Modelocked Integrated External-Cavity Surface Emitting Laser (MIXSEL) with output power up to 660 mW and repetition rate up to 10 GHz

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Abstract: We present an advanced MIXSEL, a VECSEL with integrated saturable absorber. Improved thermal management by substrate removal substantially increased the power. The novel antiresonant design is growth-error tolerant, enables shorter pulses and higher repetition rates.

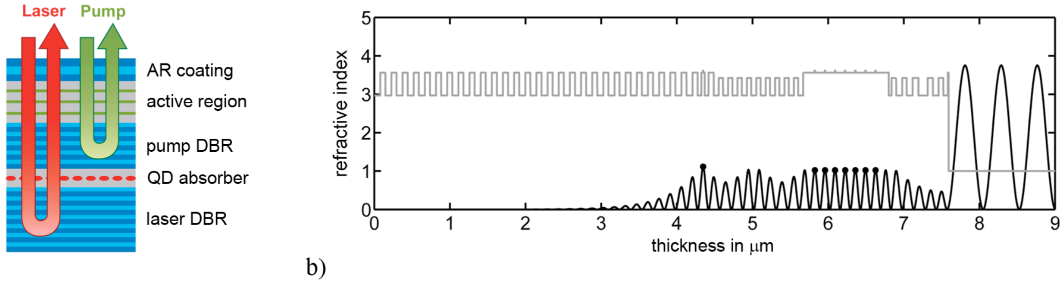
OCIS codes: (140.4050) Mode-locked lasers; (250.7260) Vertical cavity surface emitting lasers

1. Introduction

Semiconductor disk lasers (also called VECSELs) [1] combine the benefits of diode-pumped solid-state lasers and semiconductor technologies, resulting in wavelength flexibility and high power operation with excellent beam quality [2]. Modelocking VECSELs with a semiconductor saturable absorber mirror (SESAM) [3, 4] resulted in excellent performance (2.1 W in 4.7 ps pulses [4], sub-300 fs pulses with up to 25 mW [5, 6], and 50 GHz with 102 mW [7]). However, the laser contains two separate semiconductor elements in a folded cavity, which is a challenge for cost-efficient high volume fabrication, as well as for reaching high repetition rates. Modelocked integrated external-cavity surface emitting lasers (MIXSELs) [8] combine gain and absorber in one semiconductor structure, enabling modelocking in a simple straight cavity and the possibility of a quasi-monolithic design.

For the MIXSEL, the beam diameters on gain and absorber are the same. For stable modelocking, the absorber has to saturate faster than the gain. In the first MIXSEL this was solved by placing the quantum dot (QD) saturable absorber layer in a resonant field enhancement [8]. Unfortunately, the resonant design leads to a large sensitivity towards growth errors and to high group delay dispersion, limiting the pulse duration to above 30 ps. Furthermore, the average output power was limited by the thermal impedance of the 600 μm thick wafer on which the structure was grown. A higher output power of 195 mW was only possible by strong cooling to -50°C [9], and repetition rates above 3 GHz could not be realized.

Here we present a substantially improved MIXSEL. We developed QD saturable absorbers with lower saturation energy, which allow for an antiresonant design [10, 11]. This relaxes the demands on the growth accuracy and avoids narrow resonances in the dispersion. Substrate removal enabled us to achieve 660 mW in 23 ps pulses for a heat sink temperature of 10°C. A higher pulse repetition rate of 10 GHz was achieved at lower output power of 200 mW and with pulses of 22 ps duration. In both cases the output power was pump limited. Further power scaling by applying more pump power and increasing the mode sizes should allow for multi-watt power levels. The simple straight cavity geometry should support repetition rates above 10 GHz.



a) b)

Fig. 1: MIXSEL concept (a); refractive index of the semiconductor layer structure and standing wave intensity pattern of the laser field (b).

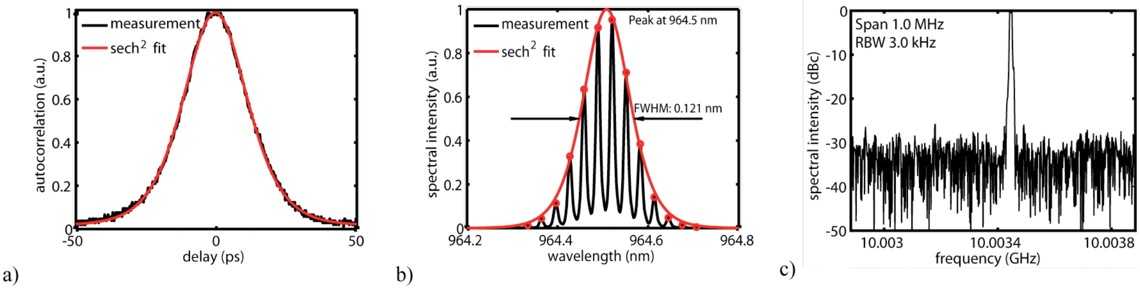
2. MIXSEL design and fabrication

Figure 1a shows the concept of the MIXSEL. The structure is composed of five sections; a DBR for the laser light (30 pairs AlAs/GaAs), the quantum dot saturable absorber layer (one layer of self-assembled InAs quantum dots embedded in GaAs spacer layers), a DBR for the pump light (9 pairs $Al_{0.2}Ga_{0.8}As$/AlAs), the quantum well gain layers (7 InGaAs quantum wells separated by GaAs spacer layers) and an anti-reflection coating ($Al_{0.2}Ga_{0.8}As$/AlAs). The intermediate mirror has the function of preventing the pump light of bleaching the absorber. Figure 1b shows the refractive index profile of the MIXSEL structure (grey line) as well as the standing wave intensity pattern for the laser light at 960 nm (black line).

The MIXSEL structure was grown by MBE in reverse order on a 600 µm GaAs wafer. First the etch stop layers were grown followed by the other sections. Smaller pieces were cleaved from the wafer, metalized and soldered to copper with a fluxless Indium soldering process under vacuum. Afterwards the GaAs substrate was removed by wet chemical etching. The reduced thickness of the semiconductor material leads to a low thermal impedance and to a nearly one-dimensional heat flow into the heat sink, which makes the device power scalable.

3. Experiment and results

The MIXSEL setup consists of a straight cavity created by the MIXSEL structure and an output coupler. Two main results are discussed here. The first result is the MIXSEL with the highest output power so far. The cavity was 51 mm long (2.94 GHz repetition rate) with a 60 mm output coupler with 0.65% transmission. The structure was pumped at 808 nm with a pump spot of 80 µm radius. The operation wavelength was selected with a 20 µm thick fused silica etalon, which acted as an intracavity spectral filter. At maximum pump power (4.3 W) stable and self-starting modelocking was obtained with 23 ps pulses at a center wavelength of 962 nm. The average output power was 660 mW, while the heat sink was held at 10°C. This output power is more than ten times higher than previous MIXSELs operated close to room temperature [8].



a) b) c)

Fig. 2: Autocorrelation (a), optical spectrum (b) and RF-signal of the 22 ps pulse train with 200 mW average power.

The second result is shown in figure 2. The cavity was 15 mm long with a 38 mm output coupler with 0.35% transmission. The resulting pulse repetition rate is 10 GHz (see Fig. 2c), which is the highest repetition rate for a MIXSEL so far. Fig. 2a shows the autocorrelation of the pulse train, fitted with the autocorrelation of an ideal 22 ps sech^2-pulse (see Fig. 2a). The operation wavelength was tuned to 964.5 nm and the spectral width was 0.12 nm, as shown in the optical spectrum in Fig. 2b. The time-bandwidth product is 2.7 times the transform limit.

4. Conclusion and outlook

We demonstrate the first antiresonant MIXSEL with substrate removal. The antiresonant design substantially relaxes the demands on the growth accuracy. Modelocking was achieved with a simple straight cavity with up to 660 mW and with pulse repetition rates up to 10 GHz. The current output powers are limited by the available pump power in our setup. Scaling of the mode areas and using a stronger pump should enable multi-Watt average output powers as previously demonstrated in the former VECSEL-SESAM modelocking experiments [4].

5. References

[1] M. Kuznetsov, et al., "High-Power (>0.5-W CW) Diode-Pumped Vertical-External-Cavity Surface-Emitting Semiconductor Lasers with Circular TEM00 Beams," *IEEE Photon. Technol. Lett.,* vol. 9, pp. 1063-65, 1997.

[2] B. Rudin, et al., "Highly efficient optically pumped vertical emitting semiconductor laser with more than 20-W average output power in a fundamental transverse mode," *Opt. Lett.,* vol. 33, pp. 2719-2721, 2008.

[3] U. Keller, et al., "Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers," *IEEE J. Sel. Top. Quantum Electron.,* vol. 2, pp. 435-453, 1996.

[4] A. Aschwanden, et al., "2.1-W picosecond passively mode-locked external-cavity semiconductor laser," *Opt. Lett.,* vol. 30, pp. 272-274, 2005.

[5] K. G. Wilcox, et al., "Ultrafast optical Stark mode-locked semiconductor laser," *Optics Letters,* vol. 33, pp. 2797-2799, 2008.

[6] P. Klopp, et al., "290-fs pulses from a semiconductor disk laser," *Opt. Express,* vol. 16, pp. 5770-5775, 2008.

[7] D. Lorenser, et al., "50-GHz passively mode-locked surface-emitting semiconductor laser with 100 mW average output power," *IEEE J. Quantum Electron.,* vol. 42, pp. 838-847, Aug. 2006.

[8] D. J. H. C. Maas, et al., "Vertical integration of ultrafast semiconductor lasers," *Appl. Phys. B,* vol. 88, pp. 493-497, 2007.

[9] A.-R. Bellancourt, et al., "Modelocked Integrated External-Cavity Surface Emitting Laser (MIXSEL)," *IET Optoelectronics,* vol. Vol. 3, pp. pp. 61-72, 2009.

[10] A.-R. Bellancourt, et al., "Low Saturation Fluence Antiresonant Quantum Dot SESAMs for MIXSEL integration," *Opt. Express,* vol. 17, pp. 9704-9711, 2009.

[11] D. J. H. C. Maas, et al., "Growth parameter optimization for fast quantum dot SESAMs," *Opt. Express,* vol. 16, pp. 18646-18656, 2008.