

# Broadly tunable femtosecond mode-locking in a Tm:KYW laser near 2 $\mu\text{m}$

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**Abstract:** Efficient mode-locking in a Tm:KY(WO<sub>4</sub>)<sub>2</sub> laser is demonstrated by using InGaAsSb quantum-well SESAMs. Self-starting ultrashort pulse generation was realized in the 1979–2074 nm spectral region. Maximum average output power up to 411 mW was produced around 1986 nm with the corresponding pulse duration and repetition rate of 549 fs and 105 MHz respectively. Optimised pulse durations of 386 fs were produced with an average power of 235 mW at 2029 nm.

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**OCIS codes:** (140.7090) Ultrafast lasers; (140.4050) Mode-locked lasers; (140.5680) Rare earth and transition metal solid-state lasers; (140.3600) Lasers, tunable.

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## 1. Introduction

High-average power (>100 mW) laser sources of ultrashort pulses near 2 μm spectral region are of considerable interest for a range of applications such as synchronous pumping of optical parametric oscillators having idler signal in the mid-IR, development of broadband coherent IR sources for remote sensing, optical coherence tomography and laser comb generation in the near-IR and three-dimensional microstructuring of semiconductor materials. Amongst the options currently available for the direct generation of ultrashort pulses at higher powers around 2 μm are Tm<sup>3+</sup> (Tm) and Ho<sup>3+</sup> (Ho) doped-fibre and crystalline gain media or semiconductor disk lasers based on gallium-antimonide (GaSb) material system. The Tm-ion when hosted in the most crystalline and amorphous materials exhibits strong absorption bands around 800 nm and thus can be pumped efficiently by low-cost and high-power AlGaAs laser diodes. The presence of cross-relaxation energy transfer processes in the Tm-Tm system converts one excited state into two upper laser level states making this class of laser systems very efficient and scalable to high power levels. Additionally, Tm-based lasers are characterised by large continuous tuning spectral range of ~1800-2100 nm compared to other trivalent lanthanide ions [1]. Alternatively, optically pumped semiconductor disk lasers can generally demonstrate watt-level output powers [2] with high spatial beam quality and have the potential to be designed in highly integrated laser cavity architectures [3].

Although, the generation of 384-fs pulses at 1960 nm from a GaSb-based disk laser was demonstrated [4], to date, 2-μm femtosecond laser sources have been based predominantly on passively mode-locked Tm-doped and Tm-Ho codoped fibre systems. In early work, *Nelson et al.* demonstrated 500-fs pulses [5] using a nonlinear polarisation evolution (NPE) mode-locking technique and 190-fs pulses were produced by a Tm-fibre laser that was passively mode-locked by a semiconductor saturable absorber mirror (SESAM) [6]. However, average output powers did not exceed a few milliwatts from such laser systems. Subsequently, somewhat higher powers were realised from mode-locked 2-μm fibre lasers by employing carbon nanotube-based saturable absorbers [7,8] where pulses as short as 750-fs were produced [8] and a 146-mW Tm-doped fibre laser generating 1.2-ps pulses at 1974 nm [9] (173 fs after dechirping outside the cavity [10]) was demonstrated using the NPE approach.

Tm doped and Tm-Ho codoped crystalline gain media offer an alternative route towards the development of high-power and efficient ultrashort-pulse lasers for the 2-μm spectral region. In the published literature to date, results are related mainly to picosecond pulse generation in Tm-doped crystals. The best results in terms of pulse duration have so far been obtained with a Tm:KLu(WO<sub>4</sub>)<sub>2</sub> laser [11] that produced 10-ps pulses at 1944 nm and a Tm:GdLiF<sub>4</sub> laser [12] that generated ~17-44 ps pulses tuned from 1868 nm to 1926 nm. By codoping with Tm and Ho, efficient lasers can be configured to provide emission in a slightly longer wavelength range (~2000-2150 nm) where weaker water absorption bands occur,

thereby enhancing the prospects for broadband and stable mode-locking. Recently, we have reported the generation of 570-fs pulses from a passively mode-locked Tm,Ho:KY(WO<sub>4</sub>)<sub>2</sub> laser [13] and pulses as short as 191 fs were produced from Tm,Ho:NaY(WO<sub>4</sub>)<sub>2</sub> [14], both operating around 2060 nm. It must be recognized though, that Tm-Ho codoped materials can suffer from the presence of increased up-conversion processes [15] compared to single Tm-doping and this in turn can lead to additional thermal loading inside the gain medium, resulting in reduced laser efficiency and limited output powers during continuous wave operation at room temperature. For this reason, direct generation of ultrashort pulses from Tm-doped materials looks more attractive for further development of laser diode pumped high-power mode-locked lasers that operate around 2 μm. Recently, we have demonstrated Tm-doped fluorogermanate glass laser producing near-transform-limited pulses of 410 fs duration centered at 1997 nm [16]. Average output power of 84 mW was, however, limited by poor thermo-mechanical properties of the glass.

Here we report, for the first time to our knowledge, a Tm-doped crystalline laser that produces sub-ps pulses in the 1985-2065 nm range by using InGaAsSb quantum-well-based SESAMs for passive mode-locking. Transform-limited pulses as short as 386 fs were generated around 2030 nm with an average output power of 235 mW.

## 2. Experimental set-up and continuous wave operation of a Tm:KYW laser

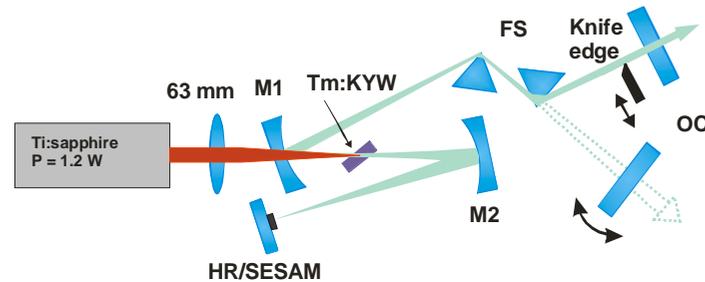


Fig. 1. Schematic of the Tm:KYW mode-locked laser. M<sub>1</sub> and M<sub>2</sub> – plano-concave high-reflector mirrors,  $r_1 = r_2 = -100$  mm; OC – output coupler ( $T = 1\%$  or  $2\%$  at 2000 nm); HR – plane high-reflector mirror; FS – pair of IR grade fused silica prisms. The dotted arrow indicates the cavity configuration with one prism in use.

The laser assessments were performed with a 2mm-long ( $N_g$  optical axis), 1.5 mm ( $N_p$ ) × 5 mm ( $N_m$ ) section Brewster-cut Tm<sup>3+</sup>:KY(WO<sub>4</sub>)<sub>2</sub> (Tm:KYW) crystal doped at 5 at.%. It was previously demonstrated that such gain medium is characterised large absorption and emission cross sections, relatively broad luminescence band around 1.9 μm and can support the laser operation with a slope efficiency above 50% under laser diode pumping [17]. In our case, the Tm:KYW crystal was oriented for optical pump propagation along the  $N_g$  axis and for a polarization along  $N_m$ . An asymmetric Z-fold resonator was configured with two folding mirrors M<sub>1</sub> and M<sub>2</sub> having radii of curvature of 100 mm, an output coupler (OC) with 1% or 2% transmission around 2 μm and a plane high-reflector mirror or a SESAM in the case of the mode-locked operation. (Fig. 1) The laser beam mode radii inside the gain crystal were calculated to be 27.5 × 55 μm. A Ti:sapphire laser producing 1.2 W of output power at 801 nm was used as the pump source and its beam was focused into the gain medium via a 63-mm focal length lens to a spot radius of 27 μm ( $1/e^2$  intensity) measured in air at the location of the input facet of the gain crystal.

In continuous wave regime, this laser operated with slope efficiencies of 63% and 73% (relative to the absorbed pump power) when output couplers of 1% and 2% transmission were used and the corresponding output powers reached 645 mW (1.15 W of the absorbed pump power) and 670 mW (1.13 W of the absorbed pump power) at 1953 nm and 1944 nm respectively. The tunability of the Tm:KYW laser was assessed with the 1% output coupling

by inserting a 2mm-thick quartz plate having its optical axis in the plane of input face to thus act as a Lyot filter or using a fused silica prism for tuning at longer wavelengths. With 1.2 W of incident pump power, the laser output could be tuned over the 1834-2074 nm range using the Lyot filter (Fig. 2, black circles) and output wavelengths up to 2111 nm were reached with the intracavity tuning prism (Fig. 2, red circles) resulting in a total tuning range of 277 nm with a corresponding FWHM of 172 nm. A maximum output power of 600 mW was obtained around 1980 nm. Continuous tuning was observed in the ~2020-2111 nm and 1970-2000 nm ranges whereas the remainder of the spectrum was characterised by discrete tuning steps due to the presence of water vapor absorption bands. The authors believe that these results represent the largest tunability range that has been observed for any Tm-doped Tm,Ho codoped double-tungstate gain media. Previously, a spectral range of 1850-2000 nm was demonstrated from Yb,Tm:KYW [18] and an overall tunability from 1790 nm to 2042 nm was achieved in Tm:KGdW [19].

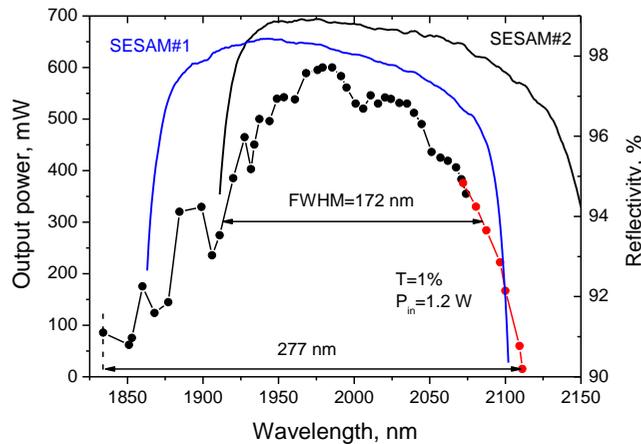


Fig. 2. Tunability of the Tm:KYW laser during continuous wave operation at room temperature (left-hand y-axis, black and red symbols indicate the tunability ranges obtained with a Lyot filter and a prism respectively) and reflectivity curves of the SESAM #1 and #2 around 2  $\mu$ m (right-hand y-axis).

### 3. Mode-locking performance of the Tm:KYW laser around 2 $\mu$ m

For optimized passive mode-locking in the Tm:KYW laser two different SESAM structures were used. These were characterized by initial reflectivity of 98.4-96.4% in the range of 1940-2080 nm (SESAM#1) and 98.9-96.9% in the range of 1970-2120 nm (SESAM#2) (Fig. 2). Both structures had an antiresonant design and comprised 22 pairs (20 in case of SESAM#2) GaSb/AlAs<sub>0.0834</sub>Sb layers (distributed Bragg reflector structure) grown on a 500 $\mu$ m-thick Te-doped GaSb(100) substrate. The absorber region was added in the topmost high-index quarter-wave layer and consisted of two In<sub>0.4</sub>Ga<sub>0.6</sub>As<sub>0.14</sub>Sb<sub>0.86</sub> quantum wells separated and surrounded by Al<sub>0.24</sub>Ga<sub>0.76</sub>As<sub>0.021</sub>Sb<sub>0.979</sub> layers. The SESAM#1 structure incorporated 5.35nm-thick quantum wells having a luminescence peak around 2035 nm, whereas the SESAM#2 had 5.5nm-thick quantum well layers with the luminescence maximum at 2100 nm. Both samples were grown by molecular beam epitaxy. To decrease the carrier recombination time, the SESAM samples were irradiated with 2-MeV N<sup>+</sup> ions at a dose of  $5 \times 10^{11}$  cm<sup>-2</sup>.

When a HR plane mirror was replaced by a SESAM, laser operated at around 1950 nm in a continuous-wave regime only. To support stable mode-locking it was necessary to shift the

laser output to longer wavelengths at or beyond 1980 nm by inserting a knife edge into the intracavity beam between the second prism and an output coupler or alternatively by using a single prism as a dispersive element. In this second option configuration and in combination

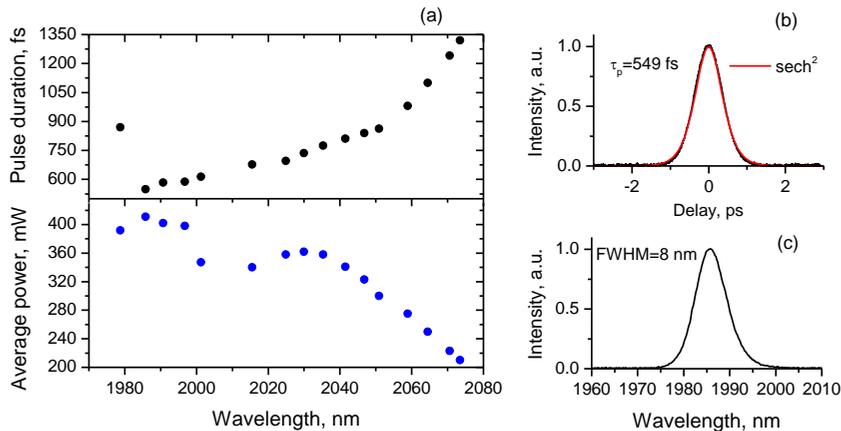


Fig. 3. (a) Tunability of the mode-locked Tm:KYW laser using one prism and the SESAM#2, (b) intensity autocorrelation of the pulses generated at 1986 nm and (c) corresponding optical spectrum.

with the SESAM#2 stable and self-starting mode-locking was realized in the 1979-2074 nm spectral range (Fig. 3(a)). The pulse durations ranged from 1.32 ps at 2074 nm to 549 fs at 1986 nm (Fig. 3(b)) where the maximum average output power reached 411 mW at a pulse repetition frequency of 105 MHz. The corresponding optical spectral bandwidth was measured to be 8 nm thereby implying a time-bandwidth product of 0.33 (Fig. 3(c)). It should be noted that the ultrashort-pulse operation was accompanied by some Q-switching instabilities in the ~2000-2020 nm range and at wavelengths below ~1980 nm only Q-switched operation could be achieved because of increased water vapor absorption in that region. During these assessments of mode-locking in the Tm:KYW laser, 7 mm of fused silica prism glass was inserted into the cavity beam resulting in a double-pass group velocity dispersion of  $-1360$  fs<sup>2</sup>. The cavity mode diameter on the SESAM was calculated to be 284  $\mu$ m.

To investigate the possibility of shorter pulse generation from the Tm:KYW laser (given that the angular dispersion could impose a limit on achievable pulse durations in the “single-prism” scheme) we employed two fused silica prisms for the dispersion management (tip-to-tip separation ~250 mm) in combination with a knife edge for the wavelength tuning. A summary of the results is included as Fig. 4. Using the SESAM#2, efficient ultrashort pulse generation was obtained in the 2030-2065 nm (Fig. 4(a), grey dots) region and a maximum output power of 235 mW around 2030 nm at a pulse repetition frequency of 97.4 MHz (Fig. 4(d)) was produced. It should be noted that this scheme gave rise to weaker wavelength selection compared to the single prism case, thus it was not possible to have stable mode-locked operation at wavelengths shorter than 2030 nm when using the SESAM#2 which possesses a lower modulation depth. By employing the SESAM#1 in the same cavity configuration, stable mode-locking was realized from 2045 nm down to 1985 nm (Fig. 4(a), black dots) where average powers up to 200 mW were generated. Both SESAM structures supported comparable pulse durations, where transform-limited pulses as short as 422 fs were generated with the SESAM#1 at 1986 nm and 386-fs pulses (Fig. 4(b)) were produced at

2029 nm with the corresponding FWHM spectra of 11.14 nm ( $\Delta\nu\Delta\tau = 0.314$ ) (Fig. 4(c)) using the SESAM#2. Mode-locking thresholds were estimated at fluences of 252  $\mu\text{J}/\text{cm}^2$  and 227  $\mu\text{J}/\text{cm}^2$  on the SESAMs #1 and #2, respectively, when operated at around 2030 nm.

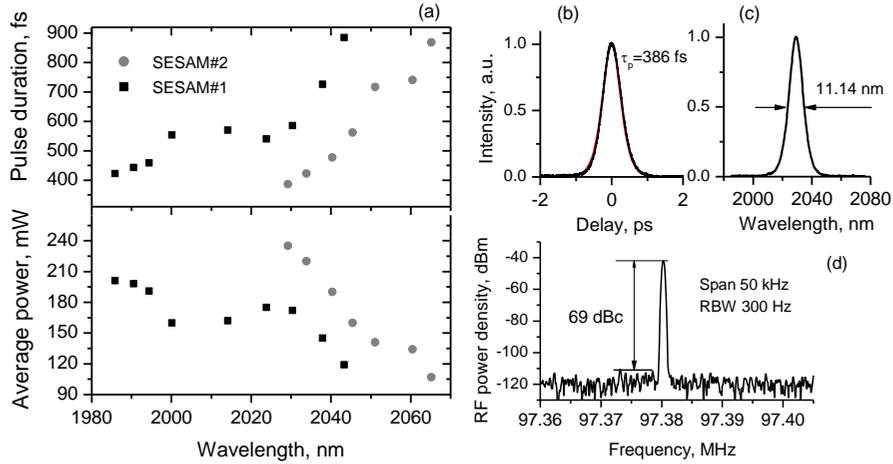


Fig. 4. Mode-locking performance of the Tm:KYW laser using a knife edge for a wavelength selection. (a) Pulse durations and corresponding average powers vs. output wavelength. (b) Intensity autocorrelation, (c) optical and (d) radio-frequency spectra of the mode-locked pulses at 2029 nm obtained with the SESAM#2.

#### 4. Conclusions

We have demonstrated what we believe to be the first mode-locked operation of a Tm:KYW laser in the femtosecond regime. Efficient and self-starting ultrashort-pulse generation was realized in the 1979-2074 nm wavelength range by using ion-implanted InGaAsSb quantum-well-based SESAMs. The maximum average output power reached 411 mW around 1986 nm at a pulse repetition frequency of 105 MHz that implied generated pulse energy of 3.9 nJ. Corresponding pulse duration and a spectral bandwidth were measured to be 549 fs (7.1 kW peak power) and 8 nm respectively. The shortest pulse durations were realized when two intracavity prisms were used for dispersion control in combination with a knife edge for wavelength selection. Transform-limited pulses as short as 386 fs were generated with an average power of 235 mW at 2029 nm and a pulse repetition frequency of 97.4 MHz. We believe that further power scaling from a femtosecond Tm:KYW laser is feasible using laser diode pumping around 800 nm instead of the presently used Ti:sapphire pump source and is the object of current investigations.