Tm:KY(WO$_4$)$_2$ waveguide laser

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Abstract: High-quality monoclinic planar waveguide crystals of Tm-doped KY(WO$_4$)$_2$ were grown by liquid-phase epitaxy with several dopant concentrations and thicknesses. Waveguide lasing in the 2 µm spectral range was demonstrated in the fundamental mode. The maximum continuous-wave output power achieved was 32 mW using a Ti:sapphire laser pump near 800 nm.

OCIS codes: (140.5680) Rare earth and transition metal solid-state lasers; (160.5690) Rare earth doped materials; (230.7390) Waveguides, planar

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1. Introduction

Tm^{3+}-activated materials are extensively studied as laser media for the 2 µm spectral range [1-6]. Lasers in this eye-safe wavelength region are in particular interesting for atmosphere monitoring, remote sensing and medical applications due to the low atmospheric absorption and the strong water and human tissue absorption [7,8]. The attraction of Tm lasers based on the $^3F_4 \rightarrow {}^3H_6$ transition is related to the possibility for diode pumping near 800 nm, while maintaining high efficiency and low thermal load. This is feasible because of a favorable Tm cross-relaxation process $^3H_4 \rightarrow {}^3F_4$ - $^3H_6 \rightarrow {}^3F_4$ of adjacent ions. This process leads to a pump quantum efficiency approaching 2, despite the large difference between the pump and laser photon energies [9]. Furthermore, Tm-doped lasers are at present the only tunable solid state sources operating near 2 µm.

The disadvantages of Tm^{3+}-lasers include the presence of energy transfer upconversion, and a relatively low emission cross-section. In addition, the $^3F_4 \rightarrow {}^3H_6$ transition acts as a quasi-three-level laser which is connected with a pronounced reabsorption and a rather high laser threshold. Optically pumped waveguide lasers have an inherent advantage over conventional bulk lasers in that the overlap between the pump light and the laser mode is necessarily quite high, because both are constrained to propagate together in the narrow waveguide, leading to high intensities for relatively low power. If the propagation loss of the passive waveguide can be maintained low, a higher gain per unit pump power and a reduced laser threshold can be achieved. Furthermore, a strong interest is denoted on waveguide lasers for integrated optical devices.

The first planar Tm-waveguide laser was demonstrated in a lead germanate glass host [10]. In crystalline hosts, planar Tm-waveguide lasing was demonstrated so far only based on YAG. The first reported Tm:YAG waveguide, grown by liquid phase epitaxy (LPE), delivered 180 mW of continuous-wave (CW) output power at a laser wavelength of 2012 nm using a longitudinal pump geometry [11]. High-power side-pumped planar Tm:YAG waveguide lasers were also studied. For this purpose, diffusion-bonded structures were applied and laser operation at 2020 nm with a CW output power of up to 15 W was achieved [12].

YAG is a cubic crystal characterized by excellent thermo-mechanical properties. The relatively narrow and weak $^3H_6 \rightarrow {}^3H_4$ absorption line of the Tm^{3+}-ion in YAG is shifted to shorter wavelengths centered at 785 nm in comparison to the $^4I_{9/2} \rightarrow {}^4F_{5/2} + {}^2H_{9/2}$ line of the Nd^{3+}-ion [3]. The monoclinic double tungstates, KY$(WO_4)_2$ (KYW), KGd$(WO_4)_2$ (KGdW) and KLu$(WO_4)_2$ (KLuW), which are strongly anisotropic biaxial crystals, exhibit generally larger absorption and emission cross-sections and broader linewidths as compared to YAG when doped with rare-earth ions [13]. Another important feature of rare-earth-doped monoclinic potassium double tungstates is the relatively large ion separation allowing highest doping levels with minimum quenching effects. In the case of Tm^{3+}-doping, an additional advantage is that the absorption line is centered near 800 nm [9] with a broader longwave wing. Therefore, these crystals are better suited for pumping with commercially available AlGaAs laser diodes at room temperature than YAG or YLF.

The first demonstration of Tm lasing on the $^3F_4 \rightarrow {}^3H_6$ transition in monoclinic double tungstates was realized in 1997 with Xe-flash lamp pumping, where Tm:KYW and Tm:KGdW rods sensitized with Er^{3+} and Yb^{3+} operated at cryogenic temperatures and wavelengths of 1920 and 1930 nm, respectively [14]. Soon afterwards, CW room temperature operation of Tm:KYW was demonstrated with longitudinal Ti:sapphire laser pumping near 800 nm [13]. Efficient CW laser operation around 2 µm was also achieved in Tm-doped KGdW [15] and KLuW [16]. The combination of high doping levels and large cross-sections permits the use of relatively thin active layers. This approach is particularly interesting for the thin-disk laser concept [17]. Very recently, the growth of a 130-µm-thick Tm:KLuW layer on a KLuW substrate and its CW laser operation under longitudinal Ti:sapphire pumping normal to the layer have been reported [18].

Recently, the advantages of the waveguide laser geometry and the spectroscopic properties of monoclinic double tungstates were successfully combined by the authors, by demonstrating the first planar waveguide laser based on Yb:KYW [19]. CW laser emission near 1 µm was achieved with excellent performance using an end-pumped Yb-doped KYW layer on a KYW substrate. An output power of 290 mW in the fundamental mode and a very high slope efficiency above 80% was obtained at room temperature.

Here we report on the epitaxial growth of high-quality Tm-doped optical waveguides and, for the first time to our knowledge, on planar waveguide laser operation around 2 µm based on a double tungstate crystal composite. This approach requires fabrication of high-quality thin layers of Tm:KYW over large areas on KYW substrates. A close-to-perfect interface between the layer and the substrate is essential, having small lattice mismatch to ensure low-loss propagation. In a waveguiding laser configuration with end-face pump coupling, the Tm^{3+} concentration can be much smaller than would be required for transverse pumping. Thus, stress due to lattice mismatch between layer and substrate is minimized and defect-free thin layers can be grown.

2. Tm:KYW waveguide fabrication

LPE is a well-known technique for the production of high-quality oxide films for laser applications, in which a single-crystal layer can be grown from a molten solution on a flat, oriented single-crystal substrate. 1-mm thick undoped KYW crystals with laser-grade polished (010) faces were used as substrates. The vertical dipping technique with partial immersion of the substrate was applied. Out of the two solvents employed recently for the fabrication of rare-earth-ion-doped KYW waveguides, a low-temperature chloride solvent [20] or $K_2W_2O_7$ [21], we chose the latter because of the much better interface and layer quality obtained with $K_2W_2O_7$ [19]. Single-crystalline layers with thickness up to 40 µm and different Tm^{3+} concentrations ranging from 0.7 to 1.2at% were obtained at a growth rate of 18 µm/h. The surface of each layer was polished to remove flux residuals and growth steps. Special alignment precautions were taken to keep the layer surface parallel to the interface. As a result, the thickness of the layers varied only about 5% over the 0.4 cm^2 layer area. The end-faces of each layer were polished to laser-grade quality.

Optical waveguiding in the layer is obtained through the refractive-index increase provided by the Tm doping. Since KTmW is isostructural to KYW, the refractive indices of Tm:KYW layers increase approximately linearly with increasing Tm concentration. In a thin KYW layer doped with 1.8at% Yb, we measured a refractive-index increase of $6x10^{-4}$ compared to the undoped KYW substrate by dark m-lines spectroscopy [19]. The Tm-doped samples used in the experiments presented in this paper were too thick for investigations by dark m-lines spectroscopy. Nevertheless, since Tm^{3+} and Yb^{3+} possess similar electron densities, we expect the refractive-index increases of our Tm^{3+}-doped waveguide layers to be in the same range.

3. Laser setup

Two Tm:KYW planar waveguides consisting of 39 and 35-µm-thick active layers were selected for initial laser experiments, the thicker being 1.2at% and the thinner 1at% Tm-doped, respectively. Due to the geometrical dimension of the structure a high number of transverse modes can be guided in the layer, both parallel and perpendicular to the surface.

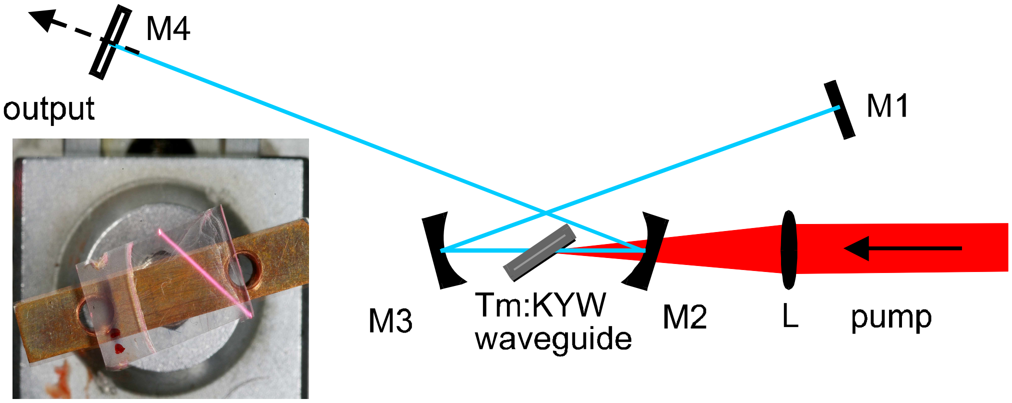

Fig. 1. Setup of the Tm:KYW/KYW waveguide laser using a Ti:sapphire laser pump source. L: AR-coated focusing lens, M1: plane total reflector, M2-M3: folding mirrors, radius of curvature: -100 mm, M4: plane output coupler. Inset: Photograph of the Tm:KYW waveguide placed on a Cu-plate in the lasing state. The reddish fluorescence indicates the pump channel.

The 3-sides polished sample was placed in an external cavity (Fig. 1). To match the resonator waist size with the waist of the transverse fundamental mode of the waveguide, an astigmatically compensated X-type cavity with a total length of 85 cm was established. The Tm:KYW waveguide was positioned between two 10-cm folding mirrors so that the resonator waist is located at both end-faces of the waveguide with a length of 6 mm and negligible diffraction losses occur for the resonator mode at the air-to-Tm:KYW/KYW interfaces. The waveguides were positioned at Brewster angle to minimize the loss in the laser cavity and to determine the laser polarization. This corresponded to propagation along the N_g-principal optical axis and polarization parallel to the N_m-axis. The pump polarization was also parallel to the N_m-axis. The sample was mounted on a copper plate, but no special care was taken for cooling. M1, M2 and M3 (Fig. 1) were highly reflecting mirrors ($R > 99{,}9\%$) from 1800 to 2075 nm and anti-reflection-coated on the rear side for high transmission from 780 to 1020 nm, and M4 was used as output coupler.

The Tm:KYW layer was pumped in a single pass absorption by a tunable CW Ti:sapphire laser delivering a maximum output power of 3 W near 800 nm when pumped with an all-lines Ar-ion laser. The output linewidth was about 0.2 nm. A 70-mm focusing lens was used to couple the nearly diffraction limited pump beam through one of the folding mirrors into the planar waveguide. At the position of the waveguide end-face, the pump spot had a Gaussian waist of 37 µm. This results in a pump intensity of about 25 kW/cm^2 for the maximum applied pump power which is roughly 5 times higher than the pump saturation intensity.

4. Tm:KYW planar waveguide laser: results

Continuous-wave laser operation could be obtained for output coupler transmissions between 1% and 5%. A photograph of the 35-µm thick Tm:KYW waveguide placed on a copper-plate in the lasing state is shown as inset in Fig. 1. The reddish fluorescence, indicating the pump

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channel, originates from upconversion fluorescence from the $^1G_4$ and possibly $^1D_2$ levels and the visible dislocations of the sample stem from the bottom side of the substrate which is not polished.

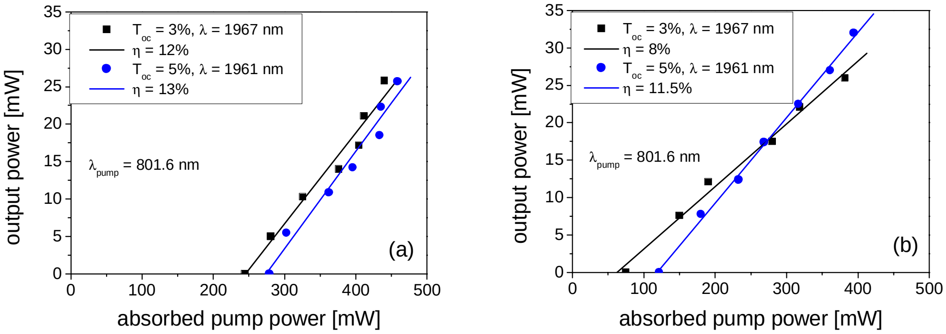

Fig. 2. Continuous-wave output power versus absorbed pump power of the Tm:KYW planar waveguide lasers for two output couplers: (a) 39-µm thick 1.2% Tm-doped active layer; (b) 35-µm thick 1% Tm-doped active layer (T_{OC}: output coupler transmission, η: slope efficiency).

The laser performance of the two Tm-doped waveguides is presented in Fig. 2. Depending on the output coupler transmission, the laser emission was between 1960 nm and 1970 nm. Best laser performance was achieved when pumping into the absorption peak at 801.6 nm. The laser threshold of the 35-µm-thick Tm:KYW layer was reached at an absorbed pump power of 244 mW. The output power amounted to 26 mW for both the 3%- and 5%-transmission output coupler T_{OC}. The slope efficiency η was maximum for $T_{OC} = 5\%$ and amounted to 13% with respect to the absorbed pump power. The lowest laser threshold was achieved with the 39-µm thick waveguide doped with 1at% Tm^{3+}. With the 3%-transmission output coupler the laser threshold was only 75 mW of absorbed pump power. The maximum output power was measured to be 32 mW with $T_{OC} = 5\%$, resulting in a slope efficiency versus absorbed pump power of $\eta = 11.5\%$. The three times lower laser threshold of the 1at% Tm:KYW waveguide is presumably a result of the lower doping concentration, which led to reduced reabsorption losses. The slope efficiencies of the two waveguides are rather similar, slightly higher for the 1.2at% Tm sample. The maximum optical-to-optical conversion efficiency achieved with the 39-µm thick sample is only about 8%, which is mainly due to the two times larger pump spot-size compared to the active layer thickness.

The absorption characteristics of the two Tm:KYW waveguides are shown in Fig. 3. The calculated small-signal pump absorption yields a value of about 90%. The measured absorption of 60% confirms roughly the overlap integral of the pump mode and the mode size inside the planar waveguide. The absorption dropped from 60% at low pump power down to about 30% at the maximum applied pump power. We could not detect a noticeable difference between the absorption in the lasing state and when lasing is interrupted as obtained in Tm-doped double tungstate bulk lasers [16]. This indicates that the pump saturation intensity is not strongly increased in the lasing state and the bleaching effect remains as can be expected from the low intracavity power of about 10 kW/cm^2. The measured difference in absorption between the two waveguides is only 3%. With respect to the different doping levels a higher difference is expected, which underlines the present pump saturation effect. Similar absorption behaviour was observed for all samples investigated.

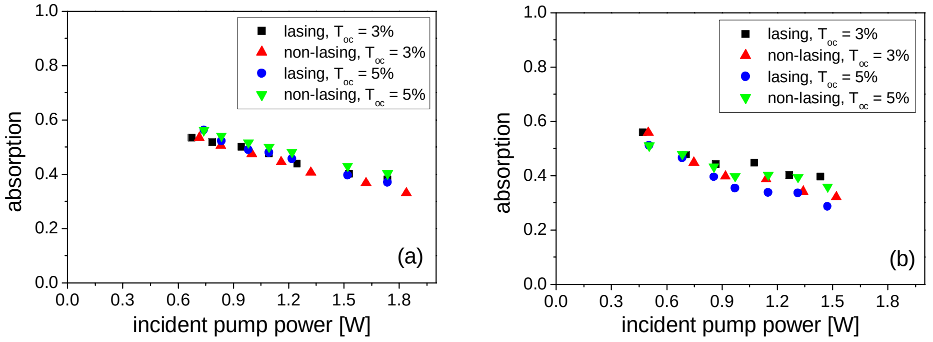

Fig. 3. Measured single-pass absorption versus incident pump power of the Tm:KYW waveguides: (a) 39-µm thick 1.2% Tm-doped active layer; (b) 35-µm thick 1% Tm-doped active layer.

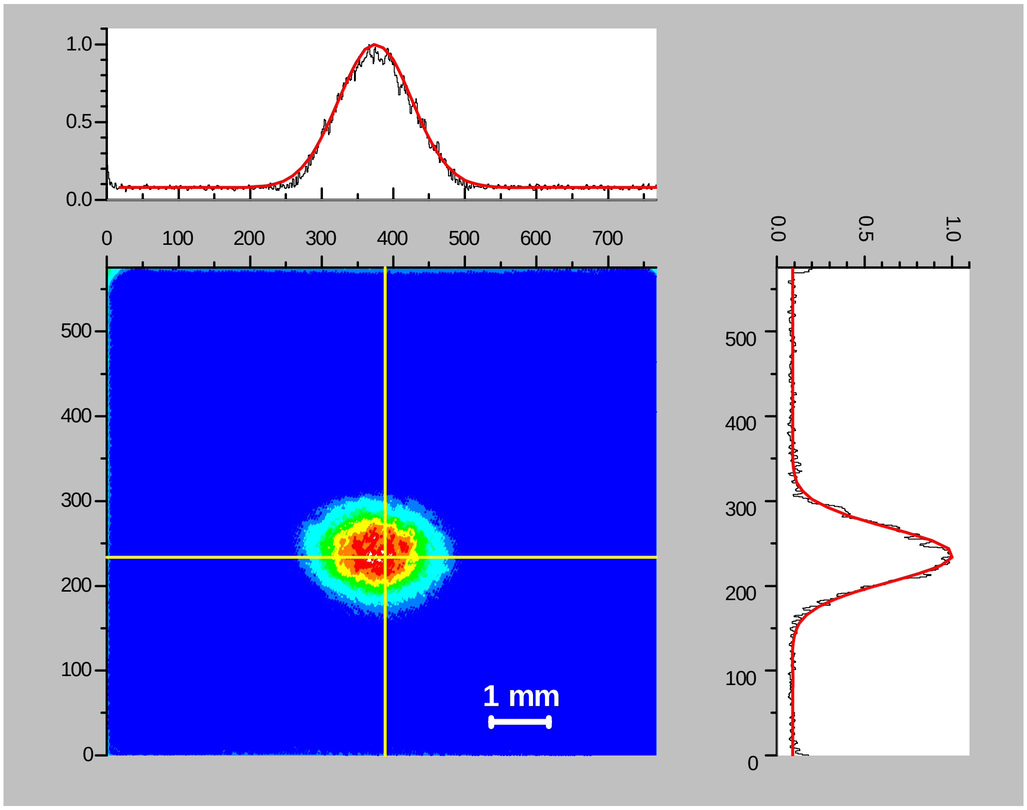

Fig. 4. Far-field intensity distribution at maximum output power of the 39-µm-thick planar Tm:KYW waveguide laser. The cuts (black lines) parallel and perpendicular to the active waveguide layer and the corresponding Gaussian-fits (red lines) are also presented (numbers on the space axis are pixels).

Thinner waveguides with a Tm:KYW layer thickness of 20 µm and 18 µm were also examined. Both were demonstrated to lase, but the maximum output power was limited to 8.5 mW and 6 mW, respectively. Their performance was slightly inferior to that of the thicker

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waveguides, although the Tm-doping concentration of 1.2at% and 1at% Tm^{3+} was comparable. We attribute the worse performance to a less good matching of the waveguide thickness to the pump mode profile and a higher diffraction loss at the waveguide/air interface.

The far-field intensity distribution of the laser output was recorded by the use of a Vidicon Camera (FJW Optical System Inc.). The observed beam profile remained basically the fundamental mode for all planar waveguides investigated, also when aligned for maximum output power. Only the output of the 35-µm-thick waveguide tended to a TEM_{10} transverse mode. The beam profile of the 39-µm-thick Tm:KYW waveguide at the highest pump-power level together with the cuts parallel and perpendicular to the plane of the waveguide is shown in Fig. 4. Both cuts can be well fitted with a Gaussian function and a beam ellipticity of only ~25% is deduced. The larger waist is always located in the plane without guiding. Most notable is that the laser output is close to the diffraction limit and the resonator mode is well matched within the physical dimensions of the planar crystal waveguide, despite the highly multimode waveguide structure.

The laser performance with respect to slope efficiency and output power was inferior in comparison to the excellent results achieved with a planar Yb:KYW/KYW waveguide laser in a similar laser configuration [19]. To identify potential loss channels, the visible fluorescence spectrum of the Tm:KYW planar waveguide was recorded in comparison to that of a Tm:KLuW bulk crystal in the same pump configuration (Fig. 5). The 3-mm thick and 3at%-Tm-doped bulk KLuW absorbed nearly the same amount of pump power and has proved its excellent suitability as laser crystal in the 2 µm spectral range [16]. The two spectra were normalized to the upconversion $^1G_4 \rightarrow {}^3H_6$ transition in Tm^{3+} at 480 nm. The Tm:KLuW fluorescence spectrum exhibits some weak green peaks, which can be attributed to Er upconversion lines. In contrast, the Tm:KYW waveguide fluorescence shows only upconversion lines which can be ascribed to Tm^{3+}. Therefore, no additional loss channels like Er impurities could be identified within this spectral window for the Tm:KYW waveguides. Waveguide lasing could not be achieved within all areas of the doped layer. An enhanced optical-to-optical conversion efficiency is expected by improving the quality of the waveguide structure.

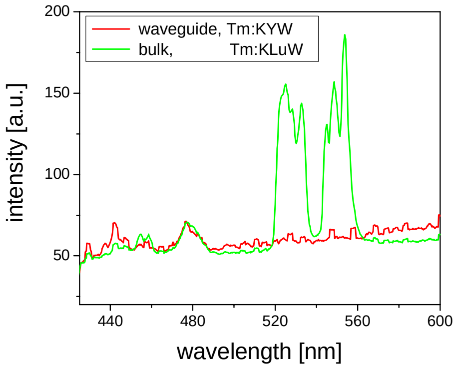

Fig. 5. Fluorescence spectra in the visible of the 39-µm thick Tm(1.2at%):KYW waveguide and a Tm(3at%):KLuW bulk crystal when excited at 800 nm.

To verify that the layered KYW structure is functioning as a waveguide, a different laser experiment had been conducted using the already mentioned planar Yb-doped KYW waveguide [19], which exhibited similar geometrical dimensions as the investigated Tm:KYW waveguides. This two-mirror cavity laser experiment was not repeated for the Tm:KYW waveguides, because the round-trip loss introduced by the uncoated waveguide end-faces prevented to reach the laser threshold in this resonator configuration. Nevertheless,

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on the basis of our experience with Yb-doped KYW planar waveguide lasers [19] we are quite confident that the investigated Tm:KYW layers operated as waveguide lasers, too.

5. Summary

Epitaxial planar waveguides of Tm-doped monoclinic double tungstate crystals have been manufactured with high optical quality by the LPE method. Tm:KYW layers with a thickness between 17 and 39 µm and doping levels from 0.7at% to 1.2at% Tm^{3+} were grown on KYW substrates and waveguide laser operation was achieved for the first time. Continuous-wave lasing at near 1960 nm with a maximum output power of 32 mW and slope efficiencies as high as 13% were obtained at room temperature. Laser emission close to diffraction-limited performance was achieved for the highly multimode planar waveguide structure.

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