Multi-gigahertz high-power femtosecond semiconductor disk lasers

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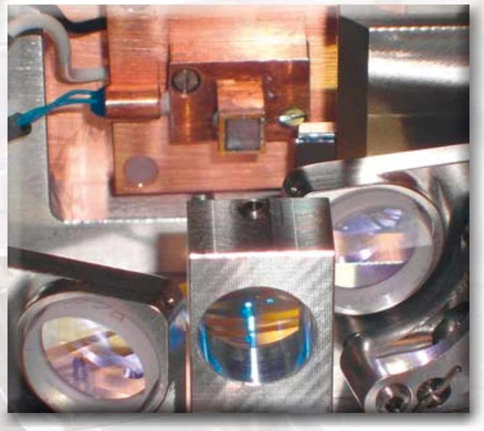
Optically pumped semiconductor disk lasers (VECSELs) combine the advantages of solid state lasers and conventional semiconductor lasers. Modelocked by a semiconductor saturable absorber mirror (SESAM), VECSELs can generate ps to fs light pulses at high repetition rates in the gigahertz range and high average output power levels. Such short light pulses are of great interest for many applications, including optical clocking of multi-core processors, free-space data transmission, multi-photon microscopy or self-referencable gigahertz frequency combs. The following article gives an overview of the recent progress made by femtosecond VECSELs with high average output powers.



1 Introduction

Since the first demonstration of an optically pumped semiconductor disk laser (Vertical-External-Cavity Surface-Emitting Laser, VECSEL [1]) more than 15 years ago, output powers of up to 20 W [2] with excellent beam quality ($M^2 < 1.1$), or more than 70 W in operation with reduced beam quality [3], have been achieved in continuous wave operation. The external resonator allows for simple integration of a semiconductor saturable absorber mirror (SESAM [4,5]), with which all passive modelocking results have been realized to date. Previously, picosecond laser pulses were achieved with output powers of >2 W, and fundamental mode-locking with repetition rates up to 50 GHz has been demonstrated [6]. The relatively short lifetime of the excited states of the semiconductor gain material (in the range of a few nanoseconds), compared to conventional amplifier materials of solid state lasers (typically milliseconds), suppresses instabilities of the pulse formation such as Q- switching [7].

The highest output powers have been generated by MIXSELs [8] (Mode Locked Integrated eXternal-cavity Surface Emitting Lasers), in which the gain structure as well as the saturable absorber are integrated into one single structure. More challenging is the generation of femtosecond pulses: for example, sub-300-fs pulses have been reported [9], but with output powers limited to <25 mW. The shortest pulse duration achieved in fundamental modelocking was 107 fs--an impressive demonstration of the potential of this technology, yet the power performance was limited to 3 mW [10]. **Figure 1** shows an overview of the achieved performances as a function of pulse duration for different mode-locked VECSELs.

Many potential applications, such as self-referencable gigahertz frequency combs or multi-photon microscopy, depend not only on short pulses, but also on a high peak power of the pulse, i.e. a combination of femtosecond pulses and high output power. Figure 1 shows clearly that the output power significantly decreases for shorter pulse durations. Below, we present our latest results, where we combined for the first time femtosecond operation and watt-level output power (figure 1: red). This was also possible due to a better qualitative understanding of the pulse forming mechanism of these semiconductor lasers.

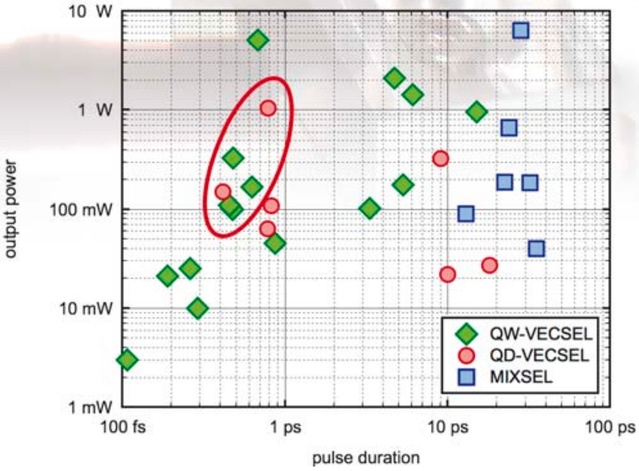


Figure 1: Overview of the pulse duration and output power of all SESAM-modelocked semiconductor disc lasers. The highlighted results will be presented in this article

2 VECSEL structure

The laser chip of a VECSEL consists of several semiconductor layers (**figure 2**), grown consecutively by molecular beam epitaxy (MBE). The structure consists in our case of two separated distributed Bragg reflectors (DBR). The first DBR is designed for a high reflectance at the wavelength of the pump laser (808 nm), followed by the second DBR, which has a high reflectance at the laser emission wavelength (around 960 nm). Each individual DBR consists of multiple periodically arranged semiconductor layers with alternating high and low refractive indices. This

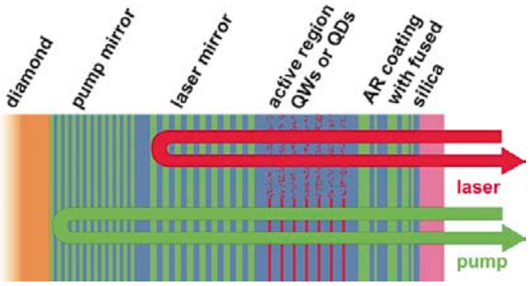


Figure 2: Illustration of the semiconductor layers of a VECSEL gain chip

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arrangement leads to a reflection of more than 99.9% for the laser wavelength.

The active region is grown directly on top of these DBRs. It consists of seven indium gallium arsenide (InGaAs) quantum wells (QWs) amplifying the laser at 960 nm. These QWs are surrounded by gallium-arsenide (GaAs), which is responsible for the necessary absorption of the pump laser at 808 nm. As an alternative to InGaAs QWs, indium arsenide (InAs) quantum dots (QDs) can be used as gain layers.

The transition between the active region and air is done by an anti-reflective coating (AR), consisting of several semiconductor layers and a layer of fused silica (FS) on top. The last FS layer is deposited by plasma enhanced chemical vapor deposition (PECVD). The AR coating prevents not only reflections of the laser light at the surface of the laser chip, but is also designed to minimize the dispersion over a wide spectral range. This property is very important for mode-locked VECSELs, which we explain in more detail in Section 5.

3 Cavity setup

Usually, the cavity of a modelocked VECSELs consists of the gain structure itself, described above, an output coupler and a SESAM to start and stabilize modelocking (**figure 3**).

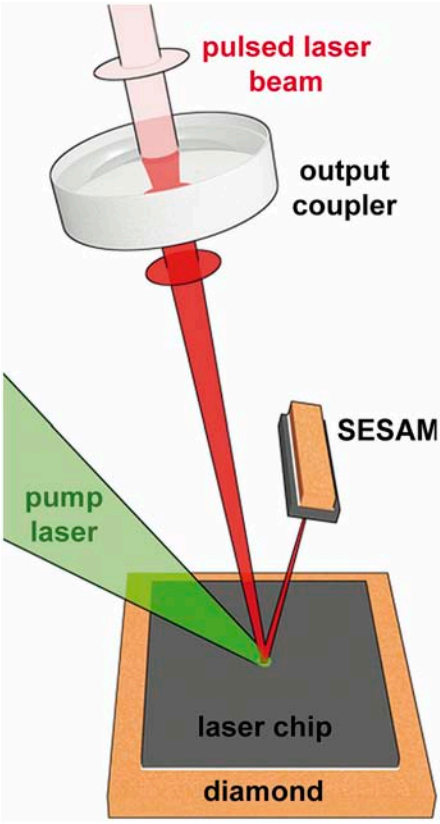

Figure 3: Illustration of a typical cavity of a modelocked VECSEL

The optical pumping is done by a commercial diode laser at a wavelength of 808 nm. However, the pumping also deposits an enormous heat load in the structure. To achieve a high performance, the laser chip is therefore soldered onto a diamond disk. In turn, this disk is mounted on a copper heat sink. The high thermal conductivity of diamond (1800 $\mathrm{Wm^{-1}K^{-1}}$) enables the rapid transfer of heat from the active region of the laser chip to the heat sink. By using a Peltier element, the laser chip can be stabilized to a temperature between -20°C and 60°C.

4 Pulse formation of modelocked VECSELs

The structure of the SESAM, employed to start and stabilize modelocking, is very similar to the one of VECSELs but somewhat simpler: it consists of just one DBR, followed by a thin absorbing semiconductor layer grown by MBE whose absorption decreases with increasing light intensity. As a result, the optical losses in the continuous wave operation are much higher than for modelocked operation, which leads to self-starting modelocked operation.

In addition to the saturable absorption, other mechanisms can contribute to the pulse shaping. In conventional solid-state lasers, the most common mechanism is soliton-modelocking (sech^2 pulse, hyperbolic secant squared envelope) [11]. The principle of soliton-modelocking is based on the interplay between self-phase modulation (SPM) and negative group delay dispersion (GDD). SPM is a nonlinear optical effect in which the spectrum of the pulse is extended symmetrically by new frequency components. Higher frequencies are generated in the trailing edge, and lower frequencies are generated in the leading edge. Simultaneously, a negative GDD causes the high-frequency components of the pulse to travel faster than the low-frequency components. By carefully choosing the parameters, these two effects are able to balance out each other and thus form very short light pulses.

In mode-locked VECSELs, a similar mechanism is responsible for the pulse formation. The gain material, as well as the saturable absorber, consist of very thin semiconductor layers (QWs or QDs) and SPM is therefore negligible. But another important property of semiconductor gain is the relatively high gain (typically 5%), despite the short interaction length of only a few 10 nm. As a result, the excited state can be almost totally emptied by a pulse (strong gain saturation). Accordingly, the gain changes during the pulse passage and this induces a change in the refractive index, and thus a change in phase due to the Kramers-Kronig relations.

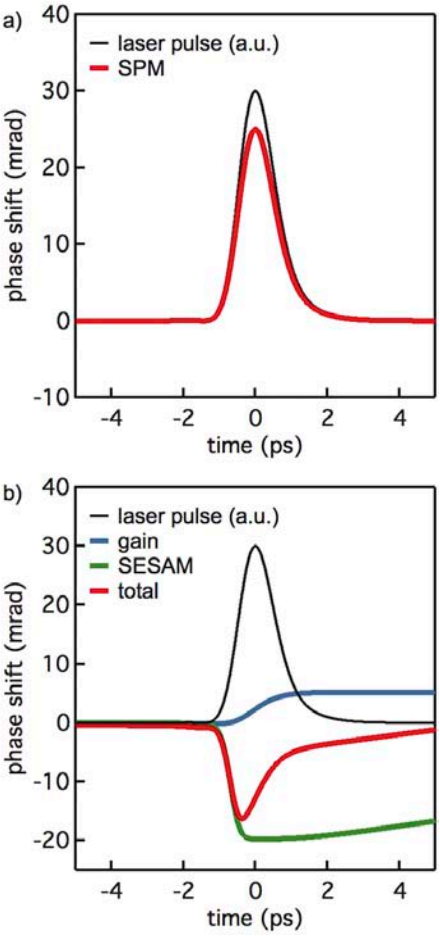

Figure 4: a) Phase changes (red) induced by SPM. b) Phase changes induced by the saturation of the gain (blue) and the SESAM (green) leading to a total phase change (red) similar to SPM, but with a negative sign

The absorber also causes a phase shift due to the saturation of the absorption, but in the opposite direction than the phase shift of the gain. These phase changes of gain and absorber result in a total phase change (**figure 4a**), which is similar but negative compared to the phase shift induced by SPM (illustrated in **figure 4b**), and which occurs in soliton modelocking of the conventional solid-state lasers with ion-doped crystals. Since in soliton modelocking, the phase change from SPM is compensated by negative GDD, the phase shifts of the saturation effects are compensated by positive GDD in modelocked VECSELs. This pulse forming mechanism was confirmed experimentally in the picosecond regime and because the pulses are not "real solitons", they are called "quasi-solitons" [12].

Figure 5 illustrates a numerical simulation of the pulse duration, as a function of the

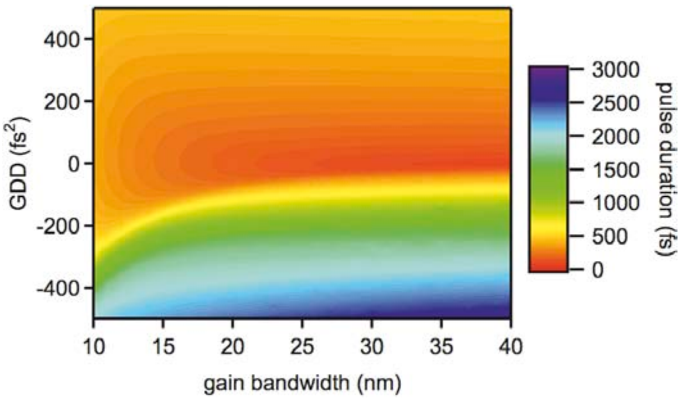

Figure 5: Numerical simulation of the pulse duration in dependence of the GDD and the gain bandwidth

GDD and the spectral gain bandwidth. It is clear that slightly positive GDD is important to achieve short pulses in the femtosecond range. With negative GDD, the pulse duration can rapidly rise to several picoseconds (200 fs^2 are extremely small GDD values). To achieve femtosecond pulses, it is therefore essential to manage the GDD precisely.

5 Low dispersion leads to femtosecond operation

The gain structure causes the largest amount of GDD in the cavity, as it is hit twice by the pulse per cavity round-trip (figure 3). The GDD of the remaining elements, such as the SESAM or the output mirror, are negligible. A measurement of the GDD as a function of the wavelength (**figure 6**: black) shows that our structures usually had very high GDD values of several 1000 fs^2. To compensate for these large values, a novel AR-coating has been developed to minimize the GDD over a wide wavelength range. The result is impressive: With the new AR coating, the gain chip has almost no GDD (± 10 fs^2) over a range of 30 nm, as the simulation shows (**figure 6**: red).

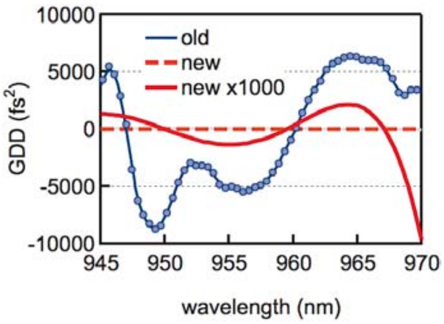

Figure 6: Wavelength dependent GDD of an old structure (blue) compared to a novel dispersion compensated structure (red)

In the experiment it was proven that this dispersion compensation, combined with a fast SESAM absorber, is the key to even shorter pulses. The active region in the laser chip can consist of QWs or QDs. With QDs, 784-fs pulses were achieved at an average output power of 1.05 W [13]. The cavity length was only 2.7 cm, which corresponds to a repetition frequency of 5.4 GHz. This was the first time where femtosecond pulses with such a high average output power were obtained. Shorter pulse durations were achieved with 416 fs at a lower repetition rate of 4.5 GHz and an average output power of 143 mW.

With QWs as an active gain material, we obtained comparably short pulse duration of 455 fs with 110 mW and a repetition frequency of 5.4 GHz. A higher repetition rate of 7 GHz led to 300 mW average output power at a pulse duration of 480 fs.

Moreover, the influence of the repetition rate on the pulse duration was investigated. A simple continuous change in the repetition rate enables new applications, as for example time-resolved optical measurements [14]. It turned out that VECSELs are excellently suited to this application, because changes in the repetition rate from 6.5 to 11.3 GHz did not change the pulse duration (625 fs) or the output power (169 mW) significantly (**figure 7**) [15]. The repetition rate was varied by moving the output coupler during laser operation. To facilitate this measurement, the resonator was designed such that the laser beam on the gain chip as well as on the SESAM changed only slightly.

These results show clearly that this semiconductor laser technology has a great potential to combine high output power, gigahertz repetition rates and femtosecond pulses. This combination is very difficult to achieve in conventional solid-state lasers, but is essential for applications including optical clocking of multi-core processors, free-space communication, and compact, stabilized frequency combs.

6 Conclusion

To obtain femtosecond pulses with a VECSEL, it is essential to have a low and slightly positive GDD in the cavity. The main contribution to the GDD in a mode-locked VECSEL is caused by the gain structure itself. Therefore, a new low-dispersion AR coating was designed to minimize the GDD of the gain chip over a range of 30 nm. With these new low-dispersion gain structures, 784-fs pulses with >1 W of average output power at 5.4 GHz have been achieved. A VECSEL was demonstrated where the repetition rate could be varied from 6.5 GHz to 11.3 GHz without significant changes in the average output power or the pulse duration. This laser is interesting for metrology applications, especially pump-probe measurements. Shorter pulses below 500 fs with output powers up to 300 mW show the enormous potential for applications requiring high peak power. If it is possible to achieve a pulse duration of 200 fs at high output power, self-referencable gigahertz frequency combs of a compact mode-locked VECSEL could become a reality.

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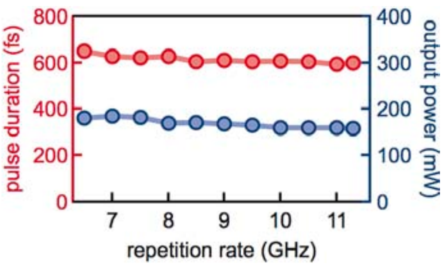

Figure 7: Measurements done at varied repetition rates, where pulse duration as well as average output power remained stable

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