Polarization-anisotropy of mid-infrared emission properties of Er³⁺ ions in YAIO₃ crystal - INVITED

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Abstract. We report on a polarization-resolved study of mid-infrared emission properties of E^{3+} ions in the orthorhombic YAlO₃ crystal. For the ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ transition, σ_{SE} reaches 0.20×10^{-20} cm² at 2919 nm (for light polarization $E \parallel c$). Pump-induced polarization switching between the $E \parallel b$ and $E \parallel c$ eigen-states is observed in an 10 at.% Er:YAlO₃ laser. Pumped by an Yb-fiber laser at 976 nm, this laser delivers 0.77 W at 2919 nm with a slope efficiency of 31.4% being close to the Stokes limit and a laser threshold of 33 mW.

1 Introduction

Laser sources emitting at 3 µm are of practical importance for medical applications, including painless monitoring of blood sugar levels, laser treatment of soft tissues and dentistry. This spectral range can be addressed by Erbium (Er³⁺) lasers operating on the ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ transition. The bottleneck effect associated with this laser channel can be overcome through employing high Er³⁺ doping levels in crystals with low phonon energies leading to enhanced energy-transfer upconversion emptying the terminal laser level and suppressed non-radiative path from the emitting state [1]. Recently, the YAlO₃ crystal heavily doped with Er³⁺ ions was proposed as a promising gain material for 3 µm lasers [2]. Furthermore, 2.92 µm Er:YAlO3 lasers have been employed for pumping Fe²⁺:ZnSe lasers at 4.1 µm [3]. However, the polarization-resolved mid-infrared emission properties of this anisotropic material have not been studied so far.

In the present work, we aimed to investigate the peculiarities of ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ stimulated-emission of Er^{3+} ions in the YAlO₃ crystal.

2 Spectroscopy

YAlO₃ belongs to the orthorhombic class (sp. gr. *Pnma*) and it is optically biaxial. The stimulated-emission (SE) cross-sections, σ_{SE} , for the ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ transition of Er³⁺ ions were calculated using the Füchtbauer–Ladenburg equation using the radiative lifetime of the ${}^{4}I_{11/2}$ state (τ_{rad} = 7.39 ms) and the luminescence branching ratio (β_{JJ} = 21.9%) obtained by the Judd-Ofelt analysis [4], see Fig. 1. Er³⁺ ions exhibit relatively weak anisotropy of σ_{SE} values suggesting possible polarization-switching phenomenon. Due to the resonant excited-state absorption (ESA, ${}^{4}I_{13/2} \rightarrow {}^{4}I_{11/2}$) from the long-living terminal laser level, midinfrared Er lasers tend to operate at the long-wave part of the emission spectrum. For Er³⁺ ions in YAIO₃, in this spectral range, σ_{SE} is 0.20×10^{-20} cm² at 2919 nm (for light polarization $E \parallel c$).

For the 10 at.% Er^{3+} -doped YAIO₃ crystal, the measured luminescence lifetimes for the ${}^{4}I_{11/2} / {}^{4}I_{13/2}$ excited-states were 6.68 / 1.08 ms, respectively. The bottleneck effect is avoided by the energy-transfer upconversion process (ETU, ${}^{4}I_{13/2} + {}^{4}I_{13/2} \rightarrow {}^{4}I_{9/2} + {}^{4}I_{15/2}$) whose rate is boosted by the high Er^{3+} doping level.



Fig. 1. Stimulated-emission (SE) cross-sections, σ_{SE} , for the ${}^{4}\text{I}_{11/2} \rightarrow {}^{4}\text{I}_{13/2}$ transition of Er³⁺ in YAlO₃ for light polarizations $E \parallel a, b, c$ (sp. gr. *Pnma*). Arrows indicate the laser wavelengths.

3 Mid-infrared laser operation

The rectangular laser element from 10 at.% Er:YAlO₃ was oriented for light propagation along the *a*-axis having an

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aperture of $2.0 \times 2.0 \text{ mm}^2$ and a thickness of 5.0 mm. Both its faces were polished to laser quality and left uncoated. The crystal was mounted on a passively cooled massive Cu-holder and placed in a hemispherical cavity formed by a plane pump mirror (HT at 0.98 µm, HR at 2.6-3 µm) and a set of concave (RoC = -100 mm) output couplers with a transmission at the laser wavelength T_{OC} in the range of 0.33% - 4.0%. The cavity length was ~99 mm. The pump source was a commercial Ytterbium fiber laser (YFL, ALS-IR-122) at 976 nm. Its output was focused into the crystal using an AR-coated achromatic lens (f = 75 mm). The pump polarization corresponded to $E \parallel b$ in the crystal. The polarization state of laser emission was studied using a metal grid polarizer.

The power transfer characteristics of the Er:YAlO₃ laser are shown in Fig. 2. For $T_{OC} = 1.7\%$, the laser generated 0.77 W at 2919 nm with a slope efficiency η of 31.4% being close to the Stokes limit and a laser threshold of only 33 mW. The pump absorption efficiency was 86.2% (including the Fresnel loss at the uncoated input crystal face). On decreasing the output coupling, the threshold decreased from 64 mW (4% OC) to 15 mW (0.33% OC).



Fig. 2. Input-output dependences for the mid-infrared 10 at.% Er:YAlO₃ laser pumped by an Yb-fiber laser at 976 nm, η – slope efficiency. *a*-cut crystal.



Fig. 3. Spectra of laser emission from the Er:YAlO₃ laser: (a) Spectra for different output couplers measured well above the laser threshold; (b) Polarization-resolved spectra as a function of absorbed pump power, $T_{\rm OC} = 1.7\%$.

The typical spectra of laser emission measured well above the threshold are shown in Fig. 3(a). The laser emission was linearly polarized ($E \parallel c$) in line with the anisotropy of σ_{SE} spectra. For all used OCs, the mid-infrared Er-laser operated at 2919 nm (except of 4.0% OC for which two lines at 2731 and 2919 nm appeared). More complicated spectral behavior associated with polarization switching was observed at intermediate pump powers, Fig. 3(b). For the optimum $T_{OC} = 1.7\%$, near the threshold, the laser first operated at 2796 nm (with a linear polarization $E \parallel b$), then within a certain range of absorbed pump powers two orthogonal eigen polarization states ($E \parallel b$ and $E \parallel c$) coexisted leading to three observed laser lines and at even higher pump levels, polarization switching to the latter state ($E \parallel c$) occurred.



Fig. 4. Pump-induced polarization switching in the mid-infrared Er:YAlO₃ laser: (a) Power fraction X_{vert} of emission with $E \parallel c$ (vertical) polarization for different output coupler transmissions; (b) Polarization state measurement for $T_{OC} = 1.7\%$ at high pump power.

Figure 4 summarizes the observed polarization switching behavior for different output couplers. For small output coupling, the laser oscillations occurred for $E \parallel c$ even at the threshold power and no switching was observed. Upon increasing T_{OC} , the range of polarization switching shifted towards higher pump powers. As shown in Fig. 4(b), the laser emission well above the threshold was completely polarized. The observed polarization switching is induced by the similarity of σ_{SE} values for the orthogonal eigen polarization states (cf. Fig. 1) and the quasi-three-level nature of the ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ transition with reabsorption at the laser wavelength induced by ESA.

4 Conclusion

To conclude, due to the relatively weak polarization anisotropy of stimulated-emission cross-sections of Er^{3+} ions in the YAlO₃ crystal, it is prone to pump-induced polarization-switching resulting in generation of multiple laser lines (2731, 2796, and 2919 nm). Still, at high pump levels, linearly polarized emission is obtained. The observed laser behavior correlates with the polarizationresolved spectroscopic study performed in this work. We also show a proof-of- concept of using commercial Ybfiber lasers at 976 nm for efficient pumping heavily doped Er:YAlO₃ crystals. Further power scaling is expected employing high-power Yb-fiber laser pumping.

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