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Watt-Level Thulium Laser Operating on the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ Transition with $\sim 70\%$ Slope Efficiency

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Abstract: A Thulium laser operating on the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ transition in high-phonon-energy KLu(WO₄)₂ generates 1.12 W at 2.22&2.29 μm with a record-high slope efficiency of 69.2% representing a two-for-one pump process through efficient energy-transfer upconversion. © 2020

1. Introduction

Coherent light sources operating at 2.3 μm (short-wave infrared, SWIR) are of practical importance for gas sensing, optical metrology of combustion processes and non-invasive glucose blood measurements. One possibility for obtaining such emission is the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ electronic transition of the Tm³⁺ ion in glasses and crystals [1]. The interest to this transition was promoted by the recent demonstration of mode-locked 2.3 μm Tm lasers [2,3]. At a glance, the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ laser scheme is inefficient because of the self-quenching of the upper laser level (${}^3\text{H}_4$) by cross-relaxation (CR) and non-radiative (NR) relaxation in high-phonon-energy materials. Recently, we have shown that the slope efficiency of 2.3 μm Tm lasers may exceed the Stokes limit owing to the energy-transfer upconversion (ETU) [4].

In the present work, we demonstrate the first Tm laser operating on the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ transition based on a high-phonon-energy host material and study the effect of Tm doping level on its performance.

2. Spectroscopy

As a gain material, we selected the monoclinic Tm:KLu(WO₄)₂ crystal. It features a maximum phonon frequency $h\nu_{\text{ph}}$ of $\sim 907 \text{ cm}^{-1}$. The stimulated-emission (SE) cross-section, σ_{SE} , for the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ transition was determined using the Füchtbauer–Ladenburg formula for the principal light polarizations, for this optically biaxial crystal, $E \parallel N_p$, N_m and N_g , Fig. 1(a). The maximum σ_{SE} is $1.78 \times 10^{-20} \text{ cm}^2$ at 2289 nm and the corresponding emission bandwidth (FWHM) is 32.1 nm for $E \parallel N_m$. The scheme of the Stark splitting of the upper and lower multiplets is shown in Fig. 1(b).

The dependence of the luminescence lifetime of the upper laser level (${}^3\text{H}_4$) on the Tm doping level was analyzed yielding the intrinsic lifetime $\tau_{30} = 0.24 \text{ ms}$ and the concentration-independent CR parameter $C_{\text{CR}} = 2.70 \times 10^{-37} \text{ cm}^6 \text{ s}^{-1}$.

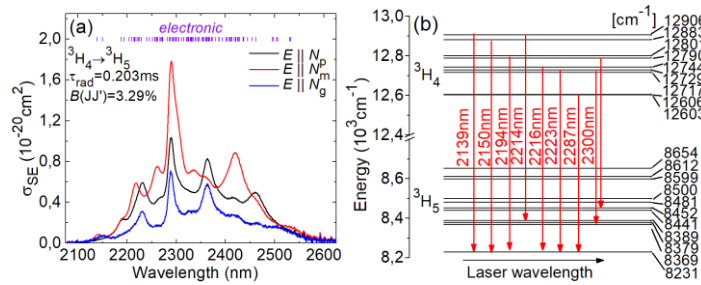


Fig. 1. Spectroscopy of the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ laser transition of Tm³⁺ in KLu(WO₄)₂ crystal: (a) stimulated-emission cross-sections, σ_{SE} , for light polarizations $E \parallel N_p$, N_m , N_g , the vertical dashes indicate the wavelengths of purely electronic transitions; (b) Crystal-field splitting of the ${}^3\text{H}_4$ and ${}^3\text{H}_5$ multiplets and the assignment of the observed laser lines.

3. Laser Operation

For the laser experiments, we used three uncoated N_g -cut Tm:KLu(WO₄)₂ crystals doped with 0.5, 1.5 or 3.0 at.% Tm. As a pump source, we employed a Ti:Sapphire laser tuned to 793.8 nm (pump polarization: $E_p \parallel N_p$). The pumping was in quasi-CW regime (duty cycle: 1:2). A simple near-hemispherical cavity was constructed by a flat pump mirror coated for high transmission (HT) at $\sim 0.79 \mu\text{m}$ and for high reflection (HR) at 2.12–2.50 μm , and a set of concave output couplers (OCs) with a radius of curvature of -100 mm and a transmission T_{OC} of 0.1%, 0.7%,

1.3% or 4.0% at 2.18–2.35 μm . To suppress the unwanted ${}^3\text{F}_4 \rightarrow {}^3\text{H}_6$ transition, the OCs had HT ($T > 90\%$) at 1.80–1.98 μm . The pump spot diameter in the focus was $65 \pm 10 \mu\text{m}$. For the 3 at.% Tm doped laser crystal, the pump absorption (double-pass) under lasing conditions reached 86.1% - 79.4%, depending on the OC (including Fresnel losses at the uncoated crystal surfaces).

The 3 at.% Tm doped crystal generated a maximum peak output power of 1.12 W at ~ 2.22 and 2.29 μm with a slope efficiency η of 69.2% (vs. the absorbed pump power), Fig. 2(a). The laser threshold was at 0.45 W and the optical-to-optical efficiency, calculated vs. the pump power incident on the crystal reached 44.4% ($T_{\text{OC}} = 1.3\%$). The laser emission was linearly polarized ($\mathbf{E} \parallel N_m$). The emission spectra were dependent both on the output coupling and the pump power, Fig. 2(b). All the observed laser lines were assigned according to the crystal-field splitting of the ${}^3\text{H}_4$ and ${}^3\text{H}_5$ multiplets, Fig. 1(b). The beam profile, Fig. 2(c), was slightly multimode with the measured $M^2_{x,y}$ factors were 2.2 ± 0.1 and 2.6 ± 0.1 , respectively.

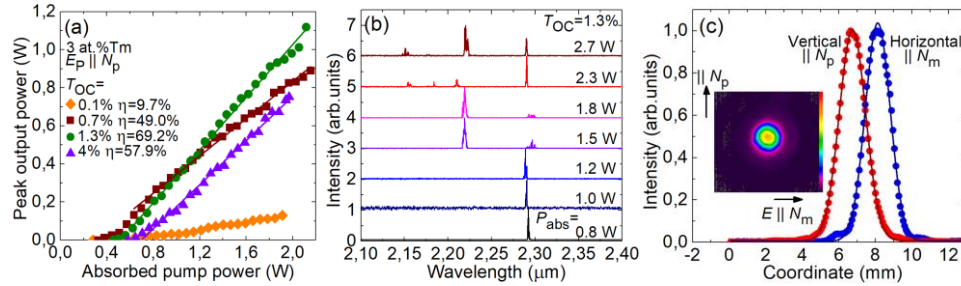


Fig. 2. Thulium $\text{KLu}(\text{WO}_4)_2$ laser operating on the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ transition: (a) input-output dependences, η – slope efficiency; (b) typical laser emission spectra for $T_{\text{OC}} = 1.3\%$; (c) 1D intensity profiles in the horizontal ($x, \parallel N_m$) and vertical ($y, \parallel N_p$) directions ($T_{\text{OC}} = 1.3\%$, $P_{\text{abs}} = 0.8 \text{ W}$), inset – 2D mode profile in the far-field. The laser polarization is $\mathbf{E} \parallel N_m$.

The performance of the Tm laser gradually improved with increasing the Tm doping from 0.5 to 3.0 at.%, Fig. 3(a). The pump quantum efficiency η_q (the number of excitations to the upper laser level, ${}^3\text{H}_4$, per number of absorbed pump photons) was calculated according to the model from [4] using the passive losses L determined from the Findlay-Clay analysis, Fig. 3(b). For the 3 at.% Tm doped crystal, η_q reached 1.7 ± 0.2 well above the laser threshold representing an almost “two-for-one” pump process which is assigned to efficient ETU, ${}^3\text{F}_4 + {}^3\text{F}_4 \rightarrow {}^3\text{H}_6 + {}^3\text{H}_4$, refilling the upper laser level manifold, Fig. 3(c). The rate-equation modeling of the laser performance supported this conclusion.

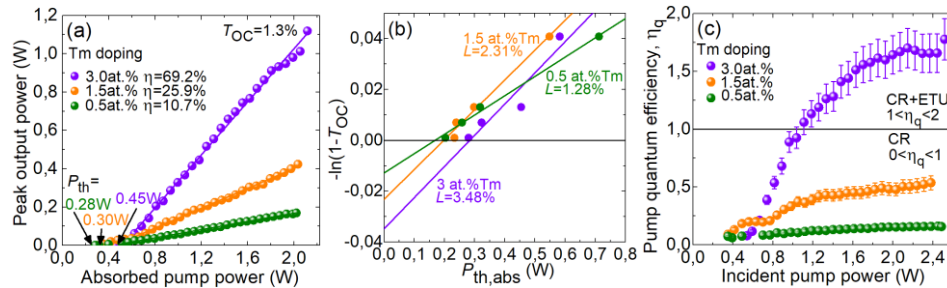


Fig. 3. Effect of the Tm doping level on the laser operation on the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ transition: (a) input-output dependences, η – slope efficiency, $T_{\text{OC}} = 1.3\%$; (b) Findlay-Clay analysis of the roundtrip intracavity losses, L ; (c) calculated pump quantum efficiency, $T_{\text{OC}} = 1.3\%$.

4. Conclusions

To conclude, we report on a watt-level Tm:KLu(WO₄)₂ laser operating on the ${}^3\text{H}_4 \rightarrow {}^3\text{H}_5$ transition with a record-high slope efficiency of $\sim 70\%$ well exceeding the Stokes limit. This, together with the broadband emission properties of this crystal at $\sim 2.3 \mu\text{m}$ (emission bandwidth: $> 30 \text{ nm}$) highlight its potential for femtosecond mode-locked SWIR lasers.

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