Watt-Level Thulium Laser Operating on the $3H_4 \rightarrow 3H_5$ Transition with 70% Slope Efficiency

Pavel Loiko, Esrom Kifle, Lauren Guillemot, Jean-Louis Doualan, Florent Starecki, A. Braud, Magdalena Aguiló, Francesc Díaz, Valentin Petrov, Xavier Mateos, et al.

► To cite this version:

Pavel Loiko, Esrom Kifle, Lauren Guillemot, Jean-Louis Doualan, Florent Starecki, et al.. Watt-Level Thulium Laser Operating on the $3H_4 \rightarrow 3H_5$ Transition with 70% Slope Efficiency. Advanced Solid State Lasers 2020, Oct 2020, Washington, United States. pp.ATH5A.2, 10.1364/ASSL.2020.ATH5A.2 . hal-03140567

HAL Id: hal-03140567

<https://hal.science/hal-03140567>

Submitted on 7 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Pavel Loiko,¹ Esrom Kifle,¹ Lauren Guillemot,¹ Jean-Louis Doualan,¹ Florent Starecki,¹ Alain Braud,¹ Magdalena Aguiló,² Francesc Díaz,² Valentin Petrov,³ Xavier Mateos,² and Patrice Camy^{1,*}

¹Centre de Recherche sur les Ions, les Matériaux et la Photonique (CIMAP), UMR 6252 CEA-CNRS-ENSICAEN, Université de Caen Normandie, 6 Boulevard du Maréchal Juin, 14050 Caen Cedex 4, France

²Universitat Rovira i Virgili (URV), Física i Cristal·lografia de Materials i Nanomaterials (FiCMA-FiCNA)-EMaS, Marcel·li Domingo 1, 43007 Tarragona, Spain

³Max Born Institute for Nonlinear Optics and Short-Pulse Spectroscopy, 2A Max-Born-Str., 12489 Berlin, Germany
*patrice.camy@ensicaen.fr

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 Tm^{3+} 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 $\text{Tm:KLu(WO}_4)_2$ 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 Fchtbauer–Ladenburg formula for the principal light polarizations of 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 Tm^{3+} in $\text{KLu(WO}_4)_2$ 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 $\text{Tm:KLu(WO}_4)_2$ 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 $2.29 \mu\text{m}$ 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 ($E \parallel N_m$). 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 KLu(WO₄)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 $E \parallel N_m$.

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.

References

- [1] R. Soulard, A. Tyazhev, J. L. Doualan, A. Braud, A. Hideur, M. Laroche, B. Xu, and P. Camy, “2.3 μm Tm³⁺:YLF mode-locked laser,” Opt. Lett. **42**(18), 3534–3536 (2017).
- [2] F. Canbaz, I. Yorulmaz, and A. Sennaroglu, “Kerr-lens mode-locked 2.3- μm Tm³⁺:YLF laser as a source of femtosecond pulses in the mid-infrared,” Opt. Lett. **42**(19), 3964–3967 (2017).
- [3] P. Loiko, R. Soulard, L. Guillemot, G. Brasse, J.-L. Doulan, A. Braud, A. Tyazhev, A. Hideur, B. Guichardaz, F. Druon, and P. Camy, “Efficient Tm:LiYF₄ lasers at $\sim 2.3 \mu\text{m}$: Effect of energy-transfer upconversion,” IEEE J. Quantum Electron. **55**(6), 1700212 (2019).
- [4] L. Guillemot, P. Loiko, R. Soulard, A. Braud, J.-L. Doualan, A. Hideur, and P. Camy, “Close look on cubic Tm:KY₃F₁₀ crystal for highly efficient lasing on the $^3\text{H}_4 \rightarrow ^3\text{H}_5$ transition,” Opt. Express **28**(3), 3451–3463 (2020).