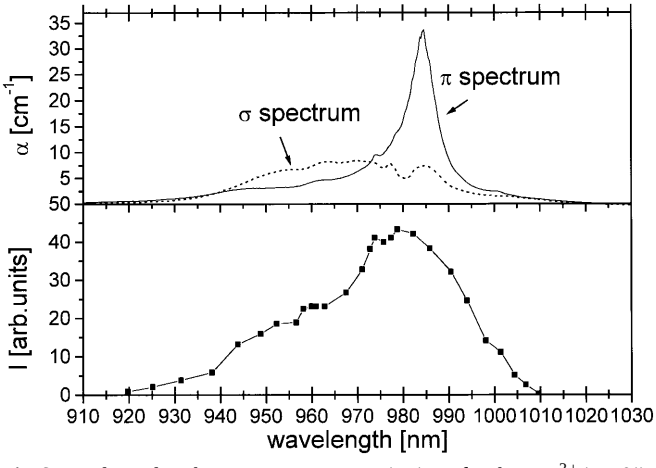

Fig. 6. Polarised absorption spectra (RT) of the Er^{3+}(1 at %), Yb^{3+}(5 at %):YVO_4 crystal in the range of the Er^{3+} $^4I_{15/2} \rightarrow {}^4I_{11/2}$ and Yb^{3+} $^2F_{7/2} \rightarrow {}^2F_{5/2}$ transition (*top layer*) and the excitation curve of the laser oscillation realised at 1604 nm for this crystal

in the σ polarisation, however within a relative narrow range of excitation, limited to the three main absorption lines at about 977 nm, 978 nm and 982 nm (compare Figs. 2a and 2c). For the laser oscillation with the Er(1 at %):YVO_4 crystal we obtained a broader excitation curve, matching well the Er^{3+} absorption spectrum in this range. The laser excitation spectrum of the Er, Yb:YVO_4 is broad and corresponds to the Yb^{3+} absorption (Fig. 6). As seen from the excitation characteristics for all crystals investigated, the spectral range between 975 nm and 980 nm is the most suitable pump range for achieving laser oscillation. Thus, the possibility of pumping these crystals by commercially available laser diodes operating around 975 nm is probable and should be examined.

2 Conclusions

In this paper we report on Er^{3+} laser oscillation in YVO_4 crystals for two Er^{3+} concentrations and for one Er, Yb:YVO_4 system. Laser oscillation was not obtained with the crystal singly doped with relatively high Er^{3+} concentration (4 at %) due to enhanced cross-relaxation processes. Energy transfer processes as well as ESA from the $^4I_{11/2}$ multiplet are present also in the lower-doped crystals, both singly and doubly-doped and certainly influence the laser performance of these systems. For Er^{3+} singly-doped crystals we have observed a significant enhancement of the intensity of the green upconverted emission during lasing at 1.6 μm. This phenomenon is probably due to some interactions involving three photons (at 1.6 μm), as such the energy matches well the transition to the $^2H_{11/2}$ multiplet (see Fig. 1). This process, as well as other processes leading to the observed up-converted emission affect the efficiency of the 1.6 μm laser. Thus, further studies of ion–ion interactions in YVO_4 crystals doped with other concentrations of Er^{3+} and Yb^{3+} as well as investigation of their laser properties still need to be carried out. However, the preliminary results achieved with Er-doped and Er, Yb-doped YVO_4 crystals are promising, as cw stable laser oscillation characterised by a relatively low threshold value, high slope efficiency and tunability was realised. Thus, we believe that optimising the Er^{3+}/Yb^{3+} concentrations in combination with improvement of the set-up elements (pump source, coatings, cooling system, crystal length and quality) can result in an efficient Er^{3+} crystalline laser for the 1.6 μm range.

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