Vixar Application Note

VCSEL Optical Properties

Contents

1 Introduction

Vertical Cavity Surface Emitting Lasers (VCSELs) are unique in their capabilities as a power-efficient optoelectronic component for low power applications requiring a narrow spectrum. With their unique design, the optical properties of VCSELs can be controlled through proper engineering of the aperture on the die.

This application note describes the optical properties for top-emitting VCSELs. This includes output angular divergence, beam quality, and spectral distribution of the optical power as a function of VCSEL properties.

2 VCSEL Design

A VCSEL is an optoelectronic device that consist of quantum wells sandwiched between two Distributed Bragg Reflectors (DBRs). To ensure for both electrical and optical confinement inside the VCSEL, oxide confinement is utilized. An oxidation layer with a high level of Al content is grown above the quantum wells. A cylindrical mesa is etched around the targeted area to expose this oxidation layer to the atmosphere before being placed in an oxide chamber. During oxidation, this high Al content layer oxides from the outside in at a significantly faster rate than the other epitaxy-grown layers and forms a confinement region in the center of the mesa. The duration of the oxidation controls the final aperture size of the VCSEL, with typical aperture sizes ranging between 4 µm and 20 µm in diameter.

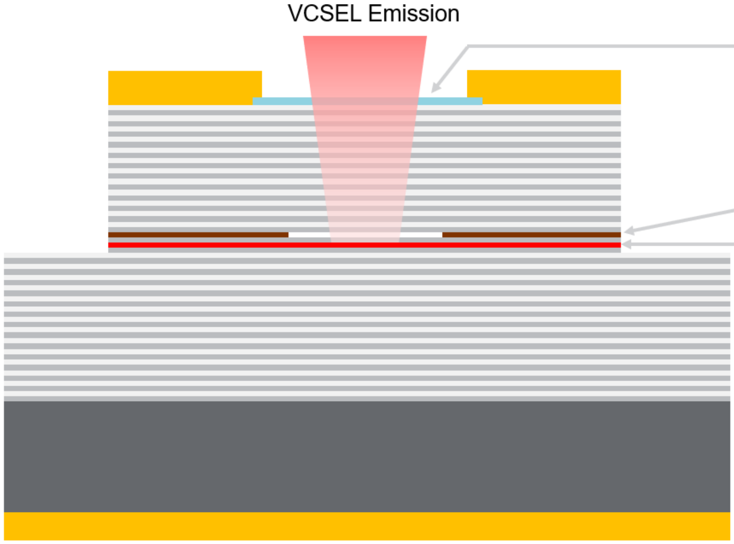

Figure 1. Illustration of the structure of a VCSEL.

In general, higher power can be obtained with VCSELs with larger apertures. The current density of small aperture VCSELs limits the maximum Wall Plug Efficiency (WPE) a VCSEL can obtain. Due to the thin dimensional ratio between the VCSEL aperture and the DBR thickness, WPE peaks around 8 µm. While larger VCSEL apertures can produce more optical power, the WPE decreases with larger aperture sizes due to the inability for current to uniformly cover the confinement region. Thus, for larger power levels, VCSEL power arrays consist of numerous apertures with 10-12 µm diameters manufactured over a large array. This optimizes both the maximum power output, power conversion efficiency, and beam properties of the VCSEL.

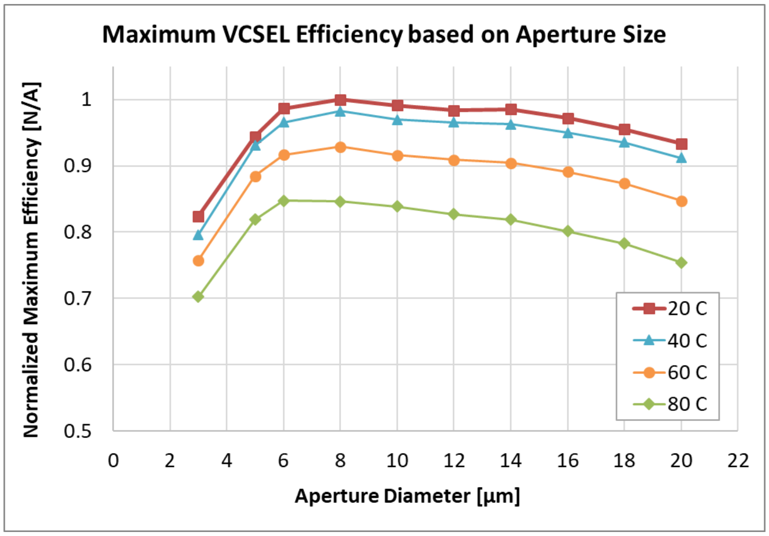

Figure 2. Plot of VCSEL WPE as a function of aperture size and temperature.

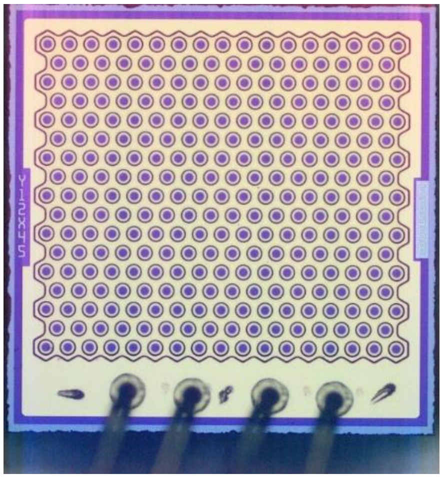

Figure 3. Image of a VCSEL power array.

3 VCSEL Beam Properties

The VCSEL's confinement layer creates a waveguide where the optical power is confined between the DBRs. The VCSEL transverse mode physics is similar to the weakly waveguiding modes in optical fibers. For a small enough aperture diameter, only the fundamental mode (LP_{01}) can exist. Expanding the aperture diameter of the region allows for the excitation of higher transverse modes LP_{lp}. The total emitted field is the sum of all supported modes at the injected current setting.

In addition, each mode has a specific divergence angle. The fundamental mode LP_{01}, the lowest mode, propagates as a Gaussian beam in the far-field. Higher order modes exhibit lower beam quality and propagate with a wider beam divergence.

A similar phenomenon occurs with the performance of VCSELs. The confinement layer in the VCSEL defines the output beam profile of the VCSEL. Vixar designs VCSEL die with various aperture sizes to balance WPE and beam quality. Each excitable mode will increase in power based on the level of current overlap inside the confinement region. The fundamental mode is best developed when current flows through the center of the aperture, overlapping with the peak of the Gaussian beam. This is best realized with smaller aperture diameters and lower currents. With larger apertures and higher forward currents, charge crowding occurs at the boundary of the aperture. This will increase the excitation of higher order modes.

Vixar offers multi-mode VCSELs (M die) with aperture diameters of 8-12 µm to maximize device WPE. To reduce the activation of higher order modes, Vixar offers Quasi-singlemode VCSELs (Q die) with a ~6 µm aperture diameter that balance both a high WPE and a Gaussian-like beam profile.

To fabricate truly single mode VCSELs, the aperture is reduced to ~4 µm in diameter (S die) to ensure that there is a >10dB power ratio between the fundamental mode and any higher order modes. However, singlemode operation is limited to a certain forward current range. Higher current densities push more charge outside of the confinement layer. In addition, thermal lensing and spatial hole burning alters the waveguiding properties of the VCSEL. Both phenomena will increase the excitation of unwanted higher order modes and will degrade the beam quality and spectrum of the VCSEL. Thus, most singlemode VCSELs are limited to forward currents to < 2 mA.

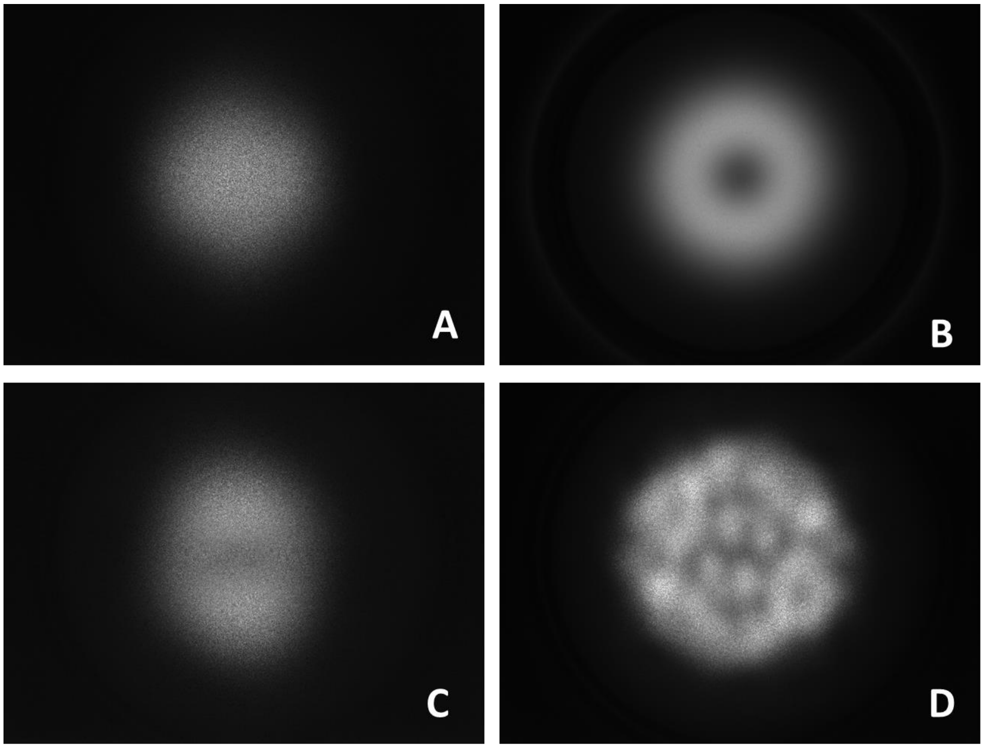

Figure 4: VCSEL beam profiles exhibiting the fundamental mode LP_{01} (A), a higher order radial (B) and angular mode (C), and a mixture of multiple higher order modes (D).

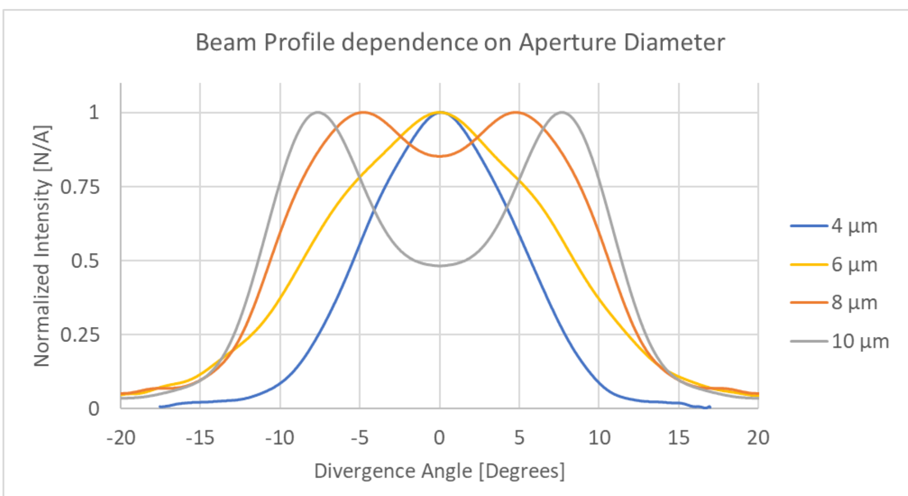

Figure 5: Expected angular beam profiles as a function of VCSEL aperture size.

4 VCSEL Beam Quality

The characteristics of a laser beam is defined by the wave nature properties of the output light. When the output beam of a laser is focused, it will create a minimum spot size (W_0) as defined by diffraction of an ideal Gaussian beam. The laser beam will increase in size (W(z)) depending on the distance z from the focal distance z_0.

Impurities in the beam, including higher order transverse modes, will increase the beam's divergence. The measure of beam quality is quantified as the M^2-factor, and it is the ratio of angular divergence between an ideal Gaussian beam (θ_0) and the measured beam (θ_m). An ideal Gaussian beam has an M^2-factor of 1.

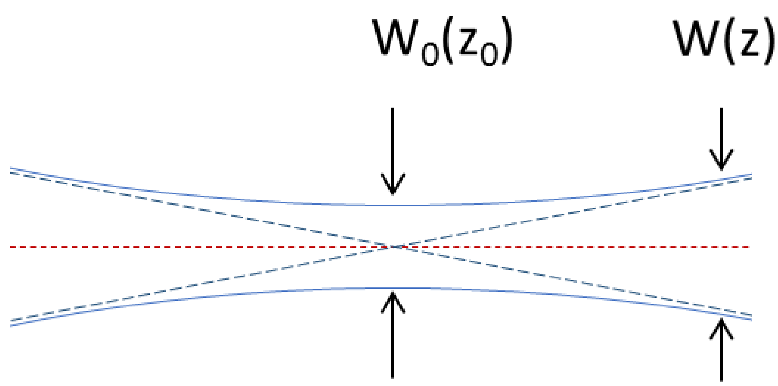

Figure 6: Beam width of a Gaussian beam.

$$W(z) = W_0\sqrt{1 + \left(M^2 . \frac{(z-z_0)}{\pi(W_0)^2}\right)^2}$$

$$M^2 = \theta_m/\theta_0; \quad M^2 \geq 1$$

Figure 7: Equation for beam waist as a function of beam quality.

The M^2-factor is easily applicable to VCSEL beam profiles. Small aperture VCSELs available from Vixar exhibit an ideal Gaussian beam ($M^2 \approx 1$) at low currents. Increasing the aperture diameter allows for more modes to be excited and reduces the beam quality ($M^2 > 1$). In addition, high currents always result in an increase of the M^2-factor, regardless of the aperture size defined by the confinement layer. Thus, there is a direct relationship between an increase in the M^2-factor and increasing both aperture size and forward current, as shown in Figure 8.

In addition, the maximum power that can be obtained with a VCSEL is limited by the size of the aperture. A VCSEL with a small aperture experiences a high current density which ultimately limits the max peak optical power. Thus, both the M^2-factor and the peak optical power increase with larger VCSEL apertures, as shown in Figures 9 and 10. Based on the application, aperture size and forward current must be appropriately chosen to optimize required power and beam quality for any secondary optics and the illumination target. Knowing the maximum M^2-factor permissible in the end-user case, appropriate VCSEL parameters can be chosen. While a 10 µm diameter VCSEL is optimal for high optical power, a smaller aperture of 6-8 µm is more ideal for balancing laser beam quality and efficient optical power production.

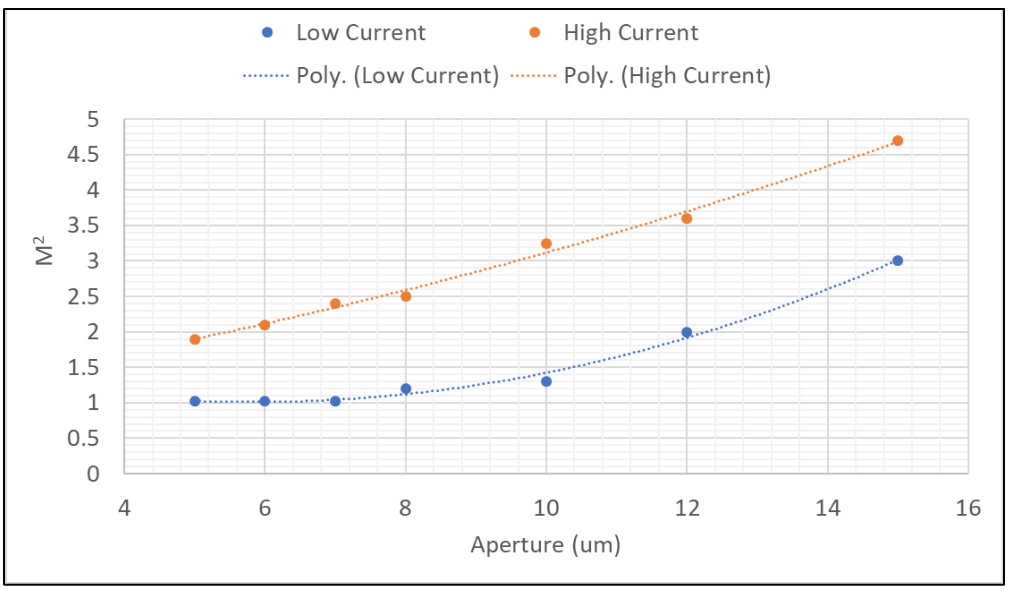

Figure 8: Measurement of beam quality (M^2) as a function of aperture size for low (2 mA) and high (10 mA) forward currents at CW [100% DC].

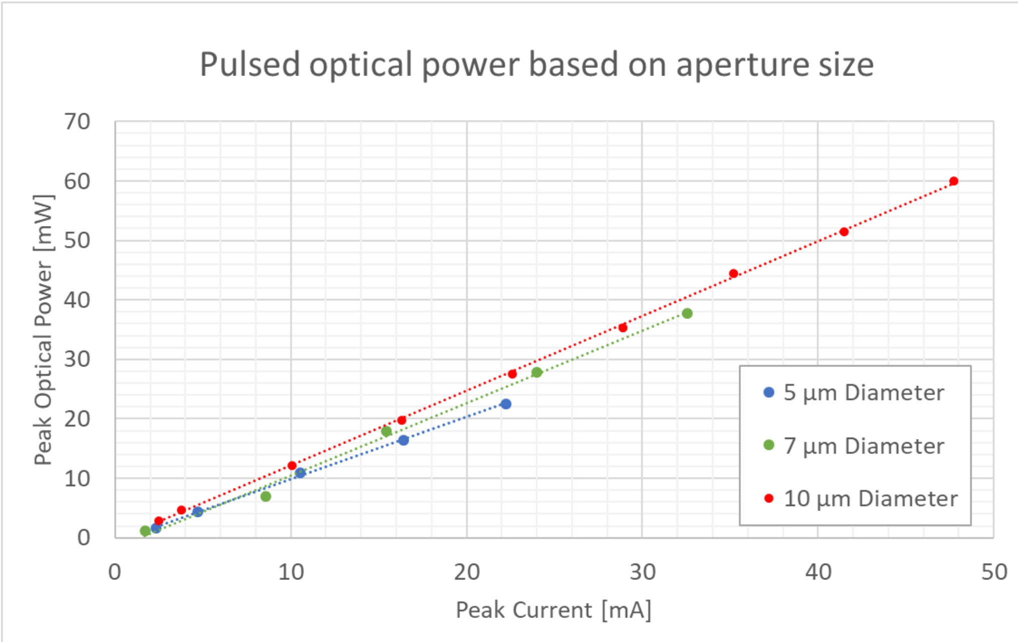

Figure 9: Peak optical power based on aperture size [2ns pulse width with a 2% duty cycle].

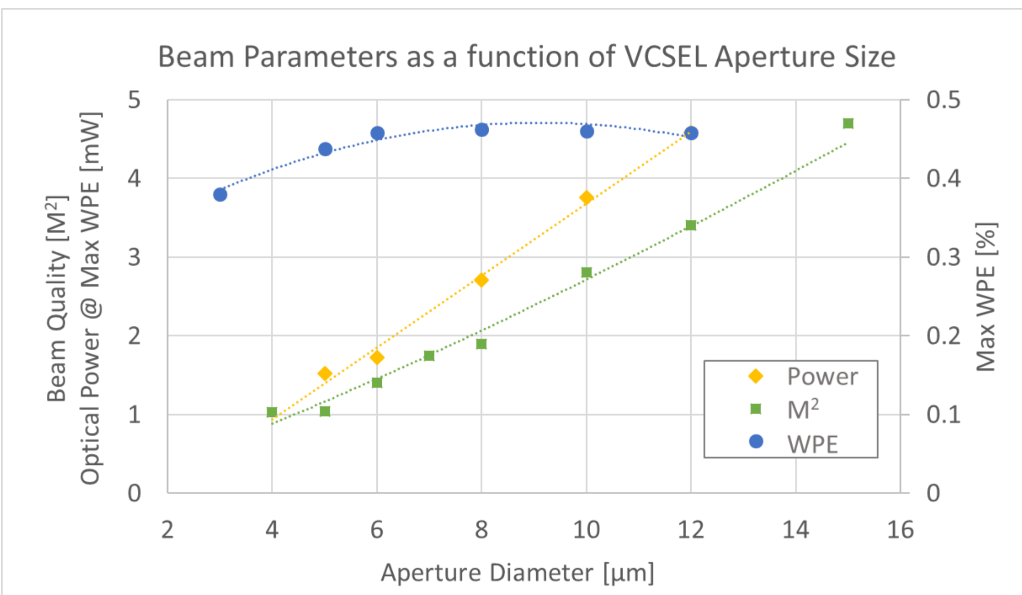

Figure 10: VCSEL properties as a function of aperture size.

5 VCSEL Spectrum Properties

The spectrum of the VCSEL is dependent on the gain medium of the VCSEL quantum wells and the design of the VCSEL DBRs. The top and bottom DBRs create a High-Q Fabry Perot resonator that result in discrete longitudinal modes. In most cases, the tight proximity between the DBRs creates only one longitudinal mode and helps define the VCSEL's peak wavelength.

The single longitudinal mode is also the main cause for the modal stability over temperature. With the longitudinal mode shaping the VCSEL spectrum, the thermal expansion and index of refraction of change with temperature of the DBR layers shift to the red the allowed mode. Thus, increasing the forward current or junction temperature of the VCSEL will increase the peak wavelength of the VCSEL.

Each transverse mode inside the VCSEL aperture also feeds into the spectral modal solutions and results in a different wavelength inside the cavity. Thus, as more transverse modes are excited inside the VCSEL, more peaks are observed in the VCSEL spectral profile. Measuring the output spectrum of a VCSEL can help determine how many transverse modes are being excited and verify if a VCSEL is truly single mode under certain operating conditions.

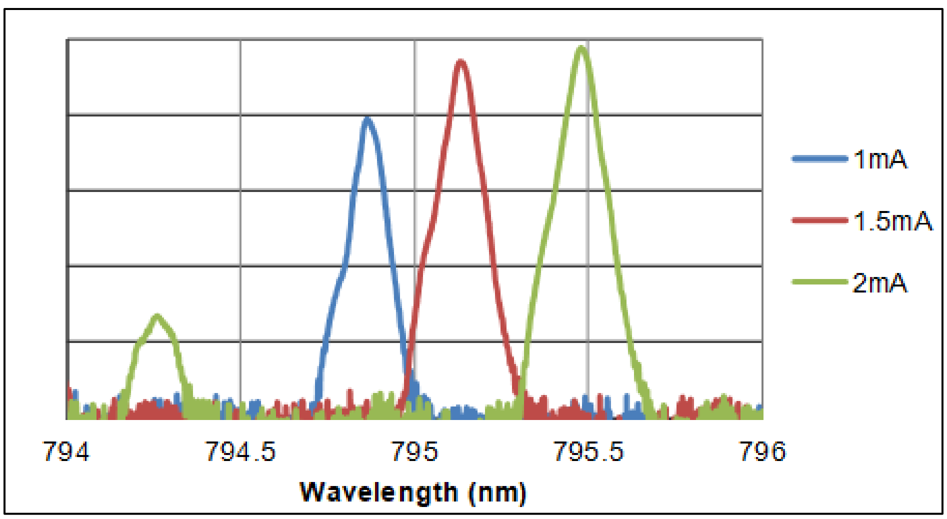

Figure 11: Power Spectrum of a Single Mode VCSEL. A second mode is excited when driven at 2 mA, as observed by two peaks in the output spectrum.

VCSEL power arrays consist of many apertures on a single die that operate in parallel. When the die is turned on, all the individual apertures on the die operate as independent lasing sources. In addition, due to growth variations along the wafer surface, longitudinal modes will be slightly different for each aperture. Thus, each aperture will create optical power with a slightly different wavelength and phase. The measured spectrum of a VCSEL power array will exhibit a spectrum with numerous peaks overlapping each other illustrating a roughly Gaussian profile due to the collective in many numerous apertures operating at slightly different operating wavelengths.

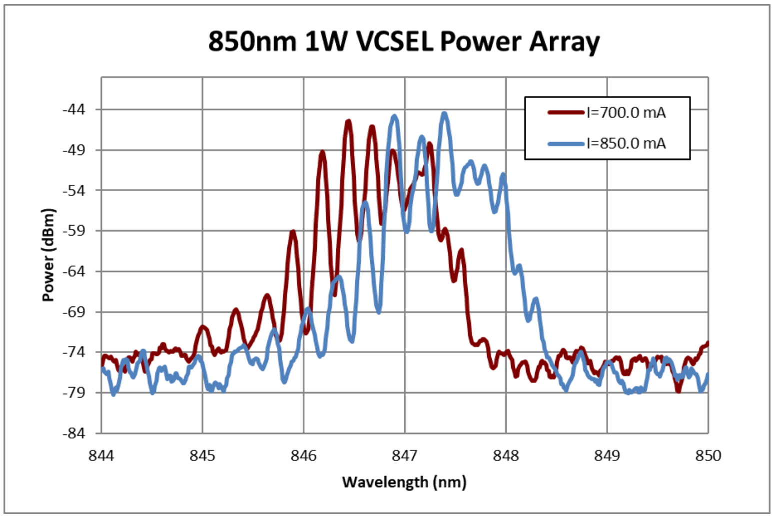

Figure 12: A Measured Power Spectrum of a VCSEL Power Array.

6 Conclusion

The optical properties of VCSELs can be controlled with the design of aperture sizes and operating conditions. Beam quality can be improved by reducing the forward current and aperture size in VCSELs. However, larger aperture size increases device efficiency in VCSELs. Thus, device specifications required for the end application must be taken into consideration for VCSEL design.

Vixar's portfolio includes VCSEL die that are geared toward favored operating traits. Vixar's multimode (M) die maximize the WPE for sensing applications. Singlemode (S) die are also available for minimum spectrum bandwidth. Vixar's quasi-singlemode (Q) die optimize both beam quality (Smaller M^2) and WPE for applications requiring high beam quality that also deliver larger power output.