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Recent advances in electrically pumped VECSELs for modelocking

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ABSTRACT

Vertical external cavity surface emitting lasers (VECSELs) are excellent high power semiconductor lasers with diffraction-limited circular output beam and outstanding modelocking performance even at tens of GHz repetition rate. The output power can be scaled up by simply increasing the mode area on the gain region. It makes them very attractive for numerous applications such as RGB displays, biomedical imaging or optical clocking of multi-core processors. Passively modelocked optically-pumped VECSELs, using a semiconductor saturable absorber mirror (SESAM), have generated shorter pulses and higher average powers than any other modelocked semiconductor laser (135-fs pulses at 35-mW average power and 2.1-W in 4.7-ps pulses).

Electrical pumping (EP) of modelocked VECSELs is the obvious next step towards compact high-power ultrafast laser sources. In 2003, Novalux Corporation reported a continuous wave (cw) output power of nearly one Watt from their proprietary EP-VECSEL (NECSEL). The modelocking of a NECSEL has been demonstrated with 40 mW of average power in 57-ps pulses. Since then, very few EP-VECSEL results have been reported. Recently, we started to develop EP-VECSELs designed for modelocking, which require an optimized balance between electrical resistance, optical losses, dispersion and beam quality. We discuss our design approach and present initial EP-VECSEL devices generating >100-mW cw power. Homogeneous current injection is achieved even for large devices, showing very good agreement with our numerical simulations. Sufficient power in a diffraction-limited beam and a carefully designed SESAM are required to modelock an EP-VECSEL.

Keywords: Semiconductor lasers, surface emitting lasers, mode-locked lasers, ultrafast lasers.

1. INTRODUCTION

Semiconductor lasers revolutionized the optical telecommunications with direct intensity modulation [1], today modelocked semiconductor lasers have the potential to replace bulky and expensive modelocked diode pumped solid-state lasers in many applications such as RGB displays, biomedical imaging or optical clocking of multi-core processors. Up to now, modelocked edge-emitting lasers (EEL) generate average output powers of up to 250 mW in picosecond pulses [2]. In EELs, the mono-mode waveguide limits the lateral scaling and the long light interaction in the waveguide introduces significant nonlinearities and noise. It is very challenging to increase the output power of modelocked EELs to the Watt regime. It can be realized by adding a tapered amplifier and an external pulse compressor like in [3], but the laser system becomes bulky and makes the use of semiconductor diodes less attractive.

Vertical external cavity surface emitting lasers (VECSELs) [4] offer excellent beam quality and high output power in the multi-Watt level and directly from the resonator. The output power can be scaled up by simply increasing the mode area on the gain region. The simple VECSEL external cavity geometry enables passive modelocking of these devices [5] using a semiconductor saturable absorber mirror (SESAM [6, 7]). The use of semiconductor materials in SESAM-modelocked VECSELs allow for cheap mass production. The SESAM can even be integrated directly in the VECSEL structure. This new type of laser is called a modelocked integrated external-cavity surface emitting laser (MIXSEL) [8-10]. Optically pumped (OP) VECSELs and MIXSELs have, to our knowledge, generated shorter pulses and higher average powers than any other modelocked semiconductor laser (i.e. 135-fs pulses at 35-mW average power [11], 210 fs pulses at 11 mW [12], 2.1 W in 4.7-ps pulses [13] and 6.4 W in 25-ps pulses from a MIXSEL [10]). In addition, SESAM-modelocked VECSELs have much better noise performance compared to modelocked EELs because of their short light interaction length and their high-Q cavity [14].

Electrical pumping (EP) of modelocked VECSELs is the clear next step towards high-power compact modelocked laser sources. In 2003, Novalux Corporation reported 900-mW output power in continuous wave (cw) from their proprietary EP-VECSEL, referred to the NECSEL [15, 16]. OSRAM in 2007 presented a different approach, which is the monolithic integration of pump diodes through a VECSEL structure. From such integrated structure, 600 mW of output power in cw operation was obtained [17]. However the coupling between the pump laser cavities and the VECSEL gain is quite challenging and the pumped spot on the VECSEL gain is not necessarily uniform in the larger devices [18]. EP-VECSELs have also been demonstrated at 1.55- μm [19, 20] and 2.3- μm [21] wavelengths, but the difficulties encountered with the distributed Bragg reflectors (DBRs) at those wavelengths currently limit the cw power to the milliwatt level.

The first modelocked electrically pumped surface emitting laser was reported in 1993 with active modelocking producing 80-ps pulses using a liquid-nitrogen cooled vertical cavity surface emitting laser (VCSEL) structure [22]. Passively modelocked EP-VECSELs have, to our knowledge, only been reported using NECSEL chips. Modelocked operation has been demonstrated with 40 mW of average power in 57-ps pulses [23]. Shorter pulses of 15 ps have also been reported but at lower output power using a reversely biased SESAM very similar to the gain chip itself [24]. Modelocked EP-VECSELs requires a design which is not only optimized for high output power in cw but also for an optimal balance between electrical resistance, optical losses and dispersion. In 2008, we presented an EP-VECSEL design which is compatible with passive modelocking [25]. A first series of EP-VECSELs have been fabricated and the initial results are presented here.

Figure 1. Schematic of our EP-VECSEL design (not to scale). The final structure as shown here is without the initial GaAs substrate and soldered on a CuW heatsink.

2. EP-VECSEL DESIGN

We previously discussed in [25] design guidelines of EP-VECSEL compatible with passive modelocking. Figure 1 shows a not-to-scale illustration of our EP-VECSEL chip, which is stretched vertically for better visibility. The confinement of the injected current into the center of the device is obtained by the use of a p-doped DBR with a small bottom disk contact (BDC) associated with on top a thick current spreading layer (CSL) with a ring electrode. The low mobility of the holes in the p-DBR confines the carriers to the volume above the BDC and the high mobility of the electrons in the thick CSL allows their recombination into the center of the device [25, 26]. The BDC determines the mode size of the EP-VECSEL as demonstrated in section 3, where the measured electroluminescence (EL) profiles are compared to the numerical model.

Figure 2: Refractive index (black line) and electrical field (green line) profiles along the EP-VECSEL structure. The doping levels are indicated on top of the diagram. The active region consists of 2 groups of 3 InGaAs QWs spaced by 10 nm.

An optical simulation for the field enhancements inside the structure is shown in Figure 2. As discussed in [25] the n-DBR enhances the field in the quantum wells (QWs) which compensates for the optical losses in the CSL, the n-doped DBR and the p-doped DBR. An antireflection (AR) section on top of the device prevents the CSL to act as a sub-cavity, which would deteriorate the device's performance.

The structure was grown by molecular beam epitaxy (MBE) in reverse order to allow for substrate removal. To reduce the resistance of the 30-pairs p-doped DBR, a 16 nm “staircase grading” with five $\text{Al}_{(1-x)}\text{Ga}_x\text{As}$ layers of different composition was inserted between each AlAs/GaAs interface. Additionally, the doping levels were increased in layers where the electrical field is low. This adds no significant additional optical losses. The doping levels in the p-DBR (from bottom to top) are $[5, 4, 3, 2] \cdot 10^{18} \text{ cm}^{-3}$ for the pairs [1-15, 16-20, 21-25, 26-30], respectively. The active region consists of two groups of three InGaAs QWs spaced by 10 nm and placed in two antinodes of the electrical field. In this first realization, the intermediate n-DBR has 11 AlAs/GaAs pairs without any grading, the doping concentration is $2 \cdot 10^{18} \text{ cm}^{-3}$. The GaAs CSL is 6- μm thick and n-doped with a concentration of $2 \cdot 10^{18} \text{ cm}^{-3}$. The top AlAs/GaAs AR section remains undoped. The epitaxial layers have been fine tuned to obtain a lasing wavelength around 965 nm at an internal temperature of about 100-120°C. Accordingly, the QWs emission wavelength has been detuned by 25 nm. The different EP-VECSELs have been processed on a single chip as shown in Figure 3. For efficient heat removal, the chip is bonded to a CuW wafer, which has the same coefficient of thermal expansion as GaAs.

Figure 3: Pictures of a realized EP-VECSEL chip and a zoom on a section with 61 EP-VECSELs. The distortion in the picture is caused by the microscope.

The presented design should be suitable to be directly modelocked using an external SESAM as it is usually done with optically pumped ultrafast VECSELs [5]. To obtain stable modelocking, the saturation energy of the absorber needs to be lower than for the gain. This ratio can be controlled by the spot size on the SESAM and the design of the SESAM [26]. The intrinsic absorber properties can also be optimized, for instance, quantum-dot (QD) saturable absorbers have

lower saturation fluence than QW saturable absorbers [27, 28]. For the generation of short pulses, the dispersion of the laser cavity needs to be optimized. We simulated and confirmed experimentally [29] that adding positive dispersion can compensate the nonlinear phase shift induced by strong semiconductor gain and absorber saturation.

3. CURRENT CONFINEMENT

Power scaling of EP-VECSELs in a fundamental laser beam mode requires an efficient supply of carriers in the center of the active region even for large device diameters. The EL emission profile is taken as a measure for the current injection into the gain. The confinement of the carriers in the active region was also simulated using a coupled electro-opto-thermal model [25, 30]. The simulation tool used incorporates microscopic carrier transport equations [30] and a thermionic emission model addresses abrupt hetero-interfaces [25]. The measured and simulated EL profiles of the EP-VECSELs for different BDC diameters are compared in Figure 4. The measured EL profiles are in very good agreement with the simulation results. The profiles become flat-top-shaped and develop an intensity dip in the center of the device for diameters larger than 120 μm . Devices with BDC diameters up to 100 μm are favorable for TEM₀₀ beams.

Figure 4: Measured (solid lines) and simulated (dashed lines) electroluminescence (EL) profiles of EP-VECSELs with different bottom disk contact diameters.

4. LASING PERFORMANCE AND POWER SCALING

We compared the lasing performance of EP-VECSELs with different aperture sizes at 3°C heatsink temperature in a simple straight cavity. The laser cavity was around 24.5 mm in length and terminated by a 25-mm radius output coupler (OC). In Figure 5, the output power is plotted for 35 devices as a function of the BDC diameter in the case of a 10% transmission OC. Despite slight variations, there is a linear increase of the output power as a function of the BDC diameter. The power scalability of the current design is up to 120 mW. We experienced that roll-over for small devices occurs at higher current densities than for larger devices. This gives some indication for thermal issues in the larger devices because the power does not increase proportionally to the active area. This could be improved by reducing the heat dissipation by a lower electrical resistance of the devices or by use of a bottom heatsink with higher thermal conductivity. The employed CuW heatsink has a thermal conductivity of $200 \text{ W} \cdot \text{K}^{-1} \cdot \text{m}^{-1}$, which is two times lower than for copper and ten times lower than for diamond. The maximum output power in the current design is therefore limited by the strong internal heating as a result of an increased electrical and thermal resistance.

The light-current-voltage (LIV) curves of the EP-VECSEL delivering 120 mW of optical power using a 10% OC is shown in Figure 6. The EP-VECSEL gain structure has a 180- μm BDC diameter and 300- μm top contact electrode diameter. The thermal roll-over is obtained at $\approx 1 \text{ A}$. The differential quantum efficiency at 750 mA is about 25% and the wall-plug efficiency about 5%.

Figure 5: Output power of EP-VECSELs in a straight cavity with a 10% transmission output coupler as function of the bottom disk contact diameter. The heatsink temperature was kept at 3°C.

Figure 6: LIV curves from an EP-VECSEL with a disk contact diameter of 180 μm , top contact diameter of 300 μm , using a 10% output coupler. The heatsink temperature was kept at 3°C.

Figure 7: LI curves from an EP-VECSEL with a disk contact diameter of 180 μm using different output coupler transmission. The heatsink temperature was kept at 20°C.

In Figure 7, the light-current curves of an EP-VECSEL with a BDC diameter of 180 μm are shown for different OC transmissions. The optimum transmission for high power would be $\approx 14\%$ at 20°C heat sink temperature. This value is much higher than what is typically used in OP-VECSELs because the EP-VECSEL intermediate n-DBR already reflects $\sim 90\%$ of the light in this initial realization.

5. CONCLUSION

We presented a first series of EP-VECSELs of different sizes based on our design guidelines published in [25]. We described the design used for the fabrication, a comparison of the EL profile to our coupled electro-opto-thermal model and the lasing performance. The challenge for high-power modelocked EP-VECSELs is first to get high power levels by scaling the devices laterally keeping a homogeneous electrical pumping and second to balance the competing requirements of low electrical resistance, low optical losses and controlled dispersion while maintaining fundamental mode operation for stable modelocking. For the EP-VECSELs presented here, the entire active area can be pumped efficiently with sufficient homogeneity even for large diameter devices. This is in very good agreement with the simulation results. Devices with BDC diameters of up to 100 μm are favorable for TEM₀₀ output beams. Promising output power levels were obtained in cw and could scale the power up to 120 mW despite a higher resistance than designed. We expect that the next generation of EP-VECSELs with improved designs will result in higher output powers to support modelocking with an external low saturation fluence QD-SESAM.

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