10-GHz MIXSEL: An Integrated Ultrafast Semiconductor Disk Laser with 2.2 W Average Power

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Abstract: We present a 10-GHz Modelocked Integrated External-Cavity Surface Emitting Laser (MIXSEL) with 2.2 W average power in 21-ps pulses, which is the highest power level from any 10-GHz modelocked semiconductor laser.
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1. Introduction

Compact high-power multi-GHz optical sources are of high interest for many applications, such as optical clocking, photonic switching or optical sampling. VECSELs (Vertical External Cavity Surface Emitting Lasers) modelocked with semiconductor saturable absorber mirrors (SESAMs) [1, 2] achieve excellent beam quality, and high power operation at high repetition rates (486-fs pulses with 30 mW average power at 10 GHz [3], 1.4 W in 6.1-ps pulses at 10 GHz [4], and 50 GHz with 102 mW [5]). 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 higher repetition rates. Modelocked integrated external-cavity surface emitting lasers (MIXSELs) [6, 7] combine gain and absorber in one semiconductor structure, enabling modelocking in a simple straight cavity and the possibility of a quasi-monolithic design [7]. Since the first MIXSEL demonstration in 2007 (40 mW in 35 ps pulses at 2.8 GHz) [6], we improved our MIXSEL design by introducing novel low saturation fluence quantum dot (QD) saturable absorbers. This allows for an antiresonant MIXSEL design with high growth tolerance. Additionally, thermal management was substantially improved by direct soldering the MIXSEL semiconductor chip onto a CVD diamond heat spreader and subsequent substrate removal. At 2.5 GHz we recently demonstrated power scaling up to 6.4 W [8].

Initial results at 10 GHz obtained with copper heat spreader limited the power to 190 mW. Here we present a 10-GHz MIXSEL with 2.2 W average power in 21-ps pulses, which is to our knowledge higher than any other 10-GHz modelocked semiconductor laser. The MIXSEL consisted of a simple 15-mm long straight cavity with only two cavity elements, the MIXSEL chip and the external output coupler.

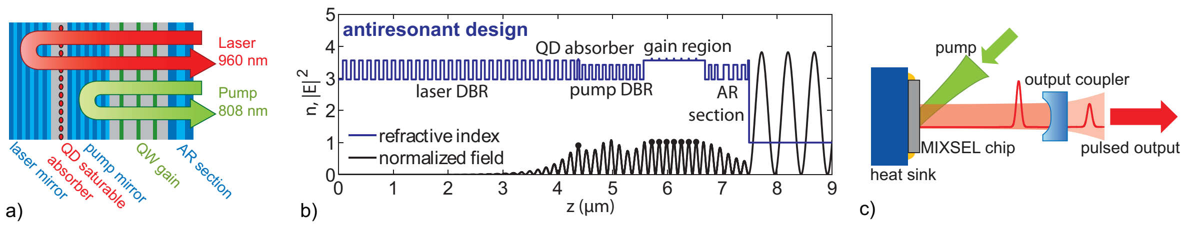

Fig. 1: MIXSEL concept (a); refractive index of semiconductor layer structure and standing wave intensity pattern (b); MIXSEL cavity (c).

2. MIXSEL design and fabrication

Figure 1a shows the concept of the MIXSEL. The refractive index profile (blue line) as well as the standing wave intensity pattern for the laser light at 960 nm (black line) are shown in Figure 1b. The structure is composed of a DBR for the laser light (30 pairs AlAs/GaAs), the quantum dot saturable absorber (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 gain region (7 InGaAs quantum wells separated by GaAs spacer layers) and an anti-reflection section ($Al_{0.2}Ga_{0.8}As/AlAs$). The intermediate mirror reduces pump light pre-saturation of the absorber.

The MIXSEL structure was grown by MBE in reverse order on a 600-µm GaAs wafer in one single run. First etch stop layers were grown followed by the other sections. The chips are processed as follows: first small pieces are cleaved from the wafer, metalized and soldered to CVD diamond heat spreaders (thermal conductivity

>1800 W·K^{-1}·m^{-1}) with a fluxless indium soldering process under vacuum. Then the GaAs substrate is removed by a chemical wet etching procedure. 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 in spot size.

3. Experiment and results

The MIXSEL setup consists of a straight cavity created by the flat MIXSEL structure and a curved output coupler (Fig. 1c) with 1.5 m radius of curvature and 0.5% transmission. The cavity was 15 mm long to obtain 10 GHz repetition rate (Fig. 2c). The heat sink temperature was controlled by a Peltier element to –10°C. The structure was pumped with a 100-W fiber-coupled laser diode array at 808 nm at an angle of 45°. The pump spot radius was 215 µm matched to the size of the laser mode on the MIXSEL chip, ensuring fundamental transverse mode operation. For a pump power of 25.4 W stable and self-starting modelocking was obtained with an average power of 2.2 W. The optical-to-optical efficiency was 8.7%. The pulse duration was ≈ 21 ps (Fig. 2a) and the center wavelength was 966 nm (Fig 2b). The rf-spectrum (Fig. 2c) shows side peaks with an offset frequency of ≈ 44 MHz. Most likely, these are caused by polarization instabilities, as they could be attenuated with a polarizer in the detection arm. Like in VCSELs, it should be possible to stabilize the polarization by introducing a surface grating [9] on our MIXSEL structure. Beam quality measurement at a slightly reduced output power of 1.2 W showed excellent M^2 values of <1.05 in both directions.

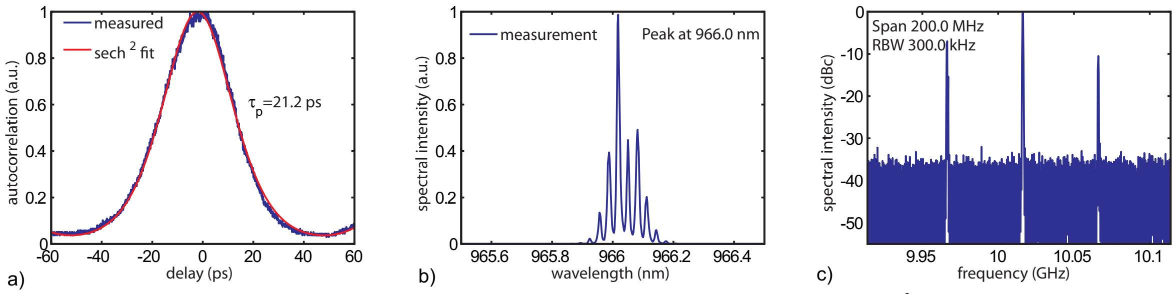

Fig. 2: Measured autocorrelation fitted with an ideal 10-GHz train of 21.2-ps sech^2-pulses (a); Optical spectrum centered at 966 nm (b); RF-spectrum (c).

4. Conclusion and outlook

We demonstrate a 10-GHz MIXSEL with 2.2 W, which is the highest output power from any modelocked 10-GHz semiconductor laser so far. This result was enabled by an optimized antiresonant MIXSEL design with low saturation fluence QD absorbers and with an improved thermal management using a bottom CVD diamond heat spreader. By increasing the mode size on the MIXSEL chip, the average output power can be further increased. Moreover, we envisage the generation of substantially shorter pulses by optimization of the QD absorber's recombination dynamics. The simple MIXSEL geometry should support repetition rates in the 100 GHz regime.

5. References

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