# Thermal crosstalk in densely packed high power VCSEL arrays

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*We present detailed investigations on the thermal interaction between closely spaced vertical-cavity surface-emitting laser diodes (VCSELs). Applying the results to simple modeling of cw output characteristics, thermally induced power limitations of two-dimensional arrays can be described. Experimentally 0.56 and 0.8 W cw output power at room temperature and -10 °C, respectively, are observed for an array of 23 elements with 40 μm active diameter and 90 μm center spacing.*

## 1. Introduction

In the last few years the optimization of VCSELs for optical data transmission led to highly efficient devices, mainly due to reduced series resistances in the Bragg reflectors [1] and improved current confinement by an oxide aperture [2]. VCSELs are limited in optical output power by thermal rollover, therefore efficient devices which benefit from reduced dissipated power show promising prospects for high optical power generation. Upscaling the active area of well established single top- and bottom emitting VCSELs results in 180 mW and 350 mW cw output power for 150 $\mu$m and 200 $\mu$m active diameter, respectively [3]. However, both approaches suffer from a disadvantegeous decrease of conversion efficiency, which is understood from modeling the cw output characteristics based on fundamental electro-optical parameters. The two dimensional arrangement of individual VCSELs designed for high efficiency operation is an obvious possibility to achieve high output powers at high efficiencies. The overall output power scales sublinear with the number of individual lasers, depending on the thermal interaction between the array elements. Therefore, the thermal crosstalk is an important parameter to describe the output characteristics of densely packed two-dimensional arrays that provide high output powers at high conversion efficiencies as well as high spatially averaged power densities.

## 2. Thermal crosstalk in bottom-emitting arrays

For the investigated arrays bottom-emitting devices are preferred because of the better beam quality and the possibility of junction-down mounting for better heat removal [4]. The device structure and the processing are described elsewhere [5]. In order to understand the thermal effects in monolithic arrays we have measured the temperature increase $\Delta T_A$ of a VCSEL $A$ as a function of dissipated power $\Delta P_{diss,B}$ in a neighboring VCSEL $B$. The thermal cross-resistance $R_{cross}$ is defined in analogy to the thermal resistance as

$$R_{cross,AB} = \frac{\Delta T_A}{\Delta P_{diss,B}}. \tag{1}$$

To separate the mutual thermal interaction between the two devices, device $A$ is driven under pulsed condition. Thus the time averaged dissipated power can be neglected. In Fig. 1 the thermal cross-resistance of unmounted lasers versus device spacing $d$ is plotted for distances from 70 up to 370 $\mu$m. From the fit function, we obtain a thermal cross-resistance which is inversely proportional to the device spacing plus

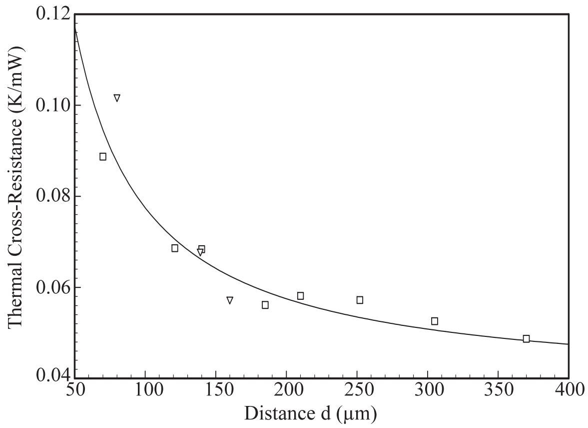


Fig. 1. Thermal cross-resistance $R_{cross}$ versus device spacing.

a certain offset.

In order to study the thermal interaction between parallel driven devices in some detail measurements are performed on a $3{\times}1$ VCSEL array mounted on a diamond heat sink. This heat sink provides structured metal pads to allow individual operation of the three devices. Fig. 2 shows an image of this test

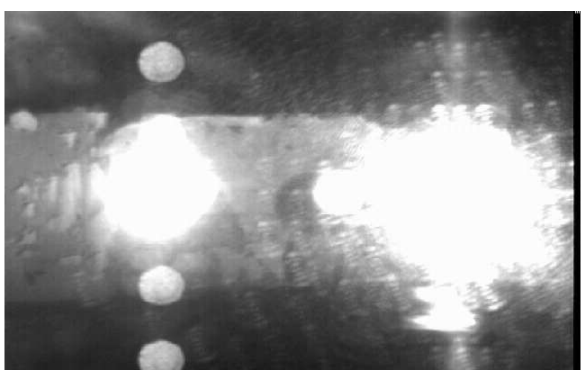

Fig. 2. Image of the separately operated 3x1 array. The left device is driven under pulsed conditions, the center device is off, and the right device runs cw.

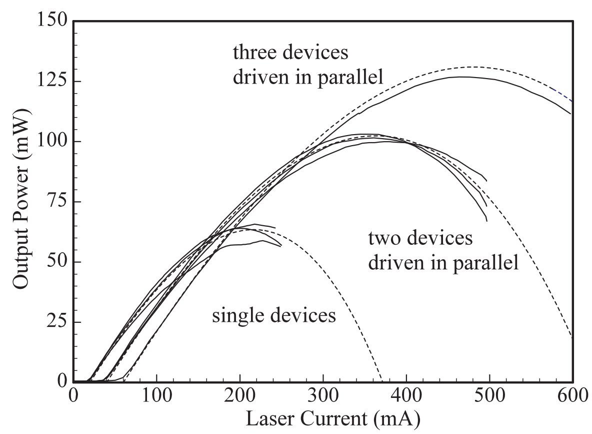


Fig. 3. Measured output characteristics of the individually addressable 3x1 VCSEL array where the devices are driven separately, two in parallel, and all in parallel under cw conditions. Dashed lines correspond to simulations including thermal crosstalk.

structure, where the left device is driven under pulsed conditions, the center device is off, and the right device runs cw. The active diameters are 50 $\mu$m and the center spacings between devices are 140 $\mu$m. Solid lines in Fig. 3 show the measured LI curves of the three devices driven separately, two in parallel, and all three in parallel, respectively. The threshold current scales perfectly with the number of devices driven in parallel. Also differential quantum efficiency is constant for all cases just above threshold. At higher driving currents the parallel driven devices suffer from additional cross heating resulting in a power penalty compared to the sum of the output powers when driven separately. The total optical power of an array can be calculated by applying the functional behavior of the thermal crosstalk versus device spacing to the simple modeling of output power versus laser current introduced in [4]. The result is

$$P_{opt,array} = \sum_{j=1}^{n} \frac{\hbar\omega}{q}(i_j - i_{th})\eta_d \cdot (1 - \frac{\sum_{m=1}^{n} R_{th,jm}((u_k + i_m \cdot R_d)i_m - P_{opt,m})}{\Delta T_{off}}). \qquad (2)$$

The first factor in the sum describes the optical output power of an undisturbed individual VCSEL of constant injection efficiency, whereas the second part accounts for the thermally induced decreasing differential efficiency due to superposition of self- and cross-heating. Mounted test structures show the same measured improvements for both the thermal resistance and the thermal cross-resistance. The simulated dashed LI curves in Fig. 3 for the individually operated elements of the test structure and the resulting simulated output characteristics for the devices driven in parallel show excellent agreement with the measured solid curves. This confirms that the presented model can be used as a powerful tool for estimating the output characteristics of densely packed arrays as a function of device size, device spacing, and number of elements.

## 3. Two-dimensional densely packed bottom-emitting array

We have fabricated two-dimensional arrays with 23 individual elements arranged in a honeycomb structure as shown in Fig. 4 in order to achieve the highest packing density and a highly symmetrical thermal interaction. The mesa diameters are 40 $\mu$m and the center spacings amount to 90 $\mu$m. Fig. 5 depicts the

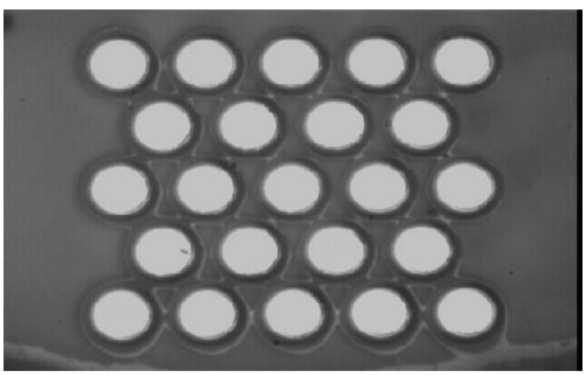

Fig. 4. Honeycomb arrangement of a 23 element VCSEL array. The device spacing is 90 $\mu$m. View of epitaxial side.

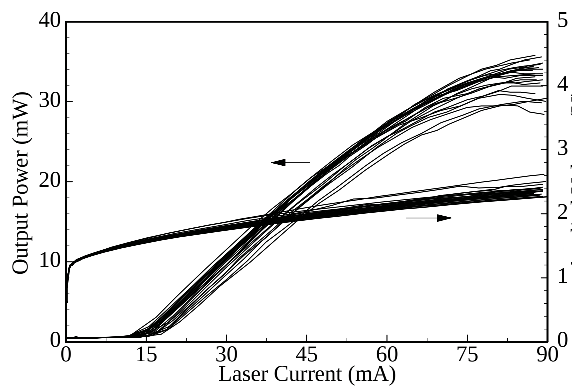


Fig. 5. Light-current and voltage-current characteristics of the 23 individual lasing array elements before mounting.

output characteristics of the unmounted individually driven elements. The 23 LI curves show good homogeneity in threshold currents of about 15 mA, threshold voltages of 1.6 V, and about 50 % differential quantum efficiency. The differential resistance is 10 Ω. The maximum conversion efficiency of 22 % is reached at three times threshold current. Thermal rollover occurs at six times threshold current at a maximum output power of about 30 mW per element.

Soldering the array junction-side down onto the heat sink, all 23 elements are electrically connected in parallel. The solid lines in Fig. 6 correspond to the experimentally obtained output characteristics of the mounted array. The threshold current of 340 mA is exactly 23 times the threshold current of an individual device. The differential quantum efficiency is slightly reduced to 43 %. Due to additional series resistances by non-optimized solder and mounting techniques, the differential resistance is 1.15 Ω. Therefore

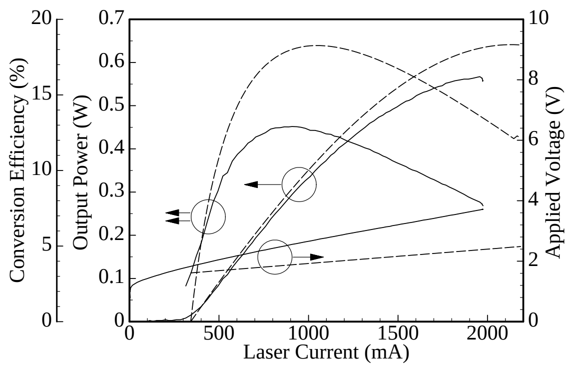


Fig. 6. Comparison of measured (solid) and simulated (dashed) total output characteristics of the mounted two-dimensional VCSEL array where all 23 lasing elements are driven in parallel.

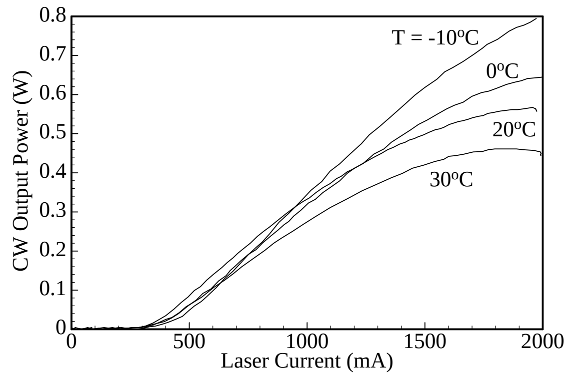


Fig. 7. Temperature dependent output characteristics of the mounted array.

threshold voltage is slightly increased to 1.8 V and conversion efficiency is limited to 13 % at almost three times the threshold current. The maximum output power at thermal rollover is 0.56 W at an array current of 2 A. The dashed lines in Fig. 6 represent the results from simulations using equation (2) and the extracted parameters from the individual unmounted VCSELs. The simulated LI curve fits the measured one quite well, although the quantum efficiency is slightly smaller in the experiment. Since the increase in series resistance due to mounting is neglected the differential resistance of 1.15 Ω is underestimated in the model giving 0.44 Ω. Therefore the maximum conversion efficiency is overestimated to about 18 %, which, however, can be taken as guideline for optimum mounting.
Temperature dependent LI characteristics of the array are presented in Fig. 7. For heatsink temperatures between -10°C and 30°C the threshold current only varies slightly, the minimum threshold current is obtained at room temperature. For lower heat sink temperature heat removal is more efficient resulting in a maximum output power of 0.8 W for a laser current of 2 A and a heat sink temperature of -10°C where no thermal rollover is observed yet. The corresponding spatially averaged power density is 0.47 kW/cm$^2$.

## 4. Summary

Densely packed two-dimensional bottom-emitting VCSEL arrays have been fabricated and mounted. Detailed investigations of the thermal interplay between individual elements considered in a simplified simulation of output characteristics show quantitatively the output power limitation by both thermal effects, self and cross heating. In experiments 0.56 W and 0.8 W optical output power at room temperature and -10°C, respectively, are observed. The maximum spatially averaged power density of 0.47 W/cm$^2$ is promising for of high power applications.

## References

[1] G. Reiner, E. Zeeb, B. Möller, M. Ries, and K.J. Ebeling, "Optimization of planar Be-doped InGaAs VCSELs with two sided output", *IEEE PTL*, vol. 7, pp. 730-732, 1995.

[2] K. Choquette, "Fabrication technologies of vertical cavity lasers", *TOPS Vol. XV, Advances in VCSELs*, pp. 200–216, 1997.

[3] R. Michalzik, M. Grabherr, and K.J. Ebeling, “High-power VCSELs: Modeling and experimental characterization (invited)”, in *Proc. Optoelectronics ’98 - Vertical-Cavity Surface-Emitting Lasers II*, vol. 3286, pp. 206–219, San Jose, California, USA, Jan., 1998.

[4] M. Grabherr, M. Miller, R. Jäger, R. Michalzik, U. Martin, H. Unold, and K. J. Ebeling, “High power VCSELs - single devices and densely packed arrays”, *submitted to IEEE J. Selected Topics Quantum Electron.*, 1998.

[5] M. Grabherr, R. Jäger, M. Miller, C. Thalmaier, J. Heerlein, R. Michalzik, and K. J. Ebeling, “Bottom-emitting VCSELs for high cw optical output power”, *IEEE Photon. Techn. Lett.*, vol. 10, pp. 1061–1063, 1998.