

CW lasing of Ho in KLu(WO₄)₂ in-band pumped by a diode-pumped Tm:KLu(WO₄)₂ laser

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Abstract: We demonstrate continuous wave (CW) room temperature laser operation of the monoclinic Ho³⁺-doped KLu(WO₄)₂ crystal using a diode-pumped Tm³⁺:KLu(WO₄)₂ laser for in-band pumping. The slope efficiency achieved amounts to ~55% with respect to the absorbed power and the maximum output power of 648 mW is generated at 2078 nm.

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OCIS codes: (140.5680) Rare earth and transition metal solid-state lasers; (140.3070) Infrared and far-infrared lasers; (140.3480) Lasers, diode-pumped

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1. Introduction

Ho³⁺ (Ho) lasers operating at wavelengths slightly above 2 μm find applications in remote sensing, medical treatments and as pump sources for mid-IR OPOs [1–3]. Diode-pumping of such lasers can be realized by co-doping the active material with Tm³⁺ (Tm) ions making profit from the well established AlGaAs laser diodes emitting around 800 nm and the energy transfer to Ho³⁺ ions [4,5]. Such energy transfer, however, ultimately limits the overall pump efficiency while up-conversion mechanisms result in excitation of higher energy levels of Tm whose population is no longer involved in the transfer of energy to Ho. Thus, direct excitation of the upper emitting level of Ho (²I₇) with a laser pump source, also known as in-band pumping or resonant pumping, remains the most promising approach for up-scaling the output power and increasing the efficiency of all-solid-state Ho-lasers emitting on the ⁵I₇→⁵I₈ transition. It ensures minimum thermal load which is essential for the quasi-three level operation scheme in order to avoid re-absorption. Although direct in-band diode-pumping of a Ho:YAG laser has been already demonstrated with (AlGaIn)(AsSb) laser diodes [6], very efficient and powerful diode-pumped Tm lasers [7], including Tm-fiber lasers, offer more flexibility with respect to the spectral and spatial characteristics and are widely used for pumping Ho-lasers, e.g [3,8], including intracavity pumping, e.g [9].

Many oxide and fluoride type crystals were shown to be suitable host materials for the Ho³⁺ ion and laser operation with high output power and efficiency has been demonstrated with quite few of them [7,10]. However, little attention has been paid to the monoclinic potassium double tungstates with the general formula KRE(WO₄)₂ (KREW) where RE is a passive trivalent ion (Y, Gd, or Lu). KYW and KGdW were known as very efficient and promising hosts for the Nd³⁺ ion at intermediate power levels for long time and more recently they showed similar nice potential for Yb³⁺ doping (near 1 μm) and Tm³⁺ doping (slightly below 2 μm). The doped KREW crystals stand out because of their very high transition cross sections (absorption and emission) and weak concentration quenching of the fluorescence which is related to the relatively large dopant-to-dopant separation. The less known KLuW was recently shown to be especially suited for Yb and Tm doping due to the matching of the ionic radii of the passive and active rare earths [11]. Thus, the maximum laser slope efficiency for a diode-pumped Yb:KLuW laser reached 80% and the output power 11 W [12]. In the case of Tm doped KLuW, these values were 69% and 4 W, respectively [13].

In this work we demonstrate, for the first time to our knowledge, continuous-wave (CW) room temperature lasing of Ho³⁺ in a singly-doped monoclinic crystalline host belonging to the KREW family (KLuW) under in-band pumping. Stimulated emission on the ⁵I₇→⁵I₈ transition of Ho in KLuW at 2079 nm was achieved before only by flash-lamp pumping at ~110 K [14], similar to the first demonstrations of Ho lasing on this transition in the other two isostructural hosts, KYW and KGdW [14,15]. Note that recently the co-doped Tm,Ho:KYW laser crystal has been investigated with indirect Ti:sapphire laser pumping at 802 nm [16]. In the present work, the pump source for the Ho:KLuW laser is a diode-pumped home-made Tm-laser based on the same host material, KLuW, and described in detail elsewhere [13]. Slope efficiency of ~55% is achieved in this initial experiment with Ho:KLuW.

2. Experiment

A series of Ho-doped KLuW crystals have been grown with doping concentration ranging from 0.5 to 7.5 at. % by the Top Seeded Solution Growth method with Slow Cooling of the solution (TSSG-SC). For the growth, a platinum crucible with a diameter 50 mm and a height

of 50 mm was used. The composition of the solution was 12 mol. % KLuW as solute and 88 mol. % $K_2W_2O_7$ as solvent. The raw materials were K_2CO_3 , Ho_2O_3 , WO_3 and Lu_2O_3 reagents from Aldrich, Fluka and Metall (with analytical grade of purity). A *b*-oriented KLuW was used as a seed positioned perpendicularly with respect to the solution surface.

Spectroscopic characterization of Ho:KLuW in terms of polarized optical absorption and luminescence at room temperature is a subject of current investigations which will be published elsewhere. However, related data on Ho:KGdW can be found in [17,18] while relevant data on Tm:Ho co-doped KYW [16] and KLuW [19] also exist. Concerning the in-band laser pumping employed in the present work, it can be seen from Fig. 1, which shows the absorption cross section (σ_a) in the 1800-2200 nm spectral range, corresponding to the $^5I_8 \rightarrow ^5I_7$ transition of Ho in KLuW, that at a pump wavelength of 1946 nm the absorption for the two polarizations, $E//N_m$ and $E//N_p$ is practically the same: $\sigma_a(E//N_m)=0.49 \times 10^{-20} \text{ cm}^2$ and $\sigma_a(E//N_p)=0.42 \times 10^{-20} \text{ cm}^2$. The principal optical axes of monoclinic crystals, N_p , N_m and N_g , are defined by $n_p < n_m < n_g$ relating to the principal refractive indices. Note that, as with other dopants, Ho-doped KLuW exhibits anisotropic absorption and emission with higher cross sections for light polarized parallel to the N_m and N_p dielectric axes in comparison to $E//N_g$.

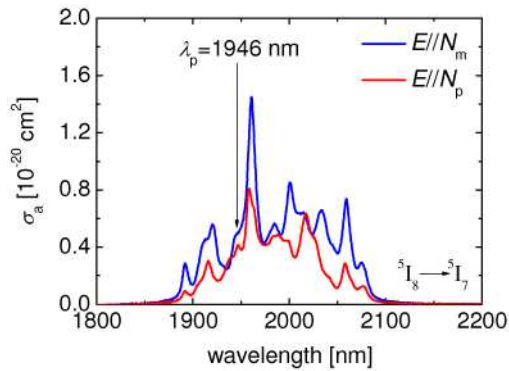


Fig. 1. Absorption cross-section of the $^5I_8 \rightarrow ^5I_7$ transition of Ho in KLuW for $E//N_m$ and $E//N_p$.

The active elements were oriented along the three orthogonal principal optical directions as parallelepipedic samples with their faces parallel to the N_m and N_p directions allowing light propagation along the N_g direction. Typically, we cut and polished the active elements to a thickness of 3 mm and an aperture of $3 \times 3 \text{ mm}^2$. They remained uncoated.

CW laser operation was studied in a near-hemispherical resonator formed by a plane pump mirror (M5 in Fig. 2), antireflection (AR) coated for the pump wavelength and high-reflection (HR) coated for the laser wavelength. The output coupler series (M6) comprised several curved mirrors with 25, 50 and 75 mm radius of curvature (RC). The transmission of the output couplers used (T_{OC}) was 1.5% and 3% in the range from 1900 to 2050 nm. This contributed to an almost double pass pumping of the Ho:KLuW crystal since 98.5% and 97% of the non-absorbed pump radiation, respectively, was retroreflected by the output coupler. Two lenses (L2) were used to pump the Ho crystals with 50 and 150 mm focal length. The active elements were mounted in a Cu holder that served as a heat sink but no active cooling was applied. They were positioned under normal incidence to the pump beam as close as possible to the plane mirror M5.

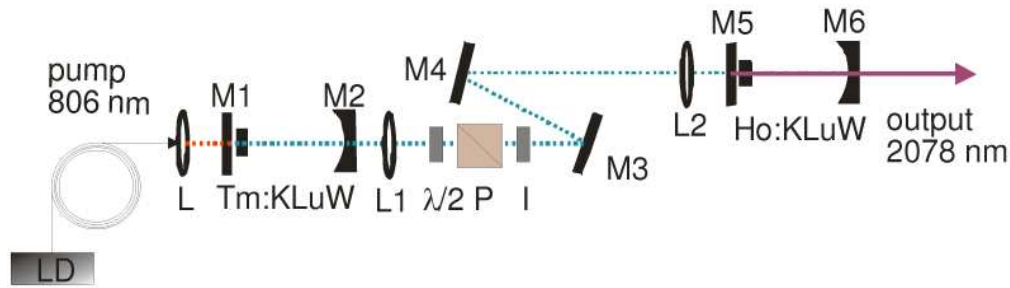


Fig. 2. Laser setup: $\lambda/2$ and P (half-wave plate and polarizer acting as attenuator), L (AR-coated lens assembly for collimation and focusing of the fiber output with $f=30$ mm), L1 (AR-coated collimating lens with $f=150$ mm), I (isolator: quarter-wave plate), L2 (AR-coated focusing lens), M3, M4 (plane bending mirrors), M1, M5 (plane pump mirrors), M2 (Tm-laser output coupler with RC=75 mm), and M6 (Ho-laser output coupler).

The pump source was a Tm:KLuW laser described elsewhere [13]. Its output was up-scaled to 5.1 W at 1946 nm using a fiber coupled and unpolarized diode-based pump source (Lumics) whose emission at high currents was centered at 806 nm. The radiation from the Tm:KLuW laser was linearly polarized along its N_m principal optical axis. After the attenuator we placed an optical isolator (I) to avoid any back coupling from the Ho-laser set-up. Since we used for this a quarter-wave plate the pump beam to the Ho-laser was circularly polarized.

3. Results and discussion

The fact that the pump beam incident onto the Ho crystal exhibited circular polarization was unimportant in our case since, as already mentioned, the absorption of the Ho:KLuW crystal at the wavelength of 1946 nm is not substantially different for the two polarizations involved. Note that according to Fig. 1, the pump absorption is quite different at the maximum near 1960 nm but the pump wavelength of 1946 nm was fixed in our case by the optimum output coupling (5%) and the natural polarization selection of the Tm:KLuW laser [13]. In any case, the Ho:KLuW laser output was always linearly polarized with $E//N_m$ although the pump was not linearly polarized. This can be explained by the higher gain cross-section for this polarization as previously observed for Yb and Tm doping of the same host [11].

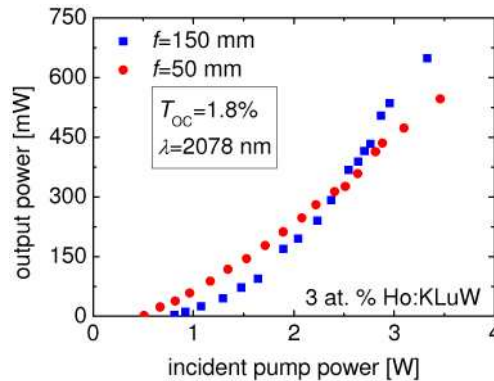


Fig. 3. Output power vs. incident pump power of the Ho:KLuW laser: comparison of the two pump lenses with focal lengths of $f=50$ mm and $f=150$ mm with an RC=25 mm output coupler ($T_{oc}=1.8\%$ @ 2078 nm).

Doping concentrations of 1, 3 and 5 at. % were tested but CW laser oscillation was possible only with the 3 at. % Ho-doped KLuW sample. Too low absorption or insufficient absorption bleaching in the three-level system are thought to be the reasons for the critical concentration dependence. The Ho:KLuW laser performance with the two pump lenses available is compared in Fig. 3 for an output coupler with RC=25 mm and physical cavity

length of 26 mm. Better mode matching at high powers and higher laser efficiency is observed for a focal length of $f=150$ mm. Note that for this measurement the Tm:KLuW pump laser was operated at maximum output power and the attenuator (Fig. 2) was applied to vary the pump level for the Ho:KLuW laser without affecting the pump beam characteristics. With $T_{OC}=1.8\%$ (at the laser wavelength), the maximum output power from the Ho:KLuW laser was 648 mW at an incident pump power of 3.3 W. It should be noted that the single pass absorption of the crystal at high incident powers was only 24% and 39% for the $f=50$ mm and $f=150$ mm lenses, respectively, and slightly higher, 28% and 42%, respectively, at low incident powers. The variation of these values is indicative of absorption bleaching effects.

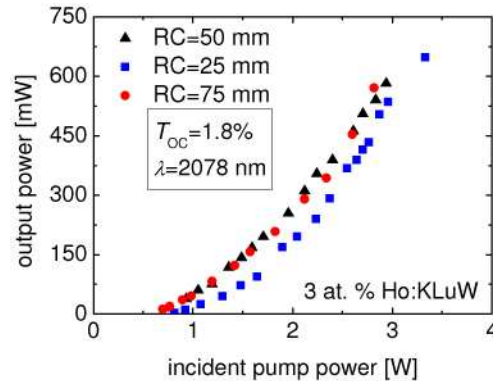


Fig. 4. Dependence of the output power of the Ho:KLuW laser on the radius of curvature (RC) of its output mirror. The pump lens is $f=150$ mm.

We also studied the influence of the radius of curvature of the output coupler of the Ho:KLuW laser and Fig. 4 shows the input-output characteristics obtained with the $f=150$ mm pump lens and $T_{OC}=1.8\%$ output coupling. Note that the values for RC=25 mm (squares in Fig. 4) are the same as those shown in Fig. 3. The RC=50 and 75 mm mirrors performed equally well and slightly better than the RC=25 mm output coupler.

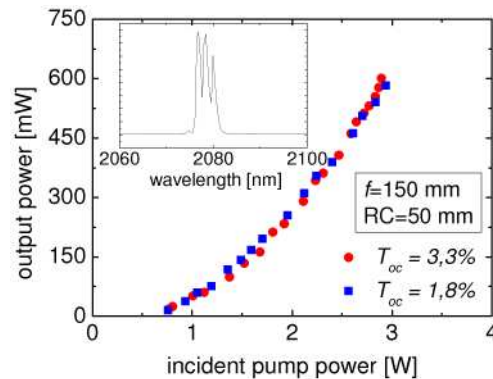


Fig. 5. Comparison of the Ho:KLuW laser performance for $T_{OC}=1.8\%$ and $T_{OC}=3.3\%$. Inset: laser spectrum centered at 2078 nm.

In all cases shown above (Figs. 3 to 5) the pump wavelength of the Tm laser was 1946 nm and the Ho:KLuW laser oscillated at 2078 nm. This gives a quantum defect of only $\sim 6\%$. The increase of the output coupler transmission had a very weak effect on the input – output characteristics of the Ho:KLuW laser. This is illustrated in Fig. 5 where an $f=150$ mm pump lens is employed and two RC=50 mm output couplers are compared. The laser wavelength remained also unchanged (2078 nm). In the whole power range, the Ho:KLuW laser operated in the fundamental transversal mode due to the relatively small pump waist diameter (e.g. of

the order of 30 μm as measured with the $f=50$ mm pump lens), which could be easily seen on an IR visualization card.

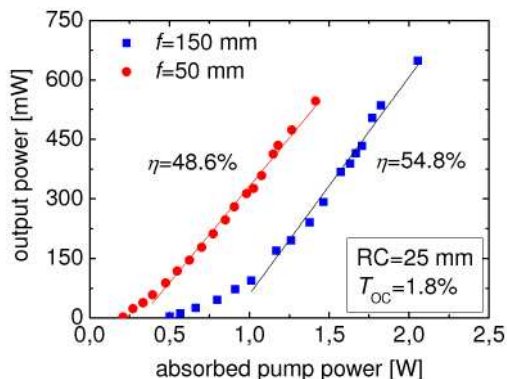


Fig. 6. Estimated slope efficiencies against absorbed power in the double pump pass Ho:KLuW laser using an output coupler with $RC=25$ mm and $T_{OC}=1.8\%$.

If we assume the single pass absorption of the Ho:KLuW crystal to be 24% and 39% for the $f=50$ and 150 mm pump lenses, respectively, the input-output characteristics with respect to the absorbed pump power are shown in Fig. 6. The maximum output power of 648 mW corresponds to an absorbed pump power of 2.05 W for the $f=150$ mm pump lens while the laser threshold is at ~ 0.5 W of absorbed power. The slope efficiency in this case amounts to 54.8%. The mode matching is better with this lens. Using a pump lens with a shorter focal length (50 mm) results in lower pump threshold (~ 200 mW) but reduced slope efficiency. These slope efficiencies seem not limited by up-conversion losses. Note that both the slope efficiency and the output power achieved in this initial experiment exceed those recently reported with co-doped Tm,Ho:KYW although the latter were obtained with Ti:sapphire laser pumping [16]. It should be also noted that the slope efficiency values in our case can be regarded as a lower limit since the second pump pass may have different spatial distribution.

4. Conclusion

In conclusion, the first results obtained with in-band pumping of a CW Ho:KLuW laser reveal promising potential of this new laser material operating at 2078 nm at room temperature. No thermal roll-off in the power dependence and no damage to the uncoated active element have been observed for the available pump power. Further work will be devoted to optimization of the crystal parameters (length and doping level), improvement of the overlap between the laser and pump modes using longer samples, AR-coating of the Ho:KLuW active elements, study of the tuning potential and the use of fiber-coupled diodes for in-band pumping.

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