Design and Continuous-Wave Characterization of Electrically Pumped VECSELs Suitable for Passive Modelocking

W.P. Pallmann[1], Y. Barbarin[1], M. Hoffmann[1], P. Kreuter[2], B. Witzigmann[2,3], M. Golling[1], T. Südmeyer[1] and U. Keller[1]

[1]Department of Physics, Institute for Quantum Electronics, ETH Zurich, Switzerland
[2]Department of Information Technology and Electrical Engineering, Integrated Systems Laboratory, ETH Zurich, Switzerland
[3]Dep. of Electrical Engineering and Computer Science, Computational Electronics and Photonics Group, University of Kassel, Germany
Author e-mail address: pallmann@phys.ethz.ch

***Abstract*—An ultrafast electrically pumped VECSEL design suitable for passive modelocking requires an acceptable trade-off in cw output power. Validating our design guidelines, 120 mW of cw output power are generated. Homogenous current injection is achieved even for large devices, as predicted by our simulations.**

Keywords-Semiconductor lasers, vertical emitting lasers, passive modelocking

I. Introduction

Optically pumped vertical external cavity surface emitting lasers (OP-VECSELs) are ideally suited for passive modelocking [1], achieving sub-100-fs pulses [2] and high average power (2.1 W in 4.7 ps pulses [3]). Furthermore, these ultrafast VECSELs generate diffraction-limited, circular output beams making them highly attractive for numerous applications such as biomedical imaging or optical clocking of multi-core processors. However, optical pumping substantially increases packaging requirements. In 2003, Novalux Corporation reported a continuous-wave (cw) output power of 900 mW from their proprietary electrically pumped VECSEL (EP-VECSEL), referred to as the NECSEL [4]. Despite this impressive cw performance, modelocked NECSELs have only generated <40 mW average output power in 15 ps pulses so far [5]. Unfortunately the detailed design parameters of the NECSEL have not been published.

Passive modelocking of EP-VECSELs requires a design optimization with an acceptable trade-off in cw output power with less field enhancement in the gain structure. This is necessary for stable modelocking which requires reduced dispersion and fundamental transverse mode operation even in larger devices. Recently, we have performed a detailed numerical analysis of EP-VECSELs and developed optimized designs compatible with passive modelocking [6]. Here we present the first experimental verification of our design in cw operation. Scaling of the average power can be achieved by different aperture diameters. We have generated a cw average output power of 120 mW with a bottom disc contact diameter (Fig. 1) of 180 µm. We realized a series of 60 EP-VECSELs of different sizes, enabling us to study the current profile as function of various design parameters. For all devices, the measured spatially resolved electroluminescence matches our numerical simulations. Even for devices with large mode diameter, a homogenous inversion profile can be realized. In a next step we will investigate the modelocking performance of our devices.

II. EP-VECSEL Design and Fabrication

The design of our EP-VECSELs has been previously simulated and the trade-off between electrical and optical properties has been discussed in [6]. Fig. 1 shows a schematic diagram of our electrically pumped semiconductor gain structure. The EP-VECSEL is a linear cavity using this structure and an external curved output coupler as the two end mirrors. A good confinement of the injected current into the center of the device is ensured by an optimized p-doped distributed Bragg reflector (DBR), a small bottom disc contact, and a thick current spreading layer (CSL) with a top ring electrode. The low mobility of the holes in the p-DBR confines the carriers to the space above the bottom disc contact and the high mobility of the electrons in the thick current spreading layer allows their recombination in the center of the device [6]. Our simulations show a homogeneous transverse inversion profile even for larger device diameters, which enables TEM_{00} mode control.

A low reflective n-DBR between the active region and the current spreading layer and an anti-reflection (AR) section on top of the structure are introduced to enhance the gain of the structure and to reduce the cavity losses by decreasing the field strength in the doped top layers. The AR section and the moderate thickness of the current spreading layer reduce the dispersion, favoring stable modelocking.

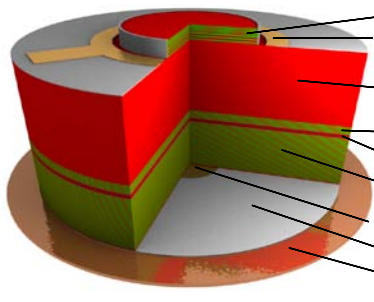

Figure 1. Sketch of our EP-VECSEL gain structure.

The structure was grown by molecular beam epitaxy (MBE) in reverse order for substrate removal. The growth of a p-doped DBR with low optical losses and low electrical resistance is challenging. To reduce the resistance of the 30 pairs p-DBR, a 16 nm "staircase grading" with five $Al_{(1-x)}Ga_xAs$ 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, which adds no significant additional optical losses. The doping levels in the p-DBR going from bottom to top are $[5, 4, 3, 2]\cdot 10^{18}$ cm^{-3} for the pairs [1-15, 16-20, 21-25, 26-30], respectively. The active region consists of two groups of three InGaAs Quantum Wells (QWs) spaced by 10 nm and placed in two antinodes of the electrical field. In this first realization, the n-DBR has 11 AlAs/GaAs pairs without any grading, the doping concentration is $2\cdot 10^{18}$ cm^{-3}. The GaAs current spreading layer is 6 µm thick and n-doped at a concentration of $2\cdot 10^{18}$ cm^{-3}. The top GaAs contact layer (between the AR section and the CSL) is 150 nm thick with a doping concentration of $6\cdot 10^{18}$ cm^{-3}. The top AlAs/GaAs AR section is undoped. The EP-VECSEL's total resistance and the heat generated in the structure have been simulated for high injection currents. 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 in the FIRST cleanroom facility at ETH Zurich. For efficient heat removal, the chip is bonded to a CuW mount, which has the same coefficient of thermal expansion as GaAs.

III. Experimental Results

The lasing performance of the 60 EP-VECSELs has been measured in a simple straight cavity and near room temperature (T=3°C) using an output coupler with a radius of curvature of 25 mm and a transmission of 10%. The output powers obtained for the different EP-VECSEL sizes are plotted in Fig. 2. The linear increase of power as function of the bottom contact diameter demonstrates power scalability up to 120 mW. The light-current-voltage (L-I-V) curves of an EP-VECSEL with more than 100 mW power using a 5% output coupler are plotted in Fig. 3, a thermal roll-over is not visible. The differential quantum efficiency at 525 mA is about 25% and the wall-plug efficiency about 5% due to the higher resistivity of the bottom p-DBR required for better laser mode control. The efficiencies will be improved by using an optimized p-doped DBR.

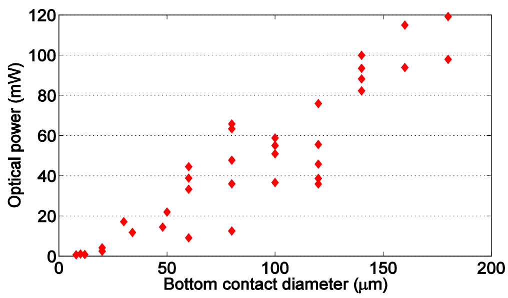

Figure 2. Output power of EP-VECSELs in a straight cavity with a 10% output coupler as function of the bottom disc contact diameter.

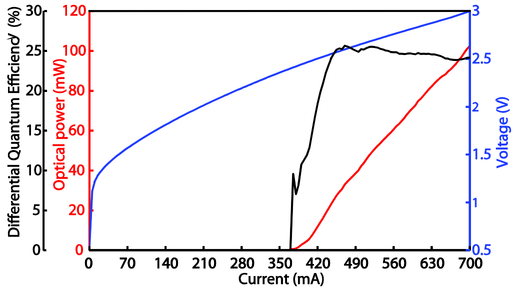

Figure 3. L-I-V curves from an EP-VECSEL with a disc contact Ø of 140 µm, top contact Ø of 300 µm and using a 5% output coupler.

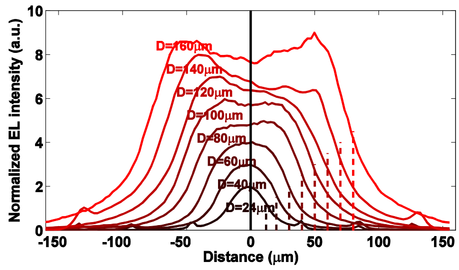

Figure 4. Electroluminescence profiles of EP-VECSELs with different back contact diameters recorded at high current injection.

A lower current threshold value could be expected but the QWs detuning of 25 nm increases the lasing threshold. The differential resistance of the laser presented in Fig. 3 is ~2.1 Ω at lasing threshold. Fig. 4 shows electroluminescence profiles of EP-VECSELs with different back contact disc diameters. Devices with p-DBR apertures larger than 100 µm diameter are not favorable for TEM_{00} beams.

IV. Conclusion And Outlook

We present a detailed experimental study on electrically-pumped VECSELs. The measured electroluminescence profiles are in very good agreement with our simulations [6]. The lasing results demonstrate scalability of the output power up to 120 mW. In a next step, we will perform modelocking experiments and further optimize the presented design.

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