Vixar Application Note

High Power VCSEL Array Technology

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1 Introduction

VCSELs arrays emitting power ranging from 500mW to 10W have emerged as an important technology for applications within the consumer, industrial, automotive and medical industries. Vixar has developed a family of high-power arrays targeting these applications. This application provides a summary of performance characteristics of interest and a sampling of performance that has been demonstrated.

VCSEL geometry traditionally limits the amount of optical power a VCSEL can provide. To illustrate the issue, Figure 1 is a diagram of the cross-section of a VCSEL. Single crystal quarter wavelength thick semiconductor layers are grown to form mirrors (n- and p-DBR) to create a laser cavity in the vertical direction. However, efficient operation of the device also requires a method for providing current confinement in the lateral direction (achieved with the electrically insulating oxidation layer shown) to force current flow through the center of the device. A metal contact on the surface of the device provides a means for injecting current into the VCSEL. The metal must have an opening or aperture in order to allow the light to leave the device. There is a limit to how far current can be spread efficiently across this aperture, and hence there is a limit to the lateral extent of the laser, and in turn, the maximum power that can be emitted from a single aperture.

The solution to this, for applications requiring more power, is to create multiple VCSELs on the chip that operate together in parallel. An important advantage of this solution is that the array of mutually incoherent sources provides a low speckle illumination source, which is also narrow linewidth. A photo of an array chip is found in Figure 2.

This application note consists of several sections that describe the applications and performance requirements for high power VCSEL arrays, the performance benefits of high power VCSEL arrays, performance attributes demonstrated at Vixar, and packaging approaches and options. The paper concludes with some information about available samples and evaluation boards.

2 Application and Requirements

Consumer applications for high powered light sources are primarily sensors, gesture recognition and 3D scanning devices for consumer electronics. Sensing targets can range from sensing of a “swipe” motion for a cell phone to a complex interpretation of gestures for an interactive gaming system. Devices can also be incorporated into consumer electronics as 3D scanners that record the shape of an object or space to create a digital CAD file that can later be manipulated or fed into a 3D printer.

Industrial applications also consist of illumination applications, sensing or scanning. IR illumination can be used for night vision in security systems, while sensors are applied to motion control for factory or logistics automation, and scanners are useful for construction.

Automotive sensors based upon optical devices are being developed for collision avoidance, and, eventually for self-driving vehicles.

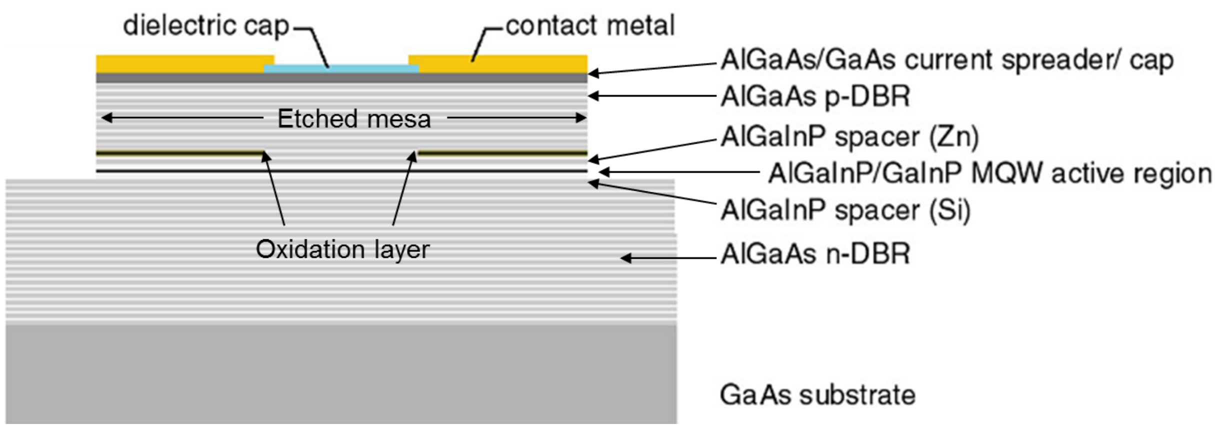


Figure 1. Illustration of the structure of a VCSEL.

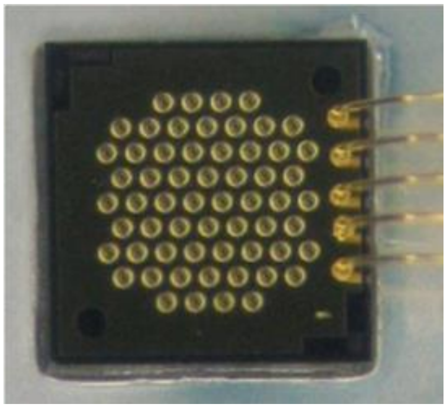
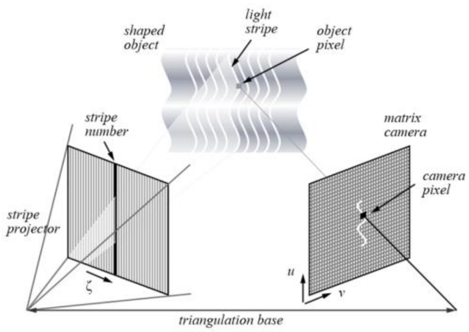


Figure 2. A VCSEL power array with 60 individual VCSELs. Wire bonds to a package are visible on the right side of the chip.

The requirements for the optical source depend upon the application and the sensing mechanism used. Illumination for night vision cameras may involve simply turning on the light source to form constant uniform illumination over a wide angle. However, sensors can be based upon a variety of mechanisms combining the light source with one or more photodetectors or cameras. Figure 3 illustrates some of the mechanisms used to gather information in all 3 dimensions.

In structured lighting a pattern is imposed upon the light source (dots, lines, etc.), and then one or more cameras are used to detect distortion in the structure of the light to estimate distance. The third dimension can also be measured with a time of flight scheme, using a time gated camera to measure the roundtrip flight time of a light pulse, or modulating a light beam and measuring the phase shift of the return light to estimate distance travelled.



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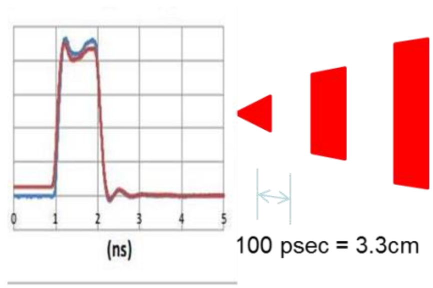

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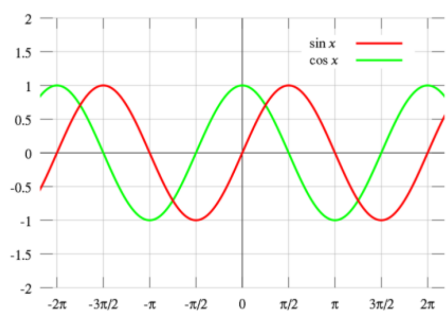


(c)

Figure 3. Illustrations of mechanisms used for gesture recognition sensors. (a) Structured illumination, (b) Time of flight, (c) Modulation phase shift.

Some of the important requirements of the optical light source for these applications include the following:

1. **Optical output power**: Sufficient power is required for illumination of the area of interest. This can range from 10's of milliwatts optical power for a sensing range of a few centimeters, to hundreds of milliwatts for games or sensing over a meter or two, to 10 watts for collision avoidance systems, and kilowatts of total power for a self-driving car.

2. **Power efficiency:** Particularly for mobile consumer devices, a high efficiency in converting electrical to optical power is advantageous.

3. **Wavelength:** For most consumer, security and automotive applications it is preferable that the illumination be unobtrusive to the human eye, and therefore in the infrared region. On the other hand, low cost silicon photodetectors or cameras limit the wavelength on the long end of the spectrum. Therefore, for these applications the most desirable range is between 800 and 900nm. However, some industrial applications prefer a visible source for the purposes of aligning a sensor, and some medical applications rely on absorption spectra of tissue, or materials with sensitivity in the visible regime, primarily around 650-700nm.

4. **Spectral width and stability: T**he presence of background radiation such as sunlight can degrade the signal to noise ratio of a sensor or camera. This can be compensated with a spectral filter on the detector or camera. However, implementing this without a loss of efficiency requires a light source with a narrow and stable spectrum.

5. **Modulation rate or pulse width:** For sensors based upon time of flight or a modulation phase shift, the speed of modulation, or modulation rate of the optical source can determine the spatial resolution in the third dimension.

6. **Beam divergence:** A wide variety of beam divergences might be specified, depending upon whether the sensor is targeting a particular spot or direction, or a large area.

7. **Packaging:** The package provides the electrical and optical interface to the optical source. It may incorporate an optical element that helps to control the beam profile and may generate a structured lighting pattern. Particularly for mobile devices the overall packaging should be as compact as possible.

3 Benefits of VCSEL Technology

VCSELs offer several benefits to optical sensing and illumination applications including power efficiency, the ability to combine a narrow spectral width with a low speckle illumination source, narrow beam divergence, and significant packaging flexibility.

Power conversion efficiency (PCE) of 40% or better can be achieved at wavelengths in the 800-900nm range. Power conversion efficiency is the ratio of optical power divided by the electrical power used to drive the device. The VCSEL PCE alone is better than that of most LEDs, and when one considers the spectral width and beam divergence, the efficiency benefits become even more pronounced.

		Requirements			
Market	**Application**	**Power**	**Spectral width**	**Modulation rate/ pulse width**	**Beam divergence**
Consumer	Gesture recognition sensor	10mW to 3W	Narrow	Up to 200MHz	Moderate to wide
	3D Scanning	1-10W	Narrow	Up to 200 MHz	Moderate to wide
Industrial	Night vision illumination	100mW to 3W	Narrow	kHz	Wide
	Motion control sensors	2-100mW	Narrow	kHz to MHz	Narrow
	3D Scanning	1-10W	Narrow	Up to 200 MHz	Moderate to wide
Automotive	Collision avoidance	1-10W	Narrow	Up to 200MHz	Moderate
	Self-Driving	W to kW	Narrow	Up to 200MHz	Wide

Power arrays have a spectral width of approximately 1nm. This allows the use of filters with the photodetector or camera in order to reduce the noise associated with background radiation. For comparison, an LED typically has a spectral linewidth of 20-50nm, resulting in the rejection of much of the light by this filter, and hence reducing the effective PCE of the LED. In addition, the wavelength of the VCSEL is less sensitive to temperature, increasing only 0.06nm per 1 degree Celsius. The VCSEL rate of wavelength shift with temperature is 4X less than in an LED. On the other hand, the fact that the VCSELs in an array are incoherent allows for the reduction in speckle as compared to a conventional high power laser. This is a unique combination: a low speckle optical source that also has a narrow spectral width.

The angular beam divergence of a VCSEL is typically 10-30 degrees full width half maximum, whereas the output beam of an LED is Lambertian. This means that all of the light of a VCSEL can be collected using various optical elements such as lenses for a collimated or focused beam profile, diffusers for a wide beam (40-90 degrees or more), or a diffractive optical element to generate a pattern of spots or lines. Due to the wide beam angle of the LED it can be difficult to collect all of the light (leading to further degradation of the PCE), and also difficult to manage it as precisely as is possible with a VCSEL.

The vertically emitting nature of the VCSEL gives it much more packaging flexibility than a conventional laser and opens the door to the use of the wide range of packages available for LEDs or semiconductor ICs. One can integrate multiple VCSELs on a single chip to form a high-power array, the subject of this paper, but can also more easily package with photodetectors or optical elements. Plastic or ceramic surface mount packaging or chips on board options are available to the VCSEL.

4 Vixar Power Array Technology

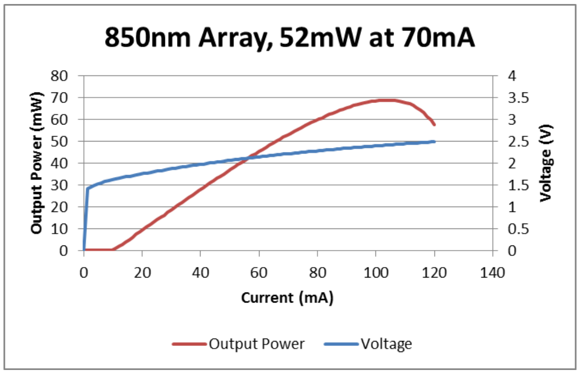
Vixar has been developing power array technology for a variety of applications and power levels, as well as associated packaging technology. This section documents some of the results to date with examples of performance that can be achieved.

4.1 Continuous Wave (CW) Power

Array size can be scaled to achieve an output power. For a specific power goal there is a size that will optimize the power efficiency. Figure 4 illustrates the output power versus current for a range of array sizes and for both 680nm and 850nm arrays.

4.2 Pulsed Power

Frequently the high-power arrays are used in pulsed operation. In this mode a high peak power is produced that improves the signal to noise ratio, while the pulsed operation can be used to keep the average power within an eye safe regime. The output power of a VCSEL array is also limited by self-heating during operation, thus pulsed operation can often produce significantly higher peak output power. Figure 5 (a) illustrates the output power from an array pulsed with a 20 μsec pulse width and 1% duty cycle. The pulsed output power is approximately doubled to 1W at 1.4A, as compared to a 600mW CW peak output power. For the 680nm VCSEL array, the pulsed output power is increased to nearly 700mW peak power, as compared to a CW peak power of 400mW as can be seen in Figure 5(b). The increase of power is a function of the pulse width, duty cycle and ambient temperature. Shorter pulses will provide even higher peak powers, for instance.



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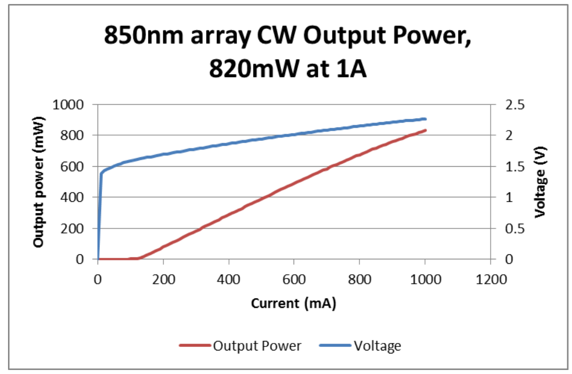

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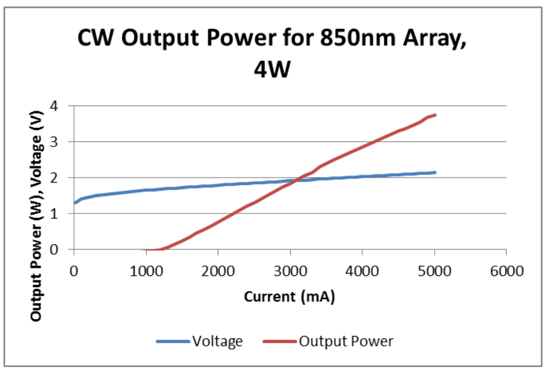

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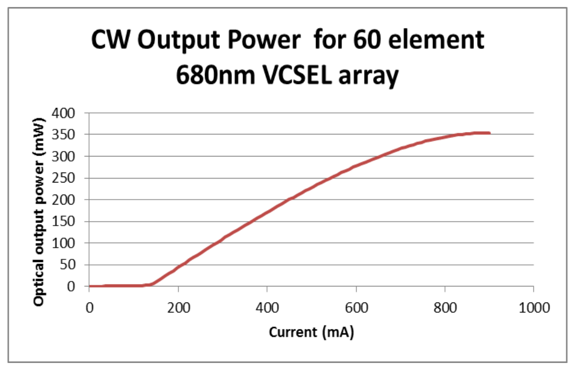
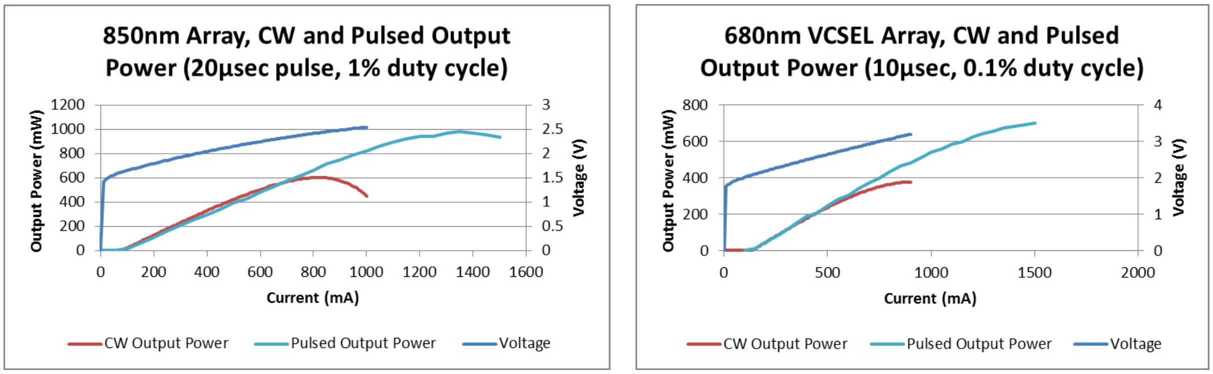


(d)

Figure 4. Examples of arrays targeted at different output powers. (a) 850nm 50mW (b) 850nm 800mW, (c) 850nm 4W, and (d) 680nm 350mW

4.3 Power Efficiency

High power conversion efficiency is particularly important for consumer mobile devices. Figure 6 plots the power conversion efficiency achieved in a device which emits 800mW at 1A. The power conversion exceeds 40% over a wide range of current drive.



(a) **(b)**

Figure 5. CW and peak pulsed output power of sample arrays. (a) 850nm VCSEL Array (b) 680nm VCSEL Array

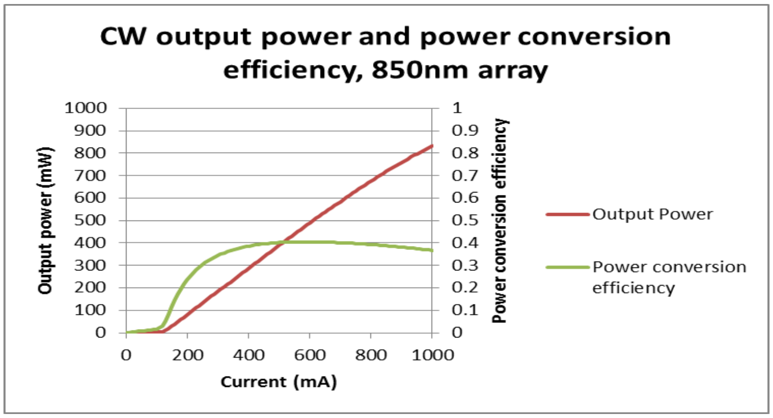


Figure 6. Illustration of a power conversion efficiency of 40% for a high-power array.

4.4 Power Density

Power density is another parameter of interest particularly for consumer devices. Space is at a premium, so a smaller die is advantageous for miniaturization as well as for cost. The VCSEL array illustrated In Figure 7 achieves a 5W/mm^2 CW output power density, and 7.8W/mm^2 output power density when pulsed with a 20 µsec pulse width at a 1% duty cycle. This array also demonstrates a power conversion efficiency of greater than 39%.

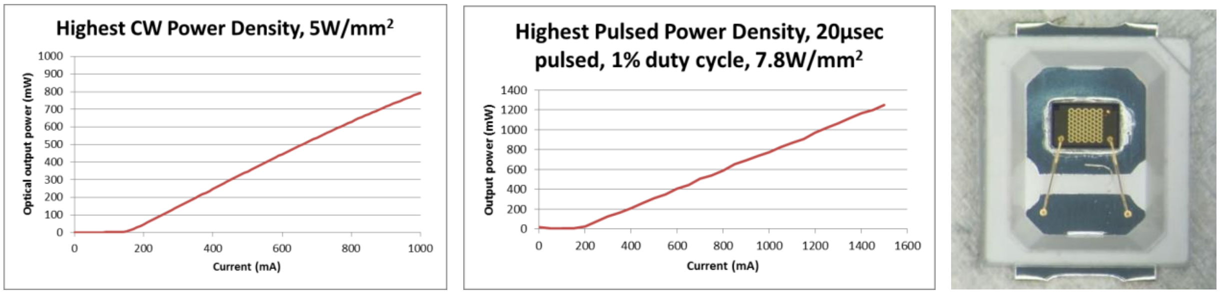
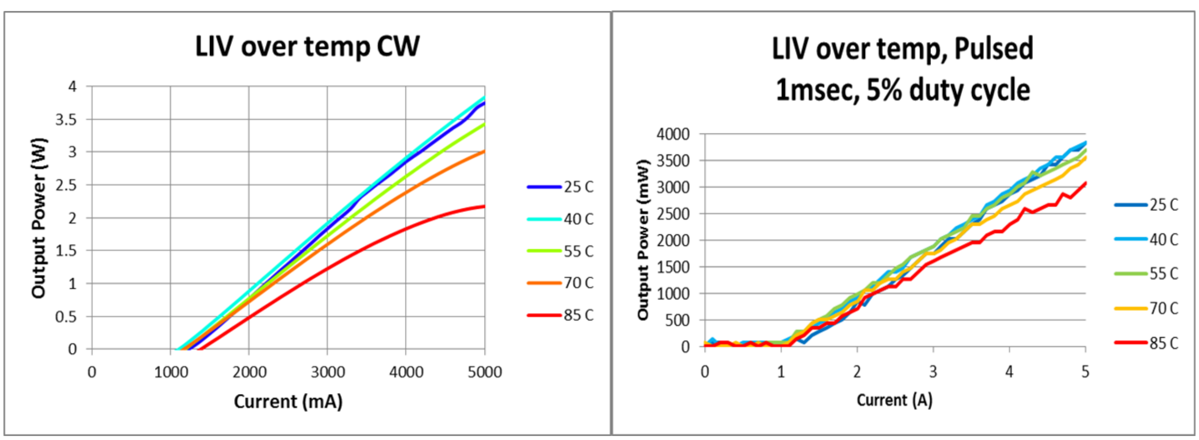


Figure 7. Illustration of a high power density array. (a) 5W/mm^2 operated CW. (b)7.8W/mm^2 operated pulsed. (c) A photo of the array with a 0.4mm x 0.4mm active area.

4.5 Output power versus temperature

High power VCSEL arrays will be implemented inside sensors, consumer, medical or automotive devices where the ambient temperature may rise due to self-heating or the heat dissipated by nearby electronic components. It is desirable that the device performance and efficiency be relatively insensitive to temperature. Figure 8 contains data collected from a 459 element high power array. Output power versus current was collected at a range of ambient temperatures from 25°C to 85°C, and also under both CW and pulsed conditions. In the latter case the pulse widths were 1msec with a 5% duty cycle. Some degradation of performance is observed at 70 and 85°C under CW conditions, but the output power remains quite stable over temperature when operated pulsed, with some mild degradation in power occurring when operated at 85°C.



(a) (b)

Figure 9. Output power versus current over a range of temperatures under (a) CW conditions, and (b) pulsed conditions with a 1msec pulse width and 5% duty cycle.

4.6 Spectral width

The spectral width of the array is important for use with filters for rejecting background radiation. Figure 9 shows the spectrum taken from an array at a 700mA drive current. The array is coupled into an integrating sphere, and a fiber is attached to a port of the integrating sphere, so all of the light emitted from the array is sampled. Note that the relative intensity is a log scale. The FWHM of the spectrum is approximately 0.7nm, which is the same as a single VCSEL device. This is to be expected as the wavelength of neighboring VCSELs on a wafer tends to be very tightly clustered. The peak wavelength of the device shifts 0.06nm per degree Celsius, which is a factor of 4 slower than an LED or conventional laser.

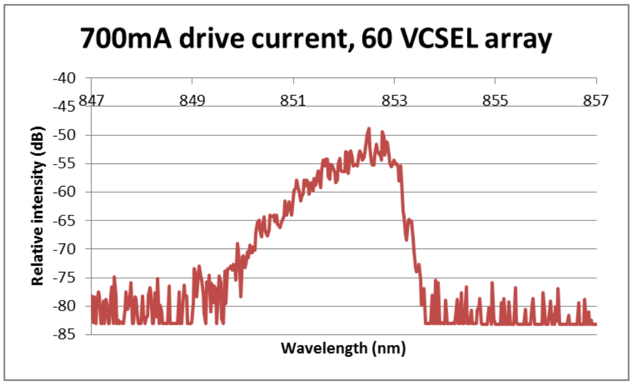
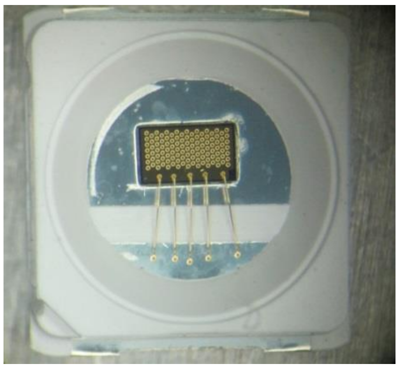


Figure 9. Spectrum of a VCSEL array with 60 separate VCSEL apertures.

4.7 Packaging

Packaging provides the electrical and optical interface to the VCSEL array, as well as mechanical protection. The packaging of high power arrays has additional challenges in that the thermal power dissipation must be managed. Less than ideal heat removal from the array can result in degradation of the device performance.

The vertically emitting nature of the VCSEL allows us to take advantage of surface mount packaging that has been developed for LEDs as well as integrated circuits. A photo of an array packaged in a plastic surface mount package (specifically a PLCC, or Plastic Leaded Chip Carrier) is shown in Figure 10(a). After attaching and wire bonding the die, it is protected by filling the cavity with an optically clear encapsulant. Figure 10(b) illustrates a custom package developed by Vixar, where the VCSEL is mounted directly on a circuit board, a spacer layer is placed surrounding the die, and then a diffuser is placed on the top surface. One could also attach a diffractive grating or a lens to the top surface of this package. Figure 10(c) provides an example of combining a variety of components into a subassembly. A circuit board incorporates multiple linear VCSEL arrays placed end to end directly on the board, together with the circuitry for controlling the VCSELs, to create a laser scanner with no moving parts. This was also integrated with a Graded Index Lens (GRIN) array to focus the light beams to an array of spots. The assembly functions as a scanner with no moving parts by sequentially lighting up each VCSEL in the array.



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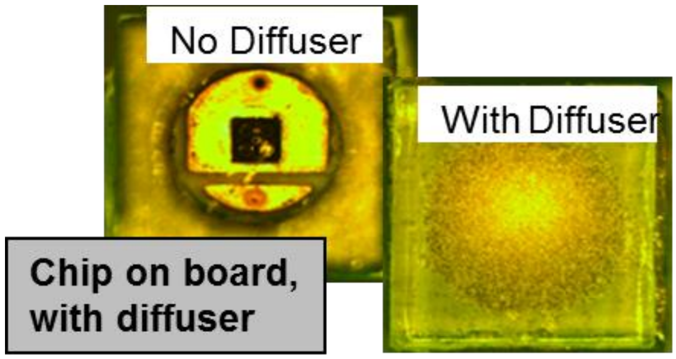

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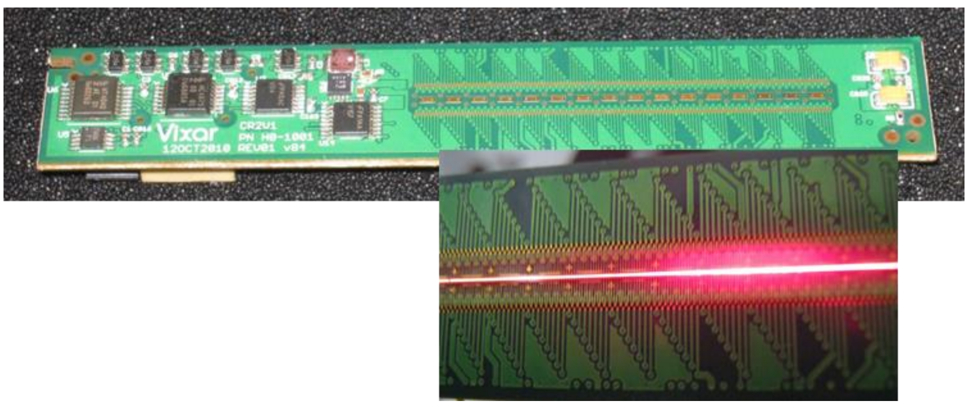
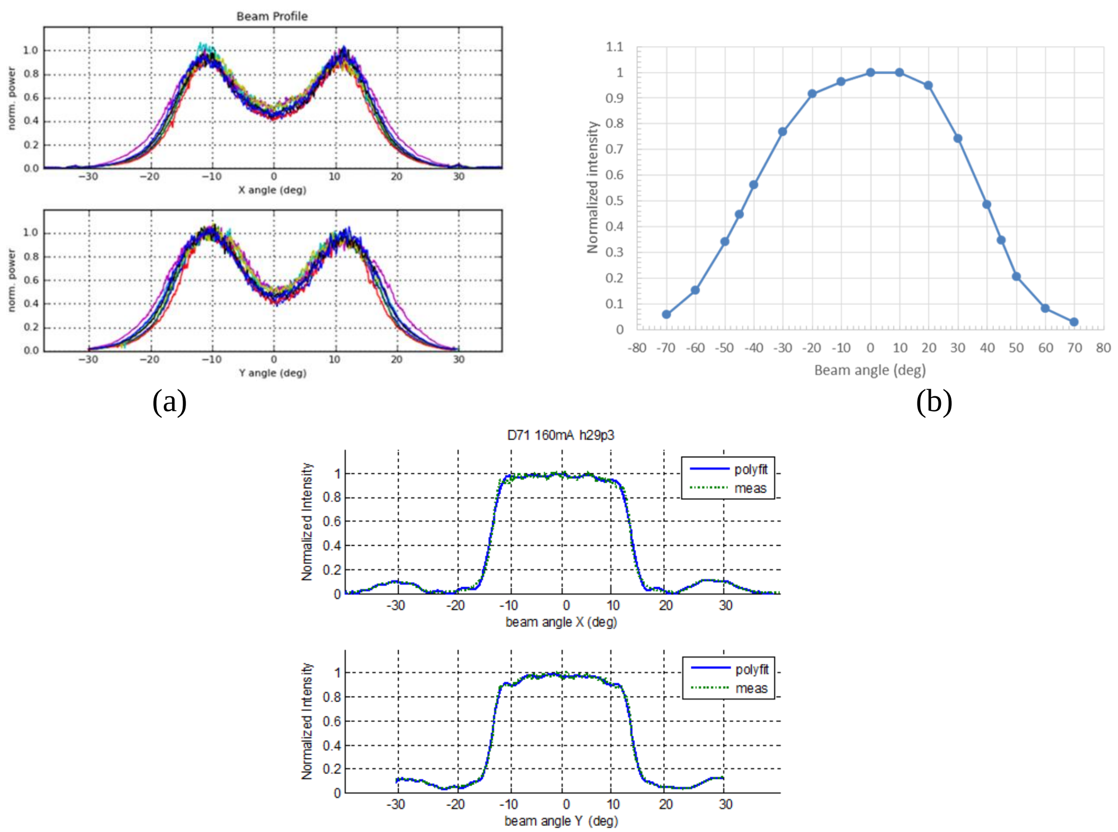


(c)

Figure 10. (a) A VCSEL array surface mount PLCC package. (b) A custom chip on board packaged with a diffuser (c) A subassembly for a scanner, incorporating linear VCSEL arrays integrated on a board with drive electronics.

These three examples illustrate some of the breadth of packaging options that exist for high power arrays, as well as how the VCSELs can be integrated with optics or other components such as ICs. There are many other packaging options. The VCSELs can also be attached to silicon or ceramic submounts which demonstrates high thermal conductivity.

One of the important aspects of packaging VCSELs is the ability to incorporate optics to control the beam profile. One may wish to collimate or focus the beam using a lens or lens array, expand and homogenize the beam using a diffuser, or create an array of spots with a holographic grating. Figure 11 provides examples of how the beam can be shaped. Figure 11(a) contains a plot of beam intensity versus angle illustrating the donut shaped beam profile often observed with multi-mode VCSELs. In 11(b) this profile is transformed into homogenized wide beam angle illumination using a diffuser. Figure 11(c) illustrates the transformation of the donut mode shaped multi-mode VCSEL array into a top hat shaped illumination in which the illumination is uniform within an array of angles, and then drops quickly to zero.



(c)

Figure 10. (a) A typical beam profile of a multi-mode VCSEL power array. (b) The angular profile of a VCSEL with a diffuser. (c) The incorporation of custom optics can create a flat-top profile within a specified angular range.

4.8 Driver integration

VCSELs are inherently fast devices. Realizing high speeds in a practical application requires attention to both packaging and matching to a suitable driver circuit. Figure 12 illustrates the integration of a high power VCSEL array with an IC-based driver designed for high power lasers. The figure displays the optical output of the VCSEL array when driven with a 1 A pulse. The pulse width is 20nsec, with rise and fall times of 5nsec or less, suitable for application to time of flight sensing.

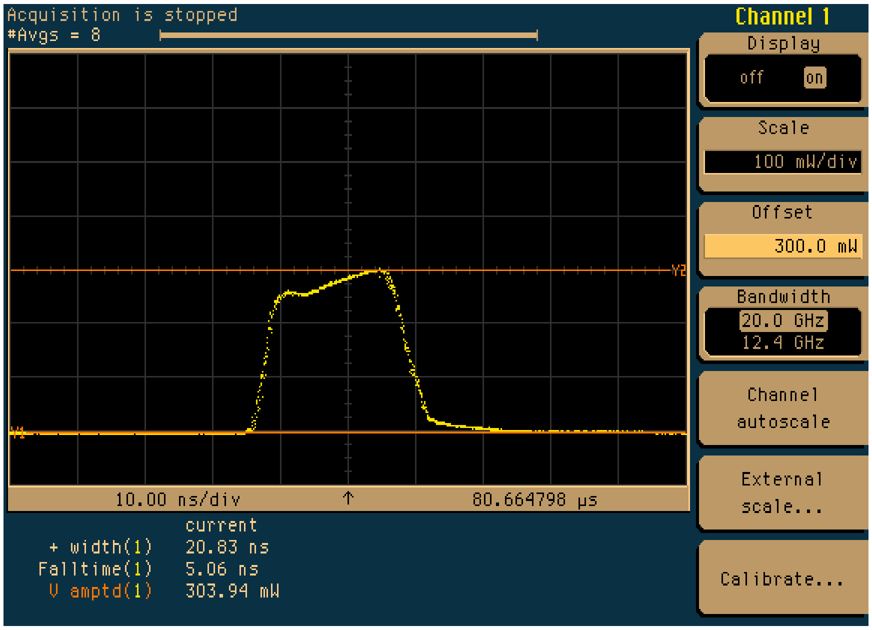


Figure 12. Optical output pulse shape of a VCSEL array driven with an I.C. based laser driver. The pulse width is 20nsec with a current of 1A. The rise and fall times of the pulse are in the range of 5 nsec.

5 Conclusions

Optical sensing is becoming a key technology in a variety of markets. The two main approaches, structured lighting and time of flight, dictate performance requirements for the optical sources. Other requirements of optical 3D sensing, such as output beam profile and eye safety requirements, are essential in the optical module design. Semiconductor lasers meet these requirements, with VCSELs being particularly beneficial in applications requiring small size, high efficiency and narrow spectrum.