Passively Q-Switched Thulium Microchip Laser

Maxim Gaponenko, Nikolay Kuleshov, and Thomas Südmeyer

***Abstract*— We present the first passively *Q*-switched thulium microchip laser. The diode-pumped laser incorporates a Tm:KYW gain medium and an InGaAs semiconductor saturable absorber mirror. The laser emits pulses with a duration of 2.4 ns at a repetition rate of 1.2 MHz with an average output power of 130 mW at a wavelength of 1905 nm. It operates in a fundamental TEM_{00} mode with $M^2 < 1.1$. The *Q*-switched pulse train is very stable with pulse-to-pulse intensity fluctuations <10% and a timing jitter of <±50 ns. Our microchip laser appears well suited as a seed in pulsed 2-μm fiber amplifier systems for applications like material processing. In addition, we present new power scaling results for continuous-wave Tm-microchip lasers, achieving 1.6 W of output power in a fundamental TEM_{00} mode. The slope efficiency relative to the absorbed pump power is as high as 74%, and the optical-to-optical efficiency is 41%. A maximum output power of 2.6 W is achieved in a TEM_{01*}-doughnutlike transverse mode. In all the cases, no active cooling is applied to the gain medium.**

***Index Terms*— Microchip lasers, *Q*-switched lasers, solid-state lasers, thulium.**

I. Introduction

Q-SWITCHED lasers operating in the wavelength range around 2-μm and emitting nanosecond pulses are of particular interest for wind velocity measurements, material processing, laser ranging, and remote sensing. Thulium (Tm^{3+}) doped laser gain media allow for an efficient laser operation in this spectral range under pumping by commercially available laser diodes at ~800 nm [1], [2], whereas a passive Q-switching technique with a saturable absorber (SA) is advantageous due to a simple, compact and reliable design. To date, different combinations of SAs and diode-pumped Tm-gain media were reported. A Tm:YLF laser with a Cr^{2+}:ZnS SA produced 14-ns pulses with energy of ~820 μJ at 120 Hz repetition rate with an average output power of 98 mW [3]. Higher pulse repetition rates were obtained using a Cr^{2+}:ZnS SA in a Tm:KLuW laser (pulse duration −30 ns, pulse repetition rate −2.7 kHz, pulse energy −145 μJ, average laser power −390 mW) [4] and a PbS-quantum dot-doped glass SA in a Tm:KYW laser (pulse duration −60 ns, pulse repetition rate –10 kHz, pulse energy −16 μJ, average laser power −160 mW) [5]. Recently, passively Q-switched Tm-lasers with a sub-10-ns pulse duration were demonstrated: a Tm:LiLuF laser with a Cr^{2+}:ZnS SA (pulse duration −7.6 ns, pulse repetition rate −161 Hz, pulse energy −1.26 mJ, average laser power −203 mW) [6] and a Tm:KYW laser with a PbS-quantum dot-doped glass SA (pulse duration −8 ns, pulse repetition rate −4.2 kHz, pulse energy −30 μJ, average laser power −120 mW) [7].

Miniaturization of pulsed Tm-laser sources in an alignment-free configuration is beneficial for many applications. This can be achieved in waveguide or microchip laser geometries. So far, no passively Q-switched thulium microchip laser has been realized before, and there is only one report on a passively Q-switched waveguide laser. It is based on a Tm:KYW planar waveguide structure pumped by a Ti:Sapphire laser source [8]. The monolithic microchip laser cavity incorporates a Cr^{2+}:ZnSe SA. The laser delivers Q-switched pulses with duration of 1.2 μs and energy of 120 nJ at a repetition rate of 7.5 kHz with an average output laser power of 1 mW [8].

Following the first demonstration of a diode-pumped continuous-wave (*cw*) Tm:YVO_4 laser with 150-mW of an output power by Zayhovski et al. [9], a progress in *cw* Tm-microchip laser power and efficiency has been achieved. A Tm:KLuW laser with a miniature plano-plano cavity was reported to deliver ~3 W of output power with ~50% of slope efficiency to the absorbed pump radiation [10]. Recently, we reported on an efficient microchip diode-pumped laser based on a Tm:KYW gain media which delivered up to 1 W of output power in TEM_{00} mode with 71% slope efficiency with respect to the absorbed pump radiation [1]. This result proved that thulium solid-state microchip lasers can achieve similar power levels and efficiencies as the best and most-efficient Tm-doped channel waveguide lasers pumped by high-brightness Ti:Sapphire laser sources (1.6 W of output power with ~80% slope efficiency to the absorbed pump power [11]). The Tm:KYW gain medium is attractive for efficient microchip lasers which operate in *cw* or Q-switched regimes. The crystal's orientation for the light propagation along the N_g optical axis provides access to high absorption cross sections for the pump radiation [12], while the positive thermal lens [13] stabilizes the laser cavity. Moreover, the relatively small laser level lifetime (~1.1 ms [12]) compared to other Tm-doped materials [14] is favorable for achieving a short pulse duration in Q-switched operation.

In this article, we present the first passively Q-switched microchip thulium laser. Our laser uses an InGaAs-SESAM for pulse formation and emits 2.4-ns pulses at a repetition rate of 1.2 MHz. In addition, we report on further power scaling results of diode-pumped Tm:KYW microchip lasers in continuous-wave operation.

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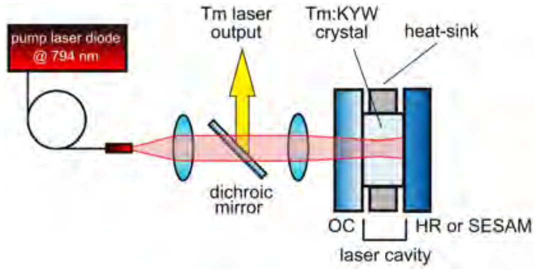

Fig. 1. Schematics of the microchip Tm:KYW laser.

II. Experimental Setup

The compact laser cavity (Fig. 1) is very similar to the one used in our previous work [1] and is formed by a plane mirror with a high reflection (HR) at the 1.9-μm laser wavelength and a plane output coupler (OC) with transmission of $T_{OC} = 6\%$. As gain medium, a Tm(5%):KY(WO$_4$)$_2$ (Tm:KYW) crystal is used. The crystal with a thickness of 2.2 mm was cut along the N_g axis. Its faces were AR-coated for the pump and laser radiation. During our experiments, we used two similar samples produced from the same boule (sample #1 and #2). The Tm:KYW crystal is mounted on an aluminum heat-sink and cooled from three sides (bottom, left and right sides). The heat-sink is placed on a small passive radiator. No active cooling is applied to the laser crystal. The laser operates at standard room-temperature conditions (~23°C). 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. This allows us to pre-align the cavity mirrors and then bring them in firm contact with the gain medium by use of the translation stages.

The Tm:KYW laser is pumped by a commercially available 794-nm multimode fiber-coupled (100-μm diameter, N.A. = 0.22) laser diode which delivers up to 8 W of power incident to the laser crystal. The focusing system provides a pump beam with a waist diameter of 100 μm and a confocal parameter of 1 mm (measured in air at the position of the laser crystal). The pump radiation is not polarized. The Tm:KYW laser is pumped through the OC. This allows us to keep the same laser configuration for both continuous-wave and Q-switched operation. A dichroic mirror is used to separate pump and output laser radiation.

For the Q-switching experiments, we replaced the HR mirror by an InGaAs semiconductor saturable absorber mirror (SESAM), which was manufactured by Batop GmbH, Germany. The SESAM has an initial unsaturated reflection of 92% at the laser wavelength, a modulation depth of 5% and nonsaturable losses of 3%. The absorption saturation fluence of the SESAM is ~20 μJ/cm^2 and the absorption recovery time is ~10 ps. The SESAM is mounted on a heat-sink.

The Tm:KYW laser 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: 17×17 μm^2). The output spectra are acquired using an APE WaveScan USB spectrometer (spectral resolution <0.5 nm). The temporal characteristics of the laser output in Q-switched operation are measured with a fast 12.5-GHz photodiode connected to an Agilent 3024A oscilloscope with an update rate of 10^6 waveforms per second. The laser pulse duration is measured using the same photodiode connected to a 1-GHz LeCroy WaveRunner 6100 oscilloscope, while the pulse repetition rate is measured with an Agilent 8561 EC radio-frequency spectrum analyzer. In order to block the scattered residual pump radiation during all the measurements, a long-pass optical filter with a cut-off wavelength of 1000 nm is used.

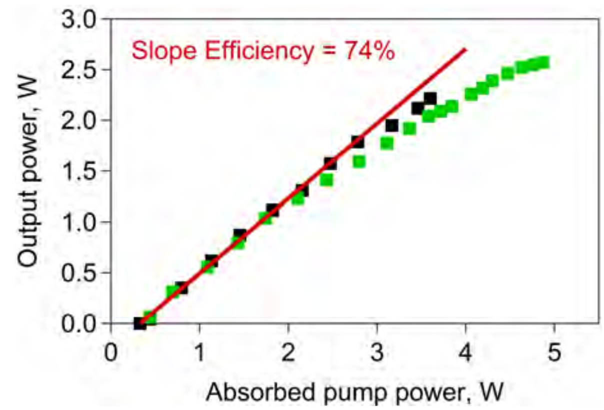

Fig. 2. Output power of the microchip Tm:KYW laser as function of the absorbed pump power for gain media samples #1 (green) and #2 (black).

III. Results

Stable *cw* laser operation with a threshold of ~600 mW of incident pump power was achieved with both Tm:KYW samples (Fig. 2). We carefully measured the fraction of a pump radiation absorbed in a Tm:KYW crystal during the laser operation. An absorbed power was retrieved as a difference between an incident pump power (measured after the focusing system) and a transmitted pump power (measured after the HR mirror). Transmission of the cavity mirrors at the pump wavelength was taken into an account. About 66% of pump radiation is absorbed during laser operation in the Tm:KYW sample #1, and ~68% in the sample #2. For both samples, a roll-over of the laser output can be observed at absorbed pump powers exceeding 3.5 W (Fig. 2). Using crystal #1, we evaluated the power limits. We obtained a maximum output power of $P_{out} = 2.57$ W for an absorbed pump power $P_{abs} = 4.9$ W (incident pump power $P_{inc} = 7.4$ W). Further increase of the pump power led to damage of the laser crystal #1.

With increasing pump power, the transverse mode profile of the Tm:KYW laser switches from a fundamental TEM$_{00}$ mode to a TEM$_{01*}$-doughnut-like mode (Fig. 3). At an output power of $P_{out} = 1.6$ W, we observe a Gaussian intensity distribution along a laser beam cross-section (Fig. 3a). The M^2 beam propagation factor is $M^2 < 1.1$. The laser spectrum contains distinct peaks which correspond to different longitudinal modes of the 2.2-mm microchip laser cavity (Fig. 3d). A further increase of the pump power leads to a flattering of the intensity distribution in the laser beam cross-section profile (Fig. 3b) with a consequent appearance of a doughnut-like mode at the output power $P_{out} = 2.2$ W (Fig. 3c). The laser output spectrum in this case is different and shows the presence of

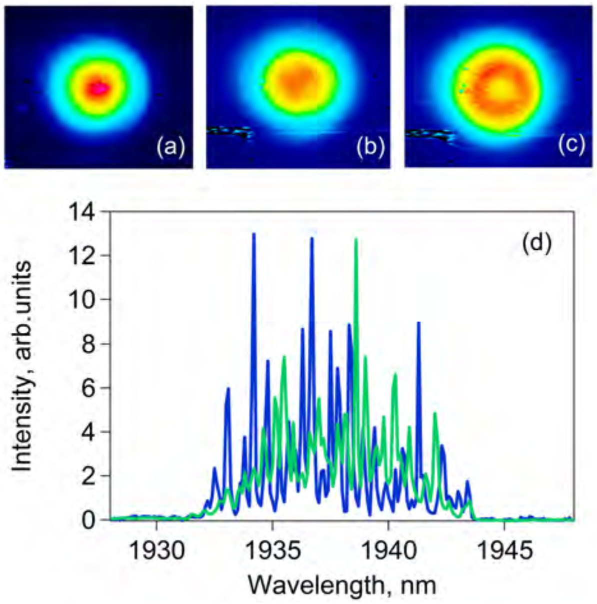

Fig. 3. Spatial profile of the laser beam at 1.6 W (a), 2 W (b), and 2.6 W (c) output power during continuous-wave operation. Output spectrum of the Tm:KYW microchip laser (d) at 1.6W (blue) and 2.6 W (green) output power.

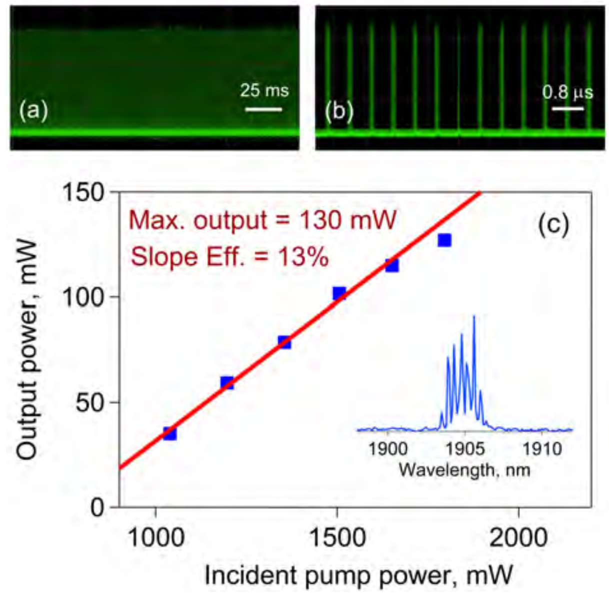

Fig. 4. (a) and (b), *Q*-switched Tm:KYW microchip laser pulse train at the maximum output power (real-time images of the oscilloscope screen at different time scales), an output power vs incident pump power (c), and output spectrum (inset in (c)).

a quasi-continuous background (Fig. 3d). This background is due to the increased number of cavity axial modes (decreased cavity free spectral range) due to the simultaneous excitation of the TEM_{00} and higher-order transverse modes. All individual peaks cannot be resolved anymore due to the limited spectral resolution of the spectrometer. We attribute the appearance of higher-order cavity modes to the influence of thermal lensing effects in the laser crystal. Increasing the absorbed pump power in the gain medium leads to an increasing positive, i.e. more strongly focusing, thermal lens. This, in its turn, leads to a decrease of the TEM_{00} mode size and favors an excitation of higher-order cavity modes.

For an operation in the fundamental TEM_{00} mode, the Tm:KYW laser slope efficiency with respect to the absorbed pump power is $\xi_{abs} = 74\%$ with the sample #2 ($\xi_{abs} = 68\%$ with the sample #1). The corresponding slope efficiency with respect to the incident pump power is $\xi_{inc} = 51\%$ and the maximum optical-to-optical efficiency is $\eta = 41\%$ (at the output power $P_{out} = 1.6$ W).

For the *Q*-switching experiments, we replaced the HR mirror with the SESAM. Stable *Q*-switched operation was achieved for an incident power range of 1.2 – 1.8 W. The laser output characteristics are presented in Figs. 4–6. The laser operates in a fundamental TEM_{00} mode ($M^2 < 1.1$) and generates pulses with a duration of $\Delta t = 2.4$ ns and energy of $E_{pulse} = 108$ nJ. To the best of our knowledge, these are the shortest pulses from a *Q*-switched solid-state thulium laser reported up to date. At an incident pump power of $P_{inc} = 1.8$ W, the laser emits pulses at a repetition rate of $\nu = 1.2$ MHz with an average output power of $P_{out} = 130$ mW. The pulse train is very stable. We estimated the pulse-to-pulse intensity fluctuations as <10% and the timing jitter <±50 ns. Compared to *cw* operation, the output spectrum of the *Q*-switched Tm:KYW laser is narrowed and shifted to 1905 nm. The narrowing is usual for *Q*-switched operation, whereas the shift of the laser emission to shorter wavelengths is probably caused by the blue-shift of the emission cross section maximum of the quasi-three level Tm gain material at the higher inversion level due to the insertion of the SESAM, and by the spectral properties of the SESAM.

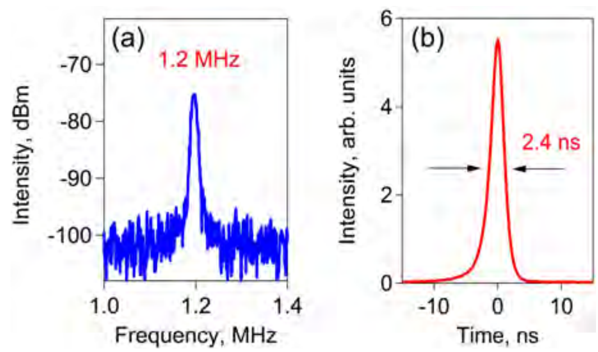

Fig. 5. Radio-frequency spectrum of the *Q*-switched Tm:KYW microchip laser pulse train (a) and a temporal profile of a single pulse with a full-width at a half-maximum of 2.4 ns (b) measured at the maximum output power.

The maximum output power appears to be limited by SESAM damage. A further increase of the incident pump power to 2 W leads to an increase of the laser pulse duration without a significant change of the output power. At this power level we observe a strong temperature increase of the SESAM heat sink. Prolonged laser operation at such a high pump intensity leads to irreversible changes in SESAM structure, which finally results in unstable laser oscillation.

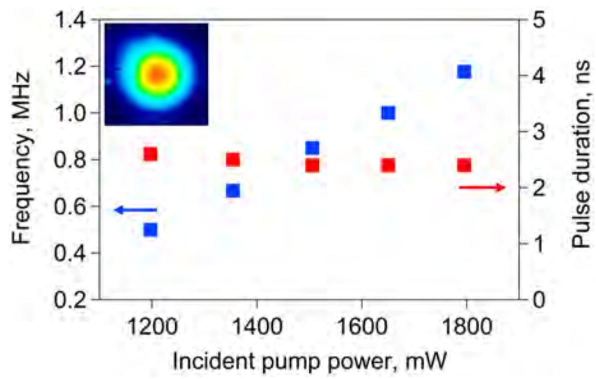

Fig. 6. Pulse repetition rate (blue) and pulse duration (red) of the Q-switched Tm:KYW laser as function of an incident pump power; inset represents the output beam profile at the maximum output power.

IV. Conclusion

In conclusion, we discuss *cw* power scaling and passively Q-switched operation of a diode-pumped Tm:KYW microchip laser. In continuous-wave operation, the laser delivers an output power of 1.6 W in a fundamental TEM_{00} mode with an optical-to-optical efficiency of 41% and a slope efficiency of 74% with respect to the absorbed pump power. This result is fairly comparable both in output power and efficiency with the best performance obtained from Ti:Sapphire-pumped thulium channel waveguide lasers. Using of an InGaAs SESAM for pulse formation, we demonstrate stable Q-switched operation of the laser. The pulse-to-pulse timing jitter is $<\pm 50$ns and intensity fluctuation is $<10\%$. The Q-switched Tm:KYW microchip laser emits pulses with a duration of 2.4 ns at a repetition rate of 1.2 MHz with an average output power of 130 mW. Further pulse shortening to the sub-ns range should be feasible by reducing the length of the gain medium and optimizing the output coupling rate and the SESAM modulation depth. A further miniaturization of the laser source should be feasible by applying an HR-coating directly on the crystal face and the implementation of a SESAM designed for an operation in transmission with an output-coupling coating. This should allow for a simple laser design with only two components that can be glued together and mounted onto a common heat-sink. Miniature Q-switched 2-μm laser sources are attractive for numerous applications, for example as a seed source in fiber amplifiers. Such systems would provide a cost-efficient and compact solution for the generation of sub-ns laser pulses with a megahertz repetition rate and a watt-level average output power in the 2-μm-wavelength region.

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