

Dynamics of the Angular Emission Spectrum of Large-Area VCSELs

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ABSTRACT

High power VCSELs can be realized by scaling up the active area of bottom-emitting devices. This results in a large Fresnel number of the laser cavity. The laser beam cannot be described with Gauss modes in a simple way anymore, but is best described in terms of tilted plane waves, called Fourier modes. The beam quality and mode spectra depending on the applied current and the temperature of the VCSEL are investigated. Two-dimensional measurements of the near and the far field are combined with power and spectral measurement to characterize the VCSEL. Polarization and Fourier filtering are used to examine the spatially-dependent emission in detail. A rich dynamic in the angular emission profile for large-area VCSELs is observed and can be explained by considering the residual reflections from the AR-coated substrate-air interface and thermal effects. The presented theoretical model simulates the dynamics of the angular emission. The calculated angular and spectral profiles match the experimental observations very well over the whole parameter range. The influence of the active area is studied for diameters of the oxide aperture from 20 up to 300 μm . For smaller diameters diffraction effects become more dominant, the Fresnel number is reduced and the emission spectrum gets closer to the Gauss mode description.

Keywords: high-power VCSEL, large Fresnel number, beam quality, Fourier modes, far field, mode spectrum

1. INTRODUCTION

Vertical-cavity surface-emitting laser diodes (VCSELs) are very popular in low-power applications like datacom or sensing due to their high reliability and low-cost production. To scale up the output power, arrays of individual¹ or coherently-coupled^{2,3} VCSELs can be used or the active area can be increased.⁴ The last measure leads to an increase of the Fresnel number $N_F = \frac{D^2}{\lambda \cdot L_{eff}}$ with the diameter D , the wavelength λ and the effective cavity length L_{eff} . The Fresnel number is an indicator for the number of allowed modes.⁵ At some point, the description of the emission with modes of the Gauss-Hermite or the Gauss-Laguerre type is not suitable, as the paraxial approximation is not valid any more.⁶ It has been shown, that the modes of large-aperture VCSELs can be described in terms of plane-waves,⁷ which are the solution of the Maxwell-Bloch equation for an infinite plano-planar resonator. These waves can be tilted by the angle θ with respect to the optical axis of the resonator and are known as Fourier modes. This tilt leads to a shift of the resonance wavelength, such that the component of the wave vector $k_{||}$, which is parallel to the optical axis fulfils the resonance condition $k_{||} = \frac{\pi m_L}{L_{eff}}$, with m_L being the longitudinal mode order. This gives a continuous mode spectrum of travelling waves to shorter wavelengths. The non-infinite aperture of the VCSELs leads to a standing wave solution and a discretization of the mode spectrum. The wavelength spacing of the modes depends on the size of the aperture⁸ and can be calculated from the transversal wave vector component $k_{\perp} = \pi m_T / nD$, where m_T is the transversal mode order and n the refractive index. The resonance wavelength and the mode spacing depending on the tilt angle are shown in the figures 1 and 2 for three different aperture diameters.

Other studies of large Fresnel number cavities have been done with top-emitting VCSELs.^{8–10} In this work, the modal behaviour of homogeneously pumped large-area bottom-emitting VCSELs and the dynamics over current and temperature is studied and explained with an analytical physical description.

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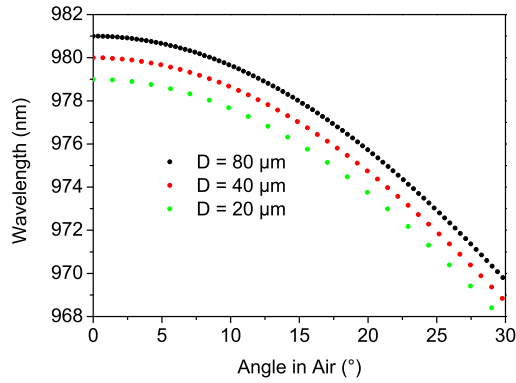


Figure 1. Mode spectrum for different aperture sizes. The resonance wavelength is shifted by 1 nm for the different diameters.

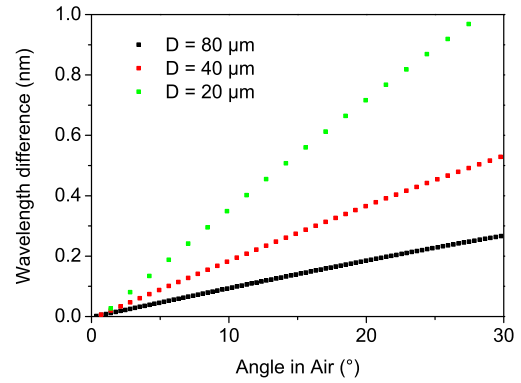


Figure 2. Mode spacing for different aperture sizes

2. EXPERIMENTAL

2.1 The VCSELs

The investigated VCSELs are supplied by Philips Technologie GmbH U-L-M Photonics. The electrically-pumped VCSELs consist of 22 n-doped AlGaAs DBR mirror pairs, a 2λ -thick cavity (1λ for wafer B) with three InGaAs quantum wells and an oxide aperture for current confinement and 33 p-doped AlGaAs DBR mirror pairs (32 mirror pairs for wafer B). Both wafers are designed for laser emission around 980 nm. Wafer B has a higher detuning at room temperature (wavelength difference between cavity resonance and the peak of the gain spectrum).

Bottom-emitting VCSELs with oxide aperture diameters between 20 and 300 μm have been processed, with both contacts on the epitaxy side. The backside of the 200 μm thick substrate is anti-reflection coated. After separation the chips are soldered with AuSn-solder on aluminum nitride submounts. The submounts are soldered on TO56 cans for easy handling.

2.2 The setup

A setup as shown in figure 3 has been implemented to measure the spatial and angular emission profiles (which are also called near field and far field) of the lasers, as well as the wavelength spectrum and the total emission power. The VCSELs (LD) are mounted on TO56 cans and contacted to the laser diode controller LDC-3700B from ILX Lighthouse (PS). The controller also monitors the heat sink (HS) temperature with an AD590 temperature sensor and can regulate the heat sink temperature with a Peltier element. The emission from the VCSEL is collimated by an aspheric lens (L1) with an NA of 0.6 and a focal length of 4.51 mm. In the back focal plane of the lens a Fourier filter (FF) can be inserted to select different parts of the angular spectrum. In addition polarization (PBS) or spectral filters (SPF) can be inserted in the optical path. A beam splitter (BS1) sends 50% of the light in an Ulbricht sphere (US), where the total power and the wavelength spectrum can be measured. The other half of the light is attenuated by a tilted neutral density filter and splitted again by the second beam splitter. In one arm, the active layer of the VCSEL is imaged with a second lens on a Pixelfly QE camera from pco (NFC). The magnification is determined by the focal lengths of the lenses L1 and L2. In the second arm, the lens L3 images the angular distribution of the VCSEL emission, which forms itself in the back focal plane of lens L1, on the second camera (FFC). The image quality of the setup has been checked by ray tracing calculations. The near field has been calibrated measuring the same VCSEL with a measuring microscope and the far field has been calibrated by a comparison with a goniometer measurement. A Labview programm controls the measurement at different currents or heat sink temperatures and calculates the beam waist diameter d_σ and the divergence angle Θ_σ (full angle) from the second order moments according to the ISO standard (ISO 11146-1:2005).

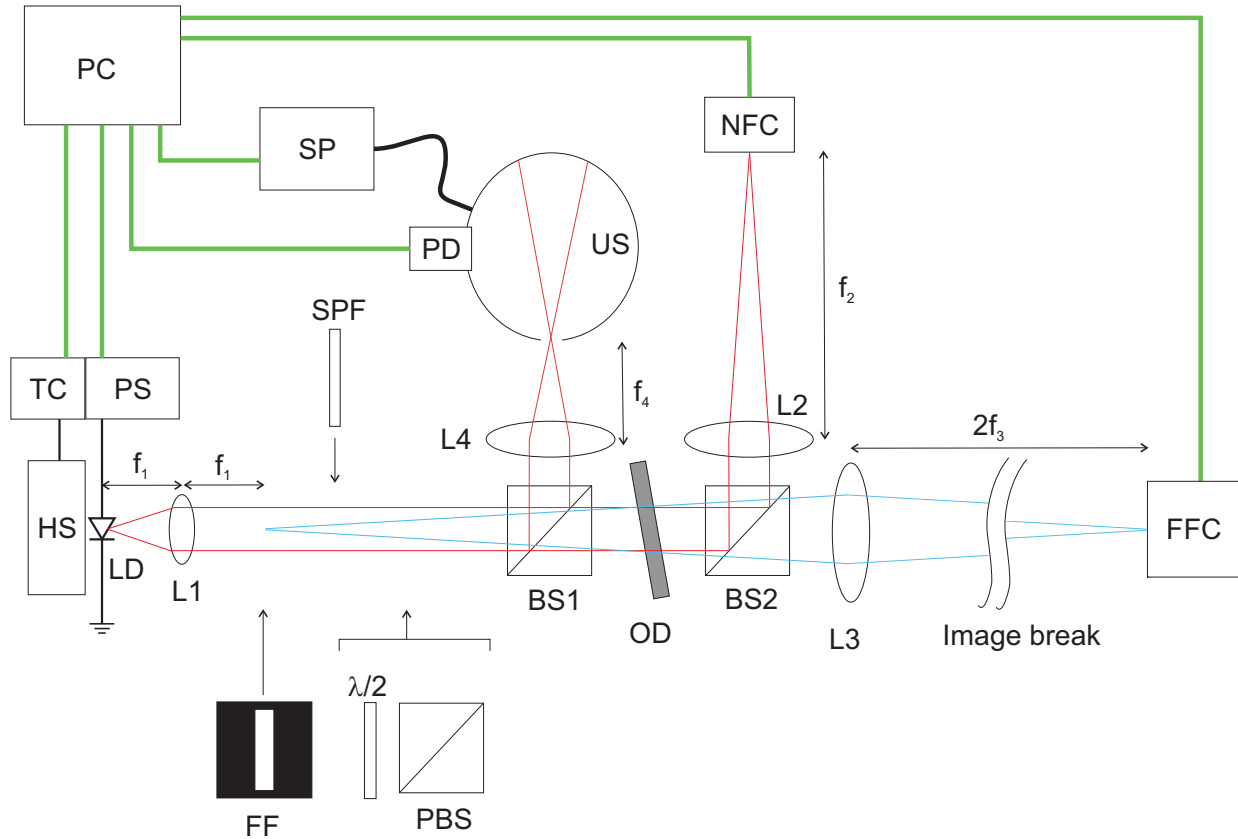


Figure 3. Schematic drawing of the experimental setup: LD: VCSEL, HS: Heatsink, TC: Temperature Controller, PS: Power Supply, SP: Spectrometer, US: Ulbricht sphere, PD: Photodiode, PC: Personal Computer, L1 to L4: Lenses, (P)BS: (Polarizing) Beamsplitter, FF: Fourier Filter, $\lambda/2$: $\lambda/2$ -plate, SPF: Short pass filter, OD: Neutral density filter, NFC: Near field camera, FFC: Far field camera

3. EMISSION CHARACTERISTICS OF BROAD-AREA VCSELS

3.1 Experimental results

A typical emission pattern of a VCSEL with an $80\ \mu\text{m}$ diameter aperture is shown in figure 4. The intensity distribution in the near field fills the complete pumped area of the VCSEL and is slightly modulated with a complex interference pattern. The angular intensity distribution is best described by a narrow ring, also modulated in the azimuthal direction. Such mode patterns are quite uncommon for most lasers and have only been observed in lasers or amplifiers with a large Fresnel number. Similar patterns have been observed for VCSELs with a square-shaped aperture¹¹ and can be described by tilted plane waves. To clarify this, a slit has been inserted in the back focal plane of the first lens L1, to select only two opposed parts of the ring. The reimaged near field in figure 5 shows that the whole active area emits in these two points in the angle space and reveals a strong interference pattern orthogonal to the direction of the two spots in the far field. This result is the same as the modal emission of a VCSEL with a square aperture at threshold¹² or with feedback from a photonic crystal.¹³ If the slit is rotated around the optical axis, similar patterns can be observed for an arbitrary tilt angle.

When the current is increased, the emission shifts to larger angles meaning that the diameter of the ring in the far field becomes larger. Therefore the interference pattern in the near field becomes more dense. When the angle of the ring reaches 15° , emission at low angles is observed and the near field becomes smeared out in the center part, while the outer part shows still the fine interference pattern (see figure 6 in the left part). At the same time, a second peak in the wavelength spectrum appears, which is 2.5 nm red-shifted, compared to the

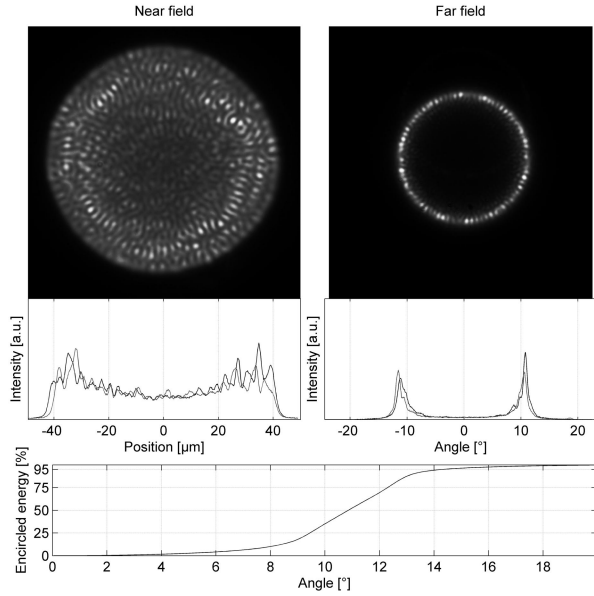


Figure 4. Typical emission profile of a 80 μm diameter device of wafer A. In the upper left corner, the intensity distribution in the near field is shown, with 2 cuts through the beam center in horizontal and vertical direction below. On the right side, the corresponding far field is shown, again with 2 cuts through the beam center.

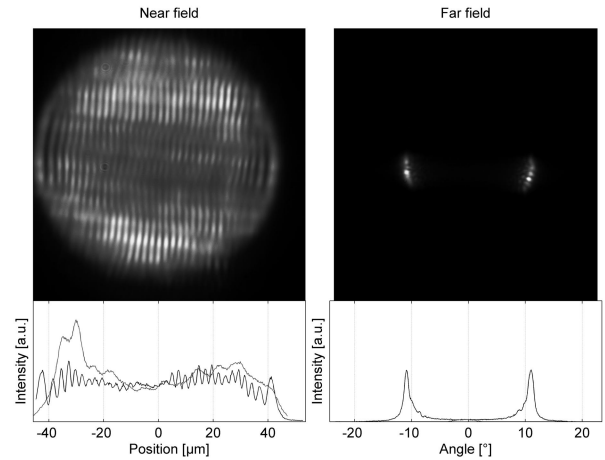


Figure 5. Same device and current as on the picture 4, but with a slit in the Fourier plane. The emission into this 2 angular regions comes from the whole active area.

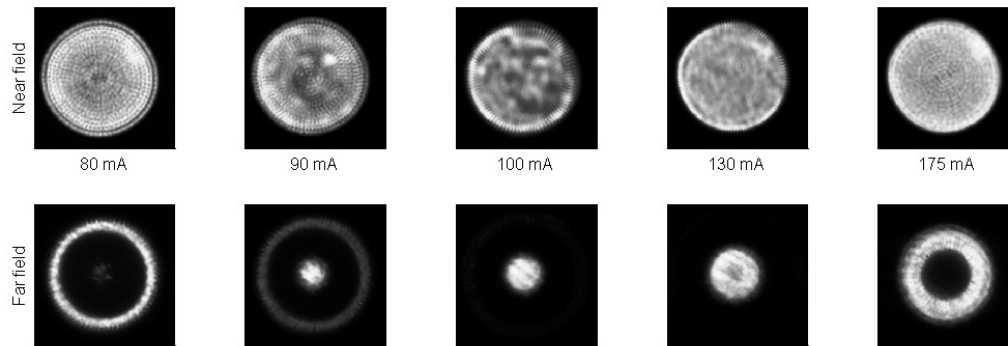


Figure 6. The emission profile of a 80 μm diameter device of wafer A for different currents.

wavelength of the ring. The ring gets weaker and disappears for higher currents (see figure 6 for currents of 100 to 130 mA). When the current is further increased the far field becomes broader. Then a dip in the far field profile appears on the optical axis and a new ring is formed. The size of the ring increases again for increasing currents and the clear interference pattern is observed in the near field. This process can be observed several times between threshold and the thermal rollover of the device. To exclude thermal effects the VCSEL is driven with 100 ns-pulses and a duty cycle of 1%. The diameter of the ring does not change if the current is increased. On the other hand, if the heat sink temperature is increased, the emission pattern shows the reversed dynamic for cw and pulsed operation. The ring becomes smaller and a new ring appears at large angles and shorter wavelength.

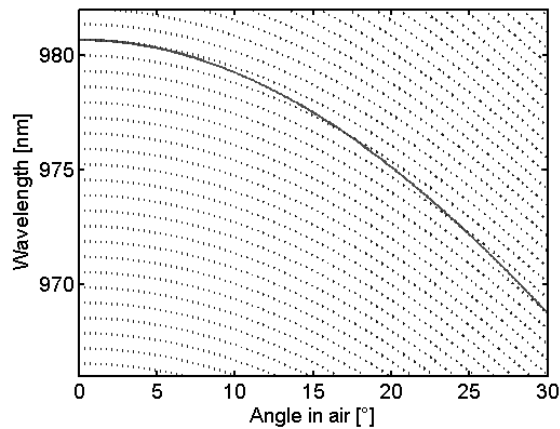


Figure 7. The mode wavelength depending on the tilt angle in air θ for the inner (red, full line) and the outer cavity (blue, dotted lines). In this example, constructive interference is observed for angles of 0° , 17° , 24° and 30° .

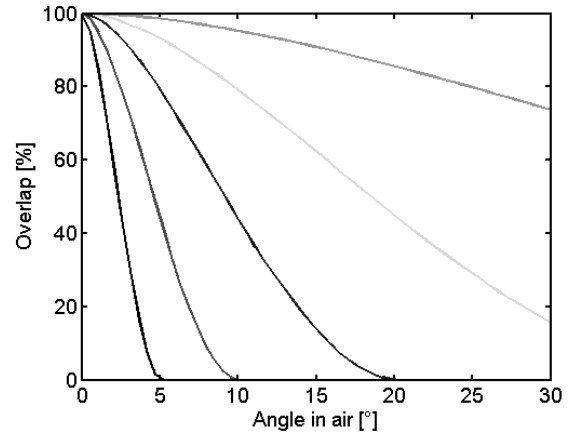


Figure 8. Calculated overlap of the back reflections from the substrate-air interface for different diameters (from left to right: $D = 10, 20, 40, 80$ and $200 \mu\text{m}$).

3.2 Interpretation and model

The ring in the far field can be understood as a superposition of many standing waves which are all tilted with respect to the optical axis by the angle θ and each is rotated around the optical axis by a different angle ϕ . The weak modulation of the interference pattern in the near field indicates an incoherent superposition of several modes.

The measurements with short pulses show no dynamics of the emission patterns. From this, we conclude that the movement of the ring is a thermal effect. Because the wavelength of each mode depends on its tilt angle θ , the detuning of the laser can determine the emission angle.⁸ As the resonance wavelength shifts with 0.07 nm/K and the gain maximum with 0.3 nm/K , the detuning is decreased for higher temperatures. But then, the observed ring in the far field should decrease in size for higher heat sink temperatures. The same is expected for increasing currents due to heating. In addition this could only be observed once, because when the detuning is zero or even smaller, the laser would be expected to prefer the fundamental mode. So another effect has to select the modes.

For a more complete model we regard the VCSEL as a three-mirror system, with both DBR-mirrors of the inner cavity and the substrate-air interface as the third mirror. Although it is AR-coated, a residual reflectivity of 0.1% can modify the intensity in the cavity by $\pm 6.3\%$ for constructive or destructive interference. The outer cavity (n-DBR to substrate-air interface) consists basically of the $200 \mu\text{m}$ thick GaAs substrate with a refractive index of 3.52 ,¹⁴ while the inner cavity has an averaged refractive index somewhere between the index of GaAs and the index of AlAs. The average index can be calculated with the transfer-matrix method and is 3.28 for wafer A and 3.21 for wafer B. Due to this index difference, the resonance conditions for the same angle in air may vary for both cavities as it is shown in figure 7.

Not only the refractive index is different for both cavities, but also the index change with temperature.^{15,16} The index change for the outer cavity is assumed to be purely determined by the refractive index shift of GaAs, which is given as $3.66 \times 10^{-4} \text{ 1/K}$. The inner cavity will shift with approximately the mean of the coefficients for GaAs and AlAs, which is $2.64 \times 10^{-4} \text{ 1/K}$. The exact values can be calculated again with the transfer-matrix method and are $2.75 \times 10^{-4} \text{ 1/K}$ for wafer A and $2.54 \times 10^{-4} \text{ 1/K}$ for wafer B, due to the different fractions of GaAs and AlAs. If the heat sink temperature is increased, the resonance wavelength of the outer cavity will shift faster to longer wavelengths than the modes of the inner cavity. Therefore, the points of constructive interference shift to smaller angles and longer wavelengths, which means that the rings shrink. This is exactly what we observe in the experiment.

On the other hand, if the current is increased the temperature distribution inside the VCSEL becomes important.

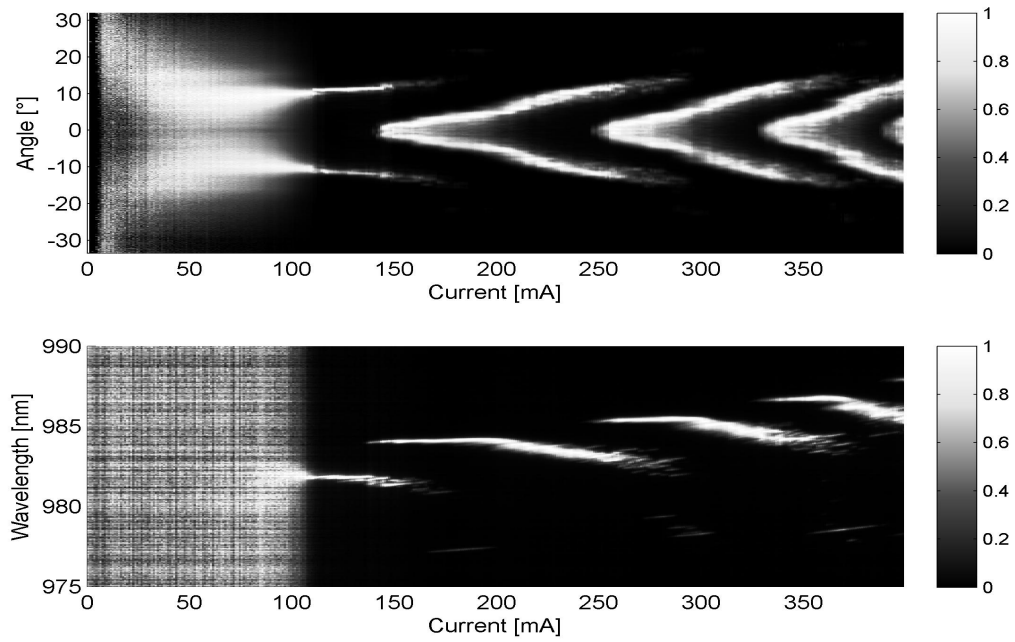


Figure 9. In the upper half the one-dimensional cuts through the normalized far field depending on the current are shown. Below the corresponding normalized wavelength spectral map is plotted for the $80\ \mu\text{m}$ aperture device of wafer A. The laser threshold is reached at a current of 100 mA.

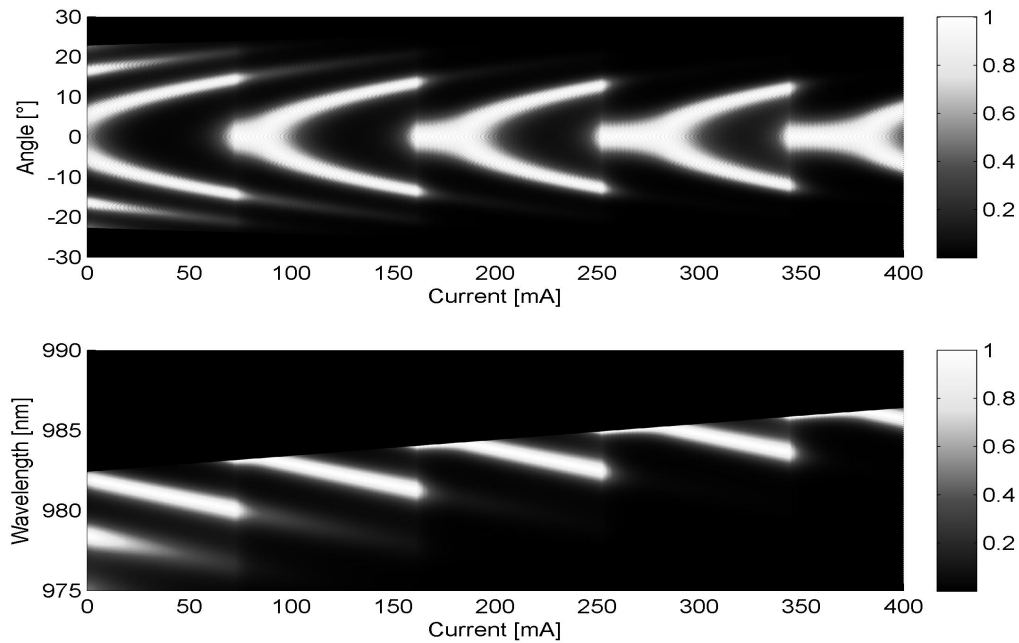


Figure 10. The calculated normalized threshold gain factor dependance on angles (upper figure) and wavelength (lower figure) of the $80\ \mu\text{m}$ aperture device of wafer A for different driving currents.

The GaAs substrate is cooler than the inner cavity, where the heat is generated due to Joule heating and non-radiative recombination. If the temperature difference is large enough, the resonance wavelength of the inner cavity shifts faster to longer wavelengths than the modes of the outer cavity and the points of constructive interference shift to larger angles and shorter wavelength. At some point, constructive interference occurs again on the optical axis and a new ring starts to develop.

A simulation of these dependencies is done by calculating the threshold gain over wavelength and angle in air. For each current the temperature in the cavity and an average temperature in the substrate can be calculated. The roundtrip gain spectrum is calculated for a specific carrier density. The gain peak will shift with the cavity temperature by 0.3 nm/K. The resonance wavelength of the cavity is calculated depending on the angle in air and the temperature in the cavity. Then the combined reflectivity of the outcoupling DBR and the substrate-air interface is calculated for the different angles. Therefore the average temperature in the substrate and the lower geometrical overlap of the reflections for larger angles (see figure 8) have to be considered. The product of roundtrip gain and the total reflectivity is then plotted in dependence on current, wavelength or angle in air. The maxima indicate the conditions with the lowest threshold gain and will show the strongest laser output. The calculation for the 80 μm aperture device of wafer A is shown in figure 10 and shows the same characteristics as the experiment. The movement of the ring with increasing temperature up to 15° and the jump back to on-axis emission are similar to the experiment in figure 9. The jump in the emission wavelength is calculated to be 2.6 nm and matches the experimental observation. Note that below 100 mA the laser has not reached the threshold and only spontaneous emission is measured, while the simulation does not include the threshold condition. In addition, we assume a linear dependence of loss power with current, which results in some deviations of the speed of the ring movement. For example is the movement of the ring over current somewhat lower in the experiment than in the simulation for currents between 100 and 150 mA. The change of voltage and wall-plug efficiency with current can be implemented in the model for a higher accuracy.

4. DIAMETER DEPENDENCE

To validate the model under different conditions we have measured the emission patterns for devices with 20, 40, 80 and 200 μm aperture diameter for wafer B. The emission of the 80 μm aperture device is shown in figure 11. At higher currents the emission pattern is similar to the ones of wafer A, but at lower currents several rings at larger angles can be observed. This can be attributed to the larger detuning of the wafer B. As the gain maximum lies at shorter wavelengths for the same temperature, larger angles are preferred by the spectral gain profile. Several modes with different angles have the same threshold condition and can be observed in experiment and simulation. When increasing the current, the detuning becomes smaller and the emission will appear at smaller angles. By adjusting the resonance wavelength and the initial detuning, the simulation shows the same dynamics in the far field and the wavelength spectra as shown in figure 12.

For the 200 μm aperture device the overlap of the backreflected light with the active area is much larger, especially for large angles. Therefore the far field is strongly modulated as shown in figure 13. With increasing current, we now observe a shrinkage of the emission angles of the different rings. Thermal simulations show that the average substrate temperature is much higher for larger diameters for the same cavity temperature. For aperture diameters larger than 150 μm the average temperature increase in the substrate is that high that the refractive index of the substrate shifts faster than that of the cavity. Therefore the resonance wavelength of the outer cavity will shift faster to longer wavelengths than the modes of the inner cavity and the rings shrink with increased driving current. By adjusting the thermal resistance and the average temperature increase in the substrate to the larger active diameter, the model shows the same dynamics in the far field and the wavelength spectra, which are shown in figure 14. Some minor differences are expected to arise from the rough approximation of the complex three-dimensional temperature profile in the cavity and the substrate by an average value.

For smaller diameters the overlap of the backreflected light with the active area becomes smaller and can be zero for large angles, as shown in figure 8. As shown in figure 15, the modulation of the far field and the spectrum is weak for angles larger than 15°. This can be also observed in the wavelength spectrum for the shorter wavelength region. The average temperature increase in the substrate is much lower for the smaller diameters and therefore the shift of the rings in the far field becomes much faster.

For the device with a 20 μm aperture, the back reflections from the substrate are only relevant for angles below 5° and do not influence the emission at larger angles, as shown in figure 16. In addition, the angular range of

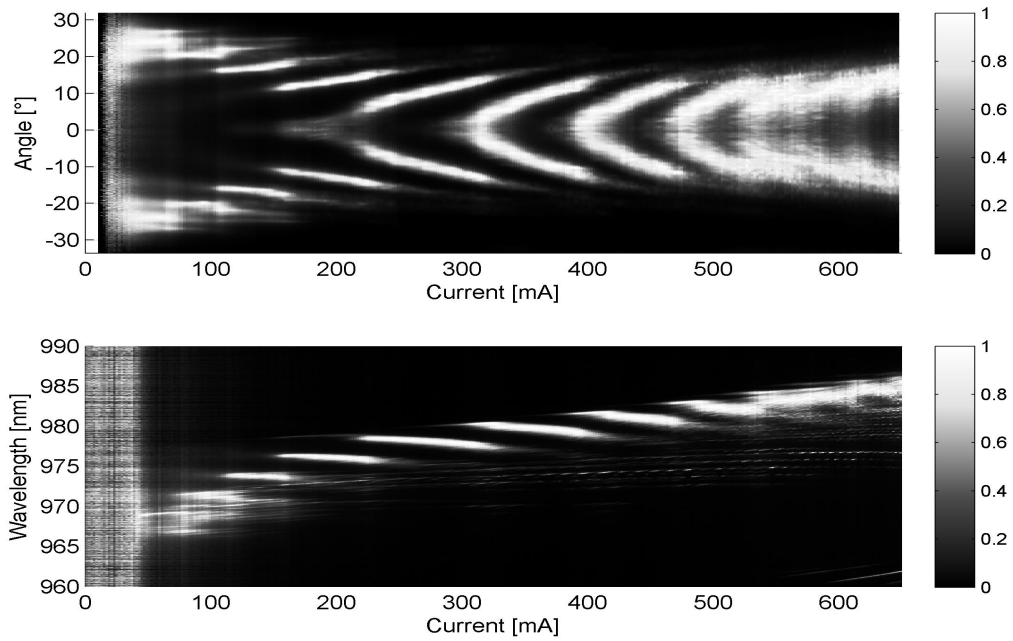


Figure 11. In the upper half the one-dimensional cuts through the normalized far field depending on the current are shown. Below the corresponding normalized wavelength spectral map is plotted for the $80\ \mu\text{m}$ aperture device of wafer B.

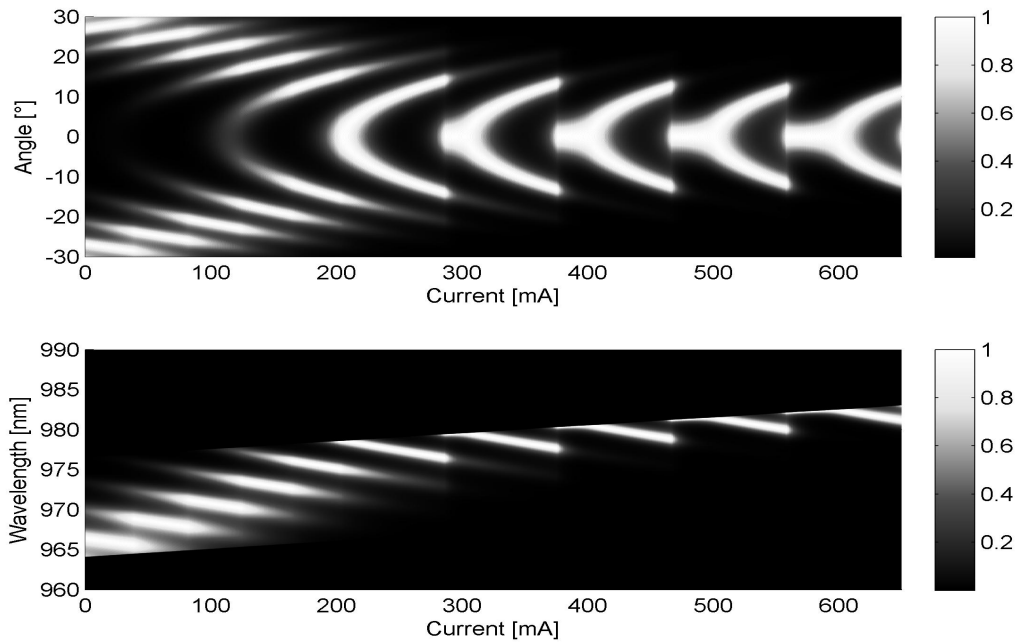


Figure 12. The calculated normalized threshold gain factor dependance on angles (upper figure) and wavelength (lower figure) of the $80\ \mu\text{m}$ aperture device of wafer B for different driving currents.

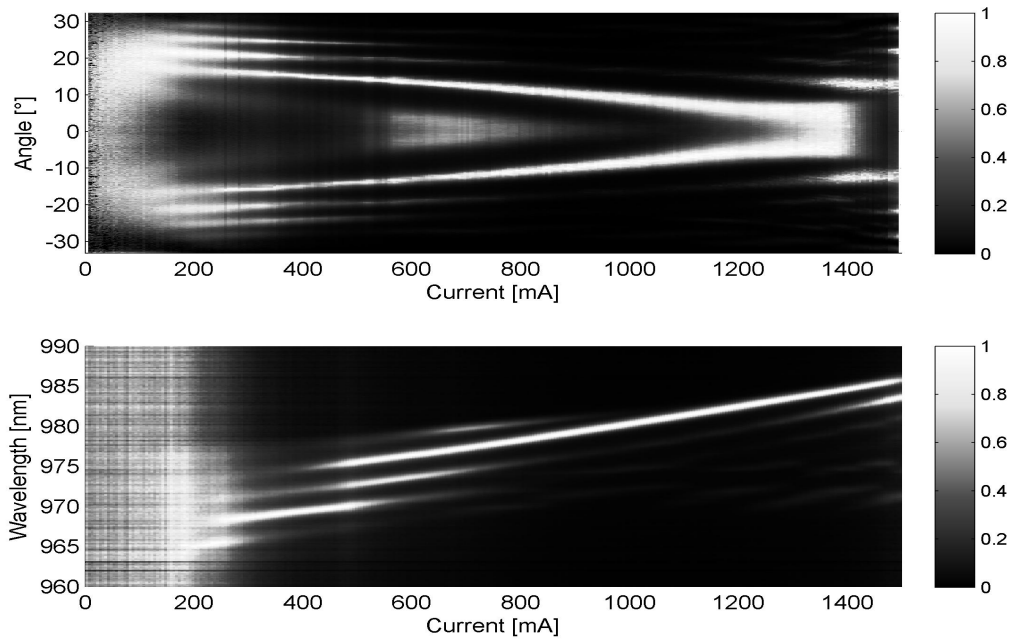


Figure 13. In the upper half the one-dimensional cuts through the normalized far field depending on the current are shown. Below the corresponding normalized wavelength spectral map is plotted for the 200 μm aperture device of wafer B.

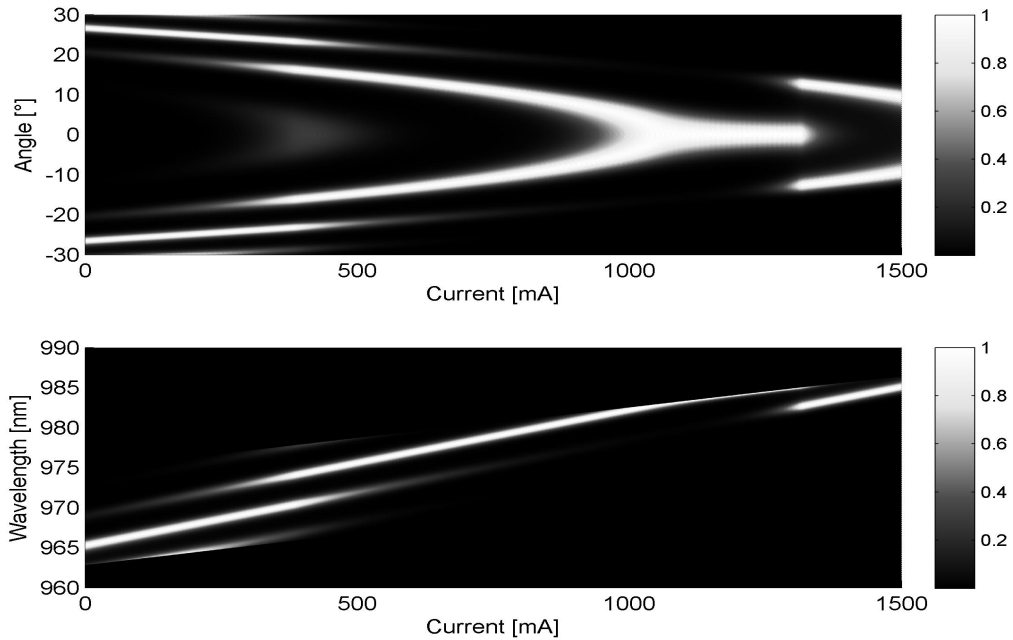


Figure 14. The calculated normalized threshold gain factor dependance on angles (upper figure) and wavelength (lower figure) of the 200 μm aperture device of wafer B for different driving currents.

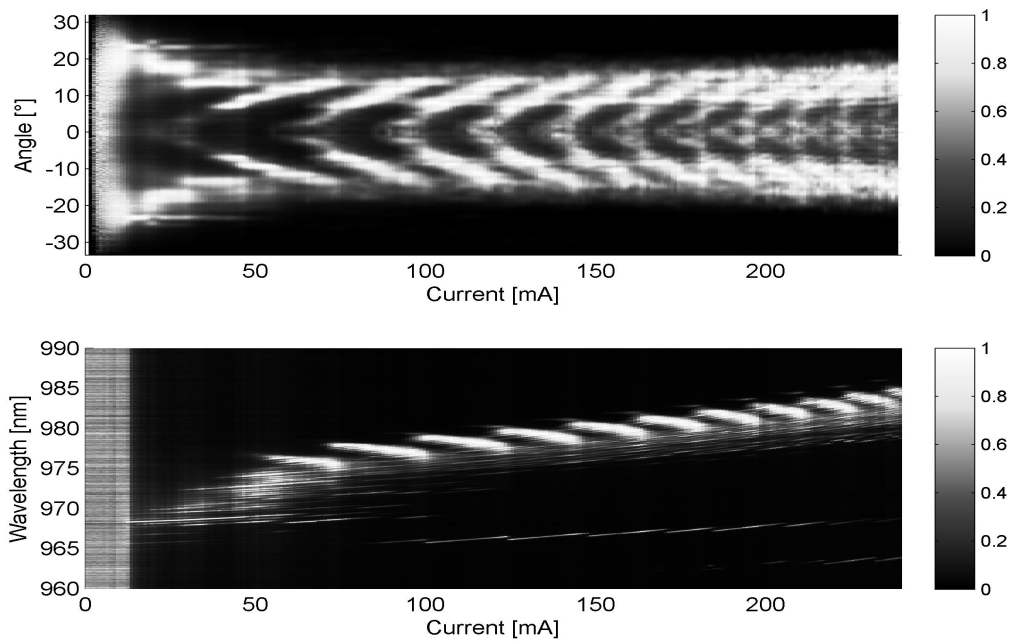


Figure 15. Normalized far field and corresponding wavelength spectral map for the 40 μm aperture device of wafer B.

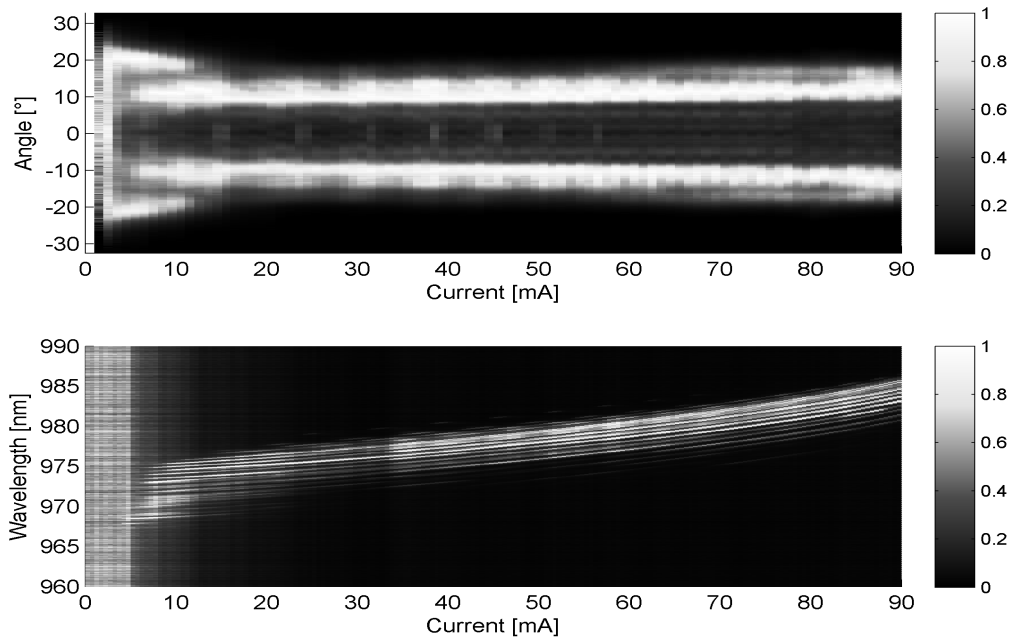


Figure 16. Normalized far field and corresponding wavelength spectral map for the 20 μm aperture device of wafer B.

each mode is broadened due to stronger diffraction for the smaller aperture diameters. The emission angle is determined by the detuning at lower currents. At higher currents, the emission is dominant for angles around 10° . On-axis emission is only weak, although the detuning should be negative at currents above 60 mA and on-axis emission should have the highest spectral gain. A different effect has to select the modes around 10° , but the origin of this is still unclear and the actual model is not suitable to fully describe the emission characteristics. Nevertheless, the mode spacing is large enough to be resolved by our setup and matches well to the calculated values shown in figure 2.

5. SUMMARY

The spectral and angular emission profiles of various high-power VCSEL designs with large Fresnel numbers have been investigated. It has been shown that for aperture diameters larger than $20\text{ }\mu\text{m}$ the modal emission can be approximated with Fourier modes, which are tilted standing waves in the plano-planar resonator. The combined effect of detuning and interference of the cavity modes and the residual reflections from the AR-coated substrate-air interface is shown to be the dominant selection mechanism for the lasing modes for aperture diameters larger or equal $40\text{ }\mu\text{m}$. A physical model based on these effects can describe the modal emission dynamics over current and temperature for the different device geometries and different wafers in good agreement with experiments.

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