

Advanced characterization techniques for high power VCSELs

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ABSTRACT

The performance of high power VCSELs in a specific application depends on the geometrical and thermal design as well as on the quality of the epitaxially grown material. Due to the relatively high heat load in densely packed high power arrays the temperature in the active zone and the DBR mirrors changes significantly with the applied current and the traditional characterization methods become less meaningful than for low power devices.

This paper presents a method to measure temperature independent power curves with the help of short pulse techniques and data mapping at different heat sink temperatures. In addition the internal quantum efficiency, the transparency current and the gain coefficient are measured by a novel method which operates the VCSEL material as an edge emitter and applies a cut-back technique. The optical losses in the DBR mirrors are determined using external feedback.

In summary all relevant parameters which determine the quality of an epitaxial design are measured independently and can be directly compared with modeling and help to optimize the high power VCSEL performance.

Keywords: high power VCSEL, efficiency, operating temperature, short pulse operation, cut-back method, internal quantum efficiency, external feedback

1. INTRODUCTION

High power VCSELs and especially arrays of high power VCSELs have recently gained a lot of interest^{1,2}. VCSELs are superior to edge-emitting diodes with respect to attainable optical properties, ease of manufacturing and reliability. Therefore they will be applied in many new applications, which can directly benefit from these unique properties.

High power applications require VCSEL operation at much higher temperature than in datacom or sensing applications. Furthermore the temperature changes significantly with injected current and so the measurement of typical laser characteristics like e.g. a power curve become more difficult to interpret. On one hand they are determined by material properties (internal quantum efficiency, transparency current density, gain coefficient, optical absorption) but on the other hand they reflect specific array lay-out choices and cooling capabilities. It is the purpose of this paper to separate these effects and to measure as much as possible parameters independently.

The optical output power of a VCSEL structure can be described by the equation

$$P_{opt} = \eta_i * \eta_d * (I - I_{th}) * h\nu, \quad (1)$$

with the internal quantum efficiency η_i , the optical efficiency η_d , the current I over the threshold current I_{th} and the photon energy $h\nu$. This can be refined to include more fundamental considerations like the out-coupling A_m , internal losses A_i , transparency current I_{tr} and gain parameter g_0 . All parameters are defined in % per round trip. This then leads to

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$$P_{opt} = \eta_i * \frac{A_m}{A_m + A_i} * \left(I - I_{tr} * \exp\left(\frac{A_m + A_i}{g_0}\right) \right) * h\nu. \quad (2)$$

A complete description of a VCSEL requires information about all these parameters, which are not easily addressable by measuring LIV curves.

Most of the parameters in equation (2) depend on the internal temperature of the active area, which in itself is only indirectly addressable and changes with the current in the device. We assume that the losses α_i , the internal quantum efficiency η_i and the gain parameter g_0 are functions of the internal temperature of the device. The threshold current also depends on the detuning of gain maximum and cavity resonance^{3,4}. Detuning can be designed for optimum performance at a certain temperature. To describe a VCSEL structure and to optimize a design to meet the needs of an application the knowledge about all these parameters and their temperature behavior is essential.

Different methods are applied to address the different parameters. Short pulse techniques are used to extract the real slope efficiency of an LIV curve. Additionally, the comparison of voltage curves for cw and pulsed measurements can be used to extract the thermal resistance of a structure. With an analysis of the internal temperatures of LIV(T) measurements in cw operation it is also possible to extract LIV curves at constant internal temperature. Edge emitters processed out of VCSEL wafer structures can be analyzed to extract the internal quantum efficiency and the transparency current density. The internal losses of VCSEL structures can be measured with a Findlay-Clay analysis of measurements with variable feedback.

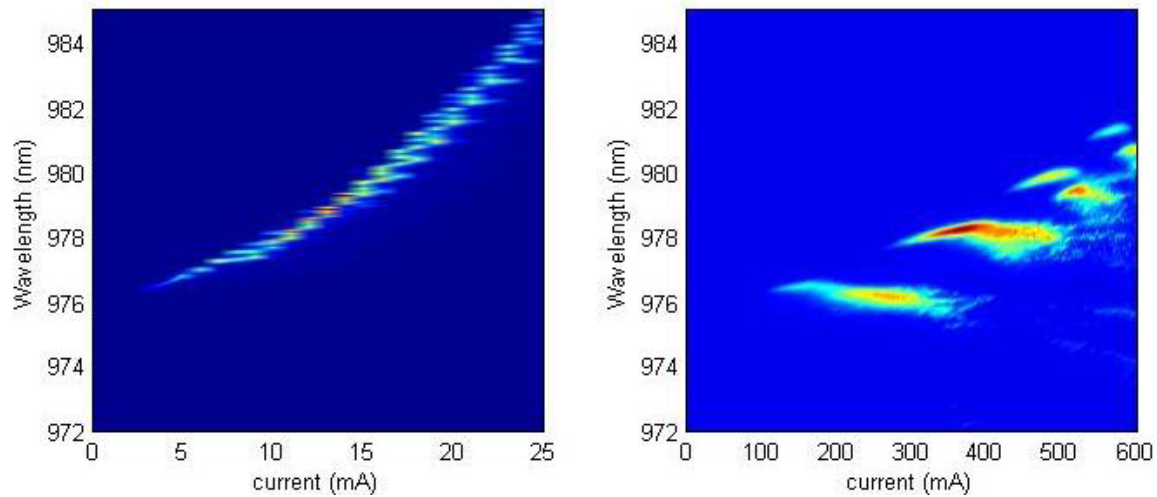


Figure 1: Wavelength shift of a 10µm (left) and a 100µm (right) diameter VCSEL over current due to internal heating.

All measurements and analysis methods are performed with large area (100µm in diameter) bottom emitting VCSELs with an emission wavelength of 980nm. The growth of the VCSEL structures is performed with MBE on n-type GaAs substrates. The AlGaAs n-type DBR grown on the substrate serves as output coupler. The active region consists of three InGaAs quantum wells. A high-Aluminum containing layer is placed close to the active region and is oxidized in the processing to form an oxide aperture. On top of the active region an AlGaAs p-type DBR with high reflectivity is grown.

In the processing metal contacts for current injection are evaporated on the p-side and on the n-side, respectively. Mesas are etched with dry-etching (reactive ion etching, RIE) to expose the Aluminum-rich layer for oxidation in a furnace containing humid atmosphere. The backside of the substrate is thinned down to 200µm and covered with an anti-reflection coating. Finally, the devices are cleaved and packaged on AlN (aluminum nitride) heat-spreading submounts for measurements.

2. SHORT PULSE TECHNIQUES

Laser diode output powers are often limited by internal heating of the laser diode. The use of short pulses allows the measurement at high current without heating up the device, while for cw measurements the internal temperature changes with current.

Figure 2 shows the voltage (a) and output power (b) characteristics of a 100 μm large VCSEL device in cw (solid curves) and with 100ns pulsed (dashed curves) operation. The internal heating of the laser in cw operation is visible in the rounded voltage curve and in the thermal roll-over in the output power.

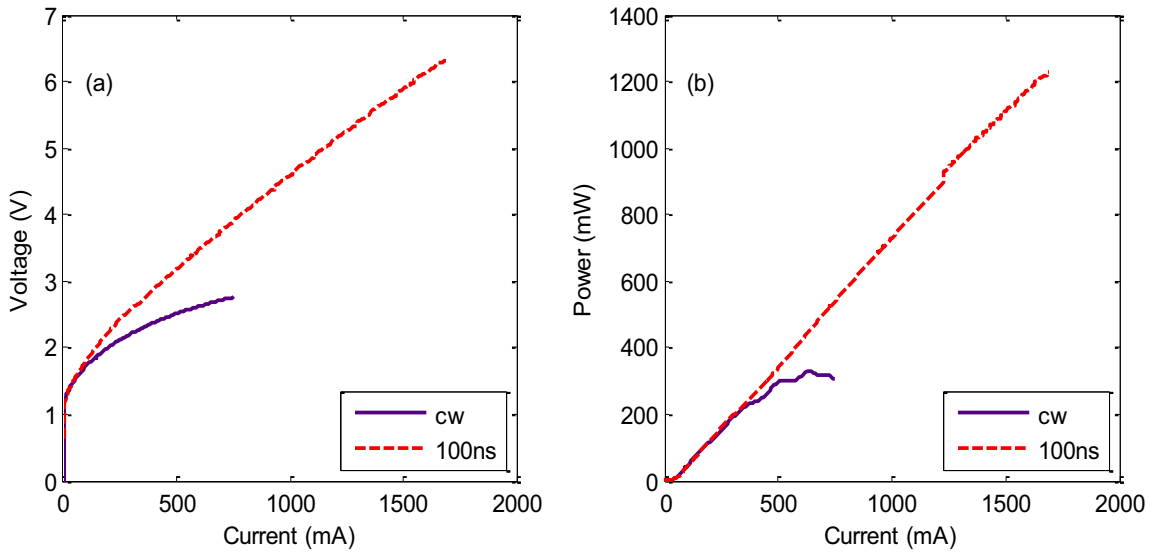


Figure 2: Voltage (a) and output power (b) of a large diameter VCSEL in CW operation and with short pulses (100ns).

The internal heating of laser diodes can be approximated by introducing a thermal resistance R_{th} :

$$\Delta T = R_{th} * P_{diss} = R_{th} * (U * I - P_{opt}), \quad (3)$$

with ΔT the temperature increase of the active region caused by the dissipated power P_{diss} . The thermal resistance of a small area VCSEL is determined by measuring the wavelength shift of the laser vs. the dissipated power. The laser resonance wavelength shifts with the temperature of the resonator due to the change in the refractive index and the change of the resonator length. For large area VCSELs the emission pattern is often distorted from a linear increase of the wavelength with the dissipated power⁵ and the thermal resistance cannot be extracted from wavelength measurements. Figure 1 illustrates this problem by showing a measurement of the emitted spectrum vs. current for a small diameter and a large diameter VCSEL. For the latter it is not possible to derive the internal temperature from the spectrum. To extract the thermal resistance independent of the emission modes of the laser we propose to use the voltage dependence of the laser on the temperature.

The voltage depends on current and temperature. While for a pulsed measurement the internal temperature equals that of the heat sink it increases with the current for cw measurements. A comparison of voltage curves in cw operation at low temperatures and voltage curves of pulsed measurements at room temperature or elevated temperatures show an intersection (see Figure 3).

At this intersection the temperature of the mirror and active area of the measurement in cw operation equals the temperature in pulsed operation, which for the pulsed measurement is equal to the heat sink temperature. The difference in heat sink temperatures of the measurements in combination with the dissipated power at the intersection of the curves

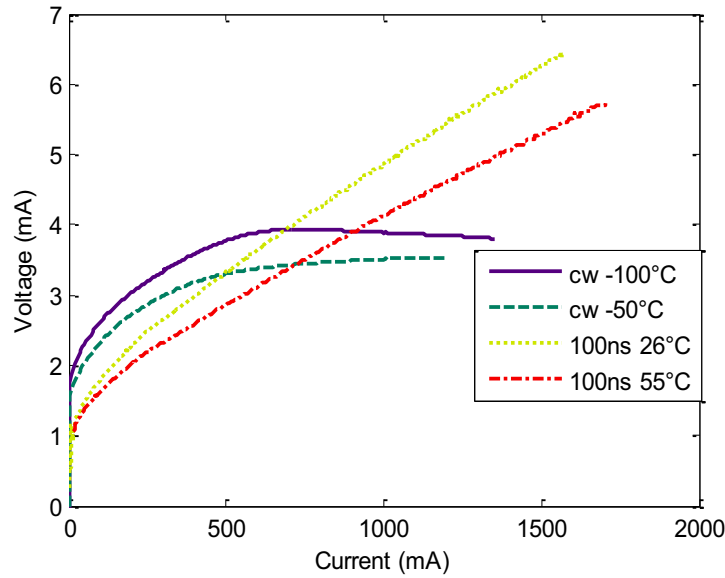


Figure 3: Voltages of a large diameter VCSEL with cw operation and with short pulse operation (100ns) for different heat sink temperatures.

allows to determine the thermal resistance. Using several measurement curves with different heat sink temperatures further increases the measurement accuracy.

We have demonstrated that it is possible to implement measurements with short pulses to overcome the problem of internal heating during the measurement process and to be able to extract relevant VCSEL parameters that are defined for constant temperature of the active zone. However measurements with short pulses (with pulse widths of 100 ns) require elaborate pulse shape preparation and are therefore not as practicable as cw measurements.

3. LIV CURVES FOR CONSTANT INTERNAL TEMPERATURES EXTRACTED FROM CW MEASUREMENTS AT VARIOUS HEAT SINK TEMPERATURES

Once the thermal resistivity of a specific device is known subsequent measurements of the cw current-power behavior over varying heat sink temperature can be used to extract LIV curves for constant internal VCSEL temperatures. To determine the behavior at constant temperature a complete series of measurements of the light-voltage-current characteristics over a wide heat sink temperatures range (-80 to +80°C) is performed. The internal temperature of the device depending on the dissipated power at every current and heat sink temperature is calculated via the formula

$$T_{int} = T_{HS} + R_{th} * P_{diss} = T_{HS} + R_{th} * (I * V - P_{opt}) \quad (4)$$

Every data point consists of its heat sink temperature, internal temperature, current, voltage and output power. There are several combinations of heat sink temperature, current, voltage and output power that result in the same internal temperature. Different data points corresponding to the same internal temperature define new LIV curves for a constant internal temperature. By this means, new LIV curves for constant internal temperatures can be compiled from the cw measurements.

Figure 4 shows a direct comparison of the measurement at 20°C heat sink temperature with the curve extracted for a constant internal temperature of 20°C.

Both curves show a similar threshold current of about 100mA and a comparable slope close above threshold. The measurement at 20°C constant heat sink temperature shows the well-known thermal roll-over behavior at 500mA. The extracted curve for constant internal temperature on the contrary shows a constant increase of the light output without thermal roll-over up to 700mA. The different behavior at constant internal temperature and at cw operation illustrates the importance of the rigorous temperature analysis presented here.

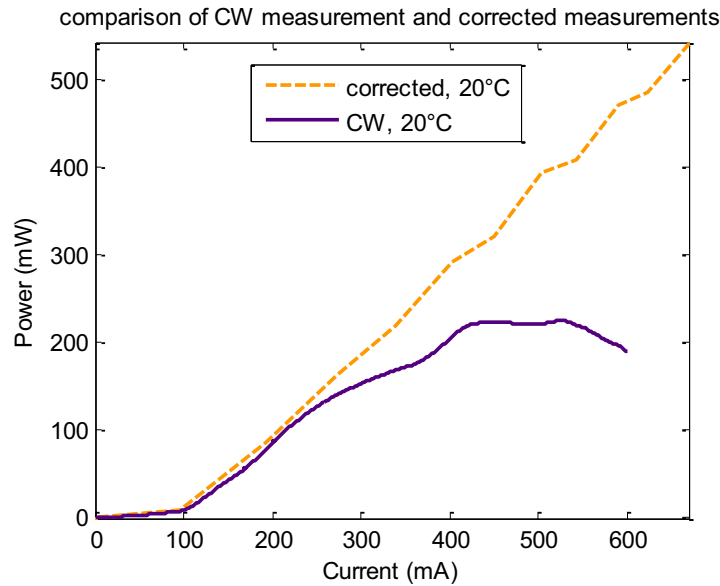


Figure 4: Comparison of LIV curves of a cw measurement at a constant heat sink temperature of 20°C and corrected for a constant internal temperature of 20°C.

Figure 5 shows a direct comparison of measurements of LI curves at different constant heat sink temperatures (-80 to 60°C) and the extracted curves for constant internal temperatures of 20 to 120°C.

4. EDGE EMITTING LASERS PROCESSED FROM WAFERS DESIGNED AS VCSELS

For edge emitter lasers parameters like the internal quantum efficiency, internal losses and transparency current normally are extracted by measuring the L-I characteristics at various cavity lengths^{6,7}. However, for VCSELs this technique is not applicable as the cavity length is fixed by the epitaxial wafer design. Also in a VCSEL the region around the active zone can be designed such that there is sufficient optical confinement in the transverse direction to support the propagation of longitudinal modes. The reflections at the DBR mirrors of the VCSEL structure only have a small effect on the edge

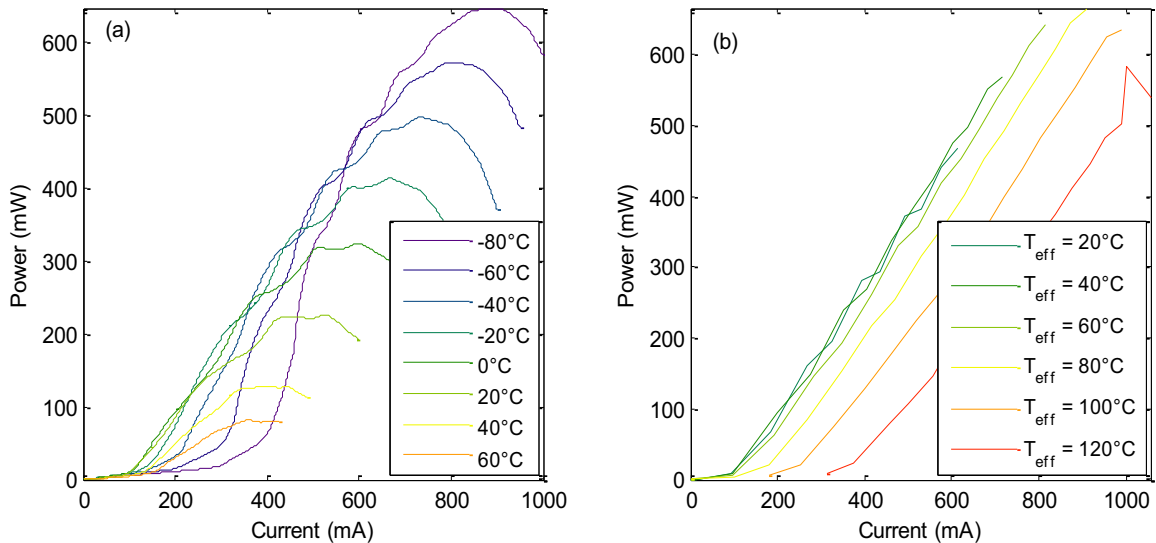


Figure 5: Measurements of LI curves at constant heat sink temperature (a) and translation to constant internal temperatures (b).

emitting properties.

A VCSEL wafer is processed as gain guided edge emitting laser. Mesa structures are etched in the top mirror to define the current injection (see Figure 6). Ohmic contacts are deposited on the n and p sides of the wafer.

Laser bars of different length are cleaved and finally laser diodes are diced and mounted p side up on an AlN ceramic submount. The submount is mounted on a heat sink which can be temperature controlled using a Peltier element. Lasers are tested in pulse mode (100ns and 0.1% duty cycle) to eliminate internal heating of the active layer. Typically a 50-100μm stripe width is used. LIV characteristics have been measured at 25°C heat sink temperature for cavity lengths ranging from 300 μm to 2000 μm. The following equation valid for all semiconductor lasers⁶ is used in the analysis:

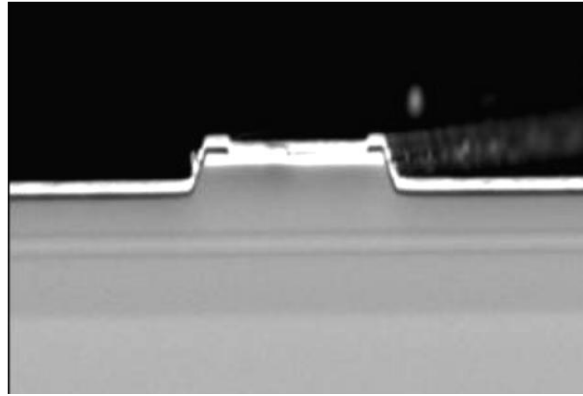


Figure 6: SEM-picture of cross section through Mesa structure, which defines the current injection.

$$\frac{1}{\eta_{ext}} = \frac{1}{\eta_{int}} \left(1 + \frac{\alpha_i L}{\ln(1/R)} \right) \quad (5)$$

with the external quantum efficiency η_{ext} , the internal quantum efficiency η_{int} , the losses α_i , the length of the laser bar L and the reflectivity of the cleaved mirror facets R . For the threshold current density J_{th} the equation

$$J_{th} = J_{tr} + (d/\Gamma\beta) [\alpha_i + \ln(1/R)/L] \quad (6)$$

with the transparency current density J_{tr} , the thickness of the quantum wells d , the confinement factor Γ and the slope β of gain over current density is used.

Plotting $1/\eta_{ext}$ versus cavity length L the internal efficiency and the internal loss can be extracted using equation (5). With the help of equation (6) the transparency current density J_{tr} is obtained by plotting the threshold current density J_{th} versus the inverse cavity length $1/L$ and using the internal loss value α_i from equation (5).

Figure 7 shows the results of a measurement at 25°C in pulsed operation. The linear fit to the inverse external efficiency over the cavity length L (see Figure 7(a)) yields $1/\eta_{ext} = 1.0536 + 5.8385 \cdot L$. The internal efficiency is the inverse of the axis intercept of the fit resulting in 95%. The losses of the edge emitting structure are extracted from the slope of the fit (mirror reflectivity $R = 0.3$) resulting in $\alpha_i = 6.7 \text{ cm}^{-1}$. It should be mentioned that the measured loss is determined by the overlap of the optical mode and the material loss. While for the dominant TE mode the latter is identical for VCSELs and edge emitters the optical mode pattern is very different and thus this loss cannot be directly translated to a VCSEL loss. The fit to the threshold current density gives $J_{th} = 141.581 + 7.1442 \cdot 1/L$. The transparency current density J_{tr} is determined by this equation and a virtual length L' at which the sum of the losses and the gain equals zero:

$$\alpha_i + \ln(1/R)/L' = 0. \quad (7)$$

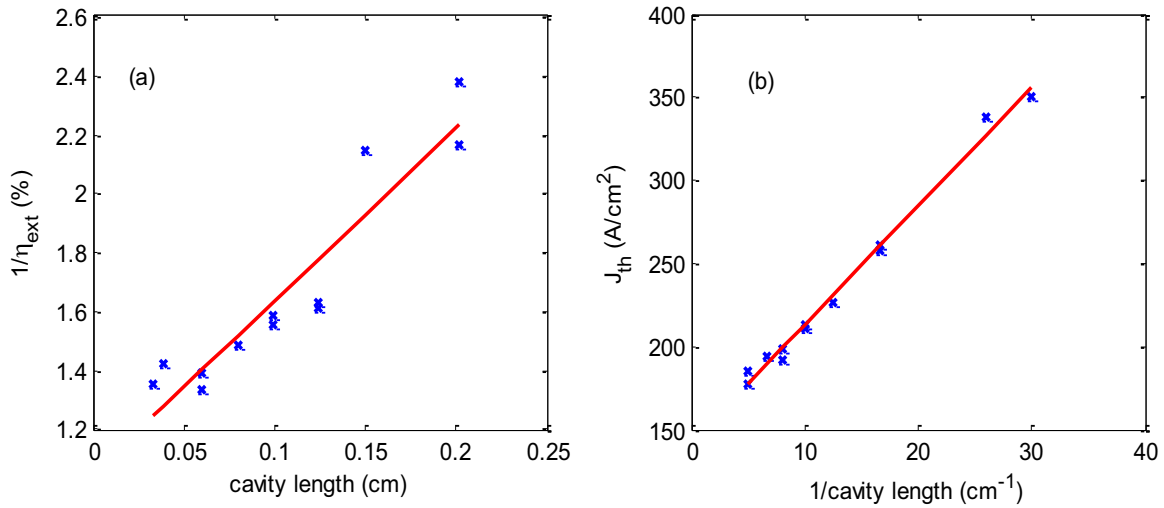


Figure 7: (a): Inverse of external efficiency over cavity length. (b) Threshold current density over inverse cavity length.

Note that the factor $d/\Gamma\beta$ drops out of the equation and does not affect the analysis of the transparency current density. With the losses to be 6.7cm^{-1} from the above analysis this results in $J_{\text{tr}} = 101\text{ A/cm}^2$.

The internal quantum efficiency $\eta_i = 0.95$ reveals the good carrier injection into our structure. Together with the transparency current density $J_{\text{tr}} = 101\text{ A/cm}^2$ this value can be used for further analysis of the VCSEL designs. These two parameters characterize the performance of the quantum wells and are relevant in a VCSEL, too. To our knowledge this is the first time that VCSEL wafers are characterized in this way to reveal the internal quantum efficiency and the transparency current.

5. DETERMINATION OF INTERNAL LOSSES IN VCSEL DEVICES

The optical losses determined with the cut-back method of edge emitters will not be the same as for a VCSEL structure as the optical path is very different for the two laser types. The optical losses in a VCSEL therefore have to be extracted in a different way. Instead of changing the cavity length the internal losses of VCSELs are determined by varying the mirror out-coupling using optical feedback^{8,9}.

We adapt the exponential gain model commonly used for the broad gain regime⁶ to derive an equation for the threshold currents:

$$I_{\text{th}} = I_{\text{tr}} \exp\left(\frac{A_m + A_i}{g_0}\right), \quad (8)$$

with the transparency current I_{tr} , the internal losses and the mirror out-coupling A_i and A_m and the gain constant g_0 . In VCSELs the mirror out-coupling is defined by the epitaxial design. However, it is still possible to vary the mirror out-coupling by using an external cavity and to feed a part of the emitted light back into the laser. The mirror out-coupling A_m is then the effective mirror out-coupling of the combined cavity consistent of the out-coupling mirror of the VCSEL and the external mirror.

Our experimental arrangement is shown in Figure 8. Light emitted from a VCSEL is collimated by a microscope lens and reflected back by different dielectric mirrors of defined reflectivities and transmissions. A variable attenuator placed inside the cavity is additionally used to further vary the amount of light coupled back into the VCSEL. The variable attenuator and the detector are slightly tilted to avoid uncontrolled feedback into the VCSEL.

We investigated several oxide confined, bottom emitting 980 nm lasers with different mirror configurations (different numbers of mirror pairs and mirror doping profiles). Light-current curves of the different VCSELs in the external cavity

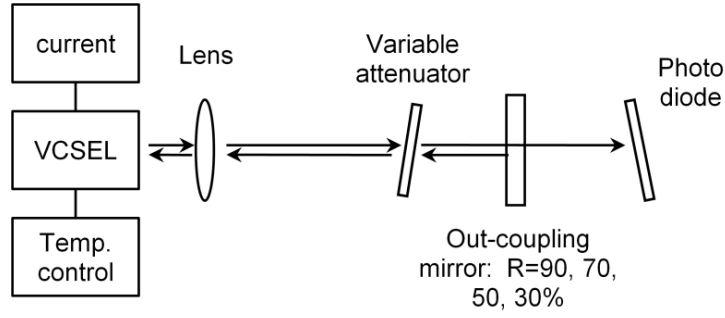


Figure 8: Schematic diagram of the experimental arrangement.

were taken for different mirror reflectivities and variable attenuator transmissions (see Figure 9), and the threshold current was determined for each value of the effective reflectivity of the coupled cavity.

The effective reflectivity of the external cavity is determined using the transfer matrix method¹⁰ by taking the coupled cavity of the VCSEL, the substrate, the variable attenuator and the out-coupling mirror into account. The complex field amplitudes of incoming and outgoing plane waves for an arbitrary optical system can be connected via the transfer matrix A_{tot} :

$$\begin{pmatrix} E_{0+} \\ E_{0-} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} * \begin{pmatrix} E_{1+} \\ E_{1-} \end{pmatrix}, \quad (9)$$

The complex transmission coefficient is then

$$t_A = \frac{E_{1+}}{E_{0+}} = \frac{1}{A_{11}}, \text{ the reflection coefficient is } r_A = \frac{E_{0-}}{E_{0+}} = \frac{A_{21}}{A_{11}}. \quad (10)$$

For a system consisting of different components like the coupled cavity in this investigation the transfer matrices of the transitions between media with different refractive indexes and the propagation in each material have to be taken into

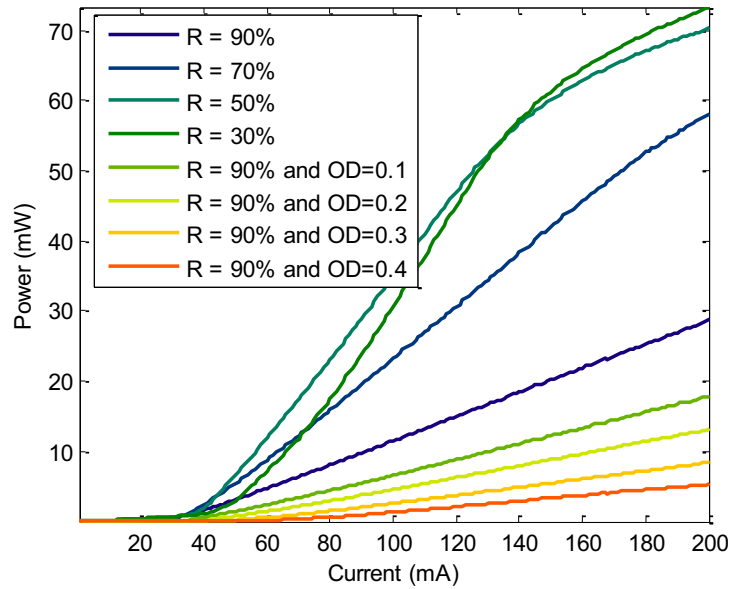


Figure 9: LIV curves with different reflectivities of the external mirror varying from 90 to 30% and with a mirror reflectivity of 90% and various attenuators with optical densities between 0.1 and 0.4.

account. To extract the absorption in the mirrors we replace the real, absorbing DBR mirrors with non-absorbing DBR mirrors. The losses due to absorption of the mirrors are then part of the losses of the external cavity and can be determined with this analysis.

Taking a transfer matrix for every component of the system and vertical propagation of the light gives

$$A_{tot} = \begin{pmatrix} \frac{1}{t_{DBR}} & \overline{\left(\frac{r_{DBR}}{t_{DBR}} \right)} \\ \frac{r_{DBR}}{t_{DBR}} & \overline{\frac{1}{t_{DBR}}} \end{pmatrix} * \begin{pmatrix} 1 & 0 \\ t_{substrate} & t_{substrate} \end{pmatrix} * \begin{pmatrix} 1 & 0 \\ t_{attenuator} & t_{attenuator} \end{pmatrix} * \begin{pmatrix} e^{i\delta} & 0 \\ 0 & e^{-i\delta} \end{pmatrix} * \begin{pmatrix} \frac{1}{t_m} & \overline{\left(\frac{r_m}{t_m} \right)} \\ \frac{r_m}{t_m} & \overline{\frac{1}{t_m}} \end{pmatrix}, \quad (11)$$

for the complete optical system, where the first term stands for the transition through the DBR mirror, the following terms account for the propagation in the substrate, in the attenuator, the propagation in air and the transition through the out-coupling mirror. A bar above a term denotes its complex conjugate.

Provided a proper adjustment of the external cavity length via the phase factor δ equations (10) and (11) result in the effective reflectivity of the complete system

$$|r_{eff}| = \frac{|r_{DBR}| + |t_{substrate}|^2 * |t_{attenuator}|^2 * |r_m|}{1 + |r_{DBR}| * |t_{substrate}|^2 * |t_{attenuator}|^2 * |r_m|}, \quad (12)$$

with r_{DBR} the reflectivity of the out-coupling DBR mirror of the VCSEL, $t_{attenuator}$ the transmission of the attenuator, $t_{substrate}$ the transmission of the substrate and r_m the reflectivity of the out-coupling external mirror. For simplicity, we assume that the reflection of the top Bragg mirror is unity for a bottom emitting structure. The top mirror losses will then be contained in the internal losses determined by the analysis. The method is transferable to top emitting structures by setting the transmission of substrate to unity. The effective mirror out-coupling is

$$A_{m,eff} = 1 - |r_{eff}|^2. \quad (13)$$

The experimental results are analyzed with the Findlay-Clay-analysis method¹¹ with the measured threshold currents and the effective mirror out-coupling for each combination of external mirror reflectivity and attenuator transmission. A Findlay-Clay analysis was first presented to extract the internal losses of a 4-level laser by analyzing the threshold currents as a function of the reflectivity and in this paper is adapted for analyzing VCSEL structures. We analyzed several VCSEL structures (A to E) designed to show different amounts of internal loss. The VCSEL structures under investigation have active areas of 100 μm . Structure A for example consists of 22 $\text{Al}_{0.87}\text{Ga}_{0.13}\text{As}$ /GaAs quarter-wavelength stacks in the n-DBR mirror. The p-DBR mirror consists of 30 $\text{Al}_{0.87}\text{Ga}_{0.13}\text{As}$ /GaAs quarter-wavelength stacks with aluminum and doping profiles adapted for good electrical conductivity. The out-coupling of the VCSEL reaches 1.128% with this mirror composition. In Figure 10 the natural logarithm of the threshold currents is depicted against the effective mirror out-coupling of the coupled cavity.

With equation (8) we extract $g_0 = 0.0066$ and $A_i = 0.81\%$ with a transparency current density of 101 A/cm^2 as measured with the same wafer structure processed as edge emitter and analyzed with the cut-back method. The transparency current density is characteristic for the active region of a device. A variation of the mirror design should leave the transparency current density unchanged and then allows a comparison of mirror losses for different mirror designs with the same active area.

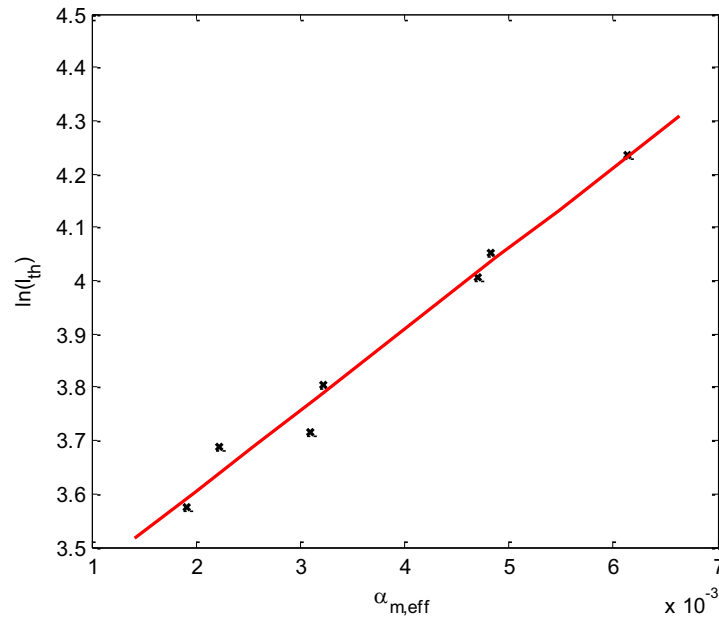


Figure 10: Threshold currents on a logarithmic scale versus effective mirror out-coupling for an exemplary device of structure A. The internal losses are extracted with the measured threshold currents and the respective mirror out-coupling of the configuration and equation (7).

With this method we analyzed several designs with different structures and different mirror pairs to reach different mirror reflectivities, out-couplings and losses. The resulting internal losses α_i are compared with calculations of the internal losses using the transfer matrix method (see Figure 11). The transfer matrix method for calculating the absorption of a mirror structure uses information about the thicknesses of each layer in the mirror, the doping and

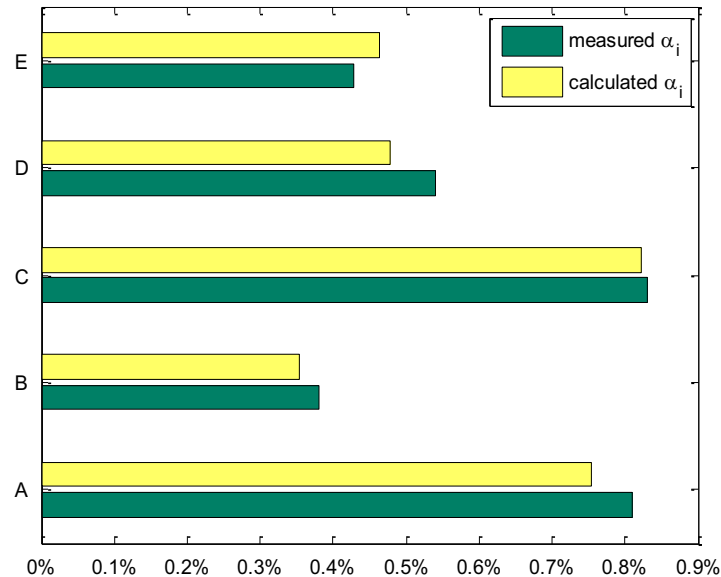


Figure 11: Measured and calculated internal losses of different VCSEL designs. The green bars indicate the losses determined with the external feedback method. The yellow bars show the results of transfer matrix calculations of the internal losses of the corresponding VCSEL designs.

aluminum concentrations and the corresponding absorption coefficients of each layer.

A very good match of calculations and measurements for all evaluated VCSEL structures could be achieved with the Findlay-Clay analysis of the threshold currents of the coupled cavity with variable feedback. Calculations with the transfer matrix method are strongly dependent on knowing the exact structure of the device and the exact correlation of the material composition and the absorption in the material. With the Findlay-Clay-analysis of threshold currents under various mirror reflectivities the sole input parameters are the transparency current density and the mirror out-coupling of the VCSEL. The transparency current density can be determined by preparing the VCSEL as an edge emitter as presented in this paper or independently by using VCSELs as proposed in ⁹. The mirror out-coupling is more easily extracted from a transfer matrix calculation than the internal losses as it is less sensitive to the variation of exact input parameters, especially of the absorption coefficients, than the calculation of the internal losses.

The measurement of internal losses with the feedback method is a valuable tool to compare different doping profiles by measuring their influence on the internal absorption. Using this knowledge a thorough mirror optimization can be carried out.

6. CONCLUSION

In this paper we present a systematic approach to the characterization of high power VCSELs. The strong underlying temperature dependence could be eliminated by a short pulse technique combined with data mapping of a large number of measurements. The method allows the calculation of power curves for a constant internal temperature and therefore easy comparison with theoretical expectations independent of the thermal and mounting boundary conditions.

A novel method uses edge-emitter measurements of VCSEL material to derive internal quantum efficiency, transparency current density or gain constant. The optical losses are determined by feedback experiments. All quantities relevant for the optical performance of a VCSEL are therefore measured independently. This allows optimizing devices for a wide range of operating temperatures in many new applications of high power VCSEL arrays.

7. ACKNOWLEDGMENT

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