MIXSEL: Picosecond semiconductor disk laser with integrated saturable absorber

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A MIXSEL (Modelocked Integrated eXternal-cavity Surface Emitting Laser) is a compact ultrafast semiconductor disk laser. The concept is based on a VECSEL, an optically pumped semiconductor disk laser with an external resonator, which is further simplified in modelocked operation by monolithically integrating the semiconductor saturable absorber mirror (SESAM) for passive modelocking. Forming a straight optical cavity with an external output coupler, the MIXSEL offers gigahertz repetition rates and picosecond pulse durations with excellent beam quality, and it has the potential for cost-efficient industrial mass production. In this article, we report on the recent development of a MIXSEL with high average output power.

1 Introduction

Many applications in the areas of multimedia, biomedicine, and metrology require compact ultrafast lasers. Those applications demand affordable laser sources that can be adapted to their specific needs. Inexpensive ultrafast semiconductor lasers, based on edge-emitters, have clear disadvantages in output power and beam quality in comparison to optically pumped VECSELs (Vertical-External-Cavity Surface-Emitting Lasers [1]) that are passively modelocked with semiconductor saturable absorber mirrors (SESAM [2,3]). Modelocked VECSELs can deliver ultrashort pulses at average output powers of several watts with excellent beam quality (**figure 1**) [4,5].

Here we report on the concept of the MIXSEL (Modelocked Integrated eXternal-cavity Surface-Emitting Laser [6]), which greatly reduces the complexity of ultrafast semiconductor disk lasers by combining the saturable absorber and the active region in a single structure. The conceptual advantages make this technology an ideal platform for clocking and short distance communication in multicore processors, RGB-generation in multimedia, multi-photon applications in biomedicine, or optical timing measurements and spectroscopy in the area of metrology. To cover all those applications, the great wavelength flexibility of the semiconductor material system can be utilised, which allows stable modelocking in a broad range of wavelengths.

One of the main advantages of the MIXSEL is the potential for cost-efficient mass-production. Moreover the compact resonator and the possibility of a monolithic integration of the output coupler [7,8] could further reduce production costs to the level of edge emitters. In contrast to edge emitters, the MIXSEL is power scalable and offers short pulses at very high average output power levels with excellent beam quality.

The main challenges of MIXSEL design, and the difficulties of the realisation will be addressed in Section 2. Sections 3 and 4 present experimental results and give an outlook for further improvements of this novel technology.

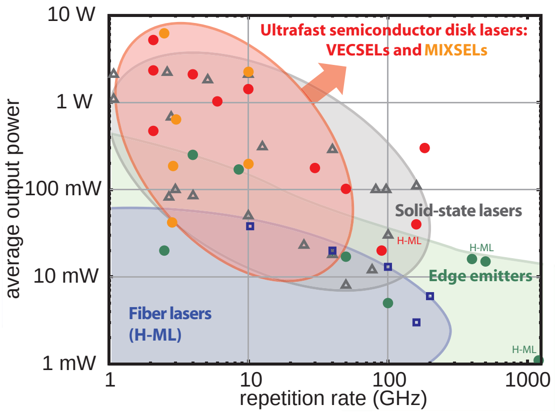

Figure 1: Overview of the average output power of MIXSELs and VECSELs compared to competing modelocked laser sources in the gigahertz repetition rate regime (H-ML: harmonic modelocking)

2 The MIXSEL concept: design and growth of the semiconductor structure

In contrast to SESAM-modelocked VECSELs, in a MIXSEL only one single semiconductor structure is required, in which the active region and the saturable absorber are combined [6]. The absorber integration simplifies the laser cavity into only two components, the semiconductor chip and the output coupler. The resulting compact, straight cavity (**figure 2a**) allows very short distances between the two cavity elements and supports pulse repetition rates up to several tens of gigahertz.

The MIXSEL structures were grown by molecular beam epitaxy (MBE) on gallium arsenide (GaAs) substrates (**figure 2b**). The bottom of the structure consists of a distributed Bragg reflector (DBR) for the laser emission wavelength of around 960 nm. Typically 30 pairs of semiconductor layers with alternating high and low refractive indices result in a reflectivity of more than 99.9% for the laser wavelength. The DBR is followed by the saturable absorber based on a single layer of self-assembled indium arsenide (InAs) quantum dots (QDs) [9]. Subsequently, a DBR for the pump wavelength was grown to prevent a pre-saturation of the saturable absorber and to increase the pump efficiency in the active region. The active region is based on indium gallium arsenide (InGaAs) quantum wells (QWs) similar to VECSELs in this wavelength range. In all MIXSEL structures realised until today, seven QWs were embedded in layers of GaAs. The largest fraction of the pump light is absorbed in those GaAs layers and the generated carriers drift into the QWs where they recombine and generate the laser radiation. To finalise the semiconductor structure,

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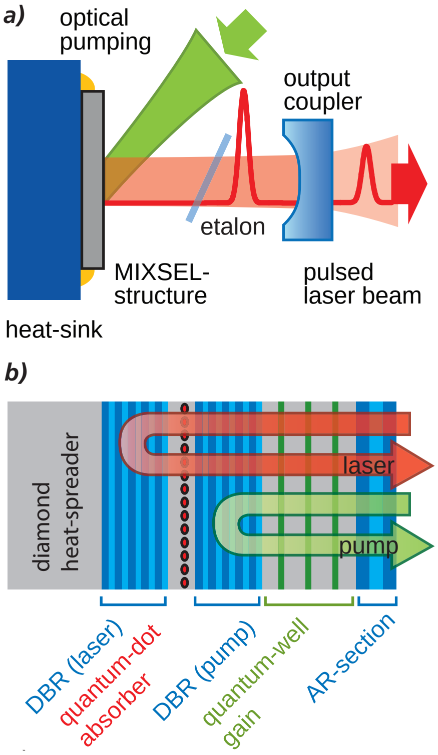

Figure 2: Schematic of a MIXSEL: a) Resonator consisting of MIXSEL structure and output coupler, optically pumped under an angle; b) Sketch of the semiconductor layer stack

a multilayer anti-reflection-section (AR-section) was grown on top of the active region to minimise reflection losses of laser and pump light at the interface between semiconductor and air.

For passive modelocking, the saturable absorber needs to saturate at lower intensities than the gain. This is necessary to achieve a net gain of the laser pulse inside the resonator [10], and it is typically achieved by adjusting the ratio between the laser mode radii on the gain and the absorber. While the intensities on the saturable absorber and the active region in modelocked VECSELs can be adapted independently by choosing an appropriate resonator geometry, in the MIXSEL, the laser mode areas are identical. In the first MIXSEL structures presented 2007, a sub-resonator was embedded (**figure 3 top**) to achieve an enhanced electric field at the absorber position, about 4.5 times higher than in the active region. However, this so-called resonant design is very sensitive to growth errors during the epitaxial production process.

The devices presented here are designed antiresonant (**figure 3 bottom**). The electric field in both the absorber and the gain are almost identical, which minimises the influence of such growth errors. However, this new design, without the sub-resonator, requires parameters of the QD-absorber, which are adapted to the lower field. These parameters are not only strongly dependent on the growth conditions, but also on post-growth treatment, for example thermal annealing. New QD-absorbers were developed especially for the integration in antiresonant MIXSEL structures [9]. A very crucial parameter is the recombination time of the absorption after being saturated by a short laser pulse, which is usually in the range between one and several tens of picoseconds. This parameter has a strong influence on the pulse duration of the laser, and stable passive modelocking is favored for recombination times that are shorter than a round-trip of the pulse in the resonator.

The MIXSEL structure is optically pumped by a commercial fibre-coupled 808 nm diode array under an angle of 45°. In order to achieve high average output power levels, high pump intensities are required, which cause a high thermal load inside the structure. For efficient heat removal, the semiconductor layer stack was grown in reverse order. After the epitaxial growth process, the chip was flip-chip bonded to a metalised diamond substrate with very high thermal conductivity. Afterwards the GaAs substrate was wet-chemically removed and only the MIXSEL structure with a thickness of a few micrometres remained on the diamond. A nearly one-dimensional heat-flow in the semiconductor structure can be achieved with this method resulting in an efficient heat removal from the active region. With this technique the average output power can be scaled by enlarging the laser mode on the structure up to a diameter of several hundred micrometres. The average output power increases to the watt-level while maintaining constant intensities and excellent beam quality.

3 Experimental results

The first experimental demonstration of a MIXSEL in 2007 showed the feasibility of integrating a saturable absorber into the semiconductor layer stack of a VECSEL. However, with an average output power of 40 mW with 35-ps-pulses and a repetition rate of around 3 GHz, the first MIXSEL was not able to compete with the performance of modelocked VECSELs [4,6]. With extreme cooling to -50°C, the average output power was improved to 185 mW at a pulse duration of 31.6 ps [7]. Now, as described in the previous section, the newly adapted QD-absorbers enabled the realisation of antiresonant structures (Figure 3 bottom) that were mounted on diamond heat-spreaders. With these novel structures two important milestones towards a semiconductor based high-power ultrafast laser were achieved: First, stable and self-starting fundamental passive modelocking with an average output power of 6.4 W at a pulse repetition rate of 2.5 GHz was achieved at a pump power of 36 W, and at the same time the pulse duration was decreased to 28 ps.

In this configuration (**figure 4**), the highest average output power of any ultrafast semiconductor laser to date was obtained [11]. Second, the pulse repetition rate was increased to 10 GHz by reducing the resonator length to 15 mm, still relying on the same MIXSEL structure. With this 17-ps-pulses were generated at an average output power of 2.4 W. This represents the highest output power of an ultrafast semiconductor laser with 10 GHz pulse repetition rate [12].

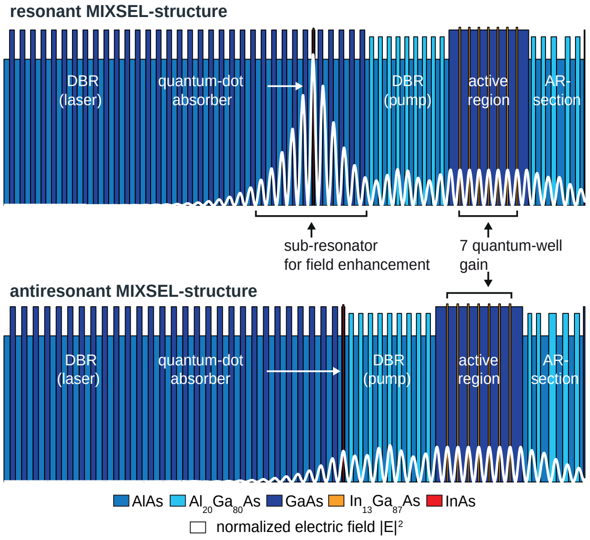

Figure 3: MIXSEL layer stack: top: resonant design with sub-resonator for field enhancement in quantum-dot saturable absorber; bottom: antiresonant design without sub-resonator with adapted parameters of quantum-dot saturable absorber

4 Conclusion and outlook

The optically pumped MIXSEL provides an ideal solution for high-power semiconductor based ultrafast lasers. Ultrashort pulses with repetition rates in the multi-gigahertz regime and record-high average output power levels can be generated in an extremely compact and simple resonator geometry.

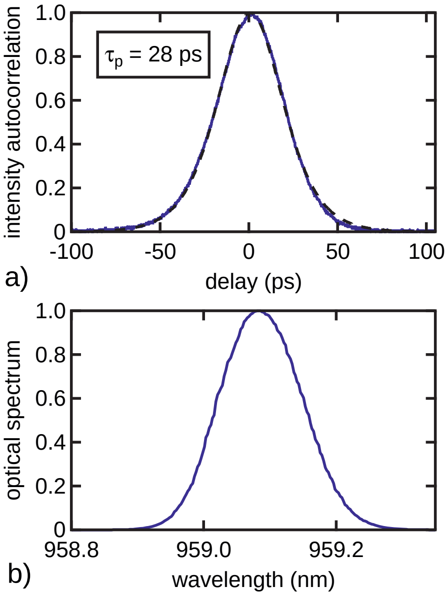

Figure 4: Characterisation of the laser pulses at 6.4 W of average output power: a) intensity autocorrelation of the 28-ps-pulses; b) optical spectrum centered at a wavelength of 959.1 nm

An important next step is the generation of even shorter laser pulses with a MIXSEL at the same high average output power levels. Two strategies that helped to scale the VECSEL technology into the femtosecond pulse duration regime [5] were applied to the MIXSEL technology as well. First, it was essential to optimise the saturable absorber for fast recombination dynamics, for which the recently developed absorbers based on InGaAs-QWs seemed to be an excellent solution. Furthermore, the AR-section on top of the device was optimised to achieve a flat and slightly positive group delay dispersion around the laser emission wavelength [5,13]. With the help of the new absorber and a modified AR-section we were able to demonstrate in a preliminary experiment the shortest pulse duration of a MIXSEL with 4.8 ps. The fast recovery dynamics of the saturable absorber of less than 10 ps allowed for even higher pulse repetition rates of up to 20 GHz [14]. Both results were demonstrated with a MIXSEL structure even without improved thermal management and will soon be repeated at significantly higher output power levels using MIXSELs on diamond substrates.

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