Coherent ring VCSELs for high power, narrow linewidth applications

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ABSTRACT

The coherent ring VCSEL (CR-VCSEL) structure developed at Dallas Quantum Devices is a monolithic, narrow linewidth high power device configuration that can be fabricated using typical VCSEL epitaxy and conventional processing techniques. So far, CR-VCSELs have demonstrated CW output power greater than 500mW with linewidths less than 0.2nm, power conversion efficiency greater than 30%, with full angle divergence angle less than 10 degrees. In applications where they are appropriate, CR-VCSELs should enjoy significant cost advantages over other high power, narrow linewidth semiconductor laser configurations.

Keywords: VCSEL, single mode, high power, narrow linewidth

1. INTRODUCTION

VCSEL oxide aperture emitter configurations can be used to tailor far field emission according to user defined needs in illumination and optical pumping applications. Figure 1 shows three different, equal aperture area designs for comparison at different drive currents. The configurations shown allow multiple optical modes in all dimensions with an aperture area of ~340 square microns. The last design in the group, the ring variant, shows significant reduction in far field divergence compared to the round emitter and cross versions also shown. In this work we further explore VCSELs with ring aperture configurations, focusing on coherence effects in designs that have single mode oxide aperture widths (around 2-5 microns one dimension) and much larger ring diameters. And we use the term “Coherent Ring VCSEL” or “CR-VCSEL” to describe emitters in a ring configuration with single mode width in one dimension.

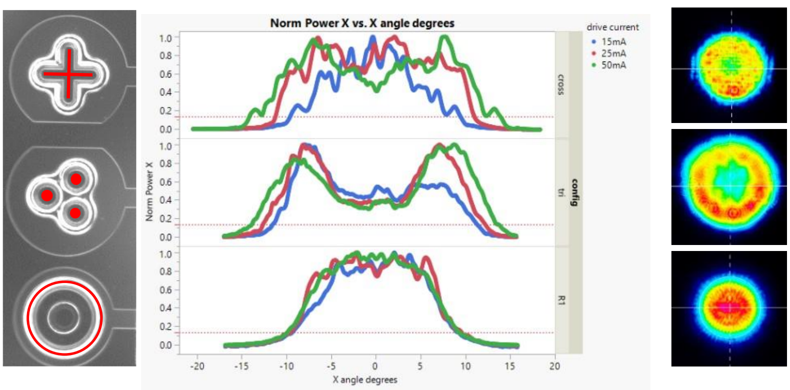

Figure 1. Emitter aperture configuration, far field cross sectional profile at 3 drive currents, and far field image are shown for an emitter cross; 3 round, 12 micron diameter emitters; and a ring emitter.

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Figure 2 shows a functional drawing for a CR-VCSEL. In some operating configurations, we observe significant reduction in both far field divergence and emission linewidth when compared to traditional round aperture VCSELs. We hypothesize that the ring configuration encourages entrainment of optical modes around the ring, and in the extreme, could lead to single mode operation via formation of an optical super mode for the entire ring structure[1]. This effect is encouraged in a ring shape by the uniform thermal conditions around the ring, especially compared to more conventional multi-emitter VCSEL arrays that see significantly higher temperature in the center of the array [2]. CR-VCSEL configurations can be engineered for many applications utilizing the full toolbox of VCSEL fabrication technologies including epitaxy wavelengths ranging from 650 to 1300nm, stacked junctions for more power and efficiency, etched gratings for mode or polarization control, backside emission, and using other confinement schemes such as buried tunnel junctions or lithographic apertures. The CR-VCSELs results discussed in this work are fabricated using DQD standard 850 nm high power oxide confined epitaxial material, using processes already in place at DQD's external foundry. A sample die image is shown in figure 3.

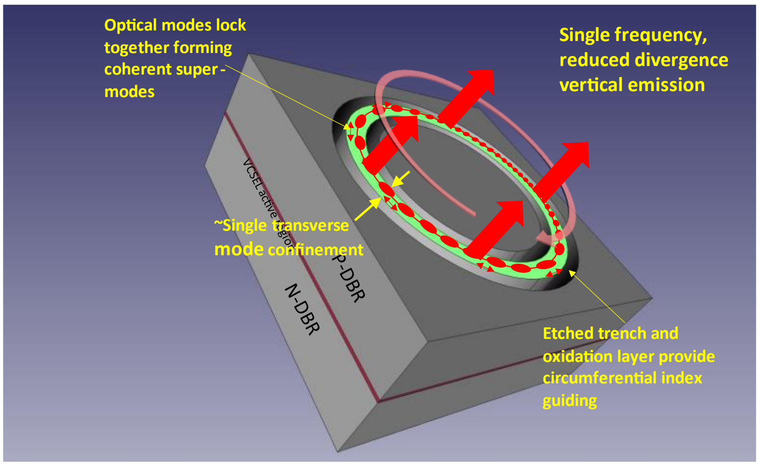

Figure 2. CR-VCSEL showing etched trench used to expose oxidation layer and entrained optical modes that form along the device.

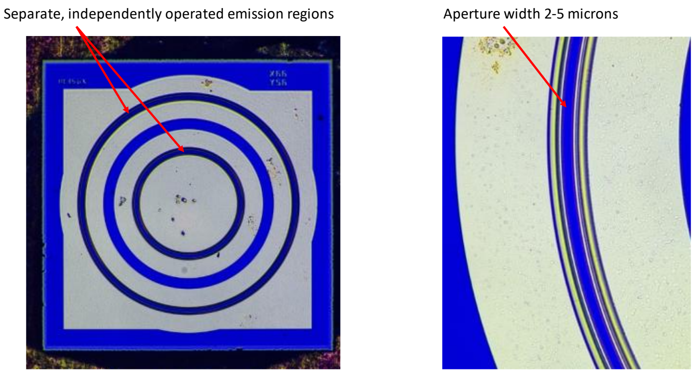

Figure 3. CR-VCSEL die image showing two different emission regions, diameters 500 and 1000 microns.

2. CR-VCSEL PERFORMANCE

The primary utility of CR-VCSELs lies in their capacity to scale up power from what is traditionally extracted from a single mode VCSEL, similar to high power VCSEL arrays, with some reduction due to the small aperture size in one dimension. The ring and the spot operating regimes may be separately optimized for different applications. Figure 4 shows

LI and PCE curves at 25, 50, and 75C for ring devices with diameters of 200, 500, and 1000 microns. Peak DC power conversion efficiency shown here is 38% for a 200 micron diameter device, and maximum power extracted is in excess of 1 watt.

Far field divergence for all three device diameters shown as images on a graduated, illuminated target 25mm from the devices at the same current density, are shown in figure 5. The far field divergence exhibits strong temperature dependence, operating in a multimode high divergence ring, suggesting slow light operation [3], at epi substrate temperatures below 55C and transitioning to a low divergence partially coherent spot above 60C. The behavior is driven by the 15nm built in quantum well gain to Fabry Perot cavity offset designed into this epi material and the availability of off axis modes in devices with a much larger physical extent than a traditional round aperture VCSEL. It is worth noting that LI curves for these devices shown in figure 4 are taken using an integrating sphere to ensure that all off axis emission is collected. Strong kinks in output power are not present, suggesting that the device does not access whispering gallery or other higher loss optical modes. Figure 5 further shows that when the device substrate temperature set to 75C emitter NA has dropped to <0.1.

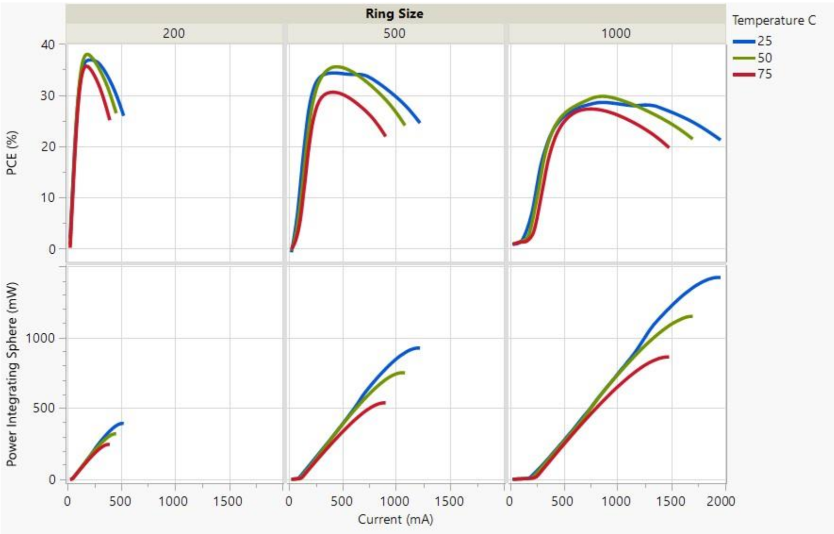

Figure 4. Power conversion efficiency (PCE) and optical power output as a function of constant current for ring diameters of 200, 500, and 1000µm taken at temperatures of 25, 50 and 75°C.

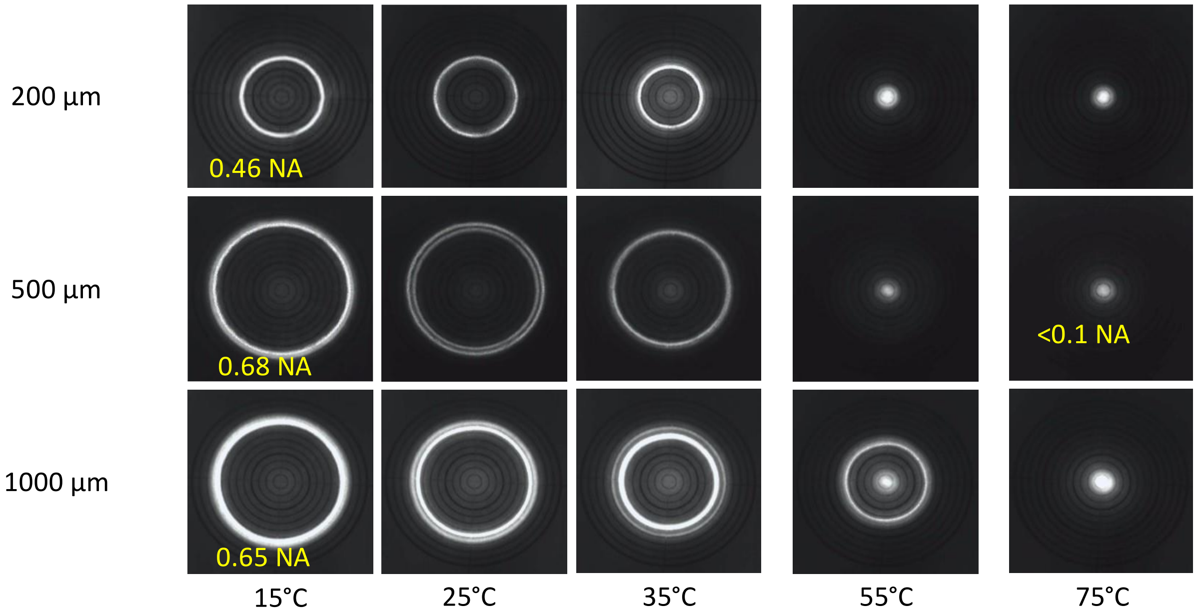

Figure 5. Far field screen images for 200, 500, and 1000 micron diameter CR-VCSEL emission for temperatures ranging from 15 to 75C. All 3 devices are driven at the same current density.

Figure 6 shows emission spectra for the same devices, collected with an integrating sphere using a 600 micron core fiber to couple adequate power to an optical spectrum analyzer. Spectral resolution is limited when using a large core fiber, but the major features of the spectrum are visible. At 25C when only high angle off axis ring modes are visible, multiple spectral peaks around 845nm are present. At 50 C both ring and spot modes are visible corresponding to spectral peaks around 845 and 853nm. Then at 75C only the spot mode is observed, and it manifests as a single peak for the entire CR-VCSEL device.

A corresponding near field emission image for the spot mode and the off-axis ring mode is shown in figure 7, with stable mode structure visible at 70C. At 25C very little light is emitted into the objective, and the mode structure is not visible.

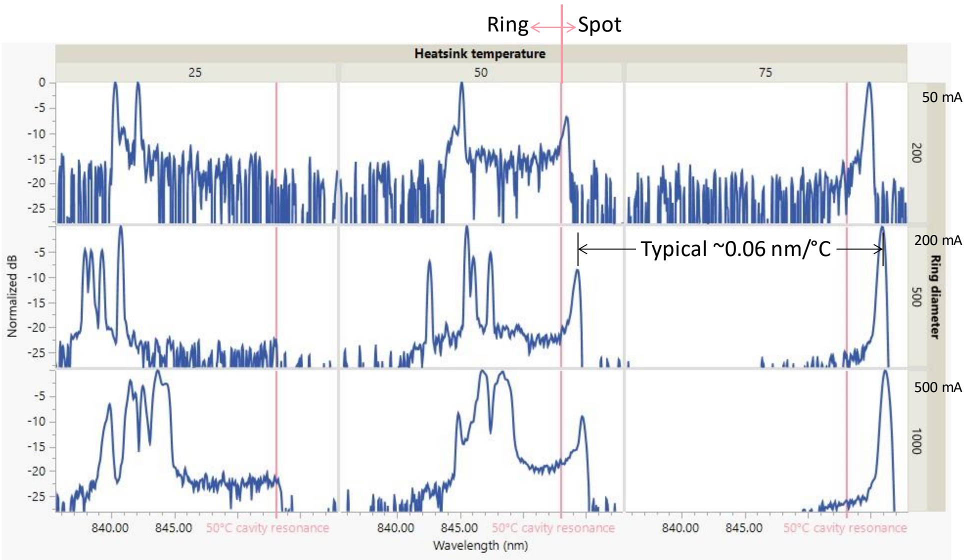

Figure 6. Emission spectra at 25, 50 and 75C for 200, 500, and 1000 micron diameter devices.

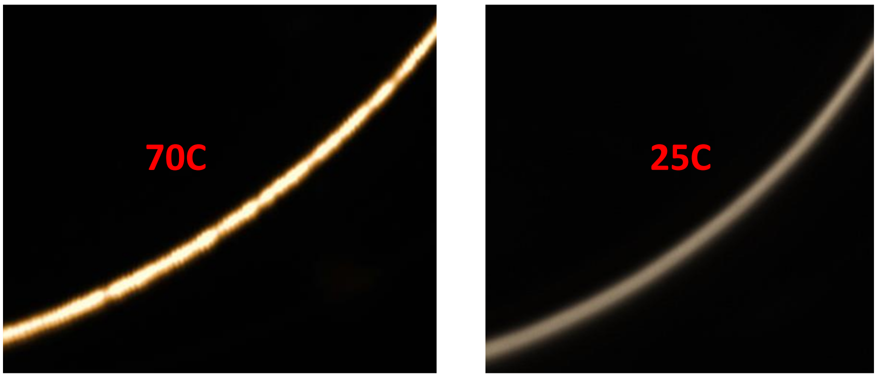

Figure 7. High magnification near field emission for a 500 micron diameter CR-VCSEL at 150mA bias. Mode near field is observable at 75C.

Figure 8 shows far field divergence the three CR-VCSEL diameters versus current density when all are operating in the narrow divergence spot mode. For comparison, we also include divergence for a conventional single mode round aperture VCSEL (diameter ~4 microns). For consistency, all divergence data in this figure is taken using a DataRay near field camera using neutral density filters, but no optics. Distance from the camera is approximately 25mm. Divergence is found based on calculation of the D86 diameter at multiple distances. CR-VCSEL NA is around 0.075, corresponding to a full angle divergence of 8.6 degrees. SM VCSEL NA is 0.125. Note the SM VCSEL was fabricated on the same epi using the same fab process and the same fab run as the CR-VCSELs. Sample far field emission is also shown in the same figure. The narrowing of the far field divergence for the CR-VCSEL suggests partial coherence of the emission and mutual entrainment of the optical modes around the CR-VCSEL ring.

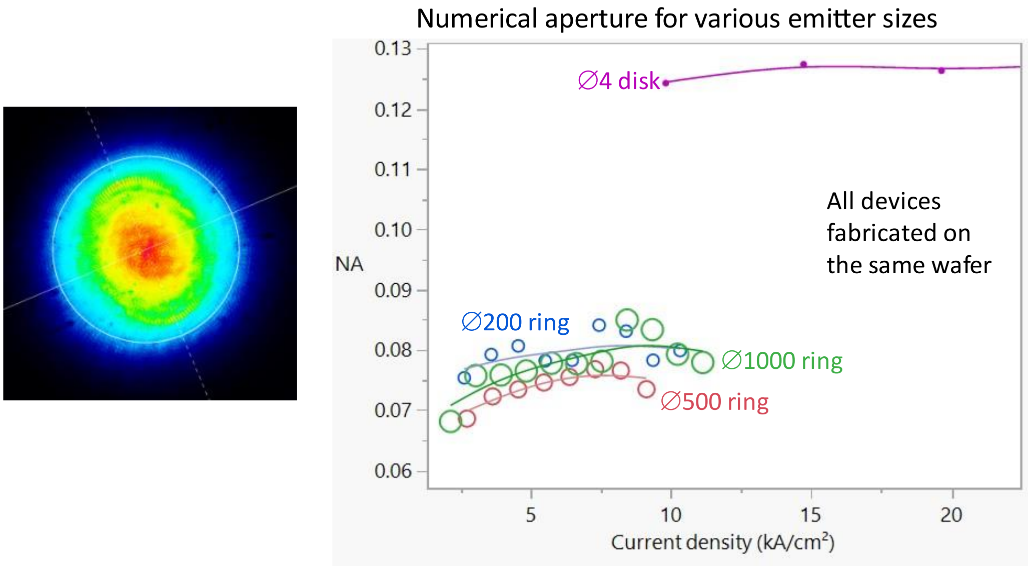

Figure 8. Numerical aperture versus current density for several ring diameters when lasing in the spot mode. Substantially narrower than same-wafer traditional single mode VCSEL.

Figure 9 shows the optical spectrum for a 500 micron diameter CR-VCSEL operating at 75C in spot mode. In this case, emission is collected using a low magnification microscope objective and a 100 micron core fiber. The observed spectral width is limited to the linewidth of the system at 0.2nm or 80GHz at 850nm at power levels up to 325mW. This narrow linewidth is already enough for some optical pumping applications and may provide the opportunity for pump and probe integration on the same chip.

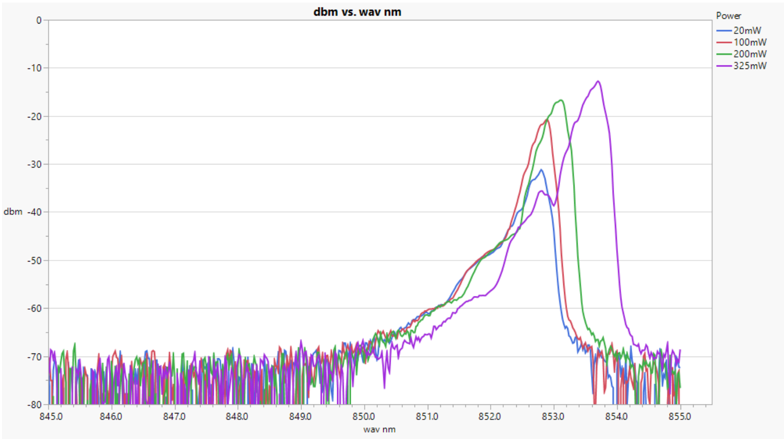

Figure 9. Spot mode CR-VCSEL emission of a 500 micron diameter device at 70C. Observed linewidth is limited by optical spectrum analyzer and fiber core size to 0.2nm.

3. CONCLUSIONS

CR-VCSELs present another possible avenue for the development of high power narrow linewidth laser sources. When compared to PCSELS[4] or DFB sources, CR-VCSELs can have power and efficiency similar to 2D VCSEL arrays, along with advantages of conventional VCSEL processing and test infrastructure, making them potentially attractive for many high volume applications.

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