Transverse mode structure and pattern formation in oxide confined Vertical Cavity Semiconductor Lasers

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Abstract

We analyse the transverse profiles of oxide-confined vertical cavity laser diodes as a function of aperture size. For small apertures we demonstrate that thermal lensing can be the dominant effect in determining the transverse resonator properties. We also analyse pattern formation in lasers with large apertures where we observe the appearance of tilted waves.

1. Introduction

Vertical cavity surface-emitting semiconductor lasers (VCSELs) provide solutions to many engineering applications and are also very interesting for quantum and nonlinear physics. Their performance has advanced greatly in recent years¹⁻⁴. Much of this progress can be attributed to improvements in electrical characteristics, reducing the large voltage drops of early distributed Bragg reflectors (DBRs)⁵, and also the development of native oxide confinement layers within the laser structure, providing both electrical and optical transverse

confinement. The 2-dimensional planar structure of the VCSEL wafer makes it ideal for technologies such as parallel optical interconnects and high brightness displays as well as for studies of micocavities, pattern formation in optical systems⁶ and dynamics of laser arrays.

In this paper, we present measurements of large⁸ and small aperture⁷ VCSELs. We first describe the transverse mode structure of selectively oxidised vertical-cavity surface-emitting semiconductor lasers as a function of aperture size and injection current. We demonstrate that thermal lensing can be the dominant factor in determining the transverse properties of the beam emitted by lasers with aperture smaller than $3\text{ }\mu\text{m}$. We also analyse the same lasers with large transverse sections. Near the lasing threshold, the laser emits a single frequency solution corresponding to an almost one dimensional standing wave. The transverse wavenumber of this pattern can be controlled with the detuning, δ , as predicted by two-level models. For higher pump levels and other detuning values, two instabilities may occur. The first instability is associated with the appearance of modes with smaller transverse wavenumbers, while the second is associated with a polarisation instability at the same wavenumber.

2. Transverse mode structure of oxide-confined VCSELS

A. The lasers

A schematic representation of the laser structure studied is shown in Fig. 1. Our samples were AlGaAs structures with monolithic semiconductor DBRs and oxide layers on both sides of the active region, which consisted of five 8 nm GaAs quantum wells contained in a 1λ cavity. The monolithic DBRs were quarter wave thick pairs of $\text{Al}_{0.16}\text{Ga}_{0.84}\text{As}/\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ with 25 pairs in the top DBR. The thin (18 nm) $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ oxide confinement layers were embedded in low index quarter-wave layers 3 mirror periods from the active region. The aim of this design was to reduce the overlap between the field and the apertures and thus reduce aperture scattering⁹, a factor implicated in the higher threshold gain of smaller devices¹⁰.

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A series of lasers with different mesa sizes ranging from $30\text{ }\mu\text{m}$ to $70\text{ }\mu\text{m}$ was fabricated by etching square mesas through the active layer using reactive ion etching and oxidising laterally the high Al content layer². The difference in side length between successive mesas was $0.5\text{ }\mu\text{m}$, making available lasers with side lengths between $< 0.5\text{ }\mu\text{m}$ and $10\text{ }\mu\text{m}$ in $0.5\text{ }\mu\text{m}$ steps. On a temperature controlled stage the devices lased with heat sink temperatures ranging from 100 K to 400 K with a minimum threshold around 300 K . Measurements of the polarisation properties of small ($\sim 3.0\text{ }\mu\text{m}$ aperture length), single mode devices suggests that the samples were strained, as a single polarisation was maintained to within $\pm 3^\circ$ over the entire temperature range, and across the wafer the same polarisation was found for all devices.

B. Experimental results

The lasers were operated on a temperature controlled probe station with high power microscope objectives and the laser emission coupled to a monochromator with 24 GHz resolution. The probe station had the ability to image the laser near field onto a CCD array and calibration targets on the VCSEL chip enabled accurate size information to be obtained. Other samples from the same chip were operated on a cryogenic stage and still other samples were wirebonded to microwave connectors to enable more detailed optical characterisation under both DC and pulsed excitation.

It is interesting at this stage to consider how the oxidised VCSEL design has produced optical confinement. In Fig. 2 is plotted the transverse mode spectra versus current of a $10 \times 10\text{ }\mu\text{m}^2$ VCSEL, with a threshold current of 3.6 mA . In proton-implanted VCSELs with weak confinement derived from gain-guiding and thermally induced lensing, it is possible at threshold to be single transverse mode even with apertures as large as $15\text{ }\mu\text{m}$ in diameter. Our structure is comparable in size but has many more modes, and as the current is increased a large number of modes begin to oscillate. From this we can deduce that even with thin apertures placed some distance from the field maximum, the apertures still present strong

confinement. It is worth noting that even when the current reaches several times threshold, the fundamental mode does not switch off because of the efficient nature of the laser.

Due to the broadness of the semiconductor gain spectrum and the high Q of the VCSEL cavity, the gain peak does not pull the lasing frequency. Instead, the lasing wavelength is set almost purely by the optical length of the cavity and this in turn is set by the refractive index of the material between the DBRs. As can be seen from Fig. 2, the lasing wavelength changes with drive current. The dominant mechanism in causing this shift is Joule heating at the heterojunction interfaces of the DBR stacks, and near the active region due to non-radiative recombination. As the temperature of the spacer layers increases, their index also increases leading to a red-shift of the laser emission. In the case of the $10 \times 10 \mu\text{m}^2$ VCSEL, which has high efficiency and reasonable thermal impedance, the wavelength shifts at around 0.16 nm/mA. The electrical power consumption of the laser diode has both a linear component due to the near-constant operating voltage and a quadratic component due to the series resistance of the device. From the slope of $d\lambda/di$ in Fig. 2 it can be seen that for these devices the linear component is the more important in setting the lasing wavelength.

With the withdrawal of the oxide confining layers from the active region it is to be expected that the problems associated with very small devices to high diffraction loss and high leakage current, would be exacerbated. The threshold current density as a function of laser size is plotted in Fig. 3. The increase in threshold current density as device size is reduced to around $3 \times 3 \mu\text{m}^2$ is not great, but becomes enormous as device size drops below $1 \times 1 \mu\text{m}^2$. That some of this can be ascribed to current spreading under the aperture and away from the lasing region is undoubted, but even without this effect, high current densities are required to achieve lasing. An examination of Fig.4, which shows the variation of laser wavelength with current for a $1 \times 1 \mu\text{m}^2$ device, will reveal that the wavelength *blue* shifts with increasing current until threshold is reached, after which the laser red-shifts with increasing current. This effect is explained by pointing out that as the carrier density increases, the index of the spacer layers will decrease. When threshold is reached, the carrier

density is essentially pinned, and only thermal effects will play a rôle, leading to a red-shift with current. Below threshold the carrier density effect must overcome the considerable Joule heating effect, demonstrating that very high current densities are indeed present in the small devices and that diffraction loss in the DBRs is a significant loss mechanism.

On Fig.5 are plotted as a function of current the wavelengths of the 0th and 1st order tranverse modes of a device with oxide aperture side length of 1 μm . The wavelength of the 0th order mode increases superlinearly with drive current as Joule heating increases the index and thus the resonance wavelength. This effect is pronounced in these very small lasers, red shifting by 6.3 nm in 3.2 mA, because their increased optical and electrical loss increases greatly the parasitic ohmic heating. However, the wavelength of the 1st order mode red shifts at a lower rate. This is emphasised in Fig.6 where the wavelength difference between the two modes is shown.

Over the current range measured, the difference increases from 4.2 nm to 6.95 nm in a near-linear manner. This result is anomalous, as the transverse mode spacing in a Fabry-Pérot cavity with near plane-plane mirrors is given by¹¹

$$\Delta\nu = c/2\pi n_o z_o \quad (1)$$

where n_o is the refractive index, and z_o the Rayleigh range. If, as is demonstrated by the red-shift of the fundamental, n_o is increasing, then the mode spacing should be lessening slightly. An increase in the mode spacing indicates that the Rayleigh range is decreasing at a faster rate with injection than n_o is increasing. This would correspond to greater curvature (increased lensing) within the laser under operation. Note that the current density of this small VCSEL is relatively high⁹ causing increased local heating. Previous theoretical work¹² indicates that the temperature difference between the centre and the sides of the laser (the thermal lens) will increase with injection, this effect being stronger the less efficient the device. Also, carrier depletion by the fundamental mode at the centre of the device will burn a hole in the carrier density and therefore increase the index at the centre. This self-focusing will be enhanced in predominantly single-mode devices without higher order modes

to lower the carrier number at the edges. As this device has high threshold current density and is predominantly single mode for most of its operating range, it is an extreme example of the lensing phenomenon. It is to be expected that, as the current aperture increases to give more efficient, multimode devices, the effect will lessen.

To demonstrate this, the rate of change of the mode separation with current was measured for different sizes of device. The results are plotted in Fig. 7. As can be seen, the lensing effect is very strong for devices $< 2 \mu\text{m}$ in side length, but diminishes in importance for devices $> 3 \mu\text{m}$. In order to investigate how this strong lensing effect interacts with the in-built native oxide index confinement, measurements were made of the fundamental mode size at 1.1 times the threshold current. An $\times 50$ IR microscope objective imaged the beam waist onto a CCD array, the results being presented in Fig. 8. For the larger devices the mode is smaller than the aperture and decreases as the aperture decreases. For apertures $\sim 3 \mu\text{m}$ the rate of mode size decrease slows and thus the mode fills the aperture more fully. Eventually for devices $< 1.5 \mu\text{m}$ the mode becomes larger than the aperture and increases as the aperture decreases. Previous work where loss in optical confinement has been observed, in VCSELs with a fully dielectric top mirror, concluded that the mode could remain confined for longer if the bottom mirror could also be made of high contrast materials¹³. However our measurements of the maximal farfield width (FWHM = 26°) agree well with the largest reported in¹³, despite the use of low contrast semiconductor DBRs for both the top and bottom mirrors, and an oxide configuration designed to have reduced optical confinement. However a direct comparison between the devices studied in Ref.¹³ and our devices is difficult as the currents employed in their study were far less than in ours.

For devices where the fundamental mode is larger than the oxide aperture, a comparison between the in-built oxide guiding and the thermal lens can be made as the thermal lens will have a characteristic formation time of hundreds of nanoseconds. We therefore operated the laser pulsed without D.C. bias at very low duty cycle and measured the time-evolution of the output power with a bandwidth of 500 MHz using an avalanche photodiode (APD) and an oscilloscope. The trace shown in Fig.9 was made with $1 \mu\text{s}$ pulses of $20 \mu\text{s}$ period.

The voltage applied corresponds to a current of 1.5 times the threshold current and has been offset for clarity. Immediately following the pulse switch-on, the laser intensity rises to a low level and does not increase for ~ 300 ns and then gradually increases, approaching asymptotically the DC intensity over a period of $1 \mu\text{s}$. Delayed turn-on is a well known feature of proton implanted VCSELs, but the onset of lasing in our case is very gradual compared with the abrupt turn-on more commonly encountered. The reason we have a gradual turn-on for these devices is that the mode size is larger than the pumped region, precluding self-focusing. The variation in the delay time with pumping is consistent with a thermal origin, shortening for increased pump level and/or duty cycle. This result suggests that the thermal lens is the dominant guiding mechanism for ultra-small $\sim 1 \mu\text{m}$ VCSELs and that they may not be able to lase without one. This is consistent with the increased threshold gain measured for decreased oxide aperture size⁹.

The issue as to whether the lasers have the ability to lase without a thermal lens can be investigated by operating the laser with pulses shorter than the turn-on time, and checking the coherence of the radiation. The (relatively) high voltages and currents required to operate the devices causes the emission to shift in time at a rate of about 1 nm per 200 ns, this shift slowing as the on-time approaches the thermal time-constant of the device, approximately $1 \mu\text{s}$. This chirp prevents linewidth measurement techniques from determining coherence. Another method, employed here, is to examine the far-field width, and to look for farfield narrowing when the laser reaches threshold. The results are given in Fig. 10. For pulses shorter than the turn-on time, in this case 150 ns, the farfield has a very broad width of $\sim 42^\circ$. For on-times of 500 ns or greater, the farfield is much narrower, on the order of 25° . This very narrow farfield suggests that the weak radiation is merely spontaneous emission and that only after the intensity turn-on, does the laser emit coherently.

3. Pattern formation in lasers with large apertures

A. Theory

When the aperture size of the lasers is increased it is expected that the transverse profile of the light will become insensitive to the boundary conditions and the emitted pattern will be determined by the nonlinearities of the medium. Pattern formation in spatially extended systems has been the subject of much research during the past twenty years¹⁵. In optics⁶, activity has centred on research into chaos in lasers¹⁶ and instabilities in passive systems¹⁷⁻²¹. From a theoretical viewpoint, lasers with large Fresnel numbers were analysed with partial differential equations derived from the Maxwell-Bloch equations²²⁻²⁶. All of these models predicted the formation of periodic structures such as travelling waves and of localised structures such as optical vortices²³ or spatial solitons²⁷. These instabilities have been investigated experimentally in many optical systems such as sodium vapour¹⁷, photorefractive crystals¹⁸⁻²⁰ and liquid crystal light valves²¹. In lasers, experiments carried out with gas lasers have shown evidence of spatio-temporal complexity²⁸⁻³⁰ but remained purely qualitative since the patterns arising from the first instability, i.e the laser threshold, differed from those predicted by the model. The mirror curvature, the small Fresnel number at threshold and the presence of several longitudinal modes probably constituted the main reasons for the discrepancies between theoretical predictions and experimental observations.

Most of the theoretical investigations on pattern formation in lasers are carried out with the two dimensional Maxwell-Bloch equations for the complex amplitude of electric field $E(\vec{r}, t)$, the polarisation $P(\vec{r}, t)$ and the population inversion $N(\vec{r}, t)$:

$$\begin{aligned}\partial_t E &= -\kappa \left[(1 - i\delta) - i\frac{a}{2} \nabla^2 \right] E - \kappa P, \\ \partial_t P &= -\gamma_{\perp} [NE + (1 + i\delta)P], \\ \partial_t N &= -\gamma_{\parallel} \left[N - J - \frac{1}{2} (E^* P + EP^*) \right],\end{aligned}\tag{2}$$

where $\vec{r}$ represents the transverse variable. κ , $\gamma_{\perp}$ and $\gamma_{\parallel}$ are the decay rates for E , P and N . Here the pump represented by J . $\delta = \frac{\omega_a - \omega_c}{\gamma_{\perp}}$ is the detuning between the atomic resonance

ω_a and the cavity frequency ω_c . The diffraction coefficient a is inversely proportional to the Fresnel number.

This model which describes the spatio-temporal evolution a two level laser may be insufficient to describe the whole dynamics of a semiconductor laser. For instance it will not describe polarisation dynamics or any phenomena connected with the semiconductor physics. More importantly the linewidth enhancement factor or α -factor is here equal to zero but its effect may be introduced by assuming a population inversion dependent detuning. A correct description of the gain curve may also require a generalisation of the Maxwell-Bloch equations to semiconductor lasers^{31,32}. However the experimental results presented here were theoretically predicted with the Maxwell-Bloch equations and may be obtained with more general models, therefore we will describe the results with the frame of the Maxwell-Bloch equations.

The laser threshold can be obtained by performing the linear stability analysis of the non lasing solution $E = P = 0$ and $D = J$ where the perturbations are developed in spatially periodic solutions $E = 0 + E_1 e^{\sigma t + i\vec{k} \cdot \vec{r}}$, $P = 0 + P_1 e^{\sigma t + i\vec{k} \cdot \vec{r}}$ and $N = 0 + N_1 e^{\sigma t + i\vec{k} \cdot \vec{r}}$. Here σ represents the growth rate of a perturbation associated with a wavevector $\vec{k}$. At threshold, $\text{Re}\sigma = 0$ and the threshold current J_{th} , laser frequency $\sigma = i\omega$ and transverse wavenumber can be easily expressed as:

$$\omega = -\frac{\kappa\gamma_{\perp}}{\kappa + \gamma_{\perp}} \frac{a}{2} k^2, \quad (3)$$

$$J_{th} = 1 + \left(\delta + \frac{\omega}{\gamma_{\perp}} \right)^2. \quad (4)$$

The dispersion relation at threshold (3) demonstrates that the mode with the largest growth rate has a negative frequency. For $\delta < 0$, the mode having the lowest threshold is thus the one with $k = 0$ and $\omega = 0$, which is a plane wave solution resonant with the laser cavity. In this case the laser threshold varies as $J_{th} = 1 + \delta^2$. For $\delta > 0$, the mode with the lowest threshold corresponds to $\omega = -\gamma_{\perp}\delta$ and $k^2 = \frac{2}{a} \frac{\kappa + \gamma_{\perp}}{\kappa} \delta$ and starts lasing for $J_{th} = 1$. The laser will therefore select a spatially periodic solution with a transverse wave vector $k_{\perp}$ such that its frequency is as close as possible to the atomic frequency.

This simple theoretical prediction has not yet been observed experimentally for a laser mainly because the experimental have been carried out with cavities where the mode spacing of a laser with curved mirrors operating with a large Fresnel number is generally of the same order of magnitude as the transverse mode spacing. The curved mirrors used in these experiments increase the Fresnel number but also break the translational symmetry and privilege Gaussian beams. The observed patterns remain highly symmetric with respect to the cavity optical axis.

Here we demonstrate that vertical cavity surface emitting semiconductor lasers (VCSELs) of very large transverse section and short cavity length³³ constitute excellent candidate vehicle to study pattern formation in lasers. Near the lasing threshold, the laser emits a single frequency solution corresponding to an almost one dimensional standing wave of the laser intensity. The transverse wavenumber of this pattern can be controlled with the detuning, δ , as is predicted by two-level models. For higher pump levels and other detuning values, two instabilities may occur. The first instability is associated with the appearance of modes with smaller transverse wavenumbers, while the second is associated with a polarisation instability at the same wavenumber. In VCSELs, as the optical axis is orthogonal to the junction plane, the polarisation constraint is weaker than in edge-emitting semiconductor lasers and gas lasers with Brewster windows. Polarisation instabilities in VCSELs has been the subject of much research during the past few years^{2,34,35}.

B. Experimental samples

The devices used for this experiment were from the same wafer as those described in the previous sections. They were square GaAs/AlGaAs structures with GaAs quantum well active regions with the oxide confining layer withdrawn from the active region by 3 mirror pairs. The aperture sizes used here ranged from $5 \times 5 \mu\text{m}^2$ to $40 \times 40 \mu\text{m}^2$. The $25 \times 25 \mu\text{m}^2$ lasers had a threshold current of $\sim 8 \text{ mA}$, threshold voltage of $\sim 2 \text{ V}$ and slope resistance of $\sim 10 \Omega$. The results obtained in these experiments are not particular to these

devices as rectangular 980 nm devices with deposited top mirrors have displayed very similar behaviour³⁶. The devices have uniform current injection across the facet as the spontaneous emission intensity does not vary with position. This result is not fully understood because we observed current-crowding around the edges of other similarly sized devices. One structural difference between the devices displaying current-crowding effects and the devices studied here is that the current confining layers were close to the active region in the former. It is also conceivable that differences between the vertical and lateral conductivities of the two sets of devices plays a role. The homogeneity of the current injection may be important for pattern formation in providing translational symmetry to the laser and, perhaps significantly, this homogeneous injection was also provided in the devices used in Ref.³⁶. Because positive detuning is such a significant parameter for pattern formation, it was important that it be determined whether this is possible here. To this end, a sample of the wafer was mounted on a cryogenic probe station and the threshold current measured as a function of heatsink temperature. The results are presented in figure 11. At zero detuning the laser will have its minimum threshold and this occurs at around 300 K. This measurement is compromised however, because the injection current will heat the active region, altering the detuning for a constant heatsink temperature. However, it has been shown¹² that the active region temperature rise is on the order of 10°C so figure 11 suggests that a region of positive detuning should be available near room temperature with this sample.

C. The experiments

The lasers were wire-bonded and operated both CW and pulsed on a temperature controlled stage. The DC source was a low noise battery supply and the pulsed source an HP 8082A pulse generator with minimum rise/fall times of 1 ns, capable of delivering 5 V into 50 Ω . The generator could deliver duty cycles from $\sim 10^{-3}\%$ to 70% and also provide positive or negative DC bias of 2 V. Most of the data presented here was for lasers with oxide apertures of $25 \times 25 \mu\text{m}^2$ but similar results were obtained for lasers with apertures between 20×20

μm^2 and $40 \times 40 \mu\text{m}^2$. For the CW experiments the two control parameters were the injection current and the heat sink temperature, and for the pulsed experiments more control was available through the use of variable low duty cycle current pulse trains. For all farfields presented in this chapter the intensities have been reversed, i.e. dark corresponds to high intensity. For the near fields, dark corresponds to low intensity.

Because the emission from the VCSELs was highly divergent, special optics were required to image the near-field intensity with minimum distortion. The lens used was a Geltech 350330 moulded glass aspheric with a numerical aperture (NA) of 0.68. A lens with a NA of 0.5 badly distorted the image. The focal length of the lens was 3.1 mm with a working distance of ~ 1.7 mm. To obtain the near-field, a CCD array with dimensions of 4×6 mm was placed at an image distance of around 45 cm from the lens yielding a magnification of around $\times 150$. To measure the farfield of the lasers, a piece of graph paper was placed on a translation stage several cm in front of the laser. A CCD camera was placed around 1 m away and recorded the scattered light. It was possible to calibrate the angular divergence of the light, by using the matrix of the graph paper as a ruler for spot separation at one distance from the laser and then translating the screen a known distance and repeating the spot separation measurement.

D. Experimental results

To contrast the results obtained with large aperture, we first show results obtained with a medium aperture devices (up to $15 \times 15 \mu\text{m}^2$), the observed patterns are quite similar to those observed with proton-implanted devices¹⁴. A typical pattern emitted by a $10 \times 10 \mu\text{m}^2$ microns lasers is depicted on Figure 13 as well as its optical spectrum.

For these devices, the optical spectrum reveals the coexistence of several transverse laser modes which can be filtered with an etalon. Three etalons were used to select certain frequencies to separate the complex intensity profiles in to their component modes. Etalon 1 had FSR = 1000 GHz and passband = 30 GHz, Etalon 2 had FSR of 500 GHz and

passband = 15 GHz, while Etalon 3 had FSR = 200 GHz and passband = 5 GHz. With the insertion of two or three etalons, a given-order transverse mode could be selected by rotating the etalons to pass the desired peak of the spectrum. Figure 14 contains the near field corresponding to the six biggest peaks in the optical spectrum 13.

The vertical and horizontal polarisation of these patterns was resolved by adding a polariser after the etalons. The result of such a measurement for the pattern in the left bottom of Figure 14 is depicted on Figure 15.

For these broad area VCSELs, just above the lasing threshold for low temperature, (typically below 25 degrees), the laser emitted a single frequency linearly polarised beam. In the far field (see left Figure 16) the light was centrally symmetric and concentrated on a cone diverging at 65 degrees. It was composed of four spots in two pairs separated by about 5 degrees. The corresponding time averaged near field (see right Figure 16) consisted of an almost regular spatial modulation of the laser intensity with wavelength around $1\text{ }\mu\text{m}$. This standing wave, associated with the fast divergence of the beam in the $\vec{i}$ direction on Figure 16, was also slowly modulated in the orthogonal $\vec{j}$ direction corresponding to the 5 degrees divergence. We note that the near field was not perfectly periodic but contained dislocations of the patterns. The total averaged near field, and the position of the dislocations, remained unchanged for the same values of temperature and injection current. However, any change of one of these two control parameters altered the pattern and caused the dislocations to move. The light was linearly polarised in the $\vec{j}$ direction parallel to the stripes as shown in Figure 17.

The symmetry of the far field and the modulation of the near field indicate a transverse standing wave of the electric field in the laser cavity. The theoretical prediction of the two-level model is for a standing wave solution to be unstable with respect to the travelling wave solution, which has an unmodulated near field (when averaged over long times). However, this prediction is made for an infinite system³⁷, whereas our system has a finite size. Theoretical analysis of the Maxwell-Bloch equations with finite size have predicted standing waves near the solitary laser threshold. In our case, the current guiding oxide layers produce

large index discontinuities with the surrounding semiconductor material. At large angles of incidence, a ray incident upon such an oxide boundary would undergo total internal reflection, generating a transverse standing wave. We constructed a Mach-Zehnder interferometer to investigate the spatial correlation of the structure. By overlapping different parts of the pattern, we observed interference fringes across the entire structure. This indicates that the observed structure is a coherent Fourier mode.

In order to investigate systematically the dependence of the broad area laser frequency upon the detuning, a VCSEL wafer was obtained with the cavity resonance varying as a function of position on the wafer. With this design, we could study lasers with different resonance frequencies but the same gain peak frequency. At each wafer position, both small ($3 \times 3 \mu\text{m}^2$) and large ($20 \times 20 \mu\text{m}^2$) VCSELs were fabricated. The small lasers always operated in the fundamental mode, thus yielding the cavity resonance wavelength at each position on the wafer, after a small correction to account for the finite transverse wavevector of the Gaussian mode. For the broad area devices the lasing wavelength at $1.1 i_{th}$ was also measured as a function of position. The results are plotted in Fig.18. For higher cavity frequency ($\lambda \lesssim 847 \text{ nm}$), the broad area laser frequency tracked the cavity resonance. Once the cavity frequency became less than a critical frequency (corresponding to 847 nm wavelength) the laser frequency remained more or less constant, and its wavevector acquired whatever $k_{\perp}$ necessary so that it lased at the gain peak frequency. For experimental reasons it was not possible to obtain $k_{\perp}$ during this measurement, but an increase in the farfield divergence with increasing detuning was observed. This result is in agreement with the theoretical predictions from the Maxwell-Bloch equations for both positive and negative detuning. However, the Maxwell-Bloch equations predict a plane wave solution for negative values of the detuning whereas the experiment shows a complicated low divergence pattern (see fig. 18 b and c) with optical spectra containing many frequencies.

The fact that plane waves are not observed for negative detuning is probably due to the boundary conditions. It is well known that borders alter the pattern selected in a nonvariational system since they generate spatial modulation of the phase⁴¹. In the Maxwell

Bloch equations, the same mechanism occurs for both positive and negative detunings²⁹. For negative detuning this effect appears clearly since a spatially modulated pattern appears instead of a plane wave solution. However, this effect is difficult to observe for positive detuning since it only modifies the selected wave number.

In the travelling wave solution the emission wavelength is very close to the peak gain wavelength, which shifts with temperature at a faster rate than the VCSEL cavity resonance. The wavelength of the laser was recorded as the heat sink temperature was changed at constant injection current, the results are shown in Figure 19. The change in wavelength occurred at a rate of $.075 \text{ nm}/^{\circ}\text{C}$. This is slightly faster than the rate of wavelength shift with temperature of small area VCSELs from the same wafer of $0.055 \text{ nm}/^{\circ}\text{C}$, see also¹⁴, but much slower than the thermal gain shift of $0.28 \text{ nm}/^{\circ}\text{C}$ ^{38,39}. This establishes the pattern as a mode of the cavity. The standing wave has properties of travelling waves, in that it attempts to lase close to peak gain, and also of spatial modes, because the allowed frequencies are set by cavity resonances. The unusually large transverse component of its wavevector means a guided photon during its ~ 100 passes through the gain region will traverse the facet several times in each direction. The role of the dielectric layers in the cavity may account for the faster rate of wavelength shift with temperature in this case than is normal. This method of confinement also explains the linear polarisation of the mode, as the Fresnel equations yield higher reflectances for p-polarised than s-polarised rays. In order to investigate how many modes are lasing, an interferometer was constructed and the different far field spots interfered. Fringes were obtained between all four spots, confirming phase-locked emission.

When the current was increased we observed the appearance of another group of four k-vectors coexisting with the previous set. These new k-vectors had the same polarisation as the previous set with a longer wavelength. The corresponding far field and optical spectrum are shown on Figure 20. The time averaged near field was quite similar to the previous one though with larger transverse wavelength and the dislocations of the near field pattern are different.

For higher values of the injection current, we observed the appearance of the orthogo-

nal polarisation. The far field k-vectors associated with this new polarisation were nearly orthogonal to the first set of k-vectors (see Figure 21) and had a wavelength close to the higher wavelength of the orthogonal polarisation. The polarisation resolved near field was very similar to that of the dominant, after a rotation of 90 degrees, so we see the appearance of squares in the unfiltered near-field.

For higher currents, a low divergence circle of k-vectors appeared in the far field (see Figure 22). The associated near field displayed a less symmetrical large scale structure and the optical spectrum contained many peaks.

At high heat sink temperatures (typically higher than 30 degrees), the quickly diverging beam never appeared, the maximum far field full width being less than 20 degrees. At threshold the divergence of the coherent emission was less than 10 degrees full width and the polarisations of its many components have not been resolved. As we increased the current, new, larger k-vectors came above threshold, but for any value of injection current in our operating range the largest k-vector stayed less than 20 degrees divergent. On Figure 23 we show the full stability diagram of the laser as the injection current and/or heat sink temperature were varied.

In order to separate the effect of Joule heating by the injection current from its effect on the inversion, the p-sides of the lasers were wire bonded to the centre conductors of SMA connectors and operated pulsed with a rise time of 1 ns. The period of the pulses was 10 μ s, and the peak current was ~ 5 times i_{th} . The duration of the pulses was varied to increase the duty cycle of the injection and thus the average heating of the laser. The results are presented in Figure 24. As can be seen from Figure 24, top row, even though the laser was pumped to many times threshold, when the average heating was kept low, the laser emitted in the same pattern as at CW threshold. As the duty cycle was increased, while the inversion was unchanged, the pattern and spectrum approach those of CW, $2.0 i_{th}$. These results suggest that the multimode instability at increased CW pumping is due to heating effects.

E. Discussion

The experiments carried out on these lasers have shown clear signs of the medium asserting itself decisively in determining the modal properties of a practical large Fresnel number laser. The very high Fresnel number available with broad area VCSELs is difficult to realise in other laser systems and the question arises as to whether true standing waves can be observed with this type of laser.

VCSELs utilise very high reflectance mirrors because the gain per pass through the active layers is very low owing to their thinness. For a VCSEL to lase using current active layers the photon must pass through the active region approximately 100 times before being lost from the cavity. Examining the pattern close to threshold, the photon reflects off the DBRs 20 times per traverse of the facet, implying that each photon traverses the facet 5 times before emission. This means there is no viable travelling wave solution to compete with the standing wave solution. For a VCSEL to move beyond standing waves and towards travelling waves, the aperture must be increased in size so that it requires several photon lifetimes to cross the mirror. Then the extra loss at the sidewall of the travelling wave laser would be compensated for by the improved overlap between the field and the carriers as the near field would have field nodes only in very localised regions. This could be aided by decreasing the angle of incidence of the radiation, but caution should be applied here. In a large but not infinite system described in Ref.³⁷, travelling waves are born in sources and are annihilated in sinks, and at the sinks localised standing waves exist. If the transverse wavevector is too short, the spatial wavelength of the standing waves will increase, raising the possibility of spatial holeburning, and hence multimode operation. In the patterns of Figure 16, the spatial wavelength is on the order of the diffusion length for carriers, so no spatial holeburning will result. It is possible to fabricate VCSELs with very large transverse section and homogeneous injection in two ways. To fabricate a one-dimensional travelling wave laser, the lasers should be not square but rectangular (see Ref.³⁶) with a narrow ($\sim 4 \mu\text{m}$) side and a long ($\sim 300 \mu\text{m}$) side. To fabricate a two-dimensional travelling wave VCSEL,

one could utilise transparent substrate devices. These have more usually been fabricated at 980 nm, as GaAs is transparent at this wavelength, but are now also available at 850 nm. A possible problem with this choice of device is the non-homogeneity of the temperature. In the large aspect ratio devices even cooling can be expected along the length of the device.

A question not discussed before is that of the structure of the laser farfield in the *slowly* diverging direction (the direction marked $\vec{j}$ in Figure 16). An important observation is that the $\vec{j}$ structure is not reproduced from device to device. In the device shown the $\vec{j}$ structure is similar to that of a TEM₀₃ Gauss-Hermite mode, and for nominally identical devices it can resemble any Gauss-Hermite from TEM₀₀ to a TEM₀₆. One possible reason for this is uneven oxide boundaries favouring one mode over others. This idea suggested that small excess gain for one mode could be sufficient to make that mode dominant. The lasers were operated with an external cavity on one side consisting of a lens and a mirror, and slight tilts of the external mirror could select both the $\vec{j}$ mode *and* the $\vec{i}$ wavevector over a wide range for identical operating conditions. Were frequency selective elements to be included in a large travelling wave laser, it might be possible to generate high single mode power, with good beam quality.

4. Conclusion

In conclusion we have characterised the spatial structure of oxide-confined VCSELs as a function of the aperture size. For the smallest lasers we have shown that a thermal lens dominates the properties of the resonators. For medium size lasers, the patterns experimentally observed are similar to those observed in ion implanted devices¹⁴. For lasers with large apertures, the laser can emit a single frequency solution corresponding to an almost one dimensional standing wave of the laser intensity. The transverse wavenumber of this pattern can be controlled with the detuning, δ , as predicted by two-level models. For higher pump levels and other detuning values, two instabilities may occur. The first instability is associated with the appearance of modes with smaller transverse wavenumbers, while the

second is associated with a polarisation instability at the same wavenumber.

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Fig. 1. Structure of a Vertical Cavity Surface Emitting Laser with dielectric oxide confining layers.

Fig. 2. Transverse mode spectra of a $10 \times 10 \mu\text{m}^2$ VCSEL, with threshold at 3.6 mA. The measurement did not include polarisation elements and only modes that lase over a large current range were recorded.

Fig. 3. Threshold current density of VCSELs with reduced optical confinement as a function of aperture size.

Fig. 4. Wavelength of a $1 \times 1 \mu\text{m}^2$ VCSEL as a function of current. The laser is operated DC and the threshold current is 1.3 mA.

Fig. 5. Spectrum of a $1 \times 1 \mu\text{m}^2$ VCSEL as a function of current. The squares correspond to the wavelength of the fundamental mode and the stars to the first order transverse mode. The laser is operated DC and the threshold current is 1.3 mA.

Fig. 6. Wavelength separation between 0th and 1st order modes versus current of a $1 \times 1 \mu\text{m}^2$ VCSEL.

Fig. 7. Rate of change of mode separation with current versus device size.

Fig. 8. FWHM of fundamental mode at 1.1 times threshold as a function of device size. A line of mode size = aperture size has been included for clarity.

Fig. 9. Pulse response of the laser intensity with low average heating of the active region. Pump = 1.8 mA, period = 20 μ s, pulsewidth=1 μ s. Top: current pulse, bottom laser intensity.

Fig. 10. Farfield width of $1 \times 1 \mu\text{m}^2$ VCSEL emission for different duty cycle pulses. Pulse period in all cases is 10 μ s. On-times, dots: 100 ns, solid line: 200ns, dashes: 500 ns, dot-dash: 1 μ s, dot-dot-dot-dash: 2 μ s, long dashes: 5 μ s.

Fig. 11. A plot of threshold current versus heatsink temperature for $5 \times 5 \mu\text{m}^2$ devices.

Fig. 12. Methods used to obtain near-field (top) and far-field (bottom) intensity distributions. A lens of high numerical aperture ($NA = 0.68$) was used to focus the highly divergent emission onto a distant CCD array to obtain a magnified image. For the far-field, a piece of paper was mounted to act as a diffusion screen, and the scattered light imaged by a CCD camera.

Fig. 13. Left: Near field distribution for a $5 \times 5 \mu\text{m}^2$ device at 2.5 times threshold. Right: Corresponding optical spectrum. The temperature is 18 degrees.

Fig. 14. Near field corresponding to the six biggest peaks in the optical spectrum 13

Fig. 15. Vertical (left) and horizontal (right) polarisation of near field distribution for corresponding to the left bottom pattern of figure 14.

Fig. 16. Left: Far field distribution of the laser intensity at 1.05 threshold and at the heat sink temperature of 15 degrees. Right: corresponding near field distribution.

Fig. 17. Left: *j*-polarised optical spectrum of the pattern shown in figure 1. Right: *i*-polarised optical spectrum of the same pattern

Fig. 18. Laser wavelength as a function of wafer position for both small and large VCSELs. Squares correspond to small Fresnel number lasers and dots to large Fresnel number lasers. The small lasers operate in the fundamental Gaussian mode and reveal the cavity resonance frequency. The large lasers are free to choose either a superposition of spatial modes or standing waves. The data demonstrate the qualitative change that results from the transition from negative detuning to positive detuning.

Fig. 19. Shift of highly divergent mode emission wavelength with heat sink temperature at constant injection current. Although the positive detuning of the laser dictates that the mode is a standing wave close to the gain peak frequency, the boundary conditions discretise the allowed frequencies.

Fig. 20. Left: Far field distribution of the laser intensity at 1.3 times threshold and at a heat sink temperature of 15 °C. Right: corresponding optical spectrum.

Fig. 21. Left: far field at 1.6 times threshold and heat sink temperature of 15 °C. Right: corresponding near field filtered to pass only h polarisation

Fig. 22. Left: far field field at 2.0 times threshold and heat sink temperature of 15 °C. Right: corresponding near field

Fig. 23. CW stability diagram for the modes of 25 μm VCSEL versus current and heat sink temperature. Triangles: highly divergent outermost ring, squares: 2nd most divergent ring, diamonds: orthogonal polarisation, asterisks: 3rd most divergent ring, crosses: low divergence modes

Fig. 24. Average near field intensities for broad area VCSELs operating pulsed with period of 10 μ s, and peak injection current of 5 i_{th} . The duty cycles are as follows; (A) 0.04%, (B) 0.1%, (C) 0.5%, (D) 5%, (E) 10%, (F) 20%, (G) 50%, (H) 60%.

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