Published in Electronic Letters 48, issue 18, 1144-1145, 2012
which should be used for any reference to this work

High-power integrated ultrafast semiconductor disk laser: multi-Watt 10 GHz pulse generation

V.J. Wittwer, M. Mangold, M. Hoffmann, O.D. Sieber, M. Golling, T. Südmeyer and U. Keller

Presented is an optically pumped modelocked integrated external-cavity surface emitting laser (MIXSEL) with a pulse repetition rate of 10 GHz, generating picosecond pulses at 2.4 W average output power at a centre wavelength of 963 nm. The MIXSEL structure integrates both the absorber and the gain layers within the same wafer. The saturable absorber is a single layer of self-assembled InAs quantum dots (QD) and the gain is obtained with seven InGaAs quantum wells. It is shown that the picosecond pulse duration is limited by the slow recovery time of the integrated QD saturable absorber.

Introduction: Compact high-power ultrafast lasers with pulse repetition rates of several gigahertz are of great interest for many applications, such as optical clocking, optical interconnects or optical sampling. VECSELs (vertical external cavity surface emitting lasers), modelocked with SESAMs (semiconductor saturable absorber mirrors), achieve excellent beam quality and high average output power at high repetition rates [1].

To date, SESAM modelocked VECSELs have achieved Watt-level operation in the femtosecond regime: 5.1 W of average output power with 682 fs pulses [2] and more than 1 W of average output power with 784 fs pulses in a configuration with a similar mode size on the VECSEL and the SESAM [3], which is crucial for vertical absorber integration within an antiresonant modelocked integrated external-cavity surface emitting laser (MIXSEL) structure [4, 5]. At a repetition rate of 10 GHz, fundamental modelocking was demonstrated with a pulse duration as short as 486 fs but at an average power of only 30 mW [6]. Higher average output power up to 1.4 W was only achieved with longer picosecond pulses [1]. Further scaling of the repetition rate beyond 10 GHz resulted in fundamental modelocking at a repetition rate of 50 GHz with 102 mW in 3.3 ps pulses [1]. In harmonic modelocking repetition rates up to 175 GHz with 300 mW in 400 fs pulses [7] were demonstrated.

SESAM modelocked VECSELs require a more complex cavity design with two separate semiconductor elements in a folded cavity. In contrast with a MIXSEL [4, 8] we combine gain and absorber in one semiconductor element and obtain modelocking in a simple linear cavity. Since the first MIXSEL demonstration with an average power of 40 mW in 2007 [4], the MIXSEL was improved with optimised low saturation-fluence quantum dot (QD) saturable absorbers [9], a n antiresonant design [5], and an improved thermal management by directly soldering the MIXSEL semiconductor chip onto a CVD (chemi-cal vapour deposition) diamond heat spreader with subsequent removal of the GaAs wafer. This enabled an average output power of 6.4 W in 28 ps pulses at 2.5 GHz repetition rate [5]. However, similar to the first MIXSEL result, the pulse repetition rate was limited to the few giga-hertz regime and the pulse duration to the multi-10 ps regime.

Here, we present 10 GHz operation of a MIXSEL, achieving 2.4 W average output power in 17 ps pulses. Furthermore, we present the macro-scopic characterisation of the integrated saturable absorber section with measurements of the nonlinear saturation and the recovery dynamics. These measurements revealed that the relatively slow recovery time of the integrated QD saturable absorber is most likely the limiting factor for further pulse repetition rate scaling and shorter pulse generation.

MIXSEL design, fabrication and characterisation: The MIXSEL is an optically pumped semiconductor gain structure with an integrated absorber for modelocking [4]. The structure consists of a DBR for the laser radiation, the absorber region, a DBR to reflect the pump radiation, the active region and an antireflection section. For significantly improved heat management, the entire semiconductor structure is grown in reverse order to enable flip-chip bonding to a diamond sub-strate with subsequent wet-chemical removal of the GaAs wafer. In this way, we gained more than an order of magnitude in output power due to the extremely high thermal conductivity of the CVD diamond substrate of $>1800\ \mathrm{WK^{-1}m^{-1}}$ and the thin semiconductor MIXSEL structure ($<10\ \mu\mathrm{m}$). A more detailed description of the design, growth or post-growth processing of the MIXSEL chip used for the modelocking results in this Letter is given in [5].

We performed time-resolved degenerate pump-probe measurements (Fig. 1*a*) and nonlinear reflectivity measurements (Fig. 1*b*) with a high-precision reflectivity measurement setup. Those measurements were performed with a passively modelocked Ti:sapphire laser with a pulse duration of 1.4 ps at a centre wavelength of 960 nm. The saturable absorber was characterised inside the MIXSEL structure at room temperature where the quantum well gain is detuned to about 940 nm and does not contribute to the absorption. We used the same setups and data evaluation as described in [9].

The pump-probe measurements were performed at a pump fluence of $50\ \mu\mathrm{J/cm^2}$ and a probe fluence of $0.9\ \mu\mathrm{J/cm^2}$. The amplitude of the slow component was dominant with 82 % and was fitted to a decay time of 188 ps (Fig. 1*a*). This is relatively slow compared to the measurement of a fast QD-SESAM used for Watt-level femtosecond operation with a similar mode size on the VECSEL and the SESAM [3]. From the nonlinear reflectivity measurements we obtained a satur-ation fluence of $19.6\ \mu\mathrm{J/cm^2}$ and a modulation depth of 1.4 %, taking into account the induced absorption (IA; also referred to as inverse satur-able absorption) in the fitting procedure as shown in Fig. 1*b* and explained in more detail in [10]. The nonsaturable losses were below 0.1 % and the IA coefficient F_2 was $43.8\ \mathrm{mJ/cm^2}$. The IA for this measurement is much more pronounced than in the modelocking experiment because the probe pulses are more than 10 times shorter than the final modelocked pulse duration. Therefore two-photon absorp-tion becomes more significant and increases the IA in the characteris-ation [10].

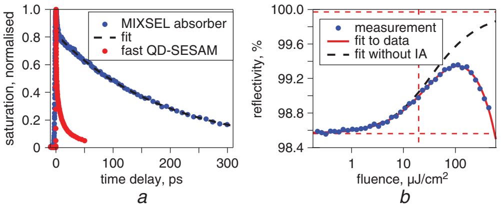

Fig. 1 *Characterisation of integrated saturable absorber in MIXSEL chip using 1.4 ps pulses at 960 nm*

a Pump-probe measurement of integrated absorber in MIXSEL (blue) and of SESAM with fast QD-absorber (red) according to [3] for comparison
b Measurement of nonlinear reflectivity of integrated MIXSEL absorber. IA: induced absorption

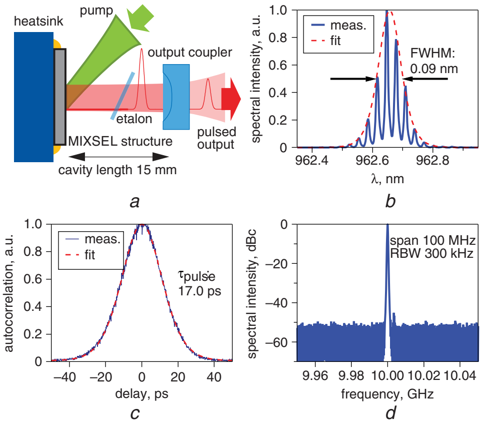

Fig. 2 *10 GHz MIXSEL result: cavity setup and characterisation of 10 GHz pulse-train*

a Setup of linear 10 GHz MIXSEL cavity
b Optical spectrum (resolution bandwidth 10 pm)
c Intensity autocorrelation fitted to a 17 ps sech^2-pulse shape
d RF spectrum (RBW: resolution bandwidth)

Modelocking result: Initially, a 10 GHz MIXSEL result was obtained with a copper heat spreader, which limited the average output power to 189 mW [5]. It was demonstrated that with better heat management the power can be scaled into the multi-Watt regime [5]. This was again confirmed here with the 10 GHz MIXSEL. The flat MIXSEL structure and a curved output coupler with 1 m radius of curvature and 0.5 % transmission formed a straight cavity (Fig. 2*a*). Furthermore, a 20 μm-thick etalon was inserted to tune the centre wavelength of the MIXSEL. The cavity length was 15 mm, which corresponds to a pulse repetition rate of 10 GHz (Fig. 2*d*). The heatsink temperature was controlled with a Peltier element and set to –10 °C. The structure was optically pumped with an 808 nm fibre-coupled laser diode array (LIMO AV5 series, maximum power 100 W, 200 μm fibre diameter) at an angle of 45°.

The pump spot was matched to the laser mode with a radius of 193 μm on the MIXSEL chip to support fundamental transverse mode operation. For a pump power of 25.4 W stable and self-starting mode-locking was obtained with an average output power of 2.4 W, a pulse duration of $\simeq$ 17 ps (Fig. 2*c*) and a centre wavelength of 962.6 nm (Fig. 2*b*). The optical-to-optical efficiency was 9.4 %. The fluence on the absorber was 41 $\mu J/cm^2$, corresponding to a saturation parameter of about 2. The time-bandwidth-product was 1.5 times the transform limit of a $sech^2$ pulse.

Conclusion and outlook: We have demonstrated a 10 GHz MIXSEL with an average output power of 2.4 W, which, to the best of our knowledge, is the highest output power from any modelocked 10 GHz semiconductor laser to date. This result was enabled by an optimised antiresonant MIXSEL design with low saturation fluence QD absorbers and with an improved thermal management using a bottom CVD diamond heat spreader. The pulse duration of 17 ps and pulse repetition rate are limited by the relatively slow integrated absorber. In comparison, a similar VECSEL with an external faster SESAM resulted in sub-pico-second pulses. We characterised the integrated MIXSEL absorber, which has a saturation fluence of 19.6 $\mu J/cm^2$, a modulation depth of 1.4 % and confirmed the slow integrated absorber recovery time of 188 ps. The simple linear MIXSEL cavity should support higher repetition rates well in the 100 GHz regime. However, for repetition rates above 10 GHz and therefore cavity round trip times below 100 ps, we need to reduce the recovery time of the integrated saturable absorber. In the future, a faster integrated saturable absorber and better dispersion management is required as recently demonstrated with a high-power femtosecond VECSEL [3].

Acknowledgments: This work was supported by ETH Zurich with the FIRST clean room facility and by the Swiss Confederation Program Nano-Tera.ch which was scientifically evaluated by the SNSF.

One or more of the Figures in this Letter are available in colour online.

V.J. Wittwer, M. Mangold, M. Hoffmann, O.D. Sieber, M. Golling, T. Südmeyer and U. Keller (*Department of Physics, Institute for Quantum Electronics, ETH Zurich, Zurich 8093, Switzerland*)

E-mail: vwittwer@phys.ethz.ch

References

1 Keller, U., and Tropper, A.C.: ‘Passively modelocked surface-emitting semiconductor lasers’, *Phys. Rep.*, 2006, **429**, (2), pp. 67–120

2 Scheller, M., Wang, T.L., Kunert, B., Stolz, W., Koch, S.W., and Moloney, J.V.: ‘Passively modelocked VECSEL emitting 682 fs pulses with 5.1W of average output power’, *Electron. Lett.*, 2012, **48**, (10), pp. 588–589

3 Hoffmann, M., Sieber, O.D., Wittwer, V.J., Krestnikov, I.L., Livshits, D.A., and Barbarin, Y., *et al.*: ‘Femtosecond high-power quantum dot vertical external cavity surface emitting laser’, *Opt. Express*, 2011, **19**, (9), pp. 8108–8016

4 Maas, D.J.H.C., Bellancourt, A.-R., Rudin, B., Golling, M., Unold, H.J., and Südmeyer, T., *et al.*: ‘Vertical integration of ultrafast semiconductor lasers’, *Appl. Phys. B*, 2007, **88**, pp. 493–497

5 Rudin, B., Wittwer, V.J., Maas, D.J.H.C., Hoffmann, M., Sieber, O.D., and Barbarin, Y., *et al.*: ‘High-power MIXSEL: an integrated ultrafast semiconductor laser with 6.4 W average power’, *Opt Express*, 2010, **18**, (26), pp. 27582–27588

6 Hoogland, S., Garnache, A., Sagnes, I., Roberts, J.S., and Tropper, A.C.: ‘10-GHz train of sub-500-fs optical soliton-like pulses from a surface-emitting semiconductor laser’, *IEEE Photonics Techol. Lett.*, 2005, **17**, (2), pp. 267–269

7 Wilcox, K.G., Quarterman, A.H., Apostolopoulos, V., Beere, H.E., Farrer, I., and Ritchie, D.A., *et al.*: ‘175 GHz, 400-fs-pulse harmonically mode-locked surface emitting semiconductor laser’, *Opt. Express*, 2012, **20**, (7), pp. 7040–7045

8 Bellancourt, A.-R., Maas, D.J.H.C., Rudin, B., Golling, M., Südmeyer, T., and Keller, U.: ‘Modelocked integrated external-cavity surface emitting laser (MIXSEL)’, *IET Optoelectron.*, 2009, **3**, pp. 61–72

9 Maas, D.J.H.C., Bellancourt, A.R., Hoffmann, M., Rudin, B., Barbarin, Y., and Golling, M., *et al.*: ‘Growth parameter optimization for fast quantum dot SESAMs’, *Opt. Express*, 2008, **16**, (23), pp. 18646–18656

10 Grange, R., Haiml, M., Paschotta, R., Spuhler, G.J., Krainer, L., and Golling, M., *et al.*: ‘New regime of inverse saturable absorption for self-stabilizing passively mode-locked lasers’, *Appl. Phys. B*, 2005, **80**, (2), pp. 151–158