More Power! VCSELs near 1 million amps per square centimeter

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ABSTRACT

While time-of-flight applications have led to VCSEL arrays operating at currents measured in the amperes and producing very high aggregate powers, the current through each individual VCSEL aperture is not substantially higher than in many other applications. Driving a single VCSEL emitter of moderate size to extremely high currents requires specialized circuits and operation in a regime where thermal effects will not destroy it, meaning low duty cycles and pulse on-times measured in single-digit nanoseconds. In that regime traditional VCSEL performance and geometry scaling rules no longer apply and surprising behaviors emerge. We describe results for small area single-emitter 850-nm VCSELs designed for high power extraction operating at peak currents of several amperes. The electrooptical behaviors observed afford opportunities for VCSELs in nontraditional areas, but they may also indicate some previously unsuspected limitations.

1. INTRODUCTION

Dallas Quantum devices is a fabless supplier of VCSEL die and assemblies that target custom applications. Available products include single mode polarization locked devices over the full 760-980nm range, datacom devices with data rates of 10-25+ Gbps, and high-power arrays at 808, 850 and 940nm. The DQD devices tested in this work used existing 850nm high power product material with conventional single junction epitaxy and a single oxide aperture for current and optical confinement, in a standard top emitting, topside anode, common bottom cathode configuration. Single emitter CW peak wall plug efficiency for these devices was observed to be 45%.

1.1 CW Characterization

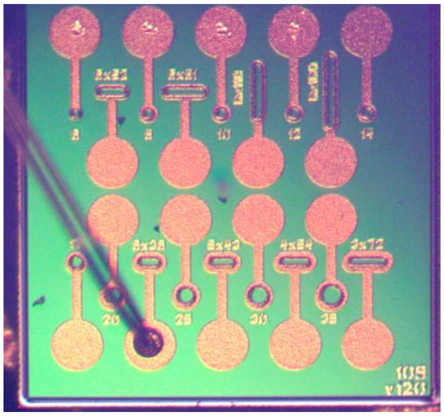

Figure 1: Wire bonded VCSEL die with single emitter common cathode slot and round aperture VCSELs used in this work. Slot and round aperture VCSELs are arranged in pairs with equal active area.

In this work we describe performance data of individual emitters on a single die as shown in figure 1, comparing performance of round aperture devices with that of slot/linear aperture devices of equivalent aperture area. Similar results for CW/DC operation have been shown in the literature [1], referred to in these references as rectangular aperture VCSELs. We will use the nomenclature “slot” aperture for the rest of this work because the aperture width used here on the order of 3-6 microns, narrow enough that in the direction perpendicular to the slot behavior

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is single mode, or nearly single mode, over the high current, pulsed operating range explored in subsequent sections.

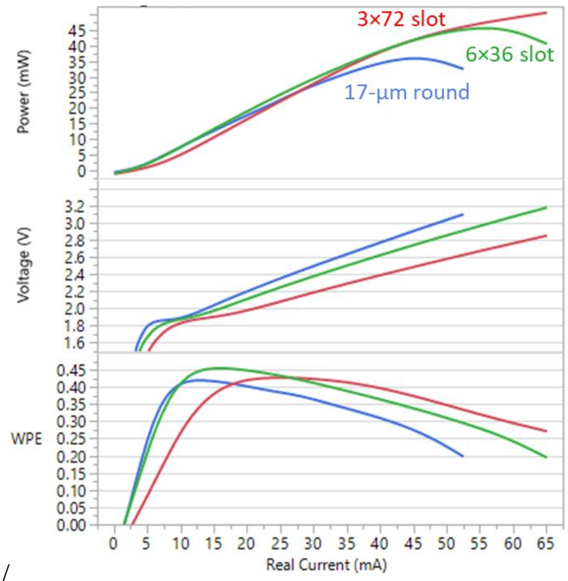

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Figure 2: Power, voltage, and wall plug efficiency under CW drive for 17um diameter round devices, 3x72 and 6x36 micron slot aperture devices, all of which have equivalent area. Slot aperture configuration increases rollover current from 45mA to 57mA for a 6x36um aperture and to 65mA for a 3x72um slot aperture device. These CW results are similar to those in prior literature.[1]

Figure 2 shows the CW performance difference between equal area slot and round aperture devices. It is not surprising that the increased perimeter to area ratio of slots reduces both electrical and thermal resistance compared to circular area-equivalent circular devices. While analytic solutions to the current/heat flow problem are confounded by the complex geometries and the property anisotropies that resulting from the laminar VCSEL structure, the general trends are well-known. The CW result here is that rollover current increases from 45 mA for a 17 µm round device to 55 mA for a 6×36 µm slot and to over 65 mA for a 3×72 µm slot. Wall plug efficiency at high current density increases in similar fashion.

2. PULSED OPERATION

2.1 Round aperture pulsed power

Devices were evaluated under pulsed drive conditions by mounting die on TO-46 headers, wire-bonding individual emitters, and soldering the assembly to a pulsed driver PCB from DEI Colorado (PCO-7115) together with an external high voltage DC power supply. This PCB is rated for 1ns pulse width at a maximum of 5A peak drive current. Current level and pulse width were observed via a sense resistor and current monitor port provided on the PCB. The pulse frequency used for single emitter evaluation was 200kHz, observed pulse FWHM was 0.65ns. With these narrow and widely-spaced pulses we could drive devices with currents two orders of magnitude higher than the CW rollover. Peak power was computed from average power measurements with an integrating sphere and assuming a rectangular optical pulse at the observed current pulse FWHM.

Figure 3 shows peak output power as a function of both current and current density for round apertures of 17 and 35 microns and equivalent area slot aperture devices. Slot aperture device data is shown for nominal dimensions of 3x73 and 6x160 microns. Maximum drive current is limited by the driver PCB. For the 17 µm diameter round and equivalent area slot aperture devices at more than 1.8 MA/cm^2 current density (achieved at 4 A) no device failures or obvious signs of degradation were observed for either round or slot aperture parts. Output power at less than 0.5 MA/cm^2 is the same for slot and round aperture devices as one might expect in the ns pulse operating regime where thermal effects should not play a significant role. However, we observe that around current densities of 0.5 MA/cm^2 slot aperture slope and output power degrades less than the equivalent round area device.

Furthermore, we see improved rollover characteristics for the 17um slot aperture design.. Figure 3 also shows similar behaviors in the 35 micron round aperture VCSEL and its equivalent area 6×160 slot VCSEL. Note that observed rollover for the 35um diameter equivalent area parts may be caused by the limitations of the drive PCB.

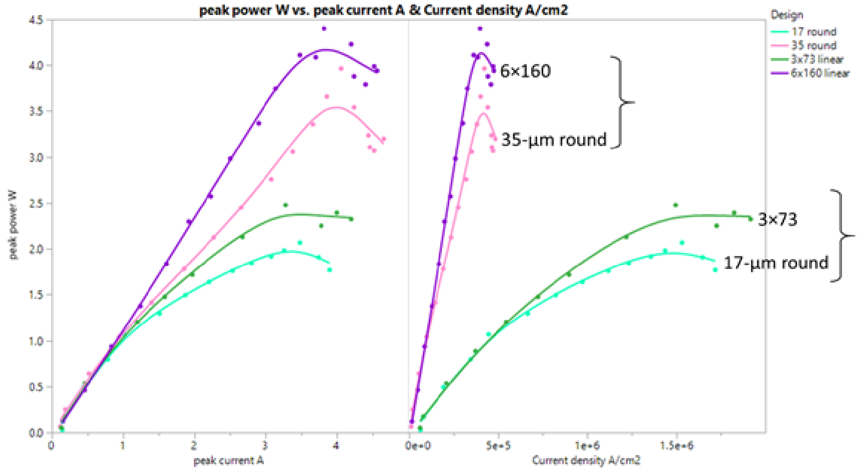
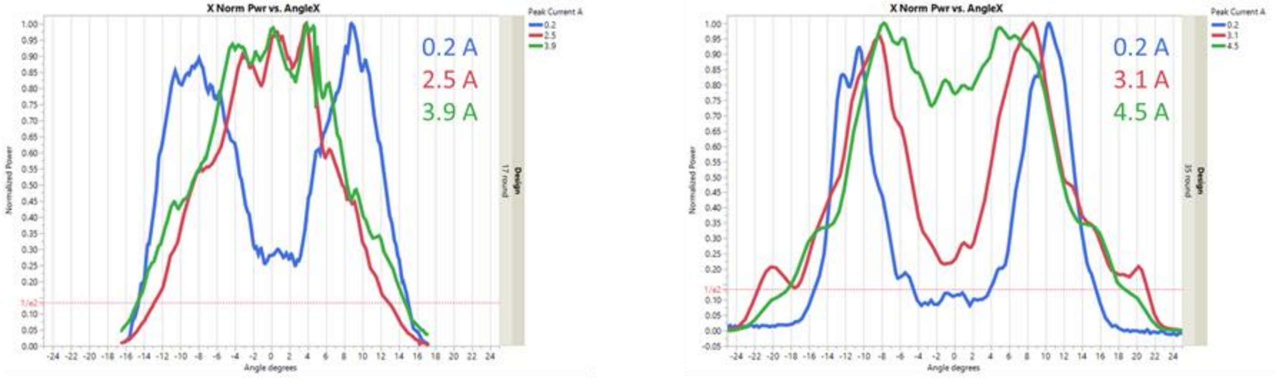


Figure 3: Pulsed peak optical power versus peak current and versus peak current density for 35 micron and 17 micron diameter round and equivalent area slot aperture devices. 17 micron round and 3x73 micron slot aperture devices are driven at more than 1 MA/cm². Pulse width is ~0.65ns at 200kHz pulse frequency.

2.2 Round aperture pulsed drive divergence

Divergence of pulsed devices was characterized by imaging the emission with an optical system consisting of an infinity corrected NIR long working distance microscope objective, a compatible tube lens, ND filters and a beam analysis camera. The focused near field image was obtained as a reference location, then the optics were moved 1-2mm away from the emitter to obtain far field images outside the Rayleigh range.

Figure 4 shows far field image cross sections for 17 and 35um diameter round emitters, plotted as intensity versus beam angle at several pulsed drive currents. At the lowest currents, shown here in blue, the far field patterns are the typical “doughnut” VCSEL emission profile expected for multimode VCSELs with oxide aperture larger than about 8 microns. But at current densities approaching 0.5MA/cm^2, the center of the “doughnut” fills in. This trend runs counter to what is observed for high CW drive currents where heating and current crowding near the outside edge of the aperture drives higher-divergence, more doughnut-like beam profiles as current increases. In this extreme pulsed drive case we can speculate that carrier-induced index change plays a role.



17 micron round aperture

35 micron round aperture

Figure 4: Sample beam profiles for round aperture devices under pulsed drive conditions, showing reduced divergence at the highest current drive, on the order of 1MA/cm².

Far field emission profile data for multiple drive currents and round aperture designs is summarized in figure 5 as a plot of numerical aperture (NA) versus current density. The diameter encircling 86.5% of the output power at 1-2mm distance from the emitter is used for the calculation of NA. Results for multiple drive currents for round devices at diameters of 10, 17 and 35um are shown for pulsed operation over the 0.0-5.0 amp drive current range allowed by the drive PCB. At lower drive currents (0.0-0.5 amps) and current densities, we see the expected monotonic increase in NA with current for all three aperture diameters. But at increasing pulsed drive current NA drops and a minimum is observed for the 10 and 17 um diameter apertures. A minimum NA is also expected for the 35um design, though it is not shown here as it is beyond the maximum current capability of the driver PCB. The decreasing NA shown in figure 5 correlates to the center "doughnut hole" filling emission shown in the beam profiles of figure 4. For the two smallest diameter devices NA reaches a minimum and then increases again as current further increases. The observed minimum is at a current density of 1.5 -2 MA/cm². One possible explanation is that even with these very short pulses a thermal lens can result when currents are sufficiently high, eventually overcoming the NA-lowering mechanism dominant at intermediate currents. The emission spectrum shown in figure 9 supports this hypothesis.

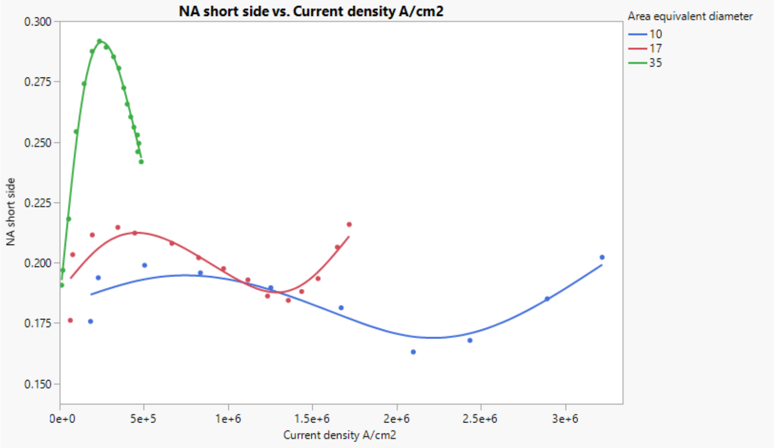


Figure 5: Numerical Aperture versus drive current is shown for 10, 17, and 35 micron diameter VCSELs under low duty cycle pulsed drive. D86.5 method was used for the NA calculation. A minimum NA is observed for 10 and 17 micron diameter emitters.

2.3 Slot aperture pulsed drive divergence

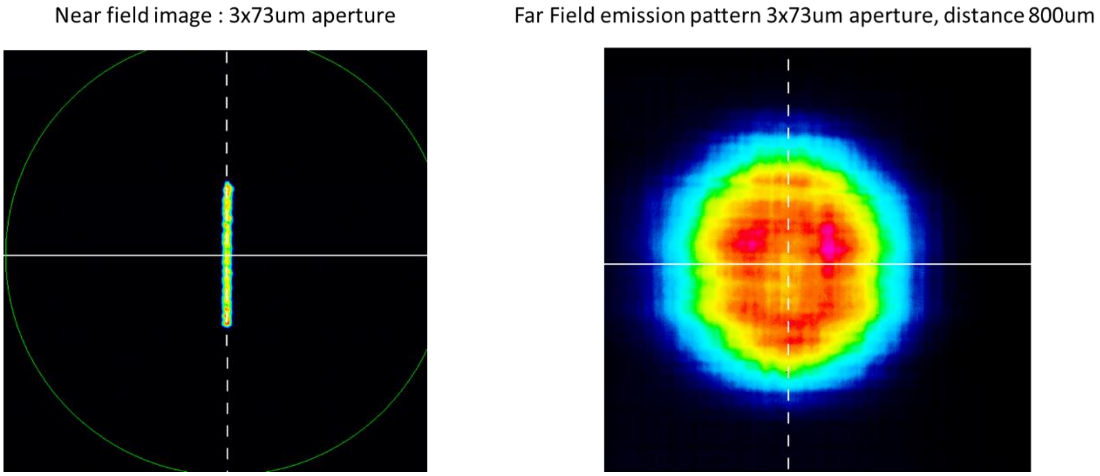


Figure 6: Near (left) and far field (right) emission patterns for a slot VCSEL with 3x73 micron aperture.

Figure 6 shows emitter near and far field images for a 3x73 micron slot aperture. Far field images were collected with the objective focal plane pulled 800 microns away from the device. The far field emission pattern of a near-single-mode slot aperture VCSEL is similar to that of an incoherent array of small aperture single mode VCSELs devices, even though it has tight optical confinement in a single transverse direction. When emitter layout requirements permit it, the slot aperture geometry can therefore be exploited to create a nearly gaussian far field illumination pattern instead of the "doughnut" far field emission associated with top emitting oxide confined VCSELs.

Quantitative far field emission patterns for two slot aperture devices under high current drive are shown in figure 7. Drive conditions and emitter area are equivalent the round emitters in figure 4. Slot aperture devices show little change in beam profile along their short axis (perpendicular to the slot), where the devices tested here show few or single mode operation at oxide aperture widths of 3 and 6 microns. The long axis of these devices (parallel to the slot, either 73 or 160 microns) shows narrowing of far field emission at high drive currents similar to what was observed in round aperture devices. Overall the beam divergence for the slot aperture devices shown here is significantly narrower than equivalent area round devices operated under the same short pulse conditions, giving slot aperture devices potential utility in imaging applications where they may allow for smaller and simpler optics.

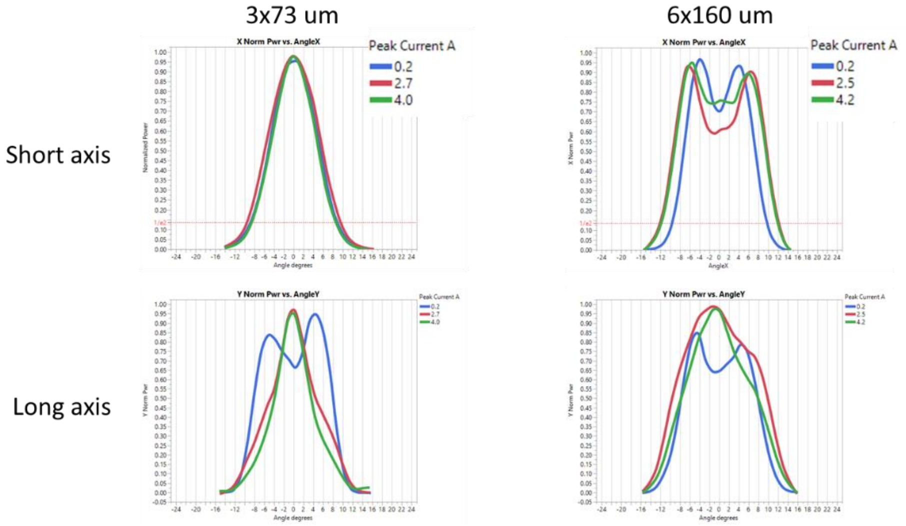


Figure 7: Far field emission profile cross sections for slot VCSELs with 3x73 and 6x160 micron apertures.

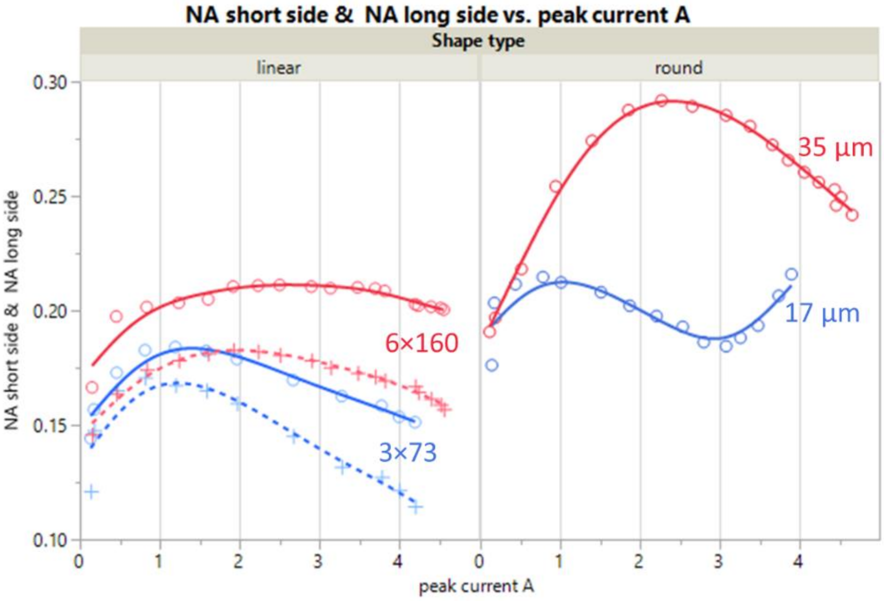


Figure 8: Numerical aperture for 17 and 35 micron diameter circular VCSELs and the equivalent-area slot aperture devices. Solid and dotted lines for slot apertures show divergence for emitter long and short axis respectively.

We compare the divergence of equivalent area round and slot aperture devices for high current pulsed drive by plotting NA versus current for 17 and 35 micron diameter and their equivalent-area slot devices in figure 8. The difference in NA and NA variability between a 35 micron round device and a 6x160um slot aperture is particularly strong and could give slot aperture devices significant utility in applications where short pulses, maximum output power, and large device area are used, such as automotive LiDAR. Under these drive conditions slot devices show that NA peaks then monotonically decreases with increasing drive current (unlike round device behavior described previously). In addition, all slot devices have lower NA—in both axes—than their round area-equivalents at any current.

Spectral data provides another hint for the large differences in NA observed between slot and round aperture devices. Figure 9 shows emission spectra for 17um round and 3x73 slot aperture devices under pulsed operation. At the relatively low current density of 80 kA/cm^2 the long wavelength emission edges align, an indication the junction temperatures are approximately the same. The spectral width of the round device is wider, with all of the difference on the short side of the spectrum, consistent with the higher effective mode order we also see in the far field profiles. At this operating point, differences in NA and output power under pulsed operation are small. As the current is increased, the long wavelength edge of the round device emission pushes out faster than in the slot devices. This is indicative of a larger increase in junction temperature for the round device, and if we assume 0.065nm/°C this corresponds to ~18 degrees higher junction temperature at 1.8MA/cm^2 for the round VCSEL compared to the slot VCSEL. The linewidth of the slot aperture device is also always narrower than the corresponding round emitter, consistent with reduced NA.

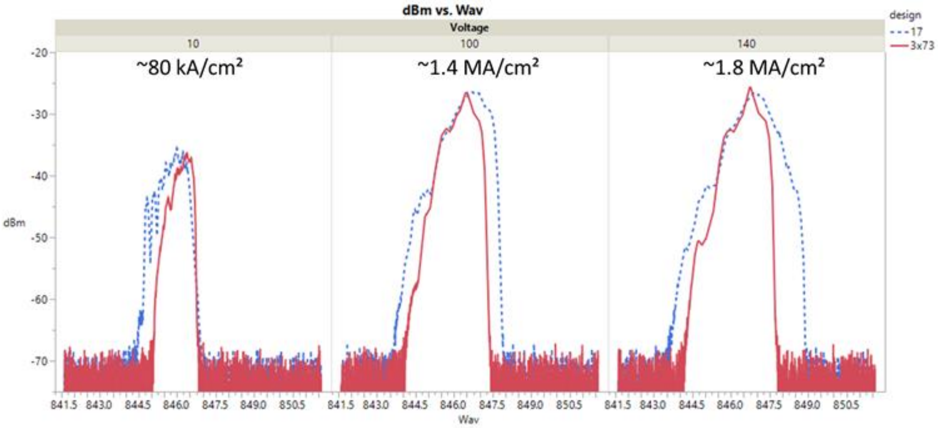


Figure 9: Emission spectra shown on log scale for 17 micron equivalent area devices under high current pulsed drive conditions.

3. CONCLUSIONS

While improved rollover and reduced voltage have been shown for rectangular VCSELs in previous work under CW operating conditions, we show in this work that slot VCSELs with 3-6um apertures in one transverse dimension have especially improved output power and greatly reduced NA compared to equal area round aperture devices under short-pulse operation. The performance benefit is particularly important for large diameter round aperture top emitting VCSELs under high current density pulsed drive conditions that may be relevant to LiDAR applications. In this high current density drive regime we also observe that VCSEL divergence can decrease for both round and slot aperture devices, likely due to carrier induced index effects. While reduced divergence may allow for simpler optics, it must also be considered when evaluating eye safety in this operating regime.

4. REFERENCES

[1] High-power VCSELs with a rectangular aperture, Gronenborn, S ; Pollmann-Retsch, J ; Pekarski, P ; Miller, M ; Strösser, M ; Kolb, J ; Mönch, H ; Loosen, P, Applied physics. B, Lasers and optics, 2011-12, Vol.105 (4), p.783-792