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GaSb-based SESAM mode-locked femtosecond 2309-nm Tm:LiYF₄ laser

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RÉSUMÉ

A Tm:LiYF₄ laser operating on the ³H₄ → ³H₅ transition with upconversion pumping by an ytterbium-fiber laser is passively mode-locked by a GaSb-based SESAM delivering 870-fs pulses at 2309 nm with >200-mW average output power. The optimized dispersion management provides soliton pulse formation.

MOTS-CLEFS: mode-locked lasers ; saturable absorbers ; thulium ions ; upconversion.

1. INTRODUCTION

Thulium (Tm) lasers emitting around 2.3 μm according to the ³H₄ → ³H₅ electronic transition are of interest for gas sensing, non-invasive glucose blood measurements, and seeding optical parametric oscillators. Tm³⁺-doped LiYF₄ is appealing for such lasers due to its high thermal conductivity, low phonon energy leading to a weak non-radiative path, and polarized emission properties. Mode-locked (ML) Tm:LiYF₄ laser emitting 94-ps pulses was reported with an average output power of 165 mW by using a commercial semiconductor saturable absorber mirror (SESAM) [1]. This oscillator was pumped by 0.78-μm Ti:sapphire laser (direct pumping). Even though there exists an alternative scheme relying on a photon avalanche mechanism based on a resonant excited-state absorption ³F₄ → ³F_{2,3} around 1 μm (upconversion pumping) [2], no upconversion-pumped ML Tm lasers have been reported to date.

In the present work, we report on the first passively ML Tm laser at 2.3 μm with upconversion pumping scheme. Femtosecond soliton pulses at high average output powers were demonstrated by employing an efficient GaSb-based SESAM.

2. LASER SET-UP

The SESAM with a single ternary strained InGaSb quantum well (16 nm, 33% In) embedded in GaSb grown by the molecular beam epitaxy method provides a potential well for holes and electrons existing in same material layer leading to high Auger recombination rate showing a broad stopband around 2.3 μm [3]. Accurately characterized nonlinear reflectivity at 2.35 μm features a saturation fluence of 21 μJ/cm², a modulation depth of 0.53%, and a non-saturable loss of 0.14%, Fig. 1(a). The fast and slow relaxation times are measured to be 0.2 ps and 1.6 ps, respectively.

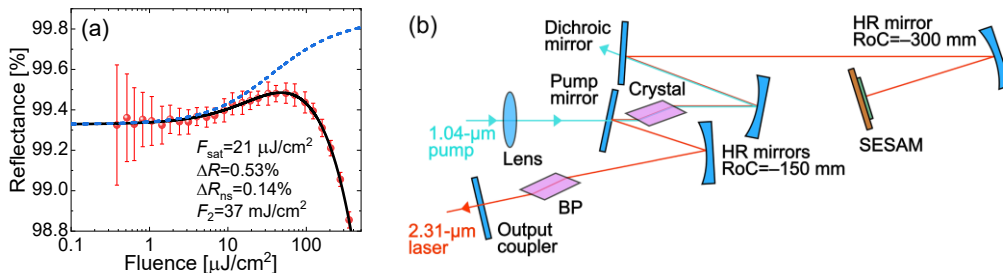


Figure 1 : (a) Nonlinear reflectance measurement of the SESAM; (b) Scheme of the SESAM ML Tm laser.

The *a*-cut 6 at.% Tm:LiYF₄ crystal was placed between two curved (RoC = -150 mm) HR folding mirrors in a Z-shaped astigmatically compensated cavity, Fig. 1(b). It was upconversion-pumped by a home-made Yb-fiber master-oscillator power-amplifier delivering up to 8 W at 1043 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 LiYF₄ Brewster plate (BP) for intracavity dispersion management and a plane-wedged output coupler ($T_{OC} = 0.5\%$).

3. PASSIVELY MODE-LOCKED OPERATION

In the continuous-wave (CW) regime (when replacing the SESAM with a HR mirror), the laser delivered an output power of 433 mW at 2316 nm with a slope efficiency η of 7.0% (vs. the incident pump power), a laser threshold of 0.96 W, and a linear polarization (π), see Fig. 2(a).

With the SESAM, the laser passed through CW, Q-switched ML (QML, at $P_{inc} > 2.95$ W), and CW ML (at $P_{inc} > 3.96$ W) operation regimes. Assuming a sech²-shaped profile, an CW ML emission bandwidth (full width at half maximum, FWHM) of 6.5 nm was obtained at a central wavelength of 2309.2 nm and the corresponding intensity autocorrelation trace was well fitted to show a FWHM pulse duration of 870 fs as shown in Fig. 2(b,c) resulting in a time-bandwidth product of 0.318 (the Fourier-transform limit is 0.315). The measured radio-frequency spectrum revealed a stable fundamental ML repetition rate of 105.08 MHz with a high extinction ratio of >80 dB above the noise and uniform harmonics over a 1-GHz-wide span.

The total round-trip intracavity group-delay dispersion (GDD) was calculated to be -1438 fs² at ML laser wavelength, Fig. 2(d). The theoretically required GDD for the observed pulse duration satisfying the soliton condition is -1552 fs² at 2310 nm considering the nonlinear phase shift from self-phase modulation in the gain medium. It agrees well with the dispersion estimation and verifies the fact that the used dispersion management leads to soliton pulse formation.

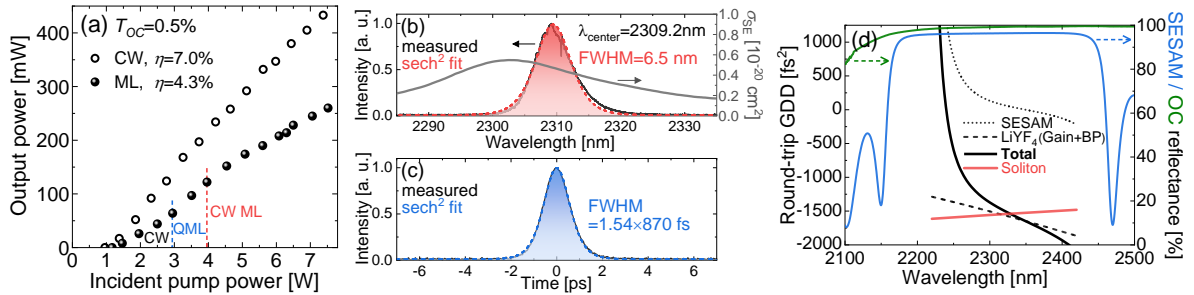


Figure 2 : GaSb-based SESAM mode-locked Tm:LiYF₄ laser with upconversion pumping: (a) Power transfer characteristics; (b,c) Characterization of shortest pulses: (b) spectrum and (c) autocorrelation trace; (d) Dispersion analysis in the laser cavity.

4. CONCLUSION

We report on a significant improvement in the field of ultrafast Tm lasers emitting around 2.3 μm in terms of both average output power and pulse duration via employing two key technologies, namely high-brightness upconversion pumping at 1 μm and an efficient GaSb-based SESAM. Further pulse shortening is expected thanks to the relatively broad gain bandwidth of Tm:LiYF₄. Power scaling and reduction of thermal effects is anticipated by 1.45- μm upconversion pumping.

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