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Continuous-wave and SESAM mode-locked 2.3-µm $Tm:LiYF_4$ lasers: Upconversion pumping at 1.45 µm

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Abstract: A $Tm:LiYF_4$ laser operating on the $^3H_4 \rightarrow ^3H_5$ transition with upconversion pumping at 1.45 µm generates 831 mW at 2313 nm with 34.0% slope efficiency. Mode-locked by a GaSb-based SESAM, it delivers 855-fs pulses at 104.4-MHz.

1. Introduction

Ultrafast lasers emitting around 2.3 µm are of interest for spectroscopy of molecular species, optical coherence tomography, and seeding optical parametric oscillators. Lasers based on Cr^{2+} ions offer unique opportunities in this spectral range in terms of few optical cycle generation and broadband wavelength tuning. Recently, Thulium-ion (Tm^{3+}) lasers operating on the $^3H_4 \rightarrow ^3H_5$ transition at 2.3 µm were intensively studied due to the availability of Tm^{3+}-doped laser crystals (*e.g.*, $Tm:LiYF_4$) and commercial pump sources. Soulard *et al.* reported on passive mode-locking of a 2.3-µm $Tm:LiYF_4$ laser using a commercial SEmiconductor Saturable Absorber Mirror (SESAM) delivering 94-ps pulses at an average output power of 165 mW with direct pumping at 0.8 µm to the upper laser level [1]. Apart from this conventional pumping scheme, upconversion pumping at ~1 µm and ~1.45 µm was proposed [2] benefiting from the well-developed fiber laser technology. Very recently, particularly upconversion pumping at 1.04 µm by an Yb-fiber laser together with the use of a GaSb-based SESAM enabled us to generate femtosecond pulses (870 fs at 2309 nm) from a passively mode-locked $Tm:LiYF_4$ laser [3].

In the present work, we further exploit upconversion pumping of 2.3-µm Thulium lasers by focusing on the resonant $^3F_4 \rightarrow ^3H_4$ excited-state absorption (ESA) transition at 1.45 µm which benefits from the reduced heat loading. Both efficient continuous-wave and GaSb-based SESAM mode-locked operations are reported.

2. Laser set-up

The gain material was a 6 at.% $Tm:LiYF_4$ crystal grown by the Czochralski method. A Brewster-oriented laser element (***a***-cut, 6-mm-thick) was placed between two curved (RoC=−150 mm) highly-reflective (HR) folding mirrors in a Z-shaped astigmatically compensated cavity, Fig. 1(b). It was upconversion-pumped through a plane dichroic mirror by a Raman fiber laser delivering up to ~8 W of unpolarized radiation at 1452 nm. One cavity arm contained a curved HR mirror (RoC=−300 mm) for creating a secondary beam waist at the SESAM, and the other arm included a passive 6-mm-long $LiYF_4$ Brewster plate (BP) for intracavity dispersion management and a plane-wedged output coupler (OC). The round-trip group-delay dispersion considering the laser crystal, BP, and SESAM was calculated to be -1422 fs^2 at the laser wavelength.

For initializing and stabilizing the mode-locked operation, we employed a type-I GaSb-based SESAM with a single ternary strained InGaSb quantum well (16 nm, 33% In) embedded in GaSb grown by the molecular beam epitaxy method. The SESAM parameters determined from a nonlinear reflectivity measurement at 2.35 µm were as follows: a saturation fluence of 21 µJ/cm², a modulation depth of 0.53%, and a non-saturable loss of 0.14%. The fast and slow recovery times measured by the pump-probe method were 0.2 ps and 1.6 ps, respectively [3].

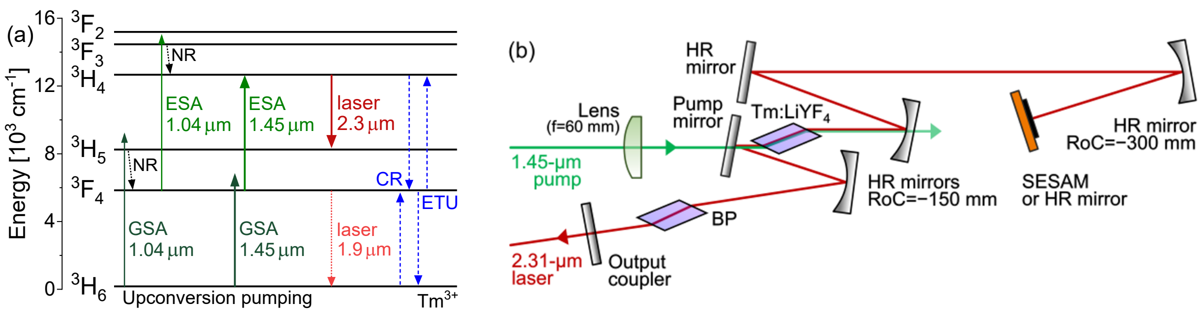

Fig. 1. (a) A simplified scheme of energy levels of Tm^{3+} ions, GSA – ground-state absorption, ESA − excited-state absorption, NR – non-radiative decay, CR – cross relaxation, ETU – energy-transfer upconversion, (b) Layout of the SESAM mode-locked $Tm:LiYF_4$ laser with upconversion pumping.

3. Continuous-wave and passively mode-locked operation

In the continuous-wave (CW) regime (when replacing the SESAM with a HR mirror), the $Tm:LiYF_4$ laser delivered a maximum output power of 831 mW at 2313 nm with a slope efficiency η of 34.0% (with respect to the absorbed pump power) and laser threshold P_{th} of 0.62 W (for T_{OC} = 3.0%), Fig. 2(a,b). The laser emission was linearly polarized (π). This result represents the record-high power for any upconversion-pumped 2.3-µm Tm laser. The pump absorption efficiency at 1.45 µm under both non-lasing and lasing conditions (single pass) was determined by monitoring the residual non-absorbed pump power, see Fig. 2(c). On increasing the incident pump power, the pump absorption gradually increased revealing the population of the intermediate metastable $^3F_4$ Tm^{3+} state by the photon avalanche mechanism. The absorption under lasing condition $\eta_{abs,L}$ was 43.3%–50.5%.

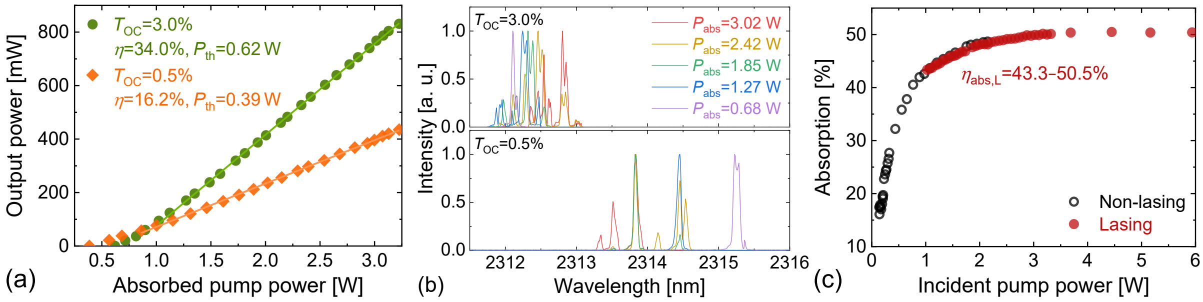

Fig. 2. Continuous-wave 2.31-µm $Tm:LiYF_4$ laser with upconversion pumping at 1.45 µm: (a) input-output dependences, η – slope efficiency, P_{th} – laser threshold; (b) typical spectra of laser emission at various pump levels; (c) measured single-pass pump absorption at 1.45 µm under non-lasing and lasing conditions.

By introducing the SESAM in the laser cavity, when using a small output coupling of 0.5%, on increasing the pump power, the $Tm:LiYF_4$ laser passed through CW, Q-switched ML (at P_{abs}>1.11 W) and CW ML (at P_{abs}>1.66 W) regimes. The shortest pulse duration (FWHM) determined from the measured intensity autocorrelation trace amounted to 855 fs at a central wavelength of 2307.7 nm (FWHM bandwidth: 7.0 nm) corresponding to an average output power of 375 mW at P_{abs} = 3.23 W, Fig. 3(a,b). Both the autocorrelation trace and the laser spectrum closely matched the sech^2-shaped profiles. The resulting time-bandwidth product was 0.337, slightly above the Fourier-transform limit for soliton pulses (0.315). The measured radio-frequency (RF) spectra revealed a stable fundamental CW ML with a repetition rate of 104.4 MHz showing a high extinction ratio of 79 dB over the noise level and uniform harmonics on a 1-GHz-wide span. Further power scaling albeit in the ps regime was achieved for 3.0% OC. The $Tm:LiYF_4$ laser delivered an average output power of 690 mW at a center wavelength of 2308.4 nm (spectral bandwidth: 3.2 nm) at P_{abs} = 3.23 W. The pulse duration was 1.75 ps.

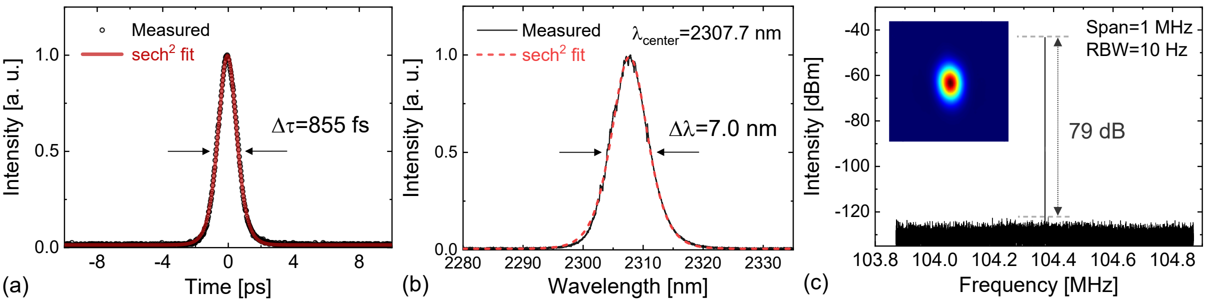

Fig. 3. SESAM mode-locked 2.31-µm $Tm:LiYF_4$ laser with upconversion pumping at 1.45 µm: characterization of the shortest pulses: (a) intensity autocorrelation trace and (b) laser spectrum, *curves* – sech^2 fits; (c) RF spectrum of the fundamental beat note recorded with a resolution bandwidth (RBW) of 10 Hz (*inset*: far-field beam profile). T_{OC}=0.5%, P_{abs}=3.23 W.

4. Conclusion

We report on the first passively mode-locked Tm laser at 2.3 µm employing the efficient 1.45-µm upconversion-pumping scheme. Using a GaSb-based SESAM, 855-fs pulses are achieved at 2307.7 nm corresponding to an average output power of 375 mW. Further pulse shortening is expected thanks to the relatively broad gain bandwidth of Tm^{3+} ions in $LiYF_4$. Optimization of the SESAM parameters and intracavity dispersion is anticipated with further power scaling.

5. References

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