

# Diode-pumped continuous-wave (Ho,Tm):KLu(WO<sub>4</sub>)<sub>2</sub> laser with >1 W output power

Xavier Mateos,<sup>1,2\*</sup> Fabrizio Di Trapani,<sup>1,3</sup> Magdalena Aguiló,<sup>2</sup> Francesc Díaz,<sup>2</sup> Uwe Griebner<sup>1</sup> and Valentin Petrov<sup>1</sup>

<sup>1</sup>Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2A, D-12489 Berlin, Germany

<sup>2</sup>Física i Cristal·lografia de Materials i Nanomaterials (FiCMA-FiCNA), Universitat Rovira i Virgili (URV), Campus Sescelades, c/ Marcel·li Domingo, s/n, E-43007, Tarragona, Spain

<sup>3</sup>Università di Pavia, Dip. Ingegneria Industriale e dell'Informazione, via Ferrata, 3, 27100, Pavia, Italy  
\*xavier.mateos@urv.cat

**Abstract:** We studied laser generation of the Ho<sup>3+</sup>-ion in (Ho,Tm):KLu(WO<sub>4</sub>)<sub>2</sub> crystals pumped by Ti:sapphire and diode lasers achieving output powers up to ~1.2 W. For polarization parallel to the N<sub>m</sub> principal axis, the lasers operated at 2078 or 2059-1960 nm depending on the transmission of the output coupler. The maximum slope efficiency with respect to the absorbed power reached ~30% for both types of pump sources. Tuning was studied with Ti:sapphire laser pumping achieving a tuning range of ~180 nm.

©2014 Optical Society of America

**OCIS codes:** (140.3070) Infrared and far-infrared lasers; (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state.

---

## References and links

1. G. H. Dieke, *Spectra and Energy Levels of Rare Earth Ions in Crystals* (Wiley Interscience, 1968).
2. K. Scholle, S. Lamrini, P. Koopmann, and P. Fuhrberg, "2 μm laser sources and their possible applications," in *Frontiers in Guided Wave Optics and Optoelectronics*, B. Pal, ed. (Intech, 2010), pp. 471–500.
3. V. Petrov, M. C. Pujol, X. Mateos, Ò. Silvestre, S. Rivier, M. Aguiló, R. M. Solé, J. Liu, U. Griebner, and F. Díaz, "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 Photon. Rev.* **1**(2), 179–212 (2007).
4. P. A. Loiko, K. V. Yumashev, N. V. Kuleshov, V. G. Savitski, S. Calvez, D. Burns, and A. A. Pavlyuk, "Thermal lens study in diode pumped N<sub>8</sub>- and N<sub>9</sub>-cut Nd:KGd(WO<sub>4</sub>)<sub>2</sub> laser crystals," *Opt. Express* **17**(26), 23536–23543 (2009).
5. A. A. Lagatsky, F. Fusari, S. V. Kurilchik, V. E. Kisel, A. S. Yasukevich, N. V. Kuleshov, A. A. Pavlyuk, C. T. A. Brown, and W. Sibbett, "Optical spectroscopy and efficient continuous-wave operation near 2 μm for a Tm,Ho:KYW laser crystal," *Appl. Phys. B* **97**(2), 321–326 (2009).
6. A. A. Lagatsky, F. Fusari, S. Calvez, J. A. Gupta, V. E. Kisel, N. V. Kuleshov, C. T. A. Brown, M. D. Dawson, and W. Sibbett, "Passive mode locking of a Tm,Ho:KY(WO<sub>4</sub>)<sub>2</sub> laser around 2 μm," *Opt. Lett.* **34**(17), 2587–2589 (2009).
7. A. A. Lagatsky, F. Fusari, S. Calvez, S. V. Kurilchik, V. E. Kisel, N. V. Kuleshov, M. D. Dawson, C. T. A. Brown, and W. Sibbett, "Femtosecond pulse operation of a Tm,Ho-codoped crystalline laser near 2 microm," *Opt. Lett.* **35**(2), 172–174 (2010).
8. V. Jambunathan, A. Schmidt, X. Mateos, M. C. Pujol, J. J. Carvajal, M. Aguiló, F. Díaz, U. Griebner, and V. Petrov, "Continuous-wave co-lasing in a monoclinic co-doped (Ho,Tm):KLu(WO<sub>4</sub>)<sub>2</sub> crystal," *Laser Phys. Lett.* **8**(11), 799–803 (2011).
9. V. Jambunathan, X. Mateos, M. C. Pujol, J. J. Carvajal, U. Griebner, V. Petrov, M. Aguiló, and F. Díaz, "Diode-pumped continuous-wave laser operation of co-doped (Ho,Tm):KLu(WO<sub>4</sub>)<sub>2</sub> monoclinic crystal," *Opt. Laser Technol.* **54**, 326–328 (2013).
10. R. Solé, V. Nikolov, X. Ruiz, J. Gavalda, X. Solans, M. Aguiló, and F. Díaz, "Growth of β-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," *J. Cryst. Growth* **169**(3), 600–603 (1996).
11. B. M. Walsh, N. P. Barnes, and B. Di Bartolo, "The temperature dependence of energy transfer between the Tm 3F<sub>4</sub> and Ho 5I<sub>7</sub> manifolds of Tm-sensitized Ho luminescence in YAG and YLF," *J. Lumin.* **90**(1-2), 39–48 (2000).
12. V. Jambunathan, A. Schmidt, X. Mateos, M. C. Pujol, U. Griebner, V. Petrov, C. Zaldo, M. Aguiló, and F. Díaz, "Crystal growth, optical spectroscopy and continuous-wave laser operation of co-doped (Ho,Tm):KLu(WO<sub>4</sub>)<sub>2</sub> monoclinic crystals," *J. Opt. Soc. Am. B* **31**(7), 1415–1421 (2014).

## Introduction

When more powerful and commercially available optical pump sources operate at wavelengths at which an active ion has no suitable absorption band for pumping, co-doped solid-state laser active media are the best choice. This is the case with the Ho<sup>3+</sup> ion once flash-lamp pumping was substituted by laser pumping. In a co-doped active medium, the so-called sensitizer ion provides sufficient energy to the active ion to promote its electrons to the suitable energy level for laser action. In the case of Ho and Tm co-doped systems, the Tm ions are efficiently excited from the ground to the <sup>3</sup>H<sub>4</sub> level with largely available AlGaAs diode lasers operating around 800 nm followed by efficient <sup>3</sup>F<sub>4</sub> (Tm) to <sup>5</sup>I<sub>7</sub> (Ho) energy transfer since these two levels are resonant [1]. This energy transfer mechanism has been utilized in numerous laser hosts for Ho-laser operation at wavelengths slightly above 2 μm, with application in medicine, and atmospheric sensing of carbon dioxide and water vapour. In-band pumping of the Ho-ion to the upper laser level by Tm lasers including fiber based and by GaSb diodes is another possibility but the former lead to complexity and higher overall price while the latter are not standard and not available commercially with the desired parameters (wavelength, power and fiber coupling) [2]. The main drawback of the co-doped Tm-Ho system is the compromised energy transfer efficiency that depends on the host and the upconversion losses which lead to an increased temperature of the crystal, clearly detrimental for the quasi-three level Ho<sup>3+</sup>-laser.

The host crystal that we study in this work is the monoclinic potassium lutetium double tungstate KLu(WO<sub>4</sub>)<sub>2</sub>, shortly KLuW, doped with trivalent Ho and Tm ions. The KLuW crystal demonstrated excellent properties as host for Tm and Yb dopant ions [ref 3] providing (i) possibility of 100% substitution of the Lu ions for Tm or Yb with little or negligible fluorescence quenching, (ii) optical anisotropy due to its monoclinic nature resulting in very large absorption (σ<sub>a</sub>) and emission (σ<sub>e</sub>) cross-sections for some of the principal polarization directions and (iii) broad absorption and emission bands supporting femtosecond laser pulse generation. On the other hand, this crystal as the whole family suffers from anisotropic thermal behaviour [4] along the principal optic axes (thermo optic coefficient (dn/dT), thermal conductivity and thermal expansion).

The formation of anisotropic thermal lens and in general the thermal stability of the laser, restrict their use to medium power levels (~10 W), where the efficiency can be fairly high.

Previous studies of the isostructural (Ho,Tm):KY(WO<sub>4</sub>)<sub>2</sub> [5], demonstrated output power of 460 mW in continuous-wave (CW) regime, limited by the Ti:sapphire pump. The same laser crystal was also employed for picosecond [6] and femtosecond [7] pulse generation achieving pulses as short as 570 fs at 2055 nm. Initial laser results obtained with (Ho,Tm):KLuW under Ti:sapphire laser pumping indicated simultaneous lasing of Ho (2061 nm) and Tm (1937 nm) with even lower output power and only 156 mW of it due to the Ho<sup>3+</sup>-ion emission [8]. Diode pumping was also studied but showed also poor performance with maximum output power not exceeding 100 mW [9]. In the present work, we compare the performance of (Ho,Tm):KLuW lasers under Ti:sapphire and diode laser pumping and report more than 10 times improvement under diode pumping, achieving what is the highest laser output power among the Ho-based double tungstate lasers including both single and co-doped. In addition, we demonstrate continuous tuning of the (Ho,Tm):KLuW laser over ~180 nm.

## Experimental

We used the Top-Seeded Solution Growth (TSSG) slow-cooling method [10] to grow a high quality defect-free KLuW crystal doped with 5 at.% Tm and 0.5 at.% Ho in the solution, an optimum ratio known from previous work with this and other hosts [5, 11]. The measured ion density, determined by Electron Probe Microanalysis (EPMA) technique was  $3.10 \times 10^{20}$  at·cm<sup>-3</sup> for Tm and  $5.29 \times 10^{19}$  at·cm<sup>-3</sup> for Ho corresponding

to a composition of  $\text{KLu}_{0.944}\text{Ho}_{0.008}\text{Tm}_{0.048}(\text{WO}_4)_2$ . All the crystal growth parameters as well as a detailed spectroscopic study concerning absorption, emission and lifetime measurements for several dopant ratios of the (Ho,Tm) co-doped KLuW crystals can be found in [12,13]. At a pump wavelength of 802 nm for instance, Tm exhibits an absorption cross section of  $\sigma_a = 5.2 \times 10^{-20} \text{ cm}^2$  for  $E//N_m$  and  $1.7 \times 10^{-20} \text{ cm}^2$  for  $E//N_p$  whereas Ho shows an emission cross section of  $\sigma_e = 2.42 \times 10^{-20} \text{ cm}^2$  at 2060 nm for  $E//N_m$ , calculated by the reciprocity method. The relevant parameter in a three-level laser system is the gain cross section which is lower and depends on the inversion rate. Assuming a maximum inversion rate of 0.5 will result in a gain cross section ( $\sigma_g$ ) of  $0.83 \times 10^{-20} \text{ cm}^2$  for Ho at 2060 nm and  $E//N_m$ .

In the present work, we used two different cavity designs and different active elements although all (Ho,Tm):KLuW samples were cut from the same bulk crystal. This ensures same composition and crystal quality. For the experiments with Ti:sapphire laser pumping (3.1 W maximum available power incident on the crystal), the active element mainly used was approximately of cubic shape, cut for beam propagation along the  $N_g$  principal optical direction ( $N_g$ -cut) with length of 2.75 mm and aperture of 2.71 mm ( $//N_m$ )  $\times$  2.95 mm ( $//N_p$ ). For comparison we also used a second sample which was 1.39 mm in length and  $N_p$ -cut, with an aperture of 3.11 mm ( $//N_m$ )  $\times$  2.97 mm ( $//N_g$ ). The uncoated samples were placed under Brewster angle between two 10-cm radius of curvature focusing mirrors in a 4-mirror X-type astigmatically compensated cavity with a total length of  $\sim 62$  cm. The two folding mirrors and the plane rear and output coupler (with transmission  $T_{OC}$ ) mirrors supported oscillation both in the Tm and Ho spectral ranges, however, the laser polarization was fixed  $//N_m$  by the Brewster condition, the same as for the incident pump. The pump was focused with an  $f = 7$  cm lens through one of the folding mirrors to a diameter of 80  $\mu\text{m}$ . The samples were mounted in a Cu-holder maintaining the temperature at 16°C. Figure 1(a) shows schematically the laser cavity.

For diode pumping we employed an active element with slab geometry,  $N_g$ -cut and 3.02 mm long, with aperture of 3.16 mm ( $//N_m$ )  $\times$  1.32 mm ( $//N_p$ ). This uncoated active element was used at normal incidence and water cooled in the same way but the Cu-holder was in contact only with the two larger lateral surfaces. The L-shape hemispherical cavity (shown in Fig. 1(b)) consisted of a plane pump mirror, a 90° bending mirror which was highly transmitting for the pump and an output coupler with a radius of curvature of  $-75$  mm. The cavity length was  $\sim 73$  mm. The unpolarized pump source was a fiber-coupled (NA = 0.15, 105  $\mu\text{m}$  core diameter) AlGaAs diode laser delivering up to 11.6 W (incident on the laser crystal). With an  $f = 30$  mm lens assembly the pump focal spot had a diameter of  $\sim 120$   $\mu\text{m}$  and the crystal was located as close as possible to the pump mirror.

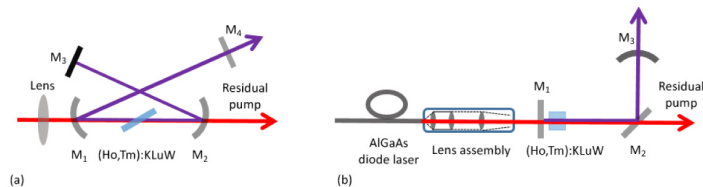


Fig. 1. Sketch of the laser cavities used with (a) Ti:sapphire laser and (b) diode laser pumping.

## Results and discussion

The optimum pump wavelength in the case of Ti:sapphire laser pumping was experimentally determined in lasing conditions and it was 801.7 nm for all output couplers. Within the accuracy of the wavemeter used this coincides with the absorption maximum [12]. At this wavelength the measured low-signal absorption of the cubic shape sample for  $E//N_m$  polarization was  $\sim 93\%$ . The calculated low-signal absorption from the spectroscopic data in the absorption peak is 99.3% (in this case the slightly lengthened beam path of  $\sim 3.07$  mm at Brewster angle was taken into account but the assumption was made that the polarization inside the crystal is pure  $E//N_m$ ). However, away from normal

incidence, the polarization inside the crystal has a small component parallel to  $N_g$ . The absorption of the crystal in lasing conditions was again  $\sim 93\%$ . Within the measurement accuracy, there was no dependence on  $T_{OC}$  under lasing conditions. Bleaching of the absorption with lasing interrupted was very weak (few %) and this effect was compensated by the recycling of the ground state population under lasing conditions.

Figure 2 shows the output power versus absorbed power obtained for the cubic shape sample with Ti:sapphire laser pumping. The transmission of the output couplers is specified at the laser wavelength, which was always 2060 nm. The maximum output power achieved was 868 mW for  $T_{OC} = 1.7\%$  at an absorbed power of 3 W. The maximum slope efficiency was 31.7% also achieved with  $T_{OC} = 1.7\%$ . The lowest laser threshold was 219 mW.

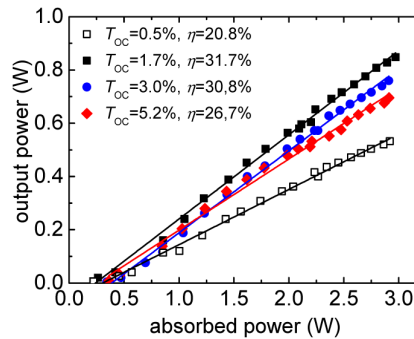


Fig. 2. CW laser performance of the (Ho,Tm):KLuW laser under Ti:sapphire laser pumping where  $\eta$  denotes the slope efficiency with respect to absorbed power.

Laser tuning was studied using a 3-mm-thick quartz plate (optical axis at  $60^\circ$  to surface), inserted also at Brewster angle, close to the output coupler. The pump power was 3.1 W or  $\sim 2.8$  W absorbed. The tuning range with  $T_{OC} = 1.7\%$  extended from 1904 to 2082.7 nm which corresponds to 178.7 nm at the zero level (Fig. 3). The tuning curve showed a certain structure within the  $^5I_7 \rightarrow ^5I_8$  transition of Ho. In fact, lasing between 1904 and 1960-1970 nm is attributed to Tm because according to the Ho gain curves [11,12] no net gain is achievable at such wavelengths.

However, in contrast to previous work [8] no simultaneous lasing of Tm at 1937 nm without tuning element was observed in the present experiment at any pump level or with any of the output couplers.

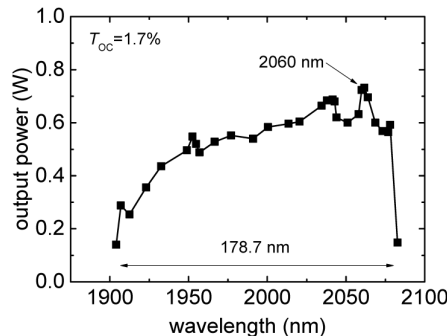


Fig. 3. Tuning of the (Ho,Tm):KLuW laser under Ti:sapphire laser pumping.

The (Ho,Tm):KLuW sample used in [8] had lower small signal absorption. The averaged over its length bleaching effect was accordingly stronger although the beam sizes were estimated to be somewhat larger. In the present experiment the absorption was too high to be bleached as we confirmed experimentally interrupting the lasing. Thus reabsorption in the unpumped exit part of the crystal could explain the absence of Tm-lasing. However, since both dopant ions operate as quasi-three level systems unpumped

regions would have detrimental effect on the efficiency of the Ho-laser as well. To study this effect we tested also the 1.39-mm long (Ho,Tm):KLuW sample with the same doping levels. Table 1 compares the results obtained with the two samples under Ti:sapphire laser pumping.

**Table 1. (Ho,Tm):KLuW laser results (E//N<sub>m</sub>-polarization) under Ti:sapphire laser pumping. T<sub>OC</sub> is the actual output coupler transmission at the oscillation wavelength (2060 nm in all cases). Thresholds and efficiencies refer to absorbed pump power.**

| T <sub>OC</sub>                          | threshold | slope efficiency $\eta$ | maximum optical efficiency | maximum output power |
|--|-----------|-------------------------|----------------------------|----------------------|
| 2.75 mm long sample, N <sub>c</sub> -cut |           |                         |                            |                      |
| 0.5%                                     | 219 mW    | 20.8%                   | 18.2%                      | 532 mW               |
| 1.7%                                     | 228 mW    | 31.7%                   | 29.0%                      | 868 mW               |
| 3.0%                                     | 342 mW    | 30.8%                   | 26.1%                      | 760 mW               |
| 5.2%                                     | 361 mW    | 26.7%                   | 23.9%                      | 696 mW               |
| 1.39 mm long sample, N <sub>p</sub> -cut |           |                         |                            |                      |
| 0.5%                                     | 230 mW    | 16.3%                   | 14.4%                      | 328 mW               |
| 1.7%                                     | 244 mW    | 23.9%                   | 21.6%                      | 484 mW               |
| 3.0%                                     | 396 mW    | 22.3%                   | 17.9%                      | 390 mW               |

As can be seen from the table, also for the thin sample, best results were obtained for T<sub>OC</sub> = 1.7%, however, they were inferior. The laser wavelength was again 2060 nm independent of T<sub>OC</sub>. Indeed, bleaching of the absorption in the absence of lasing was somewhat more pronounced with the thin sample (~10%) but also for this sample the bleaching effect was compensated by the recycling of the ground state population in lasing conditions.

Best operation with relatively low output coupling emphasizes the detrimental role of upconversion processes in the co-doped Tm-Ho system which are stronger at higher population of the upper laser level of Ho. Having in mind that the thresholds with the 3-mirror cavity used in [8] were in fact lower, the substantial improvement in terms of Ho-laser slope efficiency (roughly 3 times) achieved in the present work can be attributed to better mode matching at smaller beam waists resulting in reduced heat generation and to improved heat removal due to the higher efficiency. The laser diameter was estimated to be 120  $\mu$ m in diameter. Indeed no thermal effects (no roll-over in the input-output characteristics in Fig. 2) and no improvement under quasi-cw pumping (in contrast to [8]), as tested using a chopper, were observed in the present experiment under Ti:sapphire laser pumping.

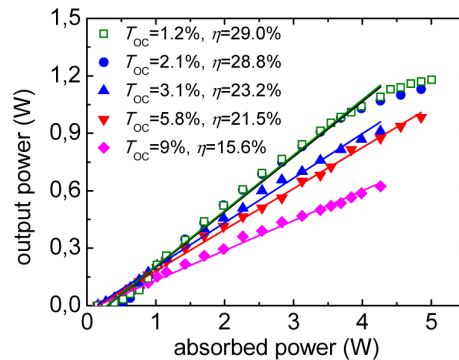


Fig. 4. Input-output CW characteristics of the diode-pumped (Ho,Tm):KLuW laser for different output couplers.

Figure 4 summarizes the results achieved with diode pumping. T<sub>OC</sub> is specified again at the laser wavelength which was 2078 nm for T<sub>OC</sub> = 1.2% and 2.1%, and 2059 nm for T<sub>OC</sub> = 3.1%, 5.8% and 9%. In fact, for T<sub>OC</sub> = 3.1% the wavelength shifted from 2059 to 2078 nm at high power levels (absorbed pump power exceeding 3 W). The pump wavelength slightly changed from 792.5 nm at low current to 793.5 nm at high current and in fact was much closer to the absorption peak for //N<sub>p</sub> polarization [12]. The

maximum output power achieved in the CW regime was 1.18 W, obtained with  $T_{OC} = 1.2\%$  at an absorbed power of 5.0 W. The average pump absorption was almost constant ( $54 \pm 1\%$ ) for the entire pump power range independent of the output coupler. No bleaching of the absorption was observed in this set-up where the pump power was distributed among two polarizations. The maximum slope efficiency with respect to the absorbed power also corresponded to  $T_{OC} = 1.2\%$ , reaching 29%. Moreover, this outcoupling yielded the lowest threshold of 150 mW with respect to the absorbed power. The slope efficiency degrades at higher  $T_{OC}$  due to up-conversion losses at higher inversion rates. The results can be compared to Ti:sapphire laser pumping at maximum absorbed power (around 3 W) and they are only slightly inferior in terms of slope efficiency or output power. This is an indication of very good overlap of the pump mode with the laser mode. The laser mode was estimated to be  $120 \mu\text{m}$ . The laser polarization was always  $//N_m$  as it should be according to the gain curves of the  $2\text{-}\mu\text{m}$  Ho transition. Only at the highest absorbed power, when the laser operated at 2078 nm, a kind of saturation of the output could be observed and the last few points have not been taken into account in the linear fitting for the slope in Fig. 4. This is related to excessive heating of the crystal leading to increased reabsorption losses which make the laser less efficient. We confirmed the presence of such thermal effects using electronic modulation of the pump diode current, as shown in Fig. 5. Although peak powers approaching 2 W could be reached with the 50% duty cycle, the linear dependence extended only up to  $\sim 1.7$  W peak output power, from which point again similar saturation roll-over effect could be seen.

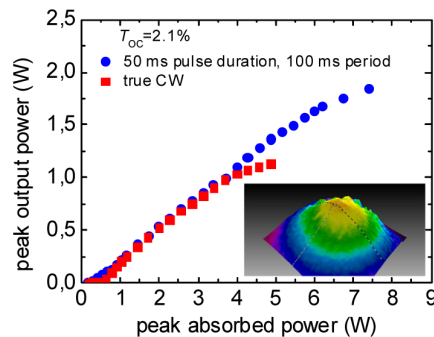


Fig. 5. Comparison of quasi-CW and true CW operation of the diode-pumped (Ho,Tm):KLuW laser.

Inset in Fig. 5 shows the spatial intensity distribution of the (Ho,Tm):KLuW laser in the true CW regime at an intermediate absorbed power of  $\sim 2.2$  W.

## Conclusions

In conclusion, we substantially improved our previous results [8,9] and other results with the related (Ho,Tm):KYW lasers [5] in terms of average power under Ti:sapphire laser pumping, and demonstrated high-efficiency diode-pumping of (Ho,Tm):KLuW with a simple standard cavity reaching for the first time almost 1.2 W of output power at 2078 nm with such kind of co-doped Ho-laser, the highest of any Ho double tungstate laser. More sophisticated designs like monolithic micro-lasers with more efficient cooling and multipass pumping are expected to provide further power scaling of this laser. The present configuration of the diode-pumped (Ho,Tm):KLuW laser could be directly used for Q-switching while the Ti:sapphire laser pumped configuration could be easily extended into a mode-locked laser cavity.

## Acknowledgments

This work was supported by the Spanish Government under project MAT2011-29255-C02-02, MAT2013-47395-C4-4-R and by the Generalitat de Catalunya under project 2014SGR1358.