Continuous-wave and Q-switched Tm-doped $KY(WO_4)_2$ planar waveguide laser at 1.84 µm

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Abstract: High-quality monoclinic planar waveguide crystals of Tm-doped $KY(WO_4)_2$ codoped with Gd^{3+} and Lu^{3+} were grown by liquid-phase epitaxy. For the first time, planar waveguide lasing was demonstrated in a monolithic cavity in the 2 µm spectral range. The laser was operated in the Q-switched mode using a Cr^{2+}:ZnSe crystal as saturable absorber and in the continuous-wave regimes. The Q-switched planar waveguide laser delivered pulse energies up to 120 nJ at a repetition rate of 7 kHz.

OCIS codes: (140.3580) Lasers, solid state; (140.3070) Infrared and far infrared lasers; (230.7390) Waveguides, planar; (140.3540) Lasers, Q-switched; (160.3380) Laser materials.

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1. Introduction

Laser emission in the 2 µm spectral range is of particular interest for applications in atmospheric monitoring, laser radar and medicine. This is mainly due to the strong absorption bands of water around this wavelength. Optical parametric oscillators (OPOs) operating in the mid-IR region also require 2 µm lasers as pumping sources [1]. Among the lanthanide ions exhibiting laser transitions around 2 µm, the trivalent thulium (Tm^{3+}) with the emission based on the $^3F_4 \rightarrow {}^3H_6$ transition is one of the most attractive, since it can be pumped directly around 800 nm with AlGaAs diode lasers [2]. Laser operation of Tm^{3+} around 2 µm has been demonstrated in several crystal hosts such as YAG ($Y_3Al_5O_{12}$) [3], $YLiF_4$ [4], YVO_4 [5] and monoclinic double tungstates $KRE(WO_4)_2$ or shortly KREW (RE=Y, Gd, Lu) [6,7]. Compared to other laser hosts such as garnets, fluorides or vanadates, the monoclinic double tungstates stand out because lanthanide ions exhibit high absorption and emission cross sections and broader linewidths when they are hosted in this family of crystals [8]. Furthermore, high doping levels of the active ions are possible in KREW crystals without quenching of the fluorescence because of the large lanthanide ion–ion distance.

Among the different Tm-doped monoclinic double tungstates, KLuW has shown the most promising laser results [8]. Up to 4 W output power at 1948 nm, with a slope efficiency with respect to absorbed power reaching 69% were obtained in bulk samples under diode pumping at 802 nm [9], improving the results previously obtained in Tm:KYW bulk crystals [10,11]. The combination of high doping levels and large cross-sections permits the use of relatively thin active media. Continuous-wave (CW) laser operation of epitaxial Tm:KLuW layers on KLuW substrates with the active layer perpendicular to the resonator axis was successfully demonstrated in a thin-disk laser geometry [12] and in a conventional 4-mirror cavity [13]. Passively Q-switched laser operation around 1.9 µm with Cr^{2+}:ZnS and Cr^{2+}:ZnSe saturable absorbers (SA) was reported with Tm:KYW and codoped Yb,Tm:KYW bulk crystals [14].

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Waveguide lasers with their simple monolithic structure are attractive for integrated optical devices with the potential for on-chip integration [15]. The inherent advantage of waveguide lasers over conventional bulk lasers is the good overlap between the pump light and the laser mode, because both are constrained to propagate together in the narrow waveguide, leading to high intensities for relatively low power. Furthermore, the waveguide laser geometry is in particular advantageous for three-level lasers in which the final level is thermally populated, such as Tm^{3+}. The successful combination of the advantages of the waveguide laser geometry and the spectroscopic properties of monoclinic double tungstates was demonstrated with planar waveguide lasers based on Yb:KYW in the 1 µm spectral range [16–18]. So far, true planar Tm-waveguide lasing has only been demonstrated based on YAG. The first Tm:YAG waveguide reported was grown by liquid phase epitaxy (LPE) and delivered 180 mW of CW output power at a laser wavelength of 2012 nm using a longitudinal pump geometry [19]. 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 [20]. The only report on lasing of a Tm-doped monoclinic double tungstate planar waveguide structure was based on Tm:KYW and the waveguide was placed in a ~1 m long external laser cavity [21].

The laser efficiency in epitaxial layers of monoclinic double tungstates seems to be strongly dependent on the lattice mismatch between the substrate and the epitaxial layer [22]. Therefore, it is important to lattice match the epitaxial layer with the substrate by maintaining a relatively high refractive index contrast to profit from the tighter pump- and laser mode confinement [23]. Our detailed evaluation of the optimum layer composition [24] confirmed the results of [23]. Subsequently, we showed that such epitaxial layers can be activated with Tm^{3+} [25]. In this paper we demonstrate, for the first time of our knowledge, CW and Q-switched planar waveguide lasing of Tm^{3+} in $KY_{0.58}Gd_{0.22}Lu_{0.17}Tm_{0.03}(WO_4)_2/KY(WO_4)_2$ in a monolithic microchip cavity. A Cr:ZnSe crystal served as SA for the Q-switched laser operation.

2. Experimental details

2.1 Epitaxial structure

Using the experimental apparatus described in [24] and following the same procedure, the $KY_{0.58}Gd_{0.22}Lu_{0.17}Tm_{0.03}(WO_4)_2$ active layer was grown by LPE on a **b**-oriented KYW substrate. The dimensions of the substrate were 7×2.3×18 mm^3 along **a***×**b**×**c** crystallographic directions and the Tm^{3+} ion concentration in the epilayer was 1.75×10^{20} cm^{-3}. After removing the epitaxial layer on one of the large faces of the substrate, the other face was polished down to a thickness of 12 µm. A 70 µm thick KYW cladding was then overgrown on top of the active layer with the aim of realizing a symmetric planar waveguide and reducing surface scattering losses. Furthermore, the cladding layer protected the polished end faces of the active layer avoiding edge rounding. The final length of the waveguide was 7 mm, after cutting and polishing the end-faces perpendicular to the N_g-optical axis. According to the refractive index data [26], refractive index differences of 3.6×10^{-3} and 6.1×10^{-3} between active layer and substrate/cladding are expected at 802 and 1800 nm, respectively.

2.2 Waveguide laser configuration

The configuration of the waveguide laser, operating in the Q-switched regime, is shown in Fig. 1(a). A Ti:sapphire laser operating at 802 nm was used as pump source for the planar waveguide. A Faraday isolator was placed in between the pump source and the input microscope objective lens to prevent back reflections from the laser cavity to the pump laser. The polarization of the pump was chosen parallel to the N_m-optical axis. The pump beam was focused by a 34 mm focal length objective into the waveguide. At the waveguide end-face, the pump spot had a Gaussian waist of 32 µm. This results in a pump intensity of about 5 kW/cm^2 for the maximum applied pump power which is in the order of the pump saturation intensity.

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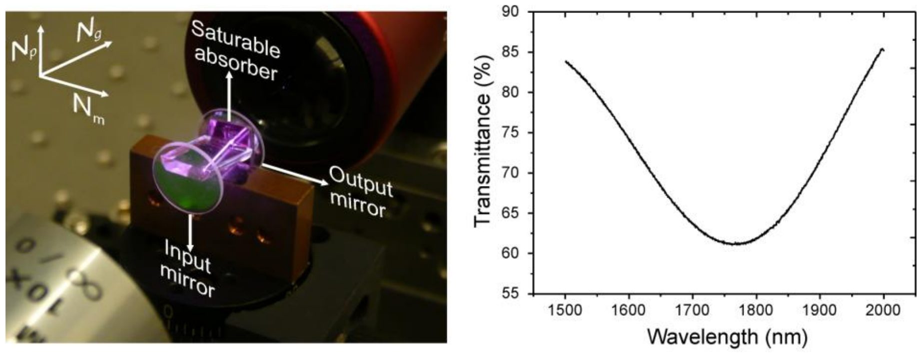

(a) (b)

Fig. 1. (a) Photograph of the $KY_{0.58}Gd_{0.22}Lu_{0.17}Tm_{0.03}(WO_4)_2$ planar waveguide laser setup with the Q-switch. (b) Transmission spectrum of the Cr:ZnSe saturable absorber.

The input and output mirrors were attached to the end faces of the waveguide by means of an index matching gel (Thorlabs G608N), Fig. 1(a). The input mirror had a dichroic coating with high transmission (93%) at 802 nm and high reflection (99%) at 1800 nm. The transmission of the output coupler at the laser wavelength was 7.5%. The microscope objective lens in the upper part of Fig. 1(a) was used to collimate the output of the waveguide laser. We utilized a 0.89 mm thick AR-coated plate of Cr:ZnSe as saturable absorber. The passive absorber crystal and the output mirror were kept fixed to the output end face of the waveguide by using again index matching gel, see Fig. 1(a). From the transmission spectrum of the passive absorber, shown in Fig. 1(b), a low-signal transmittance of ~ 64% at 1843 nm can be deduced.

3. Results and discussion

3.1 Continuous-wave planar waveguide laser

At first we studied the CW performance of the laser in the butt-coupled-mirror cavity as depicted in Fig. 1(a) without the SA. The small-signal absorption for the pump light in the Tm-doped planar waveguide was measured and estimated to be about 70% taking into account the overlap of the guided laser mode and the pump mode. The actual absorption dropped from 80% at low pump power down to about 68% at the maximum applied pump power. This indicates slight bleaching for higher pump powers. Figure 2(a) shows the input-output characteristics of the waveguide laser with the 7.5% transmission output coupler. The absorbed pump power required to reach the laser threshold was only 28 mW. At the maximum absorbed pump power of 66 mW, the output power reached 5.5 mW, leading to an optical efficiency of 8.3%. The slope efficiency obtained here with respect to the absorbed pump power amounted to 23%. The planar waveguide laser emitted at a wavelength of 1843.6 nm, inset Fig. 2(a). The laser output was found to be linearly polarized, naturally selected parallel to the N_m-optical axis.

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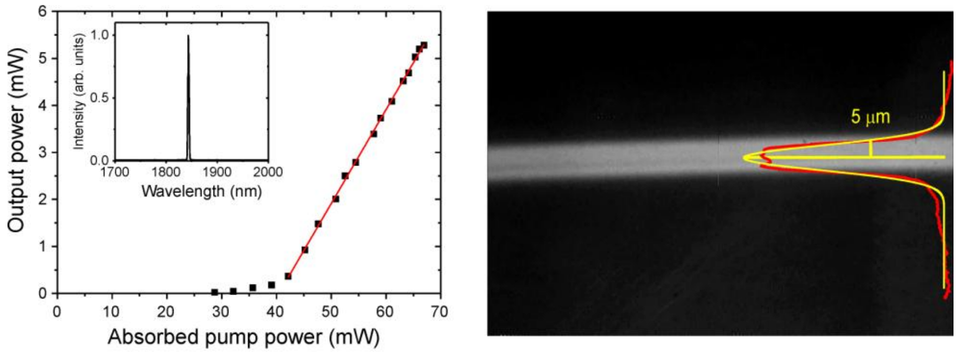


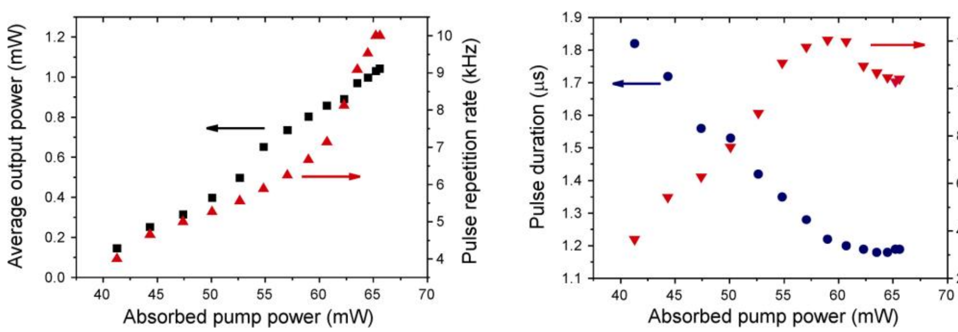
(a) (b)

Fig. 2. Continuous-wave $KY_{0.58}Gd_{0.22}Lu_{0.17}Tm_{0.03}(WO_4)_2$ planar waveguide laser at 1843.6 nm. (a) Output power vs. absorbed pump power, Inset: emission spectrum. (b) Near-field intensity distribution at maximum output power and a Gaussian-fit (yellow line) perpendicular to the active layer.

Figure 2(b) shows the near field intensity distribution of the laser mode recorded with a Hamamatsu C2400-03Er Vidicon camera. The observed beam profile represents basically the fundamental mode in the guided direction although higher order modes should be present due to the refractive index contrast and the guiding layer thickness. Despite this, the spatial profile in Fig. 2(b) could be well fitted with a Gaussian-distribution along the vertical direction. The waist size (half width at *1/e*) in the guided plane was calculated to be 5 µm. In the plane without guiding the mode size is about 20 times larger and also higher order modes are excited. The near-field measurements confirm that the resonator modes are well matched within the physical dimensions of the planar crystal waveguide.

3.2 Q-switched planar waveguide laser

Introducing the Cr:ZnSe SA into the cavity, passively Q-switched operation was achieved. The Cr:ZnSe crystal was butt-coupled between the output coupler and the end face of the $KY_{0.58}Gd_{0.22}Lu_{0.17}Tm_{0.03}(WO_4)_2$ planar waveguide, Fig. 1(a).



(a) (b)

Fig. 3. Q-switched $KY_{0.58}Gd_{0.22}Lu_{0.17}Tm_{0.03}(WO_4)_2$ planar waveguide laser. (a) Average output power and pulse repetition rate vs. absorbed pump power. (b) Pulse duration and calculated pulse energy vs. absorbed pump power.

The passively Q-switched laser reached threshold at an absorbed pump power of 41 mW. The output spectrum consisted of a single peak centered at 1844.7 nm and exhibited a spectral linewidth <0.5 nm. Figure 3(a) shows the output characteristics of the passively Q-switched $KY_{0.58}Gd_{0.22}Lu_{0.17}Tm_{0.03}(WO_4)_2$ waveguide laser. At the highest absorbed pump power of 66 mW, the total average output power reached 1.2 mW. The optical conversion efficiency with respect to the absorbed pump power was 1.8%. The average output power characteristics

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show a nearly linear dependence corresponding to a slope efficiency of 5%. The reduction in the slope efficiency compared with the CW case is due to the additional loss introduced into the cavity due to separating the mirror from the waveguide by nearly 1 mm on introduction of the saturable absorber. For passively Q-switched lasers, the pulse repetition frequency (PRF) depends on the pump power. The PRF was found to increase almost linearly from 4 kHz at threshold to 10 kHz at the highest pump level, Fig. 3(b). The maximum pulse energy was estimated to be 120 nJ at a PRF of 7 kHz.

The temporal pulse profiles (see Fig. 4) were studied with a fast (80 ps rise time) photodiode and a 2-GHz oscilloscope. The pulse duration decreased from 1.8 µs (FWHM) at threshold asymptotic to 1.2 µs for maximum pump power, see Fig. 4(b). The pulse-to-pulse fluctuations were estimated to be less than 10%.

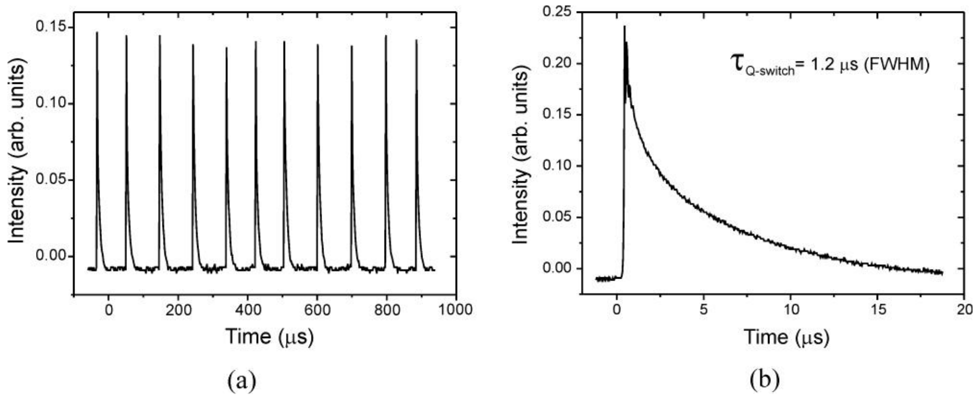

Fig. 4. Q-switched $KY_{0.58}Gd_{0.22}Lu_{0.17}Tm_{0.03}(WO_4)_2$ planar waveguide laser. (a) Monitored pulse train (b) Shape of a single pulse at maximum pump power.

4. Summary

Waveguide laser operation of a Tm^{3+}:$KY(WO_4)_2$ epitaxial layer codoped with Gd^{3+} and Lu^{3+} was demonstrated for the first time in a monolithic cavity configuration. The planar waveguide laser was operated in the CW and Q-switched laser regimes at a wavelength of 1844 nm when pumped at 802 nm. The CW laser oscillation threshold was reached at an absorbed pump power of only 28 mW. The maximum output power amounted to 5.5 mW and the slope efficiency with respect to the absorbed pump power was 23%. With a Cr^{2+}:ZnSe SA for Q-switching, pulse durations of 1.2 µs, maximum pulse energies of 120 nJ and repetition rates of up to 10 kHz were achieved. The emitted beam profile was elliptical. In the guided direction the beam profile could be well fitted with a Gaussian-distribution. However, higher order modes in addition to the fundamental one are expected to be supported due to the planar waveguide design.

Acknowledgments

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