GaSb-based SESAM Mode-Locked Tm,Ho:KLuW Laser at 2060 nm

Veselin Aleksandrov,[1,2] Alexander Gluth,[1] Uwe Griebner,[1] Valentin Petrov,[1] Ivan Buchvarov,[2] Günter Steinmeyer,[1,3] Jonna Paajaste,[3] Soile Suomalainen,[3] Antti Härkönen,[3] Mircea Guina,[3] Xavier Mateos,[4] Francesc Díaz,[4]

[1]*Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2A, D-12489 Berlin, Germany,* *griebner@mbi-berlin.de*

[2]*Physics Department, Sofia University, 5 James Bourchier Blvd., BG-1164 Sofia, Bulgaria,*

[3]*Optoelectronics Research Centre, Tampere University of Technology, P.O. Box 692, FIN-33101 Tampere, Finland,*

[4]*Física i Cristal·lografia de Materials i Nanomaterials (FiCMA-FiCNA), Universitat Rovira i Virgili (URV), Campus Sescelades, c/ Marcel.lí Domingo, s/n, 43007-Tarragona, Spain*

Abstract: Different designs of near-surface InGaSb quantum-well based SESAMs were studied in the scope of a mode-locked Tm,Ho:KLuW laser operating at 2060 nm. The laser delivered stable few picosecond pulses at 93 MHz with 150 mW average output power.

OCIS Codes: (140.4050) Mode-locked lasers; (140.5680) Rare earth and transition metal solid-state lasers

1. Introduction

The year 2009 marked the beginning of saturable absorber (SA) application for mode-locking bulk lasers operating around 2 µm. Using SESAMs for Tm-, Tm,Ho- and Ho-doped bulk materials ultrashort pulse generation was demonstrated [1-3], whereas with carbon-nanostructure-based SAs only Tm-doped hosts were mode-locked.

The recovery time of typical GaAs- and InP-based SESAMs amounts to tens or hundreds of picoseconds. Therefore, advanced growth and post-processing techniques, such as low-temperature growth, ion irradiation/implantation, or surface quantum wells (QWs), have been developed to accelerate the relaxation time of near-infrared SESAMs. GaSb-based SESAMs are utilized to further extend the wavelength range to the mid-infrared. The band-gap and band-offset in GaInAsSb/AlGaAsSb QWs can be tailored to cover emission in a wavelength range from 1.9 µm to beyond 3 µm. In mode-locked bulk laser experiments around 2 µm the recovery of the employed GaSb-based SESAMs was accelerated by irradiating the QWs with As^+-ions [1,2]. Recent studies indicate that the absorption recovery time is rather independent of the growth temperature and and strain in the QWs [4,5]. The ultrafast absorption recovery time in such high quality hetero-structures was attributed to significantly stronger Auger recombination than in GaAs and InP heterostructures [4].

Here we report passive mode-locking of a Tm,Ho:KLu(WO_4)$_2$ (Tm,Ho:KLuW) laser employing near-surface QW GaSb-based SESAMs. The SESAM design was optimized with respect to fast carrier relaxation without introduction of additional losses, leading to improved pulse performance.

2. Tm,Ho:KLuW active medium and GaSb-based SESAM

As active medium served Tm,Ho:KLuW [6]. In this class of biaxial crystals, the gain bandwidths are very broad and the absorption and emission cross-sections are exceptionally high for selected polarizations [6]. The Tm,Ho:KLuW crystal was grown by the Top Seeded Solution Growth technique with 5at.% Tm^{3+} and 0.5at.% Ho^{3+}-concentration in the solution.

As a result of our recent study, near-surface placement of the QWs and additional anti-reflection (AR) coating offer rather unique possibilities for tailoring the recovery time of GaSb-based SESAMs [5]. Therefore we applied such SESAMs with minor structure modifications for passive mode-locking of the Tm,Ho:KLuW laser. The GaSb-based SESAMs were grown at a temperature of 350°C using conventional solid-source molecular beam epitaxy. First, a GaSb-buffer was grown on a (100) n-GaSb substrate followed by a lattice-matched AlAsSb/GaSb DBR consisting of 18.5 layer pairs. The absorber region is anti-resonant at the operating wavelength of 2 µm and consists of 10-nm thick InGaSb QWs embedded in GaSb. The structure design of the four studied SESAMs, all deposited with an AR-coating, is listed in Table I. The decrease of the recovery time with additional AR-coating [5] is ascribed to increased Auger recombination owing to enhancement of the interaction between the optical field and the near-surface QW. Furthermore, dielectric coatings are often exploited for surface passivation of semiconductor samples [7].

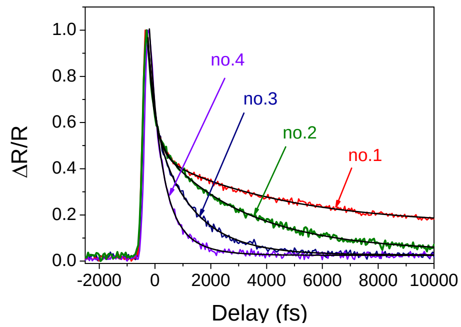

Fig. 1. Pump-probe traces (colored) and bi-exponential fits to the data (black) of the four studied near-surface QW SESAMs recorded at 2040 nm (design see Table I).

The absorption recovery dynamics were investigated by pump-probe measurements. The source was an OPO delivering 150 fs pulses at 2.04 µm. The results measured at a pulse fluence of ~50 µJ/cm^2 and the bi-exponential fits to the data are shown in Fig. 1. The time delay is plotted only to 10 ps for better discriminability. For all samples the intraband relaxation time τ_1 (fast component) behaves very similar and amounts to <0.5 ps. The interband relaxation time τ_2 (slow component) for the SESAMs with the QWs placed 10 nm below the surface is shorter than 5 ps and appears slightly decreased compared to those with at least 10 times thicker cap layers. This reduction is explained by fast recombination via surface states. In SESAM no.2 employing two QWs, the reduction of τ_2 due to surface recombination is not as pronounced as in SESAMs no.3 and no.4 since the second QW is already twice the cap layer thickness away from the surface. Extremely low τ_2 values of ~1.6 ps have been found for the samples incorporating one QW and a cap layer thickness <10 nm (no.3 and 4).

3. SESAM mode-locked Tm,Ho:KLuW laser

The laser studies were performed with a Ti:sapphire laser as pump source generating more than 2 W of output power at 802 nm. The 3-mm thick Ho,Tm:KLuW sample was positioned under Brewster angle on a copper holder for active cooling and was oriented for beam propagation along the N_g optical axis and for polarization along the N_m axis. We employed a standard X-shaped cavity with two curved folding mirrors (radius-of-curvature: ROC= -10 cm) and a 31-µm cavity waist radius. One arm contained an additional focusing mirror (ROC= -10 cm) to increase the intensity on the SESAM, which acted as an end mirror. The other arm contained the plane output coupler and two CaF_2-prisms could be implemented optionally. The pump beam was focused to a radius of ~30 µm. The single pass absorption of the Tm,Ho:KLuW crystal in the lasing state was 87% and about 95% for double-pass pumping.

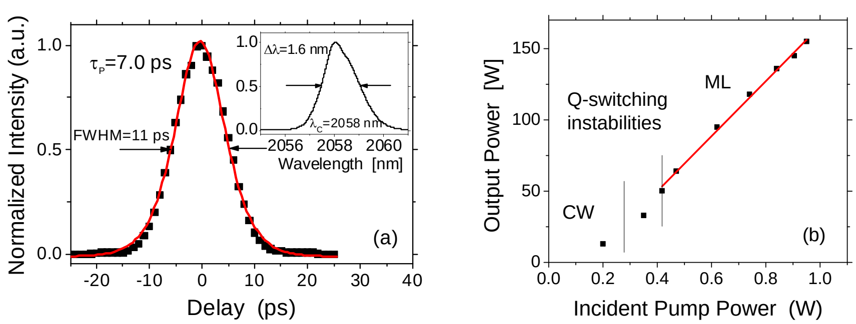

Fig. 2. SESAM mode-locked Tm,Ho:KLuW laser (Toc=3%, no.2): (a) Measured autocorrelation trace with fit (red line) and optical spectrum (inset); (b) Output vs. input characteristics, red line: linear fit in the mode-locked (ML) regime.

Passive mode-locking was achieved with all the SESAMs investigated (Table I) and output coupler transmissions (Toc) between 1.5% and 5%. The performance for SESAM no.2 and Toc=3% is shown in Fig. 2. The threshold for mode-locked operation (ML) was achieved at an absorbed pump power of ~400 mW (Fig. 2b). Below that threshold mode-locking was disturbed by some Q-switching instabilities. The mode-locked laser operated at 93 MHz repetition rate and the maximum output power amounted to 150 mW at an absorbed pump power of 900 mW resulting in a slope efficiency of 20% (Fig. 2b). The pulse duration was 7.2 ps derived from the measured autocorrelation trace, assuming a sech^2-pulse shape (Fig. 2a). The measured optical spectrum was centered at 2058 nm and had a FWHM of 1.6 nm (inset Fig. 2a). The latter supports a ~2 times shorter pulse duration, indicating slightly chirped pulses. No significant variation of the pulse performance was observed when introducing the two CaF_2-prisms in the cavity. Figure 3 shows the recorded radio-frequency spectrum of the SESAM mode-locked Tm,Ho:KLuW laser. It contains the fundamental beat note at 93.4 MHz (Fig. 3a), recorded with a resolution bandwidth of 1 kHz, and 1 GHz wide-span measurement (Fig. 3b). The high extinction ratio of 75 dBc and the absence of spurious modulation indicate very stable mode-locked operation.

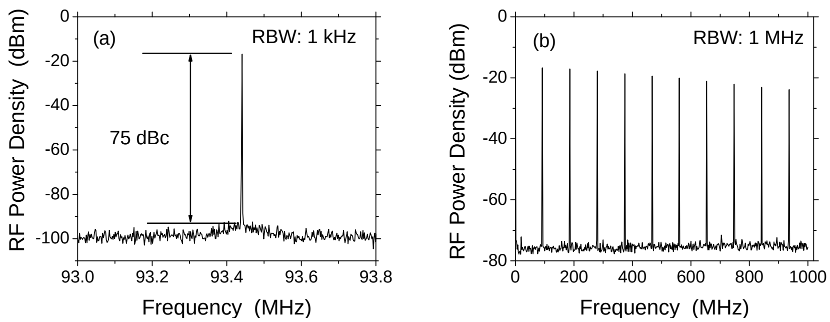

Fig. 3. Radio frequency spectra of the SESAM mode-locked Tm,Ho:KLuW laser(Toc=3%, no.2): (a) fundamental beat note; (b) 1 GHz wide-span (RBW: resolution bandwidth).

Table I lists the Tm;Ho:KLuW mode-locked laser results for all SESAMs applied. Best performance in terms of stability, damage threshold and output power was achieved with SESAM no.2. SESAM no.1 delivered the shortest pulses of 4 ps which is attributed to its 3-QW structure connected with the highest modulation depth. For the 1-QW structures (no.3 and 4) exhibiting the lowest modulation depth a weak tendency to multi-pulsing was observed.

Table I: Parameters of the studied SESAMs and results with the mode-locked Tm,Ho:KLuW laser (Toc=3%).

SESAM	No. of QWs	Cap (nm)	τ_2 (ps)	τ_p (ps)	P_{out} (mW)
no.1	3	300	9.7	4.2	110
no.2	2	5	4.1	7.0	150
no.3	1	10	1.7	7.8	150
no.4	1	5	1.6	7.2	140

4. Conclusion

SESAM mode-locking of a Tm,Ho:KLuW laser is reported for the first time to our knowledge. Within this scope different desigs of InGaSb-based near-surface QW SESAMs were characterized and compared with respect to their mode-locking performance. The obtained mode-locking stability and the pulse duration between 4 ps and 8 ps can be ascribed to specific SESAM design parameters, in particular the modulation depth. Compared to other mode-locked Tm,Ho-codoped lasers [1,2], the presented results using our near-surface QW SESAMS are quite encouraging. Applying such SESAMs designed for slightly higher modulation depth one can expect further pulse shortening in the sub-ps range with Tm,Ho:KLuW which is intended as a next step.

References

1. A. A. Lagatsky, F. Fusari, S. Calvez, S. V. Kurilchik, V. E. Kisel, N. V. Kuleshov, M. D. Dawson, C. T. A. Brown, and W. Sibbett, “Femtosecond pulse operation of a Tm,Ho-codoped crystalline laser near 2 µm,” Opt. Lett. **35**, 172-175 (2010).
2. A. A. Lagatsky, X. Han, M. D. Serrano, C. Cascales, C. Zaldo, S. Calvez, M. D. Dawson, J. A. Gupta, C. T. A. Brown, and W. Sibbett, “Femtosecond (191 fs) $NaY(WO_4)_2$ Tm,Ho-codoped laser at 2060 nm,” Opt. Lett. **35**, 3027–3029 (2010).
3. K. J. Yang, D. C. Heinecke, C. Kölbl, T. Dekorsy, S. Z. Zhao, L. H. Zheng, J. Xu, and G. J. Zhao, “Mode-locked Tm,Ho:YAP laser around 2.1 µm,” Opt. Express **21**, 1574–1580 (2013).
4. J. Paajaste, S. Suomalainen, R. Koskinen, A. Härkönen, G. Steinmeyer, and M. Guina, “GaSb-based semiconductor saturable absorber mirrors for mode-locking 2 µm semiconductor disk lasers,” phys. stat. solidi C **9,** 294–297 (2012).
5. J. Paajaste, S. Suomalainen S, Härkönen A, U. Griebner, G. Steinmeyer, and M. Guina, “Absorption recovery dynamics in 2 µm GaSb-based SESAMs,” J. Phys D **46,** 065102 (2014).
6. V. Jambunathan, A. Schmidt, X. Mateos, M. C. Pujol, U. Griebner, V. Petrov, C. Zaldo, M. Aguiló, and F. Díaz, “Crystal growth, optical spectroscopy and continuous-wave laser operation of co-doped (Ho,Tm):$KLu(WO_4)_2$ monoclinic crystals,” J. Opt. Soc. Am. B **31**, 1415-1421 (2014).
7. A. Jasik, J. Muszalski, K. Hejduk, and M. Kosmala, “The reduced temporal parameters of passivated semiconductor saturable absorber mirror,” Thin Solid Films **518,** 171–173 (2009).