

Efficient 2- μm Continuous-Wave Laser Oscillation of $\text{Tm}^{3+}:\text{KLu}(\text{WO}_4)_2$

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Abstract—Monoclinic crystals of Tm-doped $\text{KLu}(\text{WO}_4)_2$ were grown with high crystalline quality for several dopant concentrations. The relevant spectroscopic properties for the ${}^3\text{F}_4 \rightarrow {}^3\text{H}_6$ laser transition (cross sections, lifetime) were measured at room temperature. Laser oscillation in the 2- μm range was obtained both with Ti:sapphire and diode laser pumping near 800 nm using different setups. The maximum output powers achieved were 1.4 and 4 W, respectively, and the corresponding slope efficiencies with respect to the absorbed power were 60% and 69%, respectively. The novel monoclinic double tungstate thulium host $\text{KLu}(\text{WO}_4)_2$ was directly compared to $\text{KGd}(\text{WO}_4)_2$ and exhibited superior performance. The two laser polarization configurations for $\text{Tm}:\text{KLu}(\text{WO}_4)_2$, $E//N_m$ and $E//N_p$, were also compared under identical conditions with pumping by the polarized Ti:sapphire laser. Tuning was studied for both of them using an intracavity Lyot filter and the tuning range achieved was from 1800 to 1987 nm. In the case of no polarization selective cavity elements the diode-pumped $\text{Tm}:\text{KLu}(\text{WO}_4)_2$ laser naturally selected the $E//N_m$ polarization.

Index Terms—Crystals, lasers, rare earth compounds, solid lasers, thulium, tungsten compounds.

I. INTRODUCTION

RECENTLY increasing interest in diode-pumped solid state laser systems based on the ${}^3\text{F}_4 \rightarrow {}^3\text{H}_6$ Tm^{3+} -ion transition near 2 μm is observed, basically related to the possibility for efficient diode pumping with the widely spread AlGaAs laser diodes developed for Nd-lasers. Thulium lasers are at present the only tunable solid state systems operating near 2 μm and their availability in all time formats is important for various applications related to the strong water and human tissue absorption, the “eye-safe” characteristics, and the low atmospheric absorption, e.g., remote sensing (lidar) [1] or medicine (surgery) [2]. They are also very suitable for pumping both high-power nanosecond mid-infrared (IR optical parametric oscillators (OPOs) based on ZnGeP_2 [3] used for directed countermeasures and continuous-wave (CW) or gain-

switched Ho-lasers which operate at slightly longer wavelengths above 2 μm [3]. Novel applications in the future will be possible by short pulse (mode-locked) Tm-lasers in chirped pulse optical parametric amplification because their wavelength lies close to degeneracy for pumping with high-power 1- μm laser sources [4]. The output wavelength of Tm-lasers is in general very suitable for frequency conversion into the mid-IR spectral range due to the availability of highly-nonlinear crystals with low bandgap. This has been already demonstrated for a synchronously pumped picosecond OPO with a cascaded scheme [5] but should be directly possible with Tm-lasers. Moreover, realization of the CW OPO regime which will be a breakthrough in the mid-IR laser technology seems also promising.

The most intensively studied hosts for 2- μm Tm-generation in the past were YAG, YLF, the vanadates (YVO_4 and GdVO_4), and the two monoclinic double tungstates, $\text{KY}(\text{WO}_4)_2$ (KYW) and $\text{KGd}(\text{WO}_4)_2$ (KGdW). The properties of these materials were compared in our previous work [6]. The search for better Tm-host crystals, however, continues, and recent activities demonstrated promising results with BaY_2F_8 [7] and YAIO_3 [8]. The spectroscopic data available on most of the above hosts has been summarized in [9]. However, taking into account even the most recent publications we are still aware of only few hosts which provided multi watt output powers in the CW regime: These include YAG [10], [11] and the related LAG [12], YLF [13], YAIO_3 [8], and GdVO_4 [14].

The monoclinic potassium double tungstates have great potential to cover the low and medium power (up to approximately 10 W, limited by the thermo-mechanical properties) range for Tm-lasers because they possess several unique features known from doping with Nd and Yb ions. The two most important are the relatively large ion separation allowing highest doping levels with minimum quenching effect and the highest absorption and emission cross sections which is partly due to the strong anisotropy of the biaxial host [6]. Thulium-doped potassium double tungstates exhibit maximum absorption cross section for the ${}^3\text{H}_6 \rightarrow {}^3\text{H}_4$ transition slightly above 800 nm with a relatively large linewidth which makes them ideal for diode pumping with AlGaAs diodes. The relatively broad emission spectrum and the combination of high gain cross section and relatively short upper level lifetime is advantageous for passive mode-locking. Several recent laser studies were devoted to room temperature laser operation of $\text{Tm}:\text{KYW}$ [15]–[18] and $\text{Tm}:\text{KGdW}$ [6]. The maximum power achieved so far with a diode-pumped $\text{Tm}:\text{KYW}$ laser was 1.8 W [16].

In the present work, we report on the crystal growth, spectroscopy, and laser operation of the monoclinic potassium

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lutetium double tungstate $\text{KLu}(\text{WO}_4)_2$ (hereafter KLuW) doped with thulium ions at several concentrations. The absorption cross sections for the pump and laser transitions are derived from optical absorption measurements at room temperature. The energy level scheme obtained from low temperature spectroscopy allowed to compute the emission cross sections by the reciprocity method and finally the gain cross sections for the two polarizations important for laser operation. Samples with 3 and 5% Tm-doping are studied in CW lasers for different polarization configurations using both Ti:sapphire and diode laser pumping and an intracavity Lyot filter for tuning. The laser performance of Tm:KLuW is compared to that of Tm:KGdW under identical conditions.

II. THULIUM-DOPED POTASSIUM LUTETIUM TUNGSTATE

KLuW is a new member of the monoclinic potassium double tungstate family with lattice parameters in the $C2/c$ space group, $a = 10.576(7) \text{ \AA}$, $b = 10.214(7) \text{ \AA}$, $c = 7.487(2) \text{ \AA}$, $\beta = 130.68(4)^\circ$, and $Z = 4$. A detailed structural study is found in [19]. The N_p principal optical axis is parallel to the b crystallographic axis. The other two axes of the optical ellipsoid, N_m and N_g , lie in the $a - c$ crystallographic plane and the location of N_g with respect to the c crystallographic axis is at 18.5° in the clockwise direction when b is pointing towards the observer [19]. The potential of KLuW for diode-pumped lasers has been exploited so far only in the $1\text{-}\mu\text{m}$ spectral range with Nd [20], [21] and Yb [22], [23] doping.

The Tm-doped KLuW crystals were grown by the top-seeded solution growth (TSSG) technique and the methodology was the same as the one used in previous works [24], [25]. The crystal growth experiments began at 1176–1177 K and at the point of the phase diagram corresponding to a solute/solvent molar ratio of 11.5/88.5. Four different solutions corresponding to $\text{KLu}_{1-x}\text{Tm}_x(\text{WO}_4)_2$ with $x = 0.005, 0.01, 0.03$ and 0.05 were prepared. The crucible was located in a vertical furnace in such a way that the axial temperature gradient in the solution was about 1.3 K/cm (hot bottom), while the radial temperature gradient was about 1 K/cm (hot crucible wall). After the solution had been homogenized, the saturation temperature was determined with a b -oriented KLuW seed in contact with the free surface of the solution. Then, the growth began on a KLuW seed, while the solution temperature was decreased by about 20 K at a rate of 0.2 K/h for 0.5 and 1 at. % Tm, and 0.1 K/h for 3 and 5 at. % Tm. The different cooling rate was necessary because macrodefects were observed for 3 at. % Tm-doped crystals at a cooling rate of 0.2 K/h. The crystal rotation was at 40 rpm. After 4–8 or 8–10 days of growth, depending on the cooling rate, the crystals were removed slowly from the solution and cooled to room temperature at 15 K/h in order to avoid thermal shocks.

It is important to point out that thulium doping of the KGdW and KYW hosts leads to a decrease of the saturation temperature (T_S) while in the case of KLuW it leads to an increase of T_S , and that the growth rate is higher and T_S is lower for KLuW. Also, less defects appear using KLuW as a host for Tm in comparison with KGdW presumably due to the closer ionic radii of Lu and Tm. Fig. 1 shows a photograph of a grown Tm:KLuW crystal. The relevant parameters are summarized in Table I.

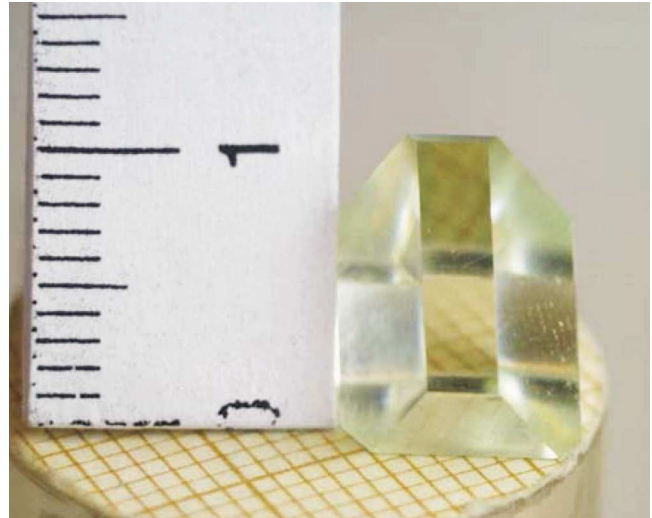


Fig. 1. Photograph of a 3% doped Tm:KLuW crystal. (Color version available online at: <http://ieeexplore.ieee.org>.)

The composition of the obtained single crystals was studied by Electron Probe Microanalysis (EPMA) using a Cameca Camebax SX 50 equipment. For the constitutional elements K, W, Lu, and O, undoped KLuW was used as standard reference. For the thulium measurement, we used the $L\alpha$ line and the REE2 standard, which gave a detection limit of 0.016 wt.%. This allowed to determine the distribution coefficient of thulium in KLuW (ratio of the Tm concentration in the crystal to that in the solution), see Table I. Distribution coefficients close to 1 are advantageous for obtaining uniform doping and hence optically homogeneous single crystals.

The samples used in the laser experiments were prepared from the Tm-doped KLuW crystals with 3% and 5% substitution of Tm_2O_3 for Lu_2O_3 in the solution. According to Table I the actual thulium concentration in the crystals corresponds to the compositions $\text{KLu}_{0.963}\text{Tm}_{0.037}(\text{WO}_4)_2$ and $\text{KLu}_{0.95}\text{Tm}_{0.05}(\text{WO}_4)_2$. The 3 at. % Tm-doped KLuW laser sample was cut for propagation along the N_g principal optical axis (thickness: 2.92 mm) so that it could be used for polarization parallel to the N_m and N_p optical axes (aperture: $3 \times 3 \text{ mm}^2$). The 5 at. % Tm-doped sample was prepared with exactly the same dimensions and orientation as a reference Tm:KGdW sample doped also with 5 at. % in the solution (composition: $\text{KGd}_{0.959}\text{Tm}_{0.041}(\text{WO}_4)_2$). These two samples were grown by the same methodology and using the same purity grade for the materials. They were cut along the N_p axis (thickness: 2 mm) and could be used only for polarization $E//N_m$ because of the extremely low cross sections characteristic for $E//N_g$ (Fig. 2). Their aperture was $\approx 3 \times 3 \text{ mm}^2$.

The polarized room temperature absorption spectra were measured with the 3% doped Tm:KLuW sample both for the $^3\text{H}_6 \rightarrow ^3\text{H}_4$ transition used for pumping, in the 750–850-nm range (Fig. 2), and for the $^3\text{H}_6 \rightarrow ^3\text{F}_4$ transition in the 1450–2150-nm range in order to calculate the emission cross sections by the reciprocity method (Fig. 3). The absorption spectrum for $E//N_m$ was measured also with the 5% Tm-doped KLuW sample in order to confirm the reliability of

TABLE I
CRYSTAL DATA FOR THE GROWN Tm:KLuW SAMPLES

Tm in the solution [at. %]	Cooling rate [K/h]	Cooling interval [K]	Crystal weight [g]	Growth rate [10^{-4} g/h]	Dimension along c [mm]	Dimension along a^* [mm]	Dimension along b [mm]	Tm in the crystal [10^{19} at/cm 3]	Distribution coefficient K_{Tm}
0.5	0.2	20	3.972	397	14.1	11.1	7.5	3.51	1.08
1.0	0.2	20	3.628	362	14.3	10.1	5.4	7.60	1.17
3.0	0.1	20	2.941	294	11.3	9.3	7.1	24.1	1.23
5.0	0.1	20	4.986	249	15.2	10.4	7.5	32.5	0.997

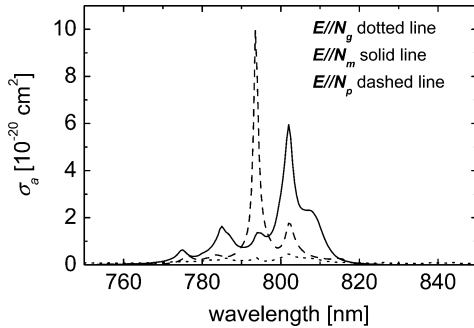


Fig. 2. Room-temperature absorption cross section of Tm:KLuW for the ${}^3\text{H}_6 \rightarrow {}^3\text{H}_4$ transition and the three orthogonal polarizations.

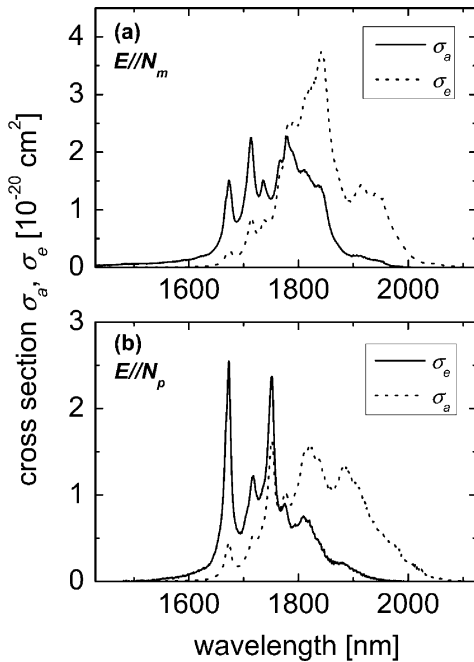


Fig. 3. Room-temperature absorption (solid lines) and emission (dotted lines) cross sections σ_a and σ_e of Tm:KLuW for the ${}^3\text{H}_6 \leftrightarrow {}^3\text{F}_4$ transition and polarization $E//N_m$ (a) and $E//N_p$ (b).

the concentration determination in Table I and hence that of the calculated absorption cross sections. Strong anisotropy is characteristic for the monoclinic double tungstates and this can be observed in Figs. 2 and 3. The maximum absorption cross section for $E//N_m$ is 5.95×10^{-20} cm 2 at 802 nm. This main line with a full-width at half-maximum (FWHM) of 4 nm is

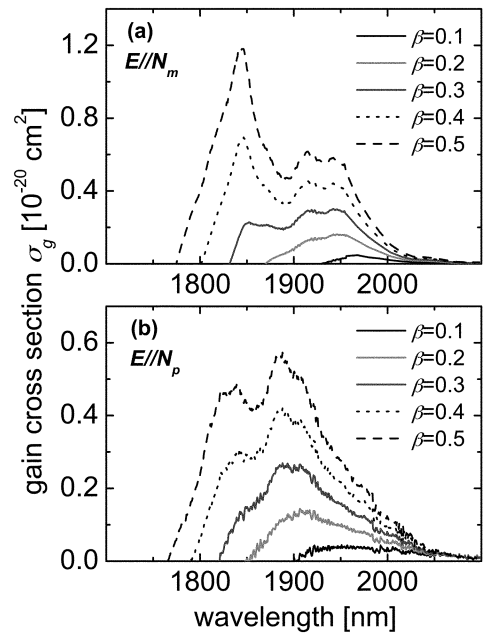


Fig. 4. Inversion dependent gain cross sections $\sigma_g = \beta\sigma_e - (1 - \beta)\sigma_a$ for polarization parallel to the (a) N_m and (b) N_p principal optical axes. The absorption (σ_a) and emission (σ_e) cross sections used are from Fig. 3.

very suitable for diode pumping. The maximum absorption cross section for $E//N_p$ is 9.96×10^{-20} cm 2 at 793.5 nm but this Stark component has a FWHM of only 1 nm.

From the measured absorption in the 1450–2150-nm spectral range, we calculated the emission cross section for the ${}^3\text{F}_4 \rightarrow {}^3\text{H}_6$ transition and the two polarizations $E//N_m$ and $E//N_p$ by the reciprocity method and the results are shown in Fig. 3. The maximum emission cross section for $E//N_m$ amounts to 3.71×10^{-20} cm 2 at 1841 nm. In the case of $E//N_p$, the maximum emission cross section is 1.58×10^{-20} cm 2 at 1820 nm.

The results shown in Fig. 3 can be used to calculate the gain cross section dependence on the wavelength for different values of the ratio β of the excited ions density to the total Tm-ion density (Fig. 4). Thus, slightly higher gain is predicted for the $E//N_m$ polarization and the trend to jump to a different Stark transition when varying the laser gain (or equivalently the loss) seems stronger here while for the $E//N_p$ polarization the lower wavelength limit seems slightly extended. Also, at lower inversion levels there is a trend that the supported gain bandwidth is larger for the $E//N_p$ polarization.

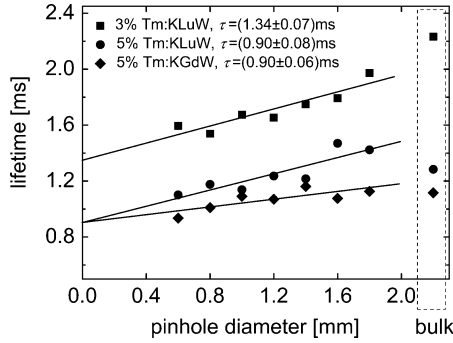


Fig. 5. Dependence of the measured lifetime τ of the upper laser level of the thulium ion on the pinhole diameter with linear fits for the three samples used in the laser experiments.

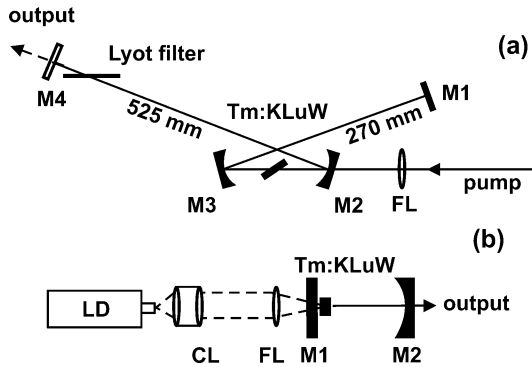


Fig. 6. (a) Cavity setup for Ti:sapphire laser pumping. FL: AR-coated focusing lens with $f = 70$ mm; M1: plane total reflector; M2-M3: $RC = -100$ mm mirrors; M4: plane output coupler. (b) Cavity setup for laser diode (LD) pumping. CL: collimating lens system with $f = 34$ mm and 80% transmission; FL: focusing lens with $f = 20$ mm and 88% transmission; M1: plane total reflector; M2: output coupler with $RC = -50$ mm.

Pinhole measurements of the lifetime which permit to eliminate the effect of radiation trapping are presented in Fig. 5. The excitation was at 796 nm by a nanosecond OPO and the fluorescence was detected at 1710 nm. The linear fits give the lifetime as an extrapolation for a vanishing pinhole diameter. In general the resulting time constants are shorter than previous measurements with Tm:KYW and Tm:KGdW without taking into account the reabsorption effect [6, Table I]. It should be noted, however, that the remeasured lifetime of Tm:KGdW in the present work is much closer to the calculated radiative lifetime in [6]. The dependence of the fluorescence lifetime of Tm:KLuW on the doping level (quenching) is better pronounced if compared to previous measurements of Tm:KGdW [26]. For (approximately) the same doping level, Tm:KLuW and Tm:KGdW exhibited the same lifetime of the upper laser level (the difference in the slopes in Fig. 5 is due to the geometry of the experiment).

III. LASER OPERATION OF $\text{TM}:\text{KLuW}$

The setup used for Ti:sapphire laser pumping [Fig. 6(a)] was an astigmatically compensated X-type cavity with a total length of 90 cm. Output couplers (M4 in the figure) with transmission $T_{OC} = 1.5\%$, 3% , 5% and 10% were used. M1, M2, and M3 were highly reflecting ($HR > 99.9\%$) from 1800 to 2075 nm

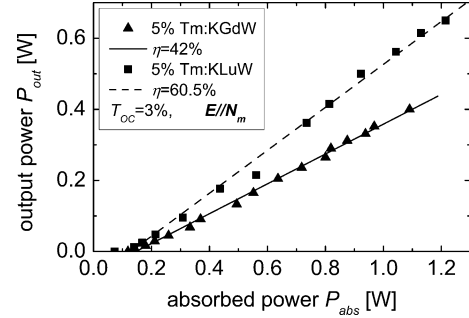


Fig. 7. Comparison of the input-output laser characteristics of the 5% Tm-doped KLuW and KGdW samples for polarization parallel to the N_m principal optical axis and pumping by a polarized Ti:sapphire laser.

and AR-coated on the rear side for high transmission from 780 to 1020 nm.

As a pump source, we employed a tunable CW Ti:sapphire laser delivering a maximum output power of 3.5 W near 800 nm when pumped with 25 W of an all-lines Ar-ion laser. The tuning element was a three-plate intracavity Lyot filter. The output linewidth was normally 0.2 nm or even less.

The active elements were positioned under Brewster angle which determines the laser polarization and the pump polarization was always in the same plane. In the position of the Tm-crystal, the pump spot had a Gaussian waist of $37 \mu\text{m}$.

At first we compared the performance of the two 5% Tm-doped KLuW and KGdW samples for the only possible E/N_m polarization. These samples were glued on thin copper plates by contacting only their rear surface, without any additional cooling. The results presented in Fig. 7 are for an output coupler with $T_{OC} = 3\%$. The absorbed power P_{abs} was estimated under lasing conditions. The resulting powers and efficiencies obtained with Tm:KGdW reproduced our previous measurements almost perfectly [6] although they were obtained with a different sample now. The maximum output powers achieved were $P_{out} = 650$ mW at $\lambda_L = 1948$ nm for Tm:KLuW and $P_{out} = 400$ mW at $\lambda_L = 1924$ nm for Tm:KGdW. The corresponding slope efficiencies with respect to the absorbed power were $\eta = 60.5\%$ and 42% . The maximum absorbed powers for an incident power of 1.32 W on the crystals were $P_{abs} = 1.21$ and 1.09 W for Tm:KLuW and Tm:KGdW, respectively. The small difference is due to the slightly different absorption cross sections and actual doping levels. The threshold (absorbed power) was 73 and 118 mW for Tm:KLuW and Tm:KGdW, respectively. The optimum pump wavelength was $\lambda_P = 802$ nm for Tm:KLuW and $\lambda_P = 801.5$ nm for Tm:KGdW. The better performance of Tm:KLuW in comparison to Tm:KGdW can be attributed to the higher gain cross sections (Fig. 4) at the corresponding operating wavelength which is related to the different spectral profile of the emission cross section at longer wavelengths Fig. 3(a) and the lower reabsorption losses.

The 3% Tm-doped KLuW sample allowed to compare accurately the two polarizations, $E//N_m$ and $E//N_p$, with the same sample using the laser setup shown in Fig. 6(a). The dimensions of this sample allowed to mount it, wrapped in an In-foil, into a Cu holder in lateral contact with all four sides and active water cooling. The water temperature was maintained at

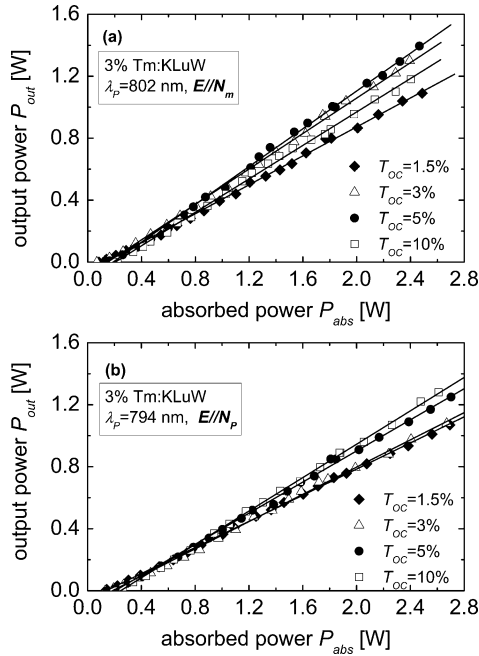


Fig. 8. Input–output laser characteristics of the 3% Tm:KLuW sample for (a) $E//N_m$ and (b) $E//N_p$. In both cases, the maximum incident power applied was 2.83 W.

5 °C which resulted in a crystal temperature of about 10 °C. However, the exact temperature and the active cooling were not of primary importance. The main improvement was due to the good lateral thermal management through the passive copper mounting.

The measured output power versus the absorbed power for the two polarizations and all output couplers used is shown in Fig. 8 together with the fits for calculation of the slope efficiency. The slope efficiency η , the lasing wavelength λ_L , and the threshold (absorbed power) data are summarized in Table II. A maximum output power of 1.4 W for $P_{abs} = 2.47$ W was achieved for $E//N_m$ with the $T_{OC} = 5\%$ output coupler. This corresponds to an optical conversion efficiency of 56.7% with respect to the absorbed power. The slope efficiency with respect to the absorbed power was $\eta = 60.1\%$ and the threshold with this output coupler was 125 mW (Table II). The absorption of the sample under lasing conditions was between 85% and 90% depending on the output coupler. The optimum pump wavelength was $\lambda_P = 802$ nm as in the case of the 5% doping which corresponds to the absorption maximum. The laser wavelength varied from $\lambda_L = 1917$ nm ($T_{OC} = 10\%$) to 1951 nm ($T_{OC} = 1.5\%$). For polarization $E//N_p$, the maximum power achieved was slightly lower ($P_{out} = 1.28$ W for $T_{OC} = 10\%$) although the absorbed power was $P_{abs} = 2.61$ W. The thresholds were in general slightly higher for this polarization and the slope efficiencies lower, see Table II. The absorption of the sample for this polarization was about 95% for all output couplers. The optimum wavelength was $\lambda_P = 794$ nm which corresponds to the absorption maximum for $E//N_p$ (Fig. 2).

The higher thresholds and lower slope efficiencies for $E//N_p$ can be attributed to the lower gain cross section as could be expected from Fig. 4. The different wavelength dependence on the output coupler losses for the two polarizations

is obviously related to the shapes of the gain curves as can be seen from Fig. 4. The laser wavelengths for $E//N_p$ were always somewhat shorter.

It was interesting to test the performance of the laser with this sample and pumping at $\lambda_P = 802$ nm for $E//N_p$. This is related in general to the feasibility of diode pumping but also with the possibility to use unpolarized diode pumps for samples cut along the N_g principal axis. We established that the slope efficiency and the threshold remained unchanged for $E//N_p$ after moving from $\lambda_P = 794$ nm to $\lambda_P = 802$ nm Fig. 9(a), while the absorption obviously dropped Fig. 9(b). As can be also seen from Fig. 9(b), the actual absorption remained constant independent of the incident pump power while in the absence of lasing (output mirror laser arm interrupted) it dropped from 95% to 64% in the case of $\lambda_P = 794$ nm and from 57% to 38% in the case of $\lambda_P = 802$ nm. This indicates that the saturation intensity at the pump wavelength is reduced in the lasing state and the bleaching effect is absent. Similar dependences for the absorption were observed for all cases depicted in Figs. 7 and 8.

The tuning of the 3% Tm:KLuW laser was studied for both polarizations introducing a 3-mm-thick quartz plate into the long arm of the cavity Fig. 6(a) containing the output coupler. The plate had a diameter of 20 mm and the optical axis was at 60° to the surface (see [27] for more details). The results obtained with $T_{OC} = 3\%$ are shown in Fig. 10. The overall tuning extended from 1800 to 1987 nm and in the shorter wavelength limit the gain for $E//N_p$ was higher as could be expected from Fig. 4. The FWHM of the tuning curves was 110 nm ($E//N_m$) and 128 nm ($E//N_p$) which is very promising not only for direct applications but also for mode-locking. Similarly to [6], the tunability could be extended to longer wavelengths for lower T_{OC} .

Since CW Ti:sapphire lasers require powerful green pump sources their output and efficiency are intrinsically limited. It is obvious that the output power of the Tm-laser could be further increased only by using direct pumping. The diode laser module used for pumping contained a single 50-W commercial bar with 19 emitters and 30% fill factor, mounted in a conduction cooled packaging. The patented clamping technology consists in mounting the laser bars without using any soldering process: the bars are clamped between two electrodes and fixed using mechanical pressure. Moreover, the laser bar mounting process is performed at room temperature. This is indeed very advantageous, because avoids the strain induced by the thermal expansion mismatching. In addition, both electrodes can serve as heat sinks, thus simplifying the thermal management. The transmission of the collimating optics used was about 80%. Only simple adapted beam shaping optics was used for the pump beam which was unpolarized. The nearly collimated beam had roughly a square cross section with a size of several millimeters. The emission wavelength depends on the operating current and changes with the output power. At an operating temperature of 25 °C the maximum output power achievable near 802 nm was 14 W (measured behind the collimating lens) for a current of 24 A. At the maximum available output power of 20 W for the current power supply the emission wavelength of the laser diode was near 804.5 nm. The single-peaked pump spectrum had a FWHM of 2 nm.

TABLE II
SLOPE EFFICIENCY, LASER WAVELENGTH, AND THRESHOLD IN DEPENDENCE ON THE T_{OC} USED FOR THE 3% $\text{TM}:\text{KLuW}$ SAMPLE

T_{OC} [%]	η [%]		λ_L [nm]		threshold [mW]	
	$E//N_m$	$E//N_p$	$E//N_m$	$E//N_p$	$E//N_m$	$E//N_p$
1.5	46.7	42.1	1951	1942	60	125
3	57.2	43.9	1947	1918	67	131
5	60.1	50.2	1947	1909	125	145
10	54	53.9	1917	1907	190	195

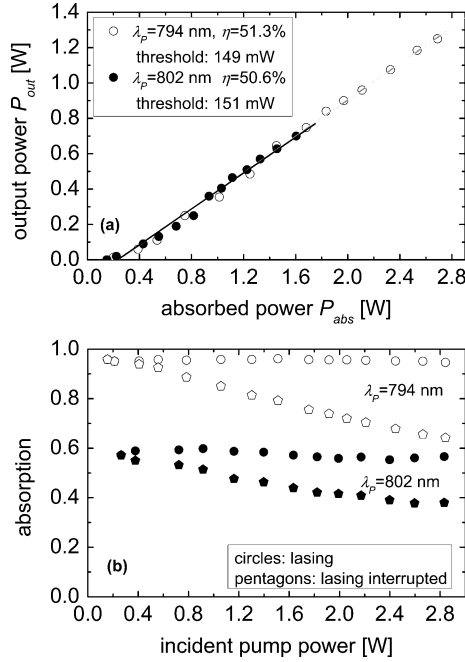


Fig. 9. (a) Input–output characteristics and (b) absorption as a function of the incident pump power of the 3% $\text{Tm}:\text{KLuW}$ laser ($T_{OC} = 5\%$) for polarization parallel to the N_p principal optical axis and pumping at 794 and 802 nm.

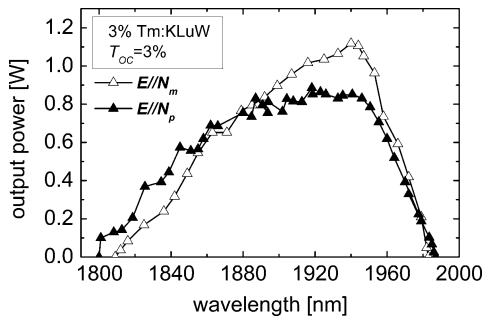


Fig. 10. Output power versus wavelength when tuning the $\text{Tm}:\text{KLuW}$ laser by an intracavity Lyot filter. The pump wavelengths are as in Fig. 8 and $P_{abs} = 2.4$ W.

To determine the beam characteristics of the diode, we measured the beam profile at the position of the waist behind a focusing optics. The results obtained using a lens with focal length of $f = 20$ mm are presented in Fig. 11. For a pump power of 14 W the nearly circular spot achieved had a cross section with a diameter of about $125 \mu\text{m}$.

The same 3% Tm -doped KLuW sample used for the $\text{Ti}:\text{sapphire}$ pumping experiments was placed in a nearly hemispherical 50-mm-long cavity close to the plane mirror through which

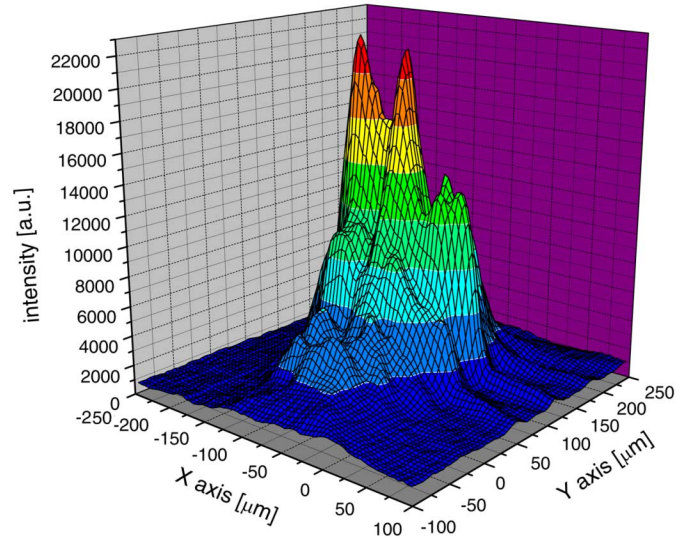


Fig. 11. Measured spot size of the 800-nm pump diode in the focus produced by an $f = 20$ mm lens. The $1/e^2$ diameters are $120 \mu\text{m}$ and $128 \mu\text{m}$ in the X and Y direction, respectively. (Color version available online at: <http://ieeexplore.ieee.org>.)

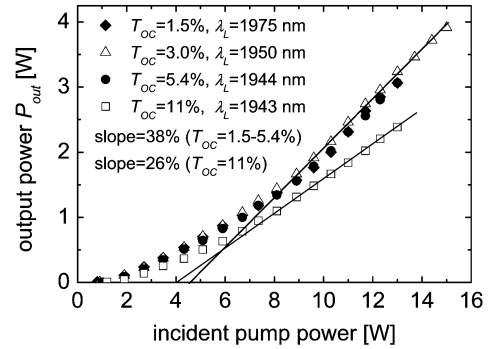


Fig. 12. Measured output power versus incident pump power for the diode-pumped 3% $\text{Tm}:\text{KLuW}$. The lines are linear fits for calculation of the slope efficiency with respect to the incident pump power.

the laser was pumped Fig. 6(b). The pump beam focus was close to the front surface of the crystal. Room temperature near the sample was maintained by water cooling the crystal (water temperature: 12°C). The curved output couplers used were with $T_{OC} = 1.5\%$, 3% , 5.4% and 11% .

The maximum output power achieved with $T_{OC} = 3\%$ was $P_{out} = 4$ W at $\lambda_L = 1950$ nm. The incident pump power in this case was 15 W (Fig. 12). The slope efficiency calculated with respect to the absorbed pump power amounted to $\eta = 69\%$ and the maximum optical efficiency reached 47%. Having in mind the normal incidence, these efficiencies were estimated

by taking into account the reflected pump light at the crystal faces (total absorption of 55%). It is the first time such high powers were generated with Tm-doped monoclinic double tungstates. Previously the highest power reported with a double tungstate Tm-host (KYW) was 1.8 W [16], obtained with a similar cavity design and pump source. Also in terms of slope efficiency the present results are superior if compared with the highest values previously reported with double tungstates (52–53% with Tm:KYW [16], [18]) or any other Tm-host. Note that assuming a quantum efficiency of 2 for the cross-relaxation process, the slope efficiency limit is 82%. Thus, we have reached 84% of the theoretical limit, while 87% have been reported only for Tm:YAG planar waveguides with Ti:sapphire laser pumping [28]. Obviously the cross-relaxation is very efficient in Tm:KLuW even at a doping level of 3% since without this process the upper limit for the slope efficiency would be 41%.

In the present work the slope efficiencies with diode pumping were even higher than with Ti:sapphire laser pumping. We note, however, that quite different cavities were used (Fig. 6) and the Ti:sapphire laser pumped cavity was designed for future tuning and mode-locking experiments. Nevertheless, Ti:sapphire laser pumping provided in our case higher optical efficiency and lower threshold. The linear dependence of the output power for the slope efficiency in the case of diode pumping, which is practically the same for $T_{OC} = 1.5 \dots 5.4\%$, is reached at higher pump levels in Fig. 12 and this is not related to the fact that the results are plotted against the incident pump power because the estimated absorption did not change with the incident power. Such a behavior is typical for three-level laser systems in the presence of reabsorption losses which increase with the crystal temperature at higher pump powers. As can be seen from Fig. 12, the indicated slope efficiencies correspond to thresholds higher than the actual ones.

For a cavity without any polarization selective elements or surfaces, a crystal cut along the N_g optical axis can only naturally (by the gain cross section) select the laser polarization and this is independent of the absorption bleaching. For all output couplers and power levels the oscillating polarization of the diode-pumped Tm:KLuW laser was $E//N_m$.

Measurements of the output beam quality were performed at high power levels. They yielded values of the M^2 parameter (deviation from the fundamental Gaussian mode) of 2.3 and 2.1 in the two planes.

IV. CONCLUSION

In conclusion, we studied the potential of the novel laser material Tm:KLuW for highly efficient tunable operation in the 2- μm spectral range and compared it with Tm:KGdW. The tuning range of 1800–1987 nm, and the high slope efficiency (69%) and output power (4 W) achieved with a diode-pumped laser configuration are promising for various applications.

Further work on this material will be focused on the improvement of the transversal heat management using crystal samples with smaller aperture and the cavity design by coating the active elements.

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