Contents lists available at SciVerse ScienceDirect

# **Optics & Laser Technology**

journal homepage: www.elsevier.com/locate/optlastec

# Diode-pumped continuous-wave laser operation of co-doped (Ho,Tm):KLu(WO<sub>4</sub>)<sub>2</sub> monoclinic crystal

Venkatesan Jambunathan<sup>a</sup>, Xavier Mateos<sup>a,\*</sup>, Maria Cinta Pujol<sup>a</sup>, Joan Josep Carvajal<sup>a</sup>, Uwe Griebner<sup>b</sup>, Valentin Petrov<sup>b</sup>, Magdalena Aguiló<sup>a</sup>, Francesc Díaz<sup>a</sup>

<sup>a</sup> Física i Cristal · lografia de Materials i Nanomaterials (FiCMA-FiCNA-EMAS), Universitat Rovira i Virgili (URV), c/Marcel · lí Domingo, s/n, E-43007 Tarragona, Spain <sup>b</sup> Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born Strasse 2A, 12489 Berlin, Germany

#### ARTICLE INFO

Article history: Received 2 October 2012 Received in revised form 28 May 2013 Accepted 17 June 2013 Available online 6 July 2013

Keywords. Potassium lutetium double tungstate  $(KLu(WO_4)_2)$ Holmium Thulium

#### ABSTRACT

We report on room-temperature continuous-wave laser operation at 2.06 µm in co-doped (0.5 at% Ho, 5.0 at% Tm):KLu(WO<sub>4</sub>)<sub>2</sub> monoclinic crystal pumped at 805 nm by a commercially available AlGaAs diode laser stack. A maximum output power of 93 mW and a slope efficiency of 14.7% with respect to absorbed power were achieved.

© 2013 Elsevier Ltd. Open access under CC BY-NC-ND license.

# 1. Introduction

Development of compact eye-safe solid-state lasers in the near infrared region based on rare earth lanthanide ions is of special interest in recent years because of their vast scientific and technological applications. For instance the Ho<sup>3+</sup> (Ho) ion which emits slightly above 2  $\mu$ m has potential applications in the field of remote sensing, medical treatments and as a pump source for mid-IR Optical Parametric Oscillators (OPOs) [1]. The main drawback of the trivalent Ho ion is that it does not exhibit suitable absorption bands for efficient pumping. In order to overcome this drawback many researchers used Tm<sup>3+</sup> (Tm) ion as sensitizer in different hosts due to the possibility to pump the co-doped system with commercially available AlGaAs laser diodes near 800 nm [2-5].

Concerning the host, potassium lutetium double tungstate with the chemical formula  $KLu(WO_4)_2$  (hereafter KLuW) [6,7] belongs to the family of the monoclinic potassium double tungstates which stand out for their very high absorption and emission cross-sections when doped with lanthanide active ions

fluorescence quenching effects. Recently KLuW has been shown to be the most suitable such host for Tm and Yb active ions and moderate power levels, around 10 W in continuous-wave (CW) regime. In the case of Yb:KLuW [8], up to 11 W output power has been achieved under fiber-coupled diode pumping (N.A.=0.22), with an absorbed power of 16.2 W corresponding to a slope efficiency of 80%. For Tm:KLuW [9] 10.4 W output power has been achieved. Here the pumping architecture is rather different. The authors in [9] used a CS-mount diode laser and launched up to 34.2 W achieving a maximum slope efficiency of 43% (with respect to the incident power) in a special designed six-passes pumping scheme.

and their capability to accept high doping levels without

In this work, we achieved for the first time to our knowledge diode-pumped continuous wave (CW) laser operation of co-doped (Ho,Tm):KLuW crystal.

### 2. Experimental details

Macro defect free single-crystal with high optical quality with a doping ratio of 0.5 at% Ho, 5 at% Tm:KLuW was grown by the Top Seeded Solution Growth Slow-Cooling method (TSSG-SC) using  $K_2W_2O_7$  as a solvent. The methodology of growth can be found elsewhere [10]. Information on the spectroscopic properties of (Ho,Tm):KLuW crystals can be found in our previous work [11,12] where we obtained lasing under Ti:sapphire pumping. The Tm ion







<sup>\*</sup> Corresponding author. Tel.: +34 977558628. E-mail address: xavier.mateos@urv.cat (X. Mateos).

shows maximum absorption cross-section of  $5.2 \times 10^{-20}$  cm<sup>2</sup> at 802 nm for light polarization with the electric field (*E*) parallel to the  $N_m$  principal optical axis (*E*// $N_m$ ). In order to obtain the gain cross-section curves of Ho, emission cross-section of Ho was calculated by the reciprocity method [13]. For the sake of brevity only gain curves for *E*// $N_m$  are presented in Fig. 1 which is sufficient to understand the laser emission reported below. The calculated gain curves of Ho for several inversion levels ( $\beta$ ) in the 1900–2100 nm range show a maximum centered at 2060 nm.

The laser experiment was carried out with a 2-mirror hemispherical resonator (see Fig. 2). M1 is the plane pump mirror, highly transmitting ( > 98%) at the pump wavelength and highly reflecting in the 1800–2100 nm range. M2 is the concave output coupler with radius of curvature RC=50 mm and transmission ( $T_{oc}$ ) 1.5% (  $\pm$  0.5%), 3.0% (  $\pm$  1%), 5.0% (  $\pm$  1.0%), and 9.0% (  $\pm$  1.0%) in the 1820–2050 nm range.

The pump source was a fiber coupled AlGaAs laser diode stack (NA=0.22) emitting at 805 nm from Lumix (model no: LU808C045-E). The pump was focused using the lens assembly L1 (consisting of a collimating and a focusing lens) to a beam diameter of the order of 200  $\mu$ m. The AR coated active medium used was a  $N_g$  cut (0.5 at% Ho, 5 at% Tm):KLuW crystal which showed best performance in experiments with Ti:sapphire laser pumping [12]. These doping levels correspond to ion density in this crystal of  $5.291 \times 10^{19}$  cm<sup>-3</sup> (Ho) and  $2.301 \times 10^{20}$  cm<sup>-3</sup> (Tm). Such values were measured for proper calculation of concentration of active ions. The thickness of the active element was 3 mm and the aperture size was  $3 \times 3 \text{ mm}^2$ . The crystal was located as close as possible to the pump mirror. We used indium foil at the top and bottom surfaces of the crystal to ensure better contact with the copper holder which was water cooled to 16 °C for dissipation of heat.



**Fig. 1.** Calculated gain cross-section curves of Ho for  $E/|N_m$  in the (Ho,Tm):KLuW crystal.



**Fig. 2.** Cavity setup of the (Ho,Tm):KLuW laser. LD—laser diode which is fiber coupled (NA=0.22) emitting at 805 nm; L1—lens assembly consisting of collimating and focusing lens, imaging ratio1:1, 200  $\mu$ m beam diameter; M1—plane pump mirror; M2—concave output coupler with radius of curvature –50 mm; Ho,Tm: KLuW crystal—thickness 3 mm.



**Fig. 3.** Output power versus absorbed pump power of the (0.5 at% Ho5 at% Tm): KLuW laser for different  $T_{oc}$ .

Table 1Summary of the laser characteristics for different  $T_{oc}$ .

T <sub>oc</sub> [%]	Maximum output power [mW]	Slope efficiency [%]	Wavelength [nm]
1.5	74	8.5	2078, 2063
3.0	93	14.7	2062
5.0	69	12.4	2062
9.0	13	2.9	2062

### 3. Results and discussion

CW laser operation on the  ${}^{5}I_{7} \rightarrow {}^{5}I_{8}$  transition of Ho was realized for all the output couplers. The output from the (Ho,Tm):KLuW laser was always linearly polarized with  $E//N_m$  although the pump is not polarized. We measured the output power as a function of the incident power for a physical cavity length of 50 mm. For the calculation of the slope efficiency, we used the measured value of the absorption without lasing (68%, taking into account a second pump pass through the reflection of the output mirror). A maximum output power of 93 mW was achieved for an absorbed power of 1470 mW. Fig. 3 and Table 1 summarize the input–output characteristics of the (0.5 at% Ho, 5 at%Tm): KLuW laser for different output coupling  $T_{oc}$ .

The  $T_{oc}$ =3% output coupler gave maximum output power and highest slope efficiency (14.7%) and in this case, we measured the quality of the beam by the knife-edge method, resulting in  $M_x^2 = M_y^2 = 1.2$ 

The laser wavelength was at 2062 nm for the  $T_{oc}$ =3%, 5%, and 9% output couplers, it was longer only for the lowest 1.5% output coupling 1.5%@2060 nm (1.7%@2080 nm) (Fig. 4), as could be expected for a three-level system.

It is interesting that for  $T_{oc} = 1.5\%$  dual wavelength operation occurs which can be attributed solely to the Ho ion. This could be explained with the help of the gain curves as shown in Fig. 1. For low inversion levels the gain exhibits two maxima which are comparable. Thus simultaneous oscillation from different Stark sub-levels of the same ( ${}^{5}I_{7}$ ) manifold is possible. Tm lasing, as in the case of using Ti:sapphire laser as a pump source [14] was not observed in the present experiment, presumably related to the lower pump intensity and Tm inversion level achieved.



**Fig. 4.** Typical emission spectra of the (Ho,Tm):KLuW laser for different output coupling  $T_{ocs}$ .

#### 4. Conclusions

In summary, we have demonstrated the diode pumped continuous wave laser action in the (Ho,Tm):KLuW system operating at 2.06  $\mu$ m and studied several transmissions of the output coupler achieving a maximum output power of 100 mW.

The present work represents additional knowledge to what is an extended work on room temperature laser operation of (Tm, Ho)-doped laser crystals like, garnets, fluorides and vanadates [15]. In our opinion, the (Ho,Tm):KLuW system should be improved with a special cooling system design to increase the output power and efficiency of the laser, such as the use of a cryogenic chamber. This is what we plan next.

### Acknowledgments

This work was supported by the Spanish Government under Projects MAT2010-11402-E, MAT2011-29255-C02-02, TEC2010-21574-C02-02, PI09/90527, DE2009-0002 and the Catalan Authority under Project 2009SGR235. It was partially funded by the European Commission under the Seventh Framework Programme, Project Cleanspace, FP7-SPACE-2010-1-GA no. 263044, LASERLAB-EUROPE, GA no. 228334, and the German–Spanish Bilateral Programme Acciones Integradas (ID 50279160).

## References

- [1] Scholle Karsten, Lamrini Samir, Koopmann Philipp, Fuhrberg Peter. 2 μm laser sources and their possible applications. In: Pal Bishnu, editor Frontiers in guided wave optics and optoelectronics. ISBN: 978-953-7619-82-4. InTech; 2010. Available from: <http://www.intechopen.com/books/frontier s-in-guided-wave-optics-andoptoelectronics/2-m-laser-sources-and-theirpossible-applications>.
- [2] Fan TY, Huber G, Byer RL, Mitzscjerlich P. Spectroscopy and diode laserpumped operation of Tm, Ho:YAG. IEEE Journal of Quantum Electronics 1988;24:924–33.
- [3] Sudesh V, Asai K. Spectroscopic and diode-pumped-laser properties of Tm,Ho: YLF; Tm,Ho:LuLF; and Tm,Ho:LuAG crystals: a comparative study. Journal of the Optical Society of America B 2003;20:1829–37.
- [4] Yao BQ, Li G, Meng PB, Zhu GL, Ju YL, Wang YZ. High power diode-pumped continuous wave and Q-switch operation of Tm,Ho:YVO<sub>4</sub> laser. Laser Physics Letters 2010;7:857–61.
- [5] Yang FG, Sun CL, You ZY, Tu CY, Zhang G, Zhu HY. End-pumped Tm,Ho:NaY (WO<sub>4</sub>)<sub>2</sub> crystal laser at 2.07 μm. Laser Physics 2010;20:1695–7.
- [6] Pujol MC, Mateos X, Aznar A, Solans X, Suriñac S, Massons J, et al. Structural redetermination, thermal expansion and refractive indices of KLu(WO<sub>4</sub>)<sub>2</sub>. Journal of Applied Crystallography 2006;39:230–6.
- [7] Petrov V, Pujol MC, Mateos X, Silvestre Ó, Rivier S, Aguiló M, et al. Growth and properties of KLu(WO<sub>4</sub>)<sub>2</sub>, and novel ytterbium and thulium lasers based on this monoclinic crystalline host. Laser and Photonics Reviews 2007;1:179–212.
- [8] Liu J, Petrov V, Mateos X, Zhang H, Wang J. Efficient high-power laser operation of Yb:KLu(WO<sub>4</sub>)<sub>2</sub> crystals cut along the principal optical axes. Optics Letters 2007;32:2016–8.
- [9] Vatnik S, Vedin I, Pavlyuk A. High-efficiency transversely pumped 5%Tm: KLuW mini-slab laser. In: Proceedings of the 4th Europhoton Conference, paper FrB3, CD ROM; 2010.
- [10] Solé R, Nikolov V, Ruiz X, Gavaldà Jna, Solans X, Aguiló M, et al. Growth of  $\beta$ -KGd<sub>1-x</sub>Nd<sub>x</sub>(WO<sub>4</sub>)<sub>2</sub> single crystals in K<sub>2</sub>W<sub>2</sub>O<sub>7</sub> solvents. Journal of Crystal Growth 1996;169:600–3.
- [11] Jambunathan V, Mateos X, Pujol MC, Carvajal JJ, Massons J, Aguilo M, et al. Near-infrared photoluminescence from Ho<sup>3+</sup>-doped monoclinic KLu(WO<sub>4</sub>)<sub>2</sub> crystal codoped with Tm<sup>3+</sup>. Journal of Luminescence 2009;129:1882–5.
- [12] Jambunathan V, Schmidt A, Mateos X, Pujol MC, Carvajal JJ, Griebner U, et al.. Crystal growth, optical spectroscopy and continuous-wave laser operation of co-doped (Ho,Tm):KLu(WO<sub>4</sub>)<sub>2</sub> monoclinic crystals, submitted for publication.
- [13] Payne SA, Chase LL, Smith LK, Kway WL, Krupke William F. Infrared crosssection measurement for crystals doped with Er<sup>3+</sup>, Tm<sup>3+</sup>, Ho<sup>3+</sup>. IEEE Journal of Quantum Electronics 1992;28:2619–30.
- [14] Jambunathan V, Schmidt A, Mateos X, Pujol MC, Carvajal JJ, Aguiló M, et al. Continuous-wave co-lasing in a monoclinic co-doped (Ho,Tm):KLu(WO<sub>4</sub>)<sub>2</sub> crystal. Laser Physics Letters 2011799–803.
- [15] Wu CT, Ju YL, Chen F, Jin GY. Research on 2 μm solid-state-lasers. Laser Physics 2012;22:635–47.