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Efficient diode-pumped Tm:KYW 1.9-µm microchip laser with 1 W cw output power

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Abstract: We report on a diode-pumped Tm:KYW microchip laser generating 1 W continuous-wave output power. The laser operates at a wavelength of 1.94 µm in the fundamental TEM_{00} mode with 71% slope efficiency relative to the absorbed pump radiation and 59% slope efficiency relative to the incident pump radiation. The optical-to-optical laser efficiency is 43%.

OCIS codes: (140.3580) Lasers, solid-state; (140.5680) Rare earth and transition metal solid-state lasers.

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1. Introduction

Thulium lasers access a wide spectral tunability range in the 2-μm wavelength region [1–3], which is highly attractive for use in atmosphere monitoring, gas analysis, remote sensing, and medical applications. The operation of such lasers is based on the $^3F_4 \rightarrow {}^3H_6$ transition in Tm^{3+} ions. The efficient cross-relaxation process $^3H_4 \rightarrow {}^3F_4$ – $^3H_6 \rightarrow {}^3F_4$ [4] enables to use laser diodes for pumping at a wavelength of 0.8 μm ($^3H_6 \rightarrow {}^3H_4$ transition in Tm^{3+} ions), thus achieving a theoretical luminescence quantum yield of ~2 with a reduced thermal load. Many applications require miniature and alignment-free sources, for which microchip or waveguide laser configurations are particularly attractive. Several diode-pumped microchip lasers based on Tm-doped YAG [5], $GdVO_4$ [6], YVO_4 [7], and $KY(WO_4)_2$ [8] crystals were reported. Their output characteristics together with the best results obtained from waveguide lasers are summarized in the Table 1.

Table 1. Summary of output characteristics of thulium microchip and waveguide lasers

Gain media	Design	P_{out}	λ	Slope Efficiency	Pump source	Ref.
Tm:YAG	microchip	450 mW	2.02 μm	ξ_{abs} = 32%; ξ_{inc} = 20%	Laser diode	[5]
Tm:YVO_4	microchip	400 mW 150 mW	1.92 μm	ξ_{abs} = 41% ξ_{abs} = 30%	Ti:Sapphire Laser diode	[6]
Tm:GdVO4	microchip	630 mW	1.91 μm	ξ_{inc} = 33%	Laser diode	[7]
Tm:$KY(WO_4)_2$	microchip	650 mW	1.95 μm	ξ_{abs} = 44%	Laser diode	[8]
Tm:YAG	planar waveguide (LPE)	180 mW 100 mW	2.02 μm	ξ_{abs} = 68% ξ_{abs} = 64%	Ti:Sapphire Laser diode	[9]
Tm:$KLu(WO_4)_2$	planar waveguide (LPE)	78 mW	1.96 μm	ξ_{abs} = 64%	Ti:Sapphire	[10]
Tm:$LiYF_4$	planar waveguide (LPE)	560 mW (not *cw* output)	1.88 μm	ξ_{abs} = 76%	Ti:Sapphire (chopped at 50% duty cycle)	[11]
Tm-doped ZBLAN glass	channel waveguide (fs-LW)	205 mW 25 mW	1.89 μm	ξ_{abs} = 67% ξ_{abs} = 40%	Ti:Sapphire Laser diode	[12]
Tm-doped ZBLAN glass	channel waveguide (fs-LW)	48 mW	1.88 μm	ξ_{abs} = 50%	Laser diode	[13]
Tm: $KLuYGd(WO_4)_2$	channel waveguide (LPE)	300 mW	1.84 μm	ξ_{abs} = 70%	Ti:Sapphire	[14]

P_{out} – laser output power; λ – laser wavelength; ξ_{abs} – slope efficiency relative to an absorbed pump power; ξ_{inc} – slope efficiency relative to an incident pump power; LPE – liquid phase epitaxy; fs-LW – fs-laser written.

The waveguide lasers demonstrated higher slope efficiencies relative to the absorbed pump power. However, most of them suffered from the weak absorption of pump radiation: even with expensive and complex TEM_{00} Ti:Sapphire laser pumping, only a low optical-to-optical efficiency of thulium lasers was initially achieved. These limitations were recently overcome by use of the channel waveguide laser design. Pumped by a Ti:Sapphire laser, a liquid phase epitaxy waveguide laser generated an output power of 300 mW with a slope efficiency of ξ_{abs} = 70% relative to the absorbed pump radiation and an optical-to-optical efficiency of η > 50% [14]. In 2012, Ti:Sapphire pumping of a fs-laser written Tm-doped ZBLAN waveguide resulted in an output power of 205 mW with a slope efficiency of ξ_{abs} = 67% relative to the absorbed pump radiation and an optical-to-optical efficiency of η ~40% [12]. However, the use of cost-efficient and compact 790-nm laser diodes as pump sources for the same Tm-doped ZBLAN glass channel waveguide lasers led to a drop of a slope efficiency relative to an absorbed pump radiation to a level of ξ_{abs} = 40-50% [12,13].

In this work, we demonstrate that diode-pumped Tm-microchip lasers can reach higher power levels and similar efficiencies as the best Ti:Sapphire-pumped Tm-waveguide lasers.

We present a 1-W diode-pumped Tm:KY(WO_4)$_2$ microchip laser which operates in a TEM_{00} mode with ξ_{abs} = 71% slope efficiency relative to the absorbed pump radiation and η = 43% optical-to-optical efficiency.

2. Experimental set-up

The compact laser cavity (Fig. 1) is formed by a plane mirror with a high reflection at the 1.9-µm laser wavelength and a high transmission at the 0.8-µm pump wavelength, and a plane output coupler (OC). We studied the laser performance for OC transmission values of T_{OC} = 1.5%, 2%, and 6%. As gain medium, we use a Tm(5%):KY(WO_4)$_2$ (Tm:KYW) crystal with a thickness of 2.2 mm, which was cut along the N_g axis. The advantages of this crystal orientation for microchip laser operation are the high absorption and emission cross-sections, which increase the laser efficiency, and the positive thermal lens, which stabilizes the laser cavity mode [8]. The crystal faces were AR-coated for the pump and laser radiation. The Tm:KYW crystal is mounted on a heat-sink and cooled from three sides. The cavity mirrors are mounted on adjustable mirror mounts placed on translation stages. The thickness of the crystal holder is 0.2 mm thinner than the laser medium. We pre-aligned the mirrors and then used the translation stages to bring the mirrors in a firm contact with the gain medium. Gluing of the cavity mirrors to the crystal should be straightforward, however was not done in order to be able to change the degree of output coupling. No active cooling is applied to the laser crystal and the laser operates at standard room-temperature conditions (~23°C).

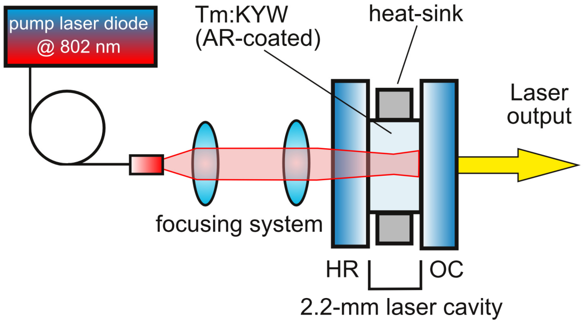

Fig. 1. Schematics of the diode-pumped Tm:KYW laser.

The pump source is a commercially available (Lumics GmbH, type LU0808T020-EI) 808-nm multimode fiber-coupled (50-µm diameter, N.A. = 0.12) laser diode with a nominal output power of 2 W. It delivers within the maximum current specifications up to 2.4 W of output power. During the experiments, we set the temperature of the laser diode controller to 14.5°C, which led to an emission at a wavelength of 802 nm. The pump radiation is not polarized. The focusing system provides a pump beam with a waist diameter of 140 µm and a confocal parameter of 3.5 mm.

The output power is measured with a Gentec UP19K-15S-H5 detector. The transverse laser beam profile is measured with a DataRay WinCamD-FIR2 imaging camera (pixel size: 17x17 μm^2). The output spectra are acquired using an APE WaveScan USB spectrometer (spectral resolution <0.5 nm). In order to block the residual pump radiation during the measurements, a longpass optical filter with a cut-off wavelength of 1000 nm is used.

3. Results

For all pump powers and output coupler transmissions, a stable Tm:KYW laser operation in a fundamental TEM_{00} mode is observed. The laser output is polarized along the N_m axis of the Tm:KYW crystal. Best results are obtained with an output coupler transmission T_{OC} = 6% (Fig. 2, Table 2). At 2.4 W of incident pump radiation, we obtained the maximum output power of 1.04 W. This corresponds to an optical-to-optical efficiency η = 43%. The slope efficiency relative to the incident pump power is ξ_{inc} = 59%. These values correspond to a 60% increase of the laser output power and efficiency compared to the results published in [8]. Key factors for the improved laser performance are the degree of output coupling and a considerably better pump beam quality with a longer Rayleigh length, and an optimized pump beam waist, which increases the pumping homogeneity and improves the overlap of the pump beam and the intracavity mode.

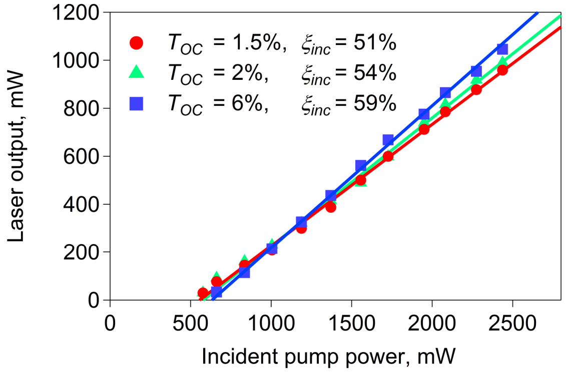

Fig. 2. Tm:KYW laser output power versus incident pump power.

Table 2. Output characteristics of the Tm:KYW laser

OC transmission	Maximum P_{out}	$\lambda_{central}$	Optical-to-optical efficiency	Slope efficiency to incident pump power
1.5%	0.96 W	1958 nm	40%	ξ_{inc} = 51%
2%	0.99 W	1949.5 nm	41%	ξ_{inc} = 54%
6%	1.04 W	1936.5 nm	43%	ξ_{inc} = 59%

The Tm:KYW laser emission spectrum shifts to the shorter wavelengths with an increase of the output coupling rate (Table 2), which is typical for a quasi-three-level laser scheme. The spectrum contained distinct peaks corresponding to the different longitudinal modes of the 2.2-mm microchip laser cavity (Fig. 3(a)). The measured laser beam profile revealed a Gaussian intensity distribution along the beam cross-section (Fig. 3(b)). The difference of the thermal lens optical power in N_p-N_g and N_m-N_g planes [8] leads to a slightly elliptic output beam with a corresponding ratio of radii of 0.9. The M^2 beam propagation factor (Fig. 3(c)) was measured using the knife-edge method [15] in the vertical and horizontal planes and was found to be M_x^2, M_y^2<1.1.

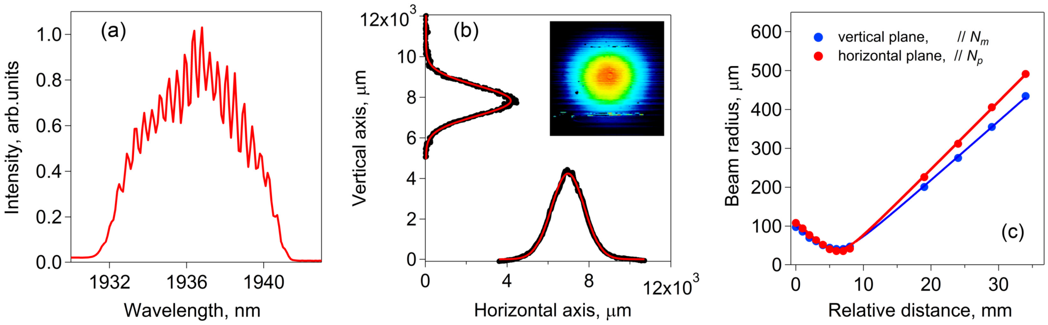

Fig. 3. Tm:KYW laser (T_{OC} = 6%, output power 1.04 W) spectrum (a) and the transverse beam profile at a distance of 23 cm from the OC (b). Red lines in (b) are Gaussian fits to the experimental data. Spots on the inset picture are due to blind pixels of the camera. Part (c) presents the measurement results of the beam propagation parameter M^2 (M_x^2, M_y^2<1.1).

In order to measure the Tm:KYW laser efficiency relative to the absorbed pump radiation, we carefully measured the fraction of pump power absorbed in the gain media during the laser operation. The power absorbed in a single pass was retrieved as the difference between the incident pump power measured after the focusing system and the transmitted pump power measured after the OC, the transmission of the cavity mirrors at the pump wavelength was also measured and taken into account (the OC reflected 36% of the pump radiation). Moreover, we did a conservative estimation for the absorption of the pump radiation reflected back into the crystal (8% of the initial incident pump power), assuming that the same fraction of it was absorbed again in the laser crystal during the second pass, and added it to the measured value to achieve the total pump power absorbed in the crystal.

The dependence of the Tm:KYW laser output power versus the absorbed pump power for T_{OC} = 6% is presented in Fig. 4. The estimated slope efficiency is ξ_{abs} = 71%. This value together with the optical-to-optical efficiency η = 43% are fairly comparable with the best results reported for the thulium channel waveguide lasers pumped by Ti:Sapphire sources.

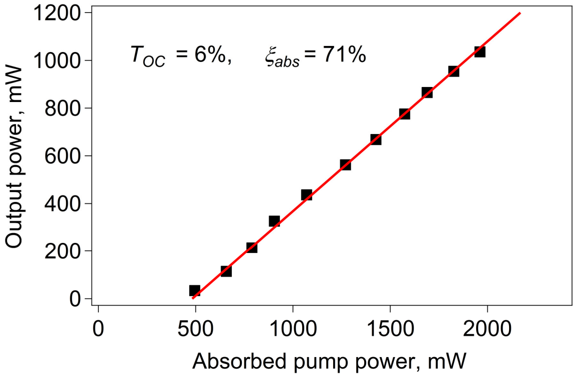

Fig. 4. Tm:KYW laser (T_{OC} = 6%) output power versus absorbed pump power.

4. Conclusion and outlook

In conclusion, we demonstrated an efficient microchip Tm:KYW laser pumped at 802 nm by a commercially available fiber-coupled multi-mode laser diode. The Tm:KYW laser delivered 1 W of cw output power at 1.94 µm and did not require any active cooling. The laser operated in fundamental TEM_{00} mode with nearly diffraction-limited transverse beam quality. The optical-to-optical efficiency was η = 43% and the slope efficiency relative to the absorbed pump power was ξ_{abs} = 71%. These results demonstrate that the simple and compact solid-state microchip laser approach is well-suited for efficient diode-pumped Watt-power level thulium lasers.

The further optimization of the laser performance and its miniaturization should be possible by use of crystals with higher Tm-doping concentration, which will allow decreasing the length of the gain medium while keeping a high absorption of the pump radiation. This should be feasible because efficient operation of 8 at. % [14] and 15 at. % [16] Tm-doped double tungstate lasers was already demonstrated. Moreover, the reduced cavity length is promising for the realization of a passively *Q*-switched thulium microchip laser generating sub-ns pulses.