

Diode-pumped Tm:KY(WO₄)₂ laser passively modelocked with a GaSb-SESAM

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Abstract: We present the first diode-pumped modelocked thulium (Tm³⁺) laser based on a double-tungstate crystalline gain material. The solid-state laser consists of a Tm:KY(WO₄)₂ crystal as gain medium and a GaInSb/GaSb quantum well saturable absorber for self-starting passive mode locking. The laser is pumped by a multi-mode fiber-coupled laser diode at a wavelength of 793 nm. An average output power of 202 mW is achieved at a center wavelength of 2032 nm. Pulses with duration of 3 ps are generated at a repetition rate of 139.6 MHz. We also report on the first noise evaluation of a modelocked solid-state laser operating in the 2-μm wavelength range. We measured a timing jitter of sub-100 fs and a relative intensity noise of only 0.04% (frequency range from 500 Hz to 1 MHz).

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1. Introduction

Thulium (Tm^{3+}) lasers allow accessing the spectral region of 1900–2100 nm and are therefore highly attractive for atmosphere monitoring, spectroscopy, gas analysis, remote sensing, semiconductor and plastic materials processing, and medical applications. Efficient cross-relaxation processes in adjacent Tm^{3+} ions enable the use of commercially-available laser diodes emitting at wavelengths of $\sim 800\text{-nm}$ as pump sources. This allows the realization of laser systems with a luminescence quantum yield of ~ 2 (with the corresponding theoretical quantum efficiency of $\sim 80\%$) and a reduced thermal load in the gain medium. Recently, diode-pumped solid-state Tm-lasers emitting several watts of output power in continuous-wave operation with diffraction-limited beam quality and slope efficiencies exceeding 70% (to the absorbed pump power) were reported [1–3]. However, the state-of-the-art modelocked solid-state lasers [Fig. 1] emitting in this spectral region (based either on Tm-doped or Tm,Ho-codoped gain materials) still mainly rely on Ti:sapphire lasers as pump sources [4–26]. Ti:sapphire lasers are expensive and complex solutions for such an application, and, moreover, can become a limiting factor for future power scaling. Switching to compact, cost-efficient, and powerful multi-mode fiber-coupled laser diodes does not seem to be a trivial task and only two reports with sub-ps pulse duration were presented so far [4,5].

Among the available Tm-doped gain media suitable for ultrafast laser applications, double-tungstate crystals such as $\text{Tm:KY(WO}_4)_2$ and $\text{Tm:KLu(WO}_4)_2$, cut along their N_g principal axis, are particularly attractive. Although, these materials possess moderate thermal properties (thermal conductivity of $\sim 3 \text{ W m}^{-1} \text{ K}^{-1}$ [27], thermo-optic coefficient of $6.6 \times 10^{-6} \text{ K}^{-1}$ [28]), they benefit from a broad tunability range over 170 nm [10], high absorption and emission cross sections (favorable for efficient laser operation) [29,30], and smooth gain cross section spectra (favorable for short pulse generation) [10,14]. Up to date, modelocked operation with such gain media was only achieved by Ti:sapphire pumping. An average output power of 360 mW with 750-fs pulses at a wavelength of 2030 nm was reported with $\text{Tm:KY(WO}_4)_2$ [10]. The shortest pulses with a duration of 141 fs were achieved at a wavelength of 2037 nm and at average output power of 26 mW, using a $\text{Tm:KLu(WO}_4)_2$ crystal [14].

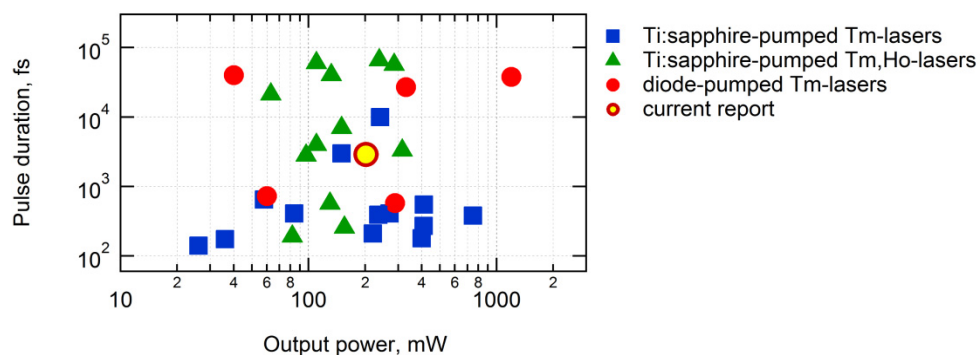


Fig. 1. State-of-the-art performance of 2- μm modelocked solid-state lasers based on Tm-doped or Tm,Ho-codoped gain materials [4–26].

In this paper, we present the first diode-pumped modelocked Tm-laser based on double-tungstate crystalline gain materials. The $\text{Tm:KY(WO}_4)_2$ laser incorporates a GaInSb/GaSb -based semiconductor saturable absorber mirror (SESAM) for self-starting passive modelocking operation. We also report on the first noise evaluation of a modelocked solid-state laser operating in the 2- μm wavelength range. The achieved integrated timing jitter of $\leq 94 \text{ fs}$ and relative intensity noise of $\leq 0.04\%$ (in the frequency range from 500 Hz to

1 MHz) demonstrate the high stability of the laser and can serve as a benchmark for future developments.

2. Experimental set-up and results

The schematics of the laser cavity for continuous-wave (*cw*) operation is shown in Fig. 2. The cavity consists of a flat output coupler ($T = 1\%$ at the laser wavelength), three flat highly reflective (HR) mirrors M1, M4, M6, and three concave HR mirrors M2, M3, M5. During modelocking experiments, the HR mirror M1 is replaced by a SESAM. The cavity length is 1.05 m. As a gain medium, we use a wedged Tm(5%):KY(WO₄)₂ (Tm:KYW) crystal with a thickness of 2 mm. The crystal faces are AR-coated for the pump and laser radiation. The gain medium is mounted on a water-cooled copper heat sink and is pumped through the flat dichroic mirror M4, which is highly-reflective for the laser radiation and highly transmissive at the pump wavelength. The pump source is a 793-nm multimode fiber-coupled (100- μ m diameter, N.A. = 0.22) laser diode with an output power up to ~ 10 W. The pump radiation is focused inside the gain medium to a spot with a radius of ~ 50 μ m (measured in air). The calculated intracavity mode radius in the gain medium is ~ 55 μ m. About 60% of pump power is absorbed in the Tm:KYW crystal during laser operation.

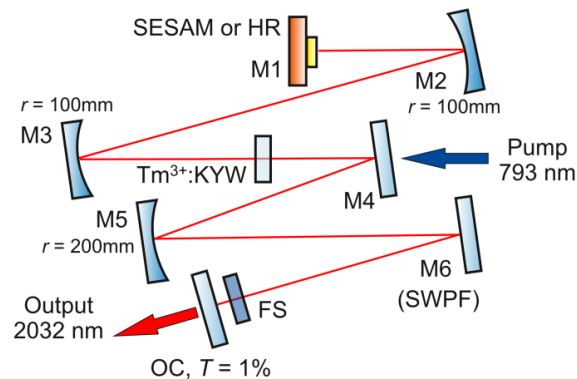


Fig. 2. Schematics of the diode-pumped Tm:KYW laser. OC: output coupler with transmission of $T = 1\%$; M1, M4, M6: flat HR mirrors; M2, M3, M5: concave HR mirrors. Mirror M6 is replaced by a short-wave pass filter (SWPF) to provide a laser operation at the wavelength of 2032 nm. HR mirror M1 is replaced by a SESAM for modelocking operation. FS is a 6-mm fused silica plate for introducing a negative GDD in the cavity during modelocking laser operation.

An output power of 1.6 W in TEM₀₀ mode is achieved in *cw* laser operation at a wavelength of 1960 nm [Fig. 3(a)]. The laser output is linearly polarized parallel to the N_m optical axes of the gain medium. However, in this spectral region, stable *cw* modelocking operation cannot be realized due to the presence of strong water absorption lines in the ambient atmosphere. In order to shift the laser emission wavelength to the spectral region beyond 2000 nm, we replaced the flat HR mirror (M6) by a short-wavelength pass filter (SWPF) with a cut-off wavelength of ~ 1990 nm. This allows generation of 0.92 W of output power in a TEM₀₀ mode at a central wavelength of 2022 nm [Fig. 3(b)]. The incident pump power is measured to be 5.6 W, which corresponds to 3.6 W of absorbed pump power during laser operation. We limited the pump power to this level, corresponding to a pump intensity at the input laser crystal surface of 35 kW/cm², to avoid crystal damage which was previously observed at higher pump intensities [1].

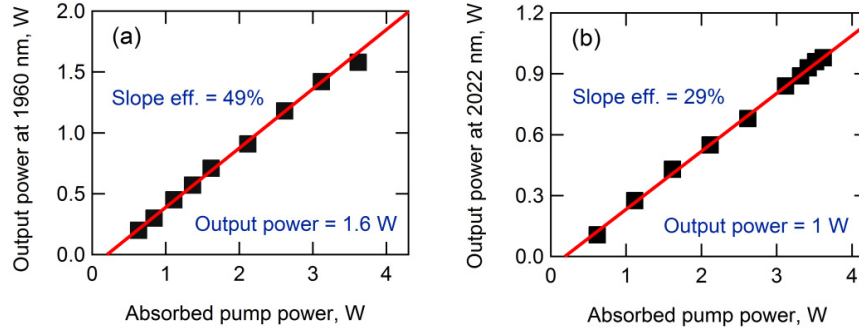


Fig. 3. Output power of the Tm:KYW laser vs. absorbed pump power in *cw* operation: a) operation at a wavelength of 1960 nm without any spectrally-selective element inside the laser cavity; b) operation at a wavelength of 2022 nm (with a short-wavelength pass filter inside the laser cavity).

To operate the laser in modelocking regime we exchanged mirror M1 with a GaSb-based SESAM. The SESAM comprises GaInSb/GaSb quantum wells and a distributed Bragg reflector consisting of 18.5 pairs of lattice-matched AlAsSb/GaSb quarter-wavelength layers, grown on a GaSb substrate. As revealed in Fig. 4, it exhibits an unsaturated reflectivity of 98% in the wavelength region of 2020–2040 nm. The typical absorption recovery dynamics for such GaSb-based SESAMs follows a double-exponential decay with the fast component shorter than 1 ps and the slow component in the range of 5–10 ps [31]. Data on the exact saturation fluence of the SESAM used are currently unavailable due to difficulties in performing accurate measurements. However, we estimated the saturation fluence to be in the range of 20–40 $\mu\text{J}/\text{cm}^2$. The SESAM is mounted on a copper heatsink. In this configuration, we did not observe stable modelocking operation. Thus, we introduced additional negative group delay dispersion (GDD) by placing an AR-coated 6-mm fused silica plate into the cavity (added GDD = -1286 fs^2 at 2030 nm per cavity roundtrip). The exact amount of intracavity GDD cannot be estimated at the moment due to unknown values of dispersion for several optical components, including the SESAM and AR-coatings of the gain element. After this, the laser switches to stable self-starting *cw* modelocked operation at a threshold of 2.7 W of absorbed pump power [Figs. 4(c) and 5]. The laser operates in a fundamental TEM_{00} mode with a maximum output power of 202 mW at an absorbed pump power of 3.6 W [Fig. 4(c)]. The laser slope efficiency in the modelocked operation decreased to 12% due to

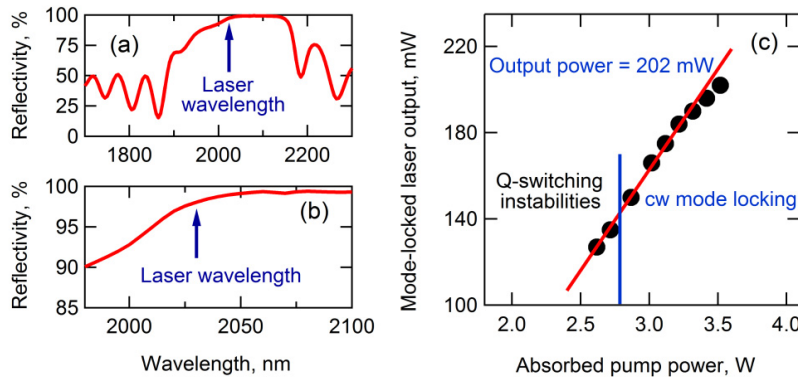


Fig. 4. Reflectivity curve of the GaSb-SESAM (a,b) and output power slope of the modelocked Tm:KYW laser (c).

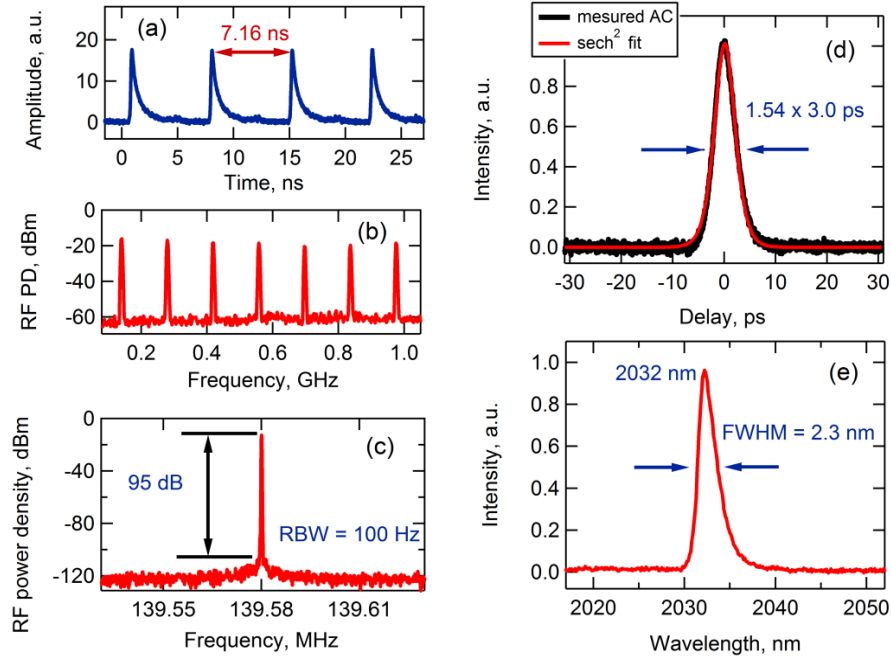


Fig. 5. Characteristics of the modelocked Tm:KYW laser at the maximum output power: a pulse train (a), a RF-spectrum measured with a resolution bandwidth of 3 MHz (b), a RF-spectrum measured with a resolution bandwidth of 100 Hz (c), an autocorrelation trace with a sech^2 fit (d), an optical spectrum (e).

the additional non-saturable loss introduced by the SESAM. Modelocked laser pulses are separated by the cavity roundtrip time of 7.16 ns [Fig. 5(a)] corresponding to the pulse repetition rate of ~ 139.58 MHz [Fig. 5(c)]. The radio-frequency (RF) spectrum of the laser output reveals a signal to noise ratio of 95 dB (at a resolution bandwidth of 100 Hz) and indicates stable single-pulse mode locking without Q -switching instabilities. The pulse duration of 3 ps is deduced from the intensity autocorrelation traces, assuming a sech^2 temporal laser pulse profile [Fig. 5(d)]. The optical spectrum is centered at 2032 nm and has a full width at half-maximum (FWHM) of 2.3 nm [Fig. 5(e)], thus giving a corresponding time-bandwidth product of 0.5. Assuming sufficient bandwidth of the gain medium and operation range of the SESAM, most likely that the pulse duration is limited by the intracavity GDD. We expect that precise engineering of intracavity dispersion and non-linear phase shift should enable generation of sub-ps pulses.

In order to evaluate the stability of the modelocked diode-pumped Tm:KYW laser we performed characterization of its phase and amplitude noise at the maximum output power. The measurements were done using a 2- μm InGaAs 12.5-GHz photodiode (model ET-5000, EOT Inc.) connected via a low-noise 1-GHz amplifier (model ZFL-1000LN+, Mini-Circuits) to the phase noise analyzer (model FSWP26, Rohde&Schwarz). Characterization of the laser noise using a higher harmonic of the repetition rate allows for more accurate phase noise measurements (without affecting the accuracy of amplitude noise measurements) [32]. The phase and amplitude noise power spectral densities (PSDs) were measured in the range of offset frequencies from 1 Hz to 50 MHz on the 7th harmonic of the laser repetition rate (977.06 MHz). The results are presented in the Fig. 6(a). The root mean square values of timing jitter [Fig. 6(b)] and relative intensity noise [Fig. 6(c)] were calculated by integrating, respectively, the measured phase and amplitude noise PSDs from the lower limit frequency to the higher limit frequency of 1 MHz. In the range of frequencies from 500 Hz to 1 MHz, the

modelocked Tm-laser exhibits an integrated timing jitter of ≤ 94 fs (and ≤ 60 fs in the range of frequencies from 1 kHz to 1 MHz) and relative intensity noise of $\leq 0.04\%$. These values are significantly affected by the shot noise of the photodiode (seen as a constant level for frequencies ≥ 0.1 MHz) and represent the upper limit, thus the genuine laser noise is even lower. The low-frequency part of the noise from 1 Hz to 500 Hz has mainly mechanical nature. The water-cooled Tm-laser is built on an optical breadboard and operates in the ambient environment under standard room conditions. Despite this, the integrated relative intensity noise at output power of 202 mW remains below 0.04% in the frequency range from 10 Hz to 1 MHz and does not exceed 0.1% in the frequency range from 1 Hz to 1 MHz [Fig. 6(c)]. These values are at least 3 times lower than parameters of the state-of-the-art 2- μm modelocked fiber lasers operating in the range of output powers below 40 mW [33,34]. Packaging the Tm:KYW laser in a mechanically stable housing should further reduce amplitude noise due to decreasing the influence of acoustic noise and noise introduced by air currents. Furthermore, similar to previous ultrafast lasers [35,36], the remaining phase noise in the frequency range below 1 kHz should be drastically reduced by stabilizing the laser cavity length with an actuator.

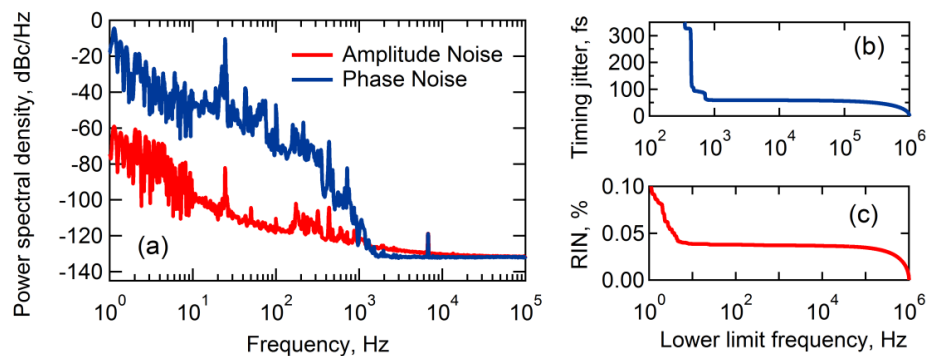


Fig. 6. Phase and amplitude noise of the modelocked Tm-laser measured on the 7th harmonic of the repetition rate (a). Integrated timing jitter (b) and relative intensity noise (c) values calculated for the shown range of lower limit frequencies.

3. Conclusion

In conclusion, we demonstrated the first modelocked operation of a diode-pumped laser based on Tm-doped double-tungstate crystalline gain media. The laser comprises a Tm:KYW gain crystal and a GaInSb/GaSb quantum well saturable absorber and is pumped at the wavelength of 793 nm by a multi-mode fiber-coupled laser diode. During modelocked operation, the Tm:KYW laser emits pulses with a duration of 3 ps at a repetition rate of 139.58 MHz. The average output power is 202 mW and the central emission wavelength is 2032 nm. The noise characterization proves excellent performance for the free-running (not-stabilized) laser system. The values of integrated timing jitter and relative intensity noise in the range of frequencies from 500 Hz to 1 MHz are 94 fs and 0.04%, respectively.

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