Vixar Application Note

Red VCSELs

Contents

1 Introduction

Vertical Cavity Surface Emitting Lasers (VCSELs) have grown in popularity as a cost-efficient laser source for sensing applications. Many applications prefer NIR wavelengths for reduced class 1 eye safety standards and the absence of visible illumination. However, many industrial and medical applications benefit from a low-cost visible laser source. The current technology for commercialized VCSELs enable the production of red VCSELs with many advantageous properties, including high efficiency at low power, narrow beam divergence, and low cost SMD packaging.

This application note goes over the red VCSEL technology and current experimental data demonstrated by Vixar. The theory behind red VCSELs is discussed along with its impact on performance. This is followed with experimental results of red VCSELs with different epi and die properties produced at Vixar. Finally, the advantages of red VCSEL in different applications are covered.

2 Red VCSEL Design

The epi structure of a red VCSEL is similar to their NIR VCSEL counterparts. Red VCSELs are epitaxially grown on a GaAs substrate before VCSEL die fabrication. The quantum wells and oxidation layer are optimally positioned between two distributed Bragg reflectors (DBRs) to form a gain medium within an optical cavity. The AlGaAs DBR epi layer chemistry, thickness, and quantities are adjusted to achieve high reflectivity for the visible lasing wavelength.

The key difference with red VCSELs is in the material composition of the quantum well layers. While most NIR VCSELs utilize a GaAs/AlGaAs chemistry to tune the quantum well's energy gap, higher quantities of Al material result in an indirect bandgap and become an inefficient gain medium at shorter wavelengths. Efficient red VCSELs are designed using GaInP materials as the quantum well material of choice. The gain medium is designed with AlGaInP barrier and spacer layers and lattice matched to the AlGaAs n-DBRs on a GaAs substrate.

The band gap limits of AlGaAs and AlGaInP also effects carrier confinement within the quantum wells. Due to the higher energy band gap of the quantum wells, the barrier heights are much lower and result in reduced carrier confinement. Electrons and holes can escape the quantum well through thermal excitation before stimulated emission can occur, resulting in non-radiative combination. The reduction of the carrier confinement energy leads to a limited temperature range of operation.

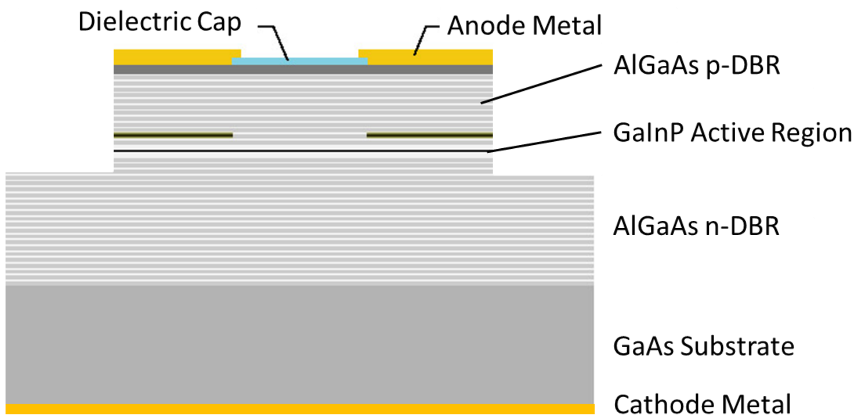

Figure 01: A cross-section illustration of the red VCSEL structure.

The VCSEL's DBRs are designed for high reflectivity at a target wavelength by utilizing repeating layer pairs of different refractive index. A DBR's reflectivity is determined by the quantity of layer pairs and the refractive index difference (Δn) in each pair. DBRs also need to be designed with energy gaps higher than the quantum well material to ensure optical transparency at the operating wavelength. The maximum Δn for AlGaAs DBRs is limited when designed for shorter wavelengths, since increasing Al content in epi layers to improve Δn would result in reliability concerns. The number of DBR pairs must be increased to ensure sufficient reflectivity levels for high laser gain, which increases both the VCSEL's electrical and thermal resistance.

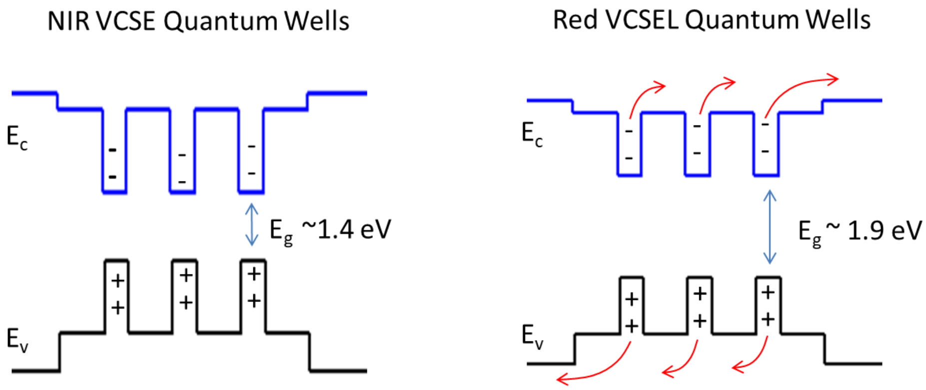

Figure 02: Illustration showing lower quantum well barriers in red VCSELs that reduce charge confinement. Red arrows depict charges exiting the quantum wells due to thermal excitation.

Reduced charge confinement and increased resistance both limit the operating temperature range of red VCSELs. Heat generated from electrical resistance will increase the junction temperature, resulting in inferior carrier confinement, additional non-radiant recombination, and further heating. The increased thermal resistance prevents efficient cooldown and could result in thermal runaway when operated outside maximum ratings. Precise bandgap design and doping management are required minimize thermal limitations, but they cannot be eliminated. Thus, the efficiency and operating range of red VCSELs are always inferior to NIR VCSELs with identical die properties.

As expected, the operating temperature range has been experimentally observed to decrease with shorter wavelengths. Red VCSELs operating at wavelengths shorter than 660nm are extremely temperature sensitive and become practically ineffective for most applications. While the human eye is more sensitive to shorter wavelength, red VCSELs operating at 680 nm provides an optimal balance between VCSEL wall plug efficiency, luminous efficacy, and thermal stability for most applications.

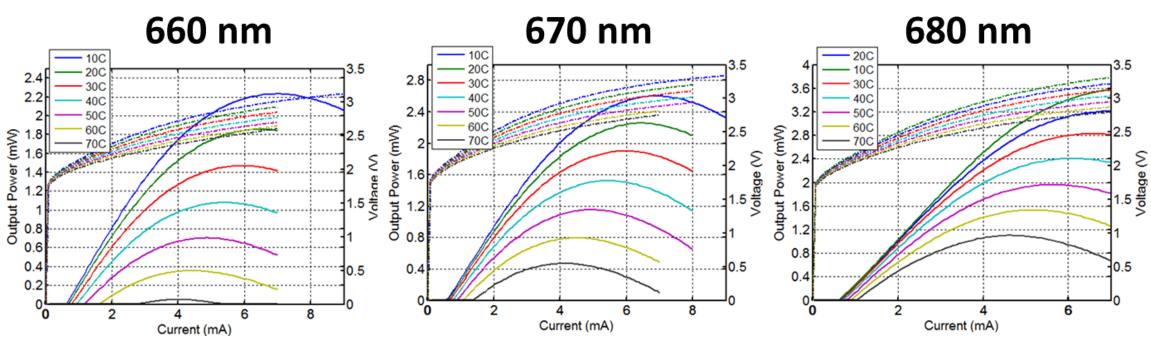

Figure 03: Optical power over temperature performance of 6 µm diameter aperture VCSELs built with operating wavelengths of 660 nm (left), 670 nm (center), and 680 nm (right).

3 Red VCSEL Performance

3.1 Single Aperture Die

A red VCSEL's performance and limitations are strongly dependent on the aperture diameter. Increasing the aperture diameter allows for higher current flow and enables higher output power. However, current crowding at the perimeter of the aperture limits the laser's radiation power efficiency at larger aperture diameters. Peak power conversion efficiency is observed to decrease for aperture diameters > 15 µm.

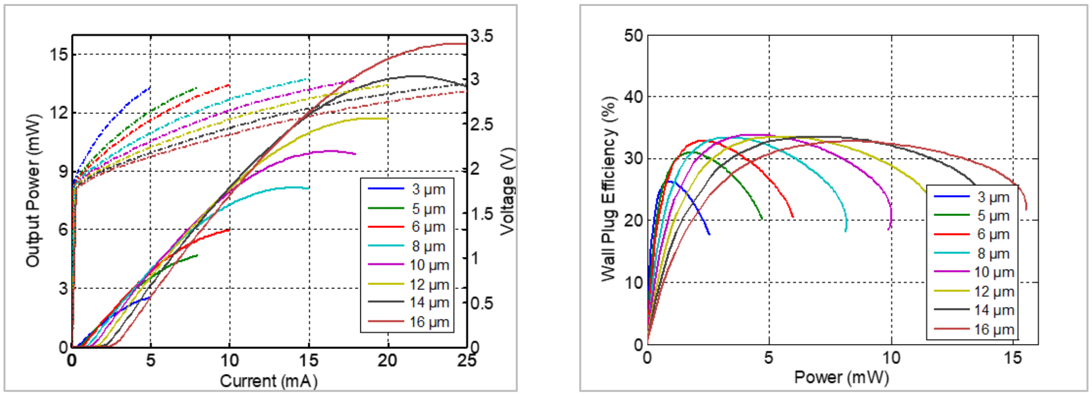

Figure 04: LIV performance (left) and power conversion efficiency (right) of single aperture 680nm VCSELs as a function of aperture diameter at room temperature (25° C).

Due to the higher temperature sensitivity of VCSELs, the thermal load on the die is important in determining the maximum output power. Larger apertures operating at a high current will result in higher junction temperatures and result in reduced output power at elevated solder temperatures. In addition, larger diameters require a higher threshold current before lasing occurs, which contributes to a higher junction temperature at low optical power. Thus, larger aperture VCSELs are experimentally observed to have a reduced operating temperature range.

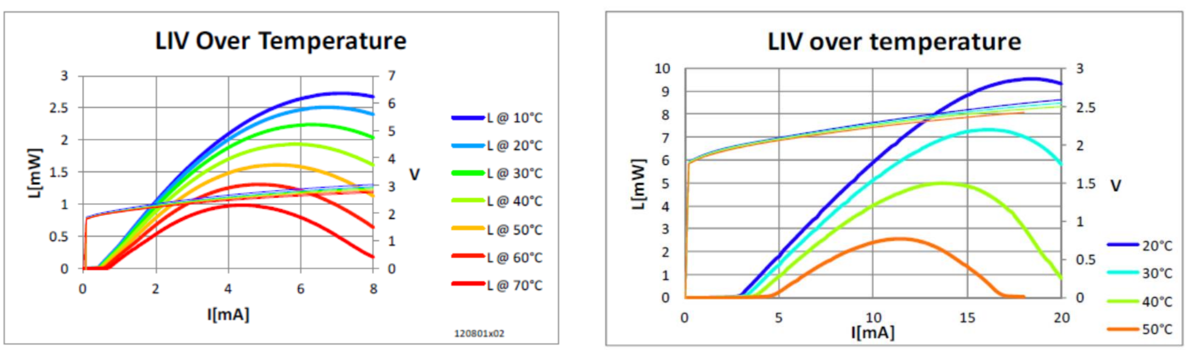

Figure 05: LIV performance over temperature for a 6 µm diameter (left) and 15 µm diameter (right) single aperture 680 nm VCSEL.

For high power red VCSELs, especially at higher ambient temperatures, it is more advantageous to manufacture a VCSEL die with a large quantity of small diameter apertures. This reduces the threshold current and evenly distributes internal heating within the VCSEL die. The aperture array can be designed with a wider pitch to reduce any thermal crosstalk during operation.

VCSELs can also be driven under pulsed condition to improve peak optical power, if continuous wave (CW) operation is not necessary for the specified application. Red VCSELs driven under 100 µs pulse widths at 1% duty cycle (DC) can deliver peak optical power up to 5x greater than what is possible under CW operation. The VCSEL's performance at a specified forward current is ultimately determined by both pulsing conditions, including pulse width and duty cycle, and die attach properties.

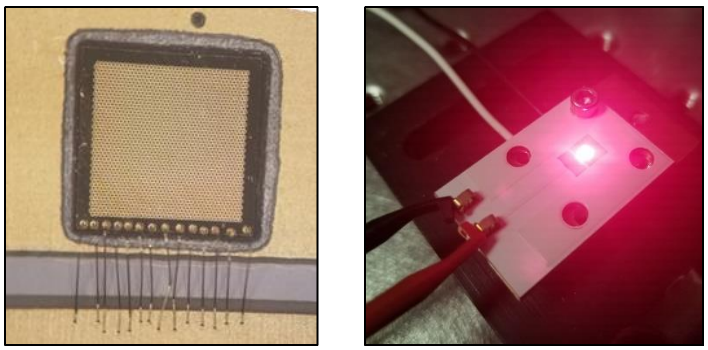

Figure 04: Red VCSEL power array die packaged on a copper PCB.

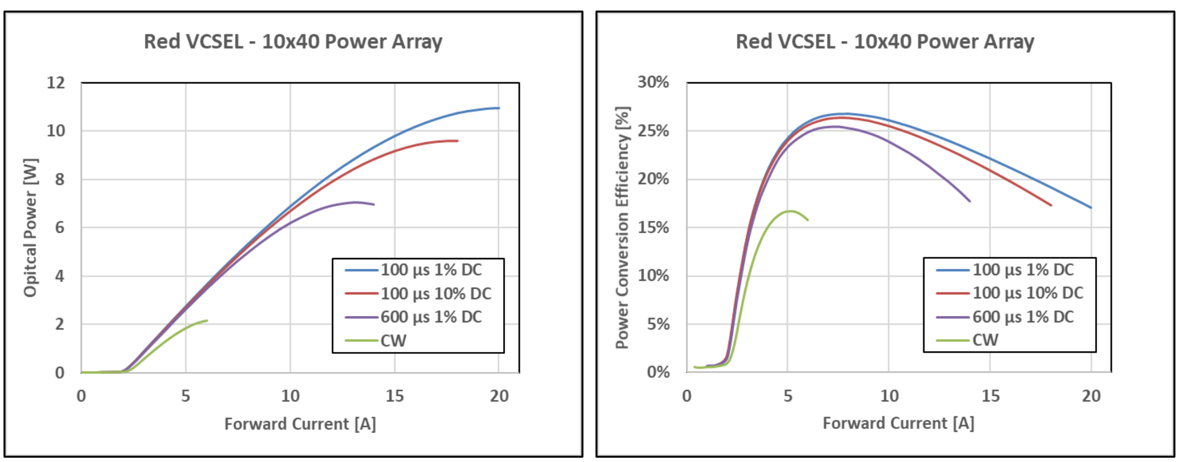

Figure 04: Optical power (left) and power conversion efficiency (right) measurements of a red VCSEL power array (4 mm^2 die) measured under both pulsed and CW operation.

3.2 Optical Properties

The VCSEL's radiation profile and field of view are strongly dependent on the aperture diameter. Apertures with a small diameter efficiently excite the fundamental transverse mode and produce a Gaussian-shaped output beam profile with a narrow divergence angle. Larger apertures result in charge crowding at the aperture boundary and excites more power into higher order modes. These multi-mode VCSELs often produce 'donut-shaped' radiation profiles that result in a dark region in the center of the far-field beam profile.

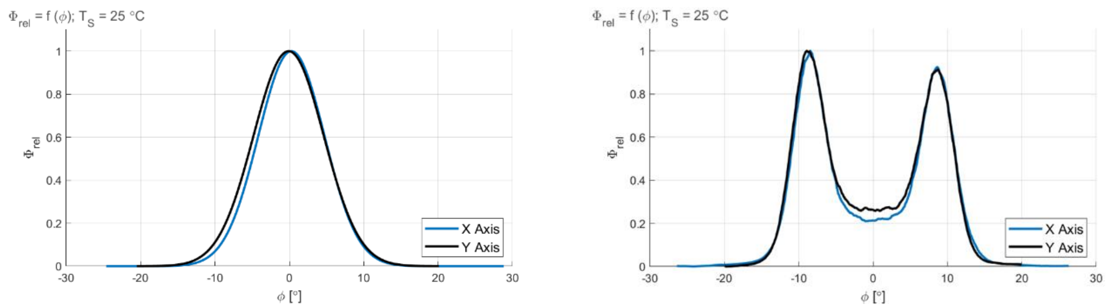

Figure 04: Radiation profiles of a single aperture red VCSEL with 6 µm (left) and 15 µm (right) aperture diameters.

The polarization of red VCSELs differs from IR VCSELs. The polarization for most IR VCSELs is random due to the symmetric design of the circular aperture and will fluctuate over changes in operating conditions. In contrast, the polarization of red VCSEL is linearly polarized and aligned with the plane of the crystal axis. It is theorized that quantum strain inside the VCSEL impacts the directionality of the cavity gain and results in a stable polarization of the output beam.

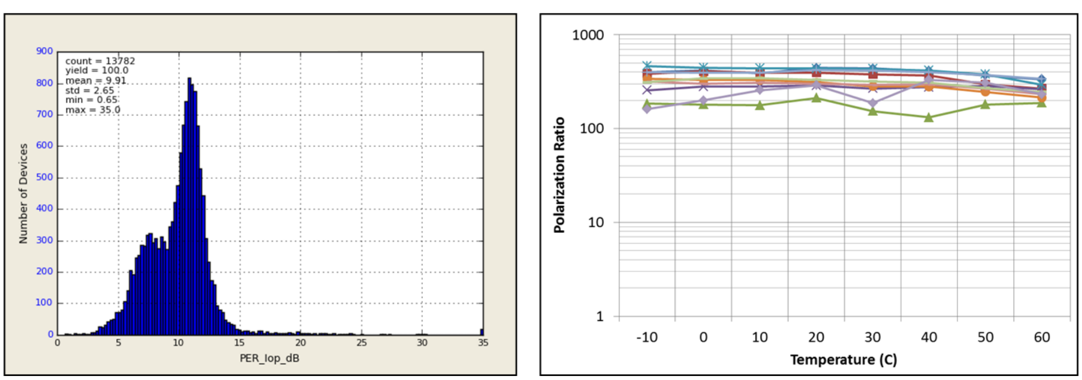

Figure 04: The measured polarization ratio for a wafer of red VCSELs measured at I = 3mA (left). The polarization ratio is observed to be independent of operating temperature (right).

4 Red VCSEL Application Benefits

The benefits of red VCSELs enable technological advances that traditional LEDs or semiconductor lasers can't efficiently achieve, despite the thermal limitations described earlier. As the development in red VCSEL technology continues to reduce the costs of these laser sources, many will find their characteristics to be advantageous for various applications.

4.1 Spectral stability

The spectral width of a red VCSEL is significantly narrower than an LED source. Multimode red VCSELs still exhibit a narrow spectral width of < 2 nm. The wavelength shift over temperature of red VCSELs is less than 0.05 nm/K, significantly less than traditional red LEDs and EELs. This can be essential for various applications requiring a narrow spectrum for efficient absorption of a target medium, from biological tissues to photosensitive inks.

VCSELs can also be used for improving method for presence detection and distance measurements. Unwanted background radiation, including sunlight, can degrade the signal-to-noise ratio of a sensor or camera. Background radiation can be eliminated with a narrow bandpass filter placed in front of the detector. The VCSELs narrow spectrum and temperature stability enables the use of extremely narrow notch filters not possible with other optoelectronic illumination sources to significantly improve the system's signal-to-noise ratio (SNR).

4.2 Modulation rate

For LiDAR applications utilizing time of flight measurements, the pulse rise time and shape determines the measurement accuracy of the system. VCSELs can be designed with low threshold currents and high modulation rates that enable data transmission rates of over 1 Gbit/s. The VCSEL cavity can also be designed with low intensity noise to improve pulse consistency for indirect Time of Flight measurements. The design of red VCSELs for high modulation bandwidths also enables optimal wavelength matching to polymer optical fibers that have a minimum absorption peak near 650nm.

4.3 Beam Control

Red VCSELs exhibit a narrow, symmetric beam profile that enables efficient beam collimation and focusing with a simple lens system. This is in contrast to EELs that produce an elliptical beam profile requiring a complex or multi-lens setup to correct and collimate the beam. The optical properties of VCSELs improve coupling efficiencies into optical fibers for sensing and communication applications.

Red VCSELs with a small aperture diameter have a high laser beam quality due to the source's low etendue and the shorter wavelength. When designed with a smaller aperture, the high beam quality of the red VCSEL minimizes the potential spot size ideal for focusing, sensing, scanning, and printing applications.

4.4 VCSEL Packaging

While most edge-emitting semiconductor lasers have traditionally been mounted in transistor outline (TO) packaging to re-orient the laser die vertically, VCSELs can be mounted in more cost-efficient packages already available to LED technology, including PLCCs and QFNs. This allows VCSEL die to be handled more effectively by end customers who may prefer to develop their own packaging or directly mount VCSELs onto electronic PCBs for applications requiring a small footprint.

Red VCSELs can be built into surface-mounted device (SMD) packaging also designed with additional optics. Packaging may incorporate an optical element that collimates the output beam or generates a structured light pattern. Alternatively, diffuser optics can be used to redesign the beam profile into a projected line or illumination area for visible laser curtains or keep-out regions for industrial safety applications.

5 Conclusions

Red VCSELs push the boundaries of current laser technology to develop a laser source with improved optical properties. The main drawback of red VCSELs is the limited operating temperature for high power applications. However, their symmetric beam profiles and their ease in packaging enables their use in many advanced technologies in the medical and industrial markets.

Red VCSELs operating at 680 nm were discussed as an optimal balance in output power, laser visibility, and thermal stability. Experimental results shown that red VCSELs can be designed as either a single aperture or as a power array to meet optical power and beam profile requirements. The benefits of red VCSELs including wavelength stability, beam shaping, and ease in packaging were also shown to be advantageous for many applications.