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Progress on vertical-cavity surface-emitting laser arrays for infrared illumination applications

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ABSTRACT

For infrared illumination with wavelength range of 808nm-1064nm, vertical-cavity surface-emitting lasers (VCSELs) offer many advantageous properties including superior beam quality (such as low divergence, circular shape beam and speckle-free image), increased eye safety, high reliability and low manufacturing cost. We report our progress on high-power high-efficiency VCSELs and two dimensional (2D) VCSEL arrays for such illumination applications. GaAs-based VCSEL wafers are grown by MOCVD and processed into either top-emitting or bottom-emitting devices depending on the emission wavelength and applications. Results from both single devices and arrays are presented. In particular, record-high power conversion efficiency (PCE) of 63.4% with 300mW output was achieved from VCSELs at 1064nm. Such VCSELs also operate with >55% PCE at 50C. For a 2mm by 10mm array, 56.4% PCE with 150W output was demonstrated. Using those VCSELs and arrays as building blocks, various high power illuminators ranging from a few Watts to over 100 kiloWatts have been fabricated.

Keywords: VCSEL, semiconductor laser, illuminator, high power, high efficiency, 2D array, speckle-free, 808nm, 976nm, 1064nm

1. INTRODUCTION

Infrared illumination (808nm – 1550nm) is broadly used in commercial and defense markets for surveillance and security, for high speed imaging, for detection (sensing) and for covert operations. Using separate illumination source and camera enables increased flexibility in performance and cost optimization. While various wavelengths can be used for the IR illumination, there are generally trade-offs among them for responsivity, eye-safety, cost and efficiency, etc. For example, 808nm light source offers the best responsivity for a CCD camera but is not considered eye-safe for high power illuminators and can not be used for covert applications. The 976nm source has lower responsivity (can be used with either Si or InGaAs based detector) but offers improved eye-safety and can be used for covert application. At 1064nm region, the responsivity is much better with an InGaAs-based camera. It is considered a covert wavelength, and offers even more improved eye-safety. Finally, the 1550nm region offers eye-safety and the best responsivity when used with an InGaAs-based camera. However, semiconductor lasers at 1550nm are generally much less efficient than their shorter wavelength counterparts.

Different technologies for the IR illumination source can be selected, ranging from lamps to semiconductor light emitting diodes (LEDs) or semiconductor lasers. The lamp, while straight-forward, is broad-band, bulky, and generally inefficient. The semiconductor LED represents an improvement over the lamp in terms of cost, efficiency, and spectral width. In addition, LEDs can be manufactured at different wavelengths of interest for illumination. However, LED-based illumination systems still suffer from the high-divergence of the LED. Semiconductor lasers on the contrary are very efficient, narrow-band, low divergence, and low-cost light sources, resulting in potentially very compact and efficient light engines for illumination purposes.

The power level of interest for illumination is also quite broad, ranging from a few hundred milliWatts to several hundreds of Watts and kiloWatts, depending on the types of applications. Recently, there are increasing needs for compact and efficient illumination systems while providing even broader range of output power. Low-cost is also a requirement for some applications.

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Among the two types of semiconductor lasers of edge emitters and vertical cavity surface emitting lasers (VCSELs), VCSEL is very attractive due to its many advantageous properties including superior beam quality, high reliability and increased eye safety. Recent progress on VCSEL technology makes it an even more ideal light source for high power IR illumination applications. It was shown [1, 2, 3] that VCSELs can be used as very high power laser sources by fabricating large two-dimensional (2D) planar arrays of low-power, high-efficiency single emitters. Power levels can range from a few hundred mWs to several hundred Watts, while maintaining high levels of power conversion efficiency (PCE) (typically >40% at 808nm and >50% at 976nm and 1064nm). Using those high performance VCSELs as building blocks, very high power illuminator such as 100 kiloWatts modules can be constructed.

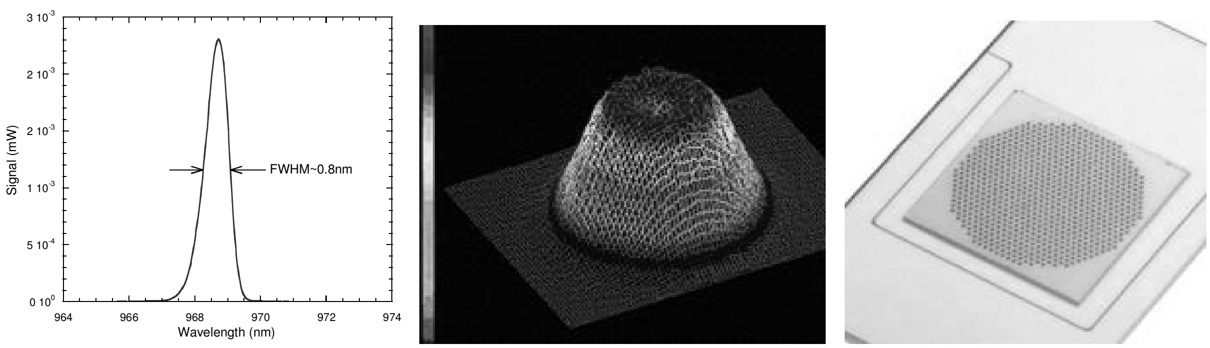
Previously we had discussed in detail our VCSEL based illuminators[4] that cover wavelength span of 800-976nm with power levels up to kiloWatts. Since then we have advanced our VCSEL technology and therefore were able to expand our illuminator portfolios by increasing the wavelength range to 1064nm and the power level to over 100 kiloWatts. In this paper we present updated results on our VCSEL devices and VCSEL based illuminators, at different wavelength and power levels. In particular, we have achieved single VCSEL device efficiency of 63.4% under CW with 300mW output, which is the highest value reported for high power VCSELs. At 50C, our device has 55.3% PCE under CW operation. We also demonstrated 56.4% array efficiency with 150W output. In this paper, we first briefly review the VCSEL advantage as IR-illuminators, and then we briefly review the VCSEL array structure and fabrication. We will present the main device characteristics, followed by results for various high power VCSEL-based illuminators using those VCSEL arrays as building blocks.

2. REVIEW OF VCSEL ADVANTAGE FOR ILLUMINATION

Compared to other light source such as LEDs and edge emitting lasers, VCSELs offer the following combined advantages when being used for illumination applications:

2.1 Beam and spectral quality

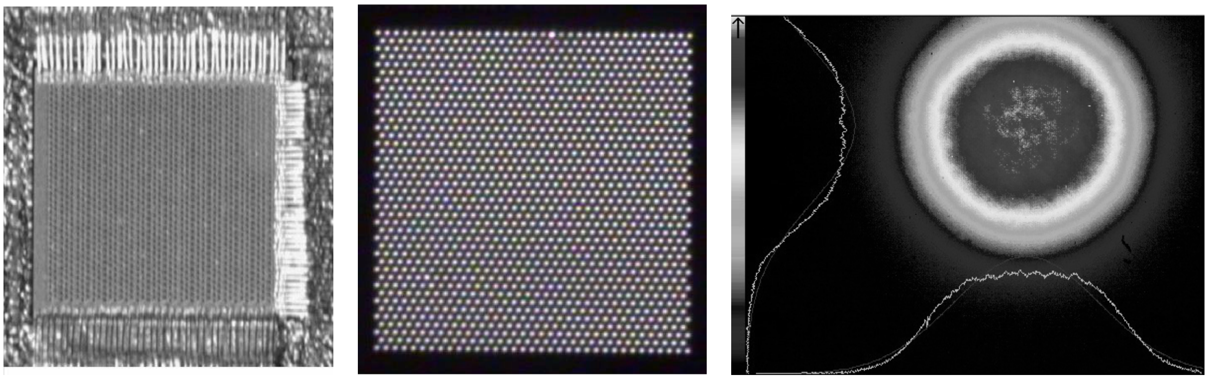
Due to its surface emission nature, the emission patterns of high-power VCSELs are intrinsically circular (or can be tailored to meet any custom configuration) with narrow divergence (numerical aperture typically between 0.15 and 0.20), eliminating the need for optics. The beam is very uniform (top-hat profile) for arrays consisting many large aperture multimode devices with very narrow spectrum (usually <2nm). Figure 1(a) shows the spectrum with FWHM<0.8nm for a 5x5mm VCSEL array operating at ~100W output. Figure 1(b) shows the top-hat beam profile with NA of ~0.15. The circular array pattern shown in Figure 1(c) is defined by photolithography.



(a) **(b)** **(c)**

Figure 1. Spectrum (a) and top-hat beam profile (b) for a 5x5mm 976nm array operating at 100W; (c) VCSEL array chip on diamond submount.

Figure 2 shows the images of a 2x2mm 808nm array with hexagon arrangement that designed for 4-10W CW operations. Figure 2(a) shows the packaged chip on submount, Figure 2(b) shows its near-field emission and Figure 2(c) is the far-field image. Again, the far-field is close to a top-hat distribution, with NA of ~0.17. Such profile is very desirable for uniform illumination applications.

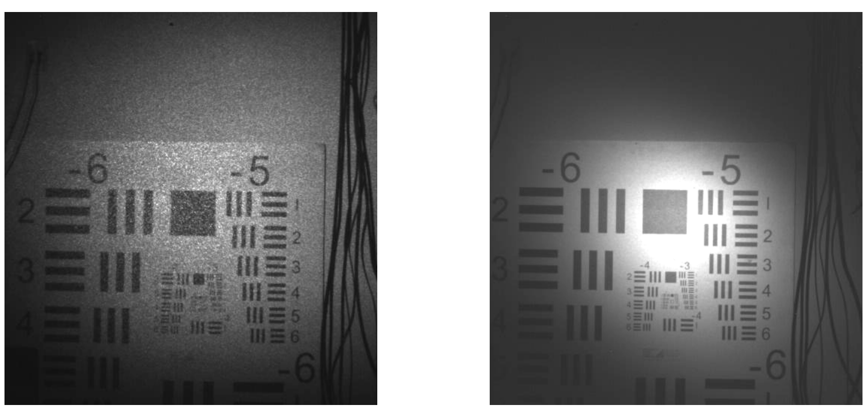


(a) (b) (c)

Figure 2. 2x2mm 808nm VCSEL array's (a) packaged chip; (b) near-field; and (c) far-field images.

2.2 Speckle-free image

For many imaging applications, it's very critical to have speckle-free patterns. Because high power VCSEL arrays are usually made up of many multimode VCSEL devices that are spatially incoherent, the interference effect is very weak. This results in superior speckle-free image quality. Figure 3 compares the images illuminated by edge emitters (Figure 3(a)) and by VCSELs (Figure 3(b)) respectively. While the image illuminated by edge emitters shows some speckles, the one illuminated by VCSELs is virtually 'speckle free'.



(a) (b)

Figure 3 Illumination images by (a) an edge-emitting laser and (b) a VCSEL.

2.3 Increased eye safety

According to the extended source criteria of ANSI Safety Standard (power density in the imaged area on the retina) Z136, the MPE (maximum permissible exposure) for laser at 800nm is 1mJ/cm^2-second. Figure 4 is the imaging process from a light source such as a 2.8x2.8mm VCSEL array to the human eye (at 20-30m distance) and Figure 5 are the images on retina with various light sources: Figure 5(a) corresponds to a 100um x 68.6mm line source, Figure 5(b) corresponds to a100um x 226.6mm line source and Figure 5(c) corresponds to a 2.8mm x 2.8mm VCSEL array source.

Clearly when using VCSEL arrays for illumination, it can not be imaged onto retina as a point source. It is estimated that the ‘effective’ MPE for VCSEL based illuminators should be increased by a factor of >36 times.

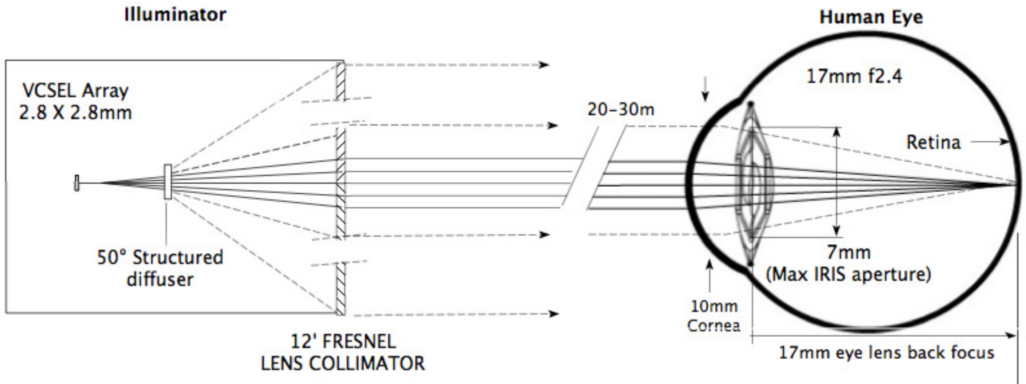
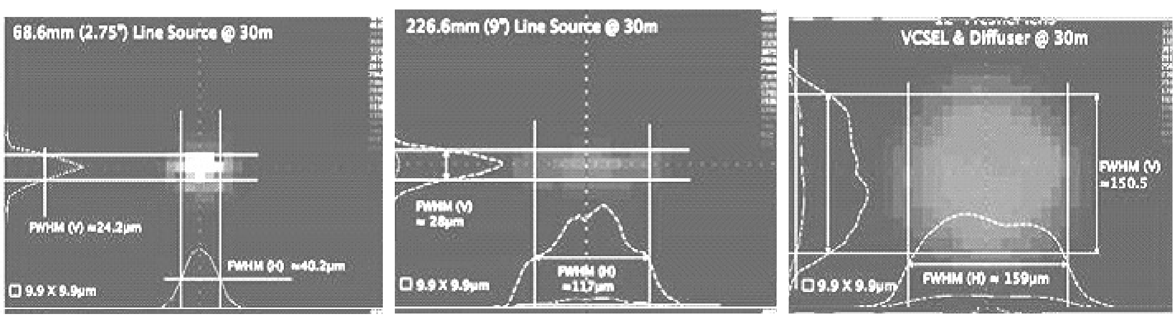


Figure 4. Imaging process from VCSEL array to human retina.



(a) (b) (c)

Figure 5. Images on retina from various light sources: (a) 100umx68.6mm line source; (b) 100umx226.6mm line source; and (c) 2.8x2.8mm VCSEL array**.**

2.4 High reliability

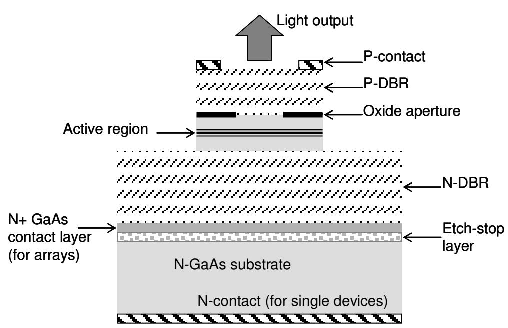
VCSEL is known for high reliability[5]. Degradation of edge-emitting lasers is well known to be dominated by catastrophic optical damage (COD) that occurs because of high optical power density at the emission facet[6]. VCSELs, in comparison, are not subject to COD because the gain region is embedded in the epitaxial structure and is therefore not exposed to the outside environment. Also, the optical waveguide associated with the edge-emitter junction has a relatively small area, resulting in significantly higher power densities compared to VCSELs. The practical result is that for a typical edge-emitter, the failure rate (the FIT rate defined as the number of failures per one billion device-hours) is 500 or higher[7]. For VCSELs the FIT rate is on the order of 10 or less[5]. This advantage provides a useful lifetime of at least 50 times longer for a system using VCSELs.

In addition, high-power, high-efficiency VCSEL sources preserve many of the advantages present in low power VCSEL devices, such as low-cost manufacturing[8] (VCSEL are capable for wafer level fabrication, test and burn in), scalability for large 2D arrays[1], wavelength temperature stability (0.065nm/C for VCSEL vs 0.3nm/C for edge emitter), and operation at high temperatures[9].

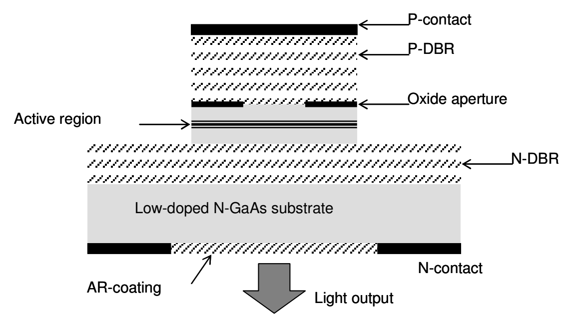
3. VCSEL DEVICE CHARACTERISTICS

3.1 Device structure and fabrication

Basic building blocks of VCSEL-based high power illuminators are single VCSEL devices and 2D VCSEL arrays. For our VCSELs lasing between 800nm-1064nm, the epitaxy materials are grown on n type GaAs substrate using MOCVD. Both p and n type DBRs are made of AlGaAs layers. Quantum wells are made of strained InGaAs, InAlGaAs or AlGaAs targeting different wavelengths. The VCSELs can be designed for "top emission" (at the epi/air interface) for 8xx nm or "bottom emission" (through the transparent substrate) for 976nm and 1064nm in cases in which "junction-down" soldering is required for more efficient heat-sinking. Such VCSEL structures are shown in Figure 6(a) and 6(b). Fabrications for both types of VCSELs are quite straightforward and similar. To fabricate bottom-emitting device, on the epitaxial side, Ti/Pt/Au disks of different diameters are evaporated to form the P-type contacts, which at the same time act as the self-aligned mask for subsequent dry-etching (RIE) of mesas, deep enough to expose the Aluminum-rich layer. The samples are then exposed to high humidity in a furnace (~400^{o}C) for the selective oxidation process[10] for electrical and optical confinement[11 - 14]. On the substrate side, the substrate is thinned to less than 150micron thickness to minimize absorption losses (in the case of substrate emission) and then polished to an optical finish. A Si3N4 anti-reflection coating is deposited using PECVD, followed by patterning, etching of the field nitride and finally Ge/Au/Ni/Au N-metals evaporation and alloy. After processing, devices are tested at wafer level to check the performance before being singulated and packaged on heat-spreading submounts such as BeO or diamond, as shown in Figure 6(c). Details of the device design and fabrication can be found in References [1, 2].



(a)



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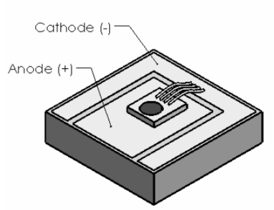
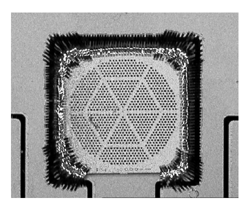


(c)



(d)

Figure 6. Schematics of (a) top-emitting and (b) bottom-emitting VCSELs; (c) packaged single device; (d) packaged array.

To achieve high-power operation with VCSELs, we fabricate 2D arrays of single devices operating in parallel. As mentioned earlier, one advantage of VCSEL over edge emitter is its capability for 2D array integrations because there are no need for individual element's facet coating and treatment. Wafer level process of such 2D array is very similar to single device, with the addition of a few steps involving extra bonding pad and Au-plating. Figure 7 shows the schematic of a completed bottom-emitting 2D VCSEL array. For top emitting arrays such as 808nm devices, the substrate can be removed (device is therefore very thin, ~10um thick) by selective wet etch to eliminate substrate absorption and reduce thermal impedance. Details of such 'ultra-thin' process can be found in Reference [2]. While such ultra-thin process is critical for densely packed high power devices operating under CW, it may not be necessary for low to mid power level arrays (such as a few Watts) or arrays operating under pulse, as shown in the next section. The finished arrays can be linear (one dimensional), triangular, rectangular, square, or any custom designed shape, which is defined by photolithography. Furthermore, the position of the individual elements in a VCSEL array is also defined by photo lithography, which permits arbitrary design layouts of the elements with placement accuracy of microns. Depending on the application, arrays containing from a few hundred to over ten thousand single devices with size ranging from 0.5x0.5mm to 6x6mm can be realized.

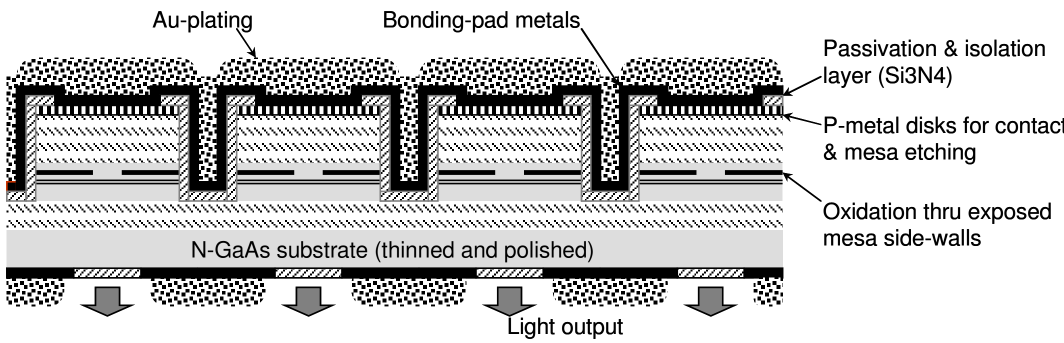


Figure 7. Schematic drawing of bottom emitting VCSEL arrays.

After array processing, the wafer goes to test, where individual chips are characterized on a pass-fail basis. Finally, the wafer is diced into individual arrays for packaging. The submounts being used can be either BeO (or AlN) for low cost, low power, or diamond for high power applications. A packaged array is shown in Figure 6(d).

3.2 Single device characteristics

Our single devices at 808nm have peak efficiencies of ~49%, as shown in Reference [2]. With the optimization of the DBR and active region designs, material growth and device fabrication, we achieved 63.4% power conversion efficiency (PCE) at 1064nm under CW operation at room temperature for a device with 80um aperture diameter. This is the highest efficiency ever reported for high power VCSELs and is comparable to that previously reported by Takaki et al (they reported 62% PCE from smaller VCSELs with 5mW output at 1060nm[15]). As shown in Figure 8, the device operates at >63% PCE with >300mW output. Such superior performance from single device makes the very high power VCSEL-based illuminators very practical.

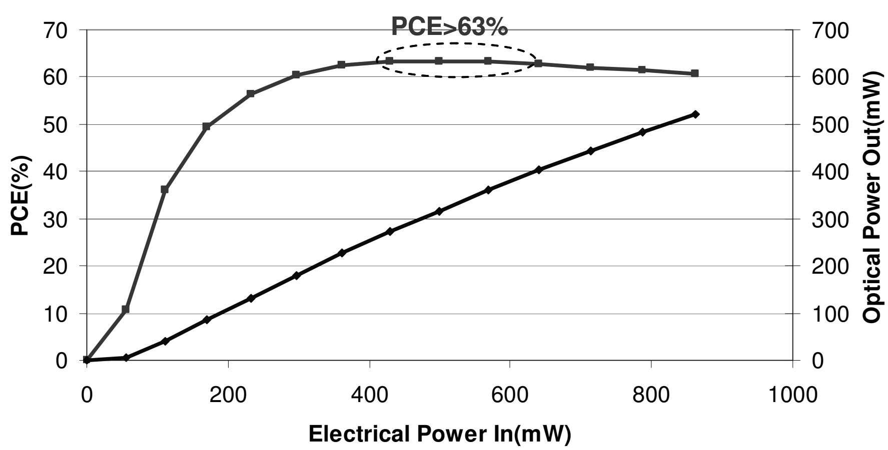


Figure 8. CW power-PCE curves for a 1064nm VCSEL device with 80um diameter oxide aperture, showing peak efficiency of 63.4% at room temperature.

Our VCSELs also perform very well at elevated temperatures. Figure 9 shows the CW power and PCE curves for a 976nm VCSEL with 100um aperture at 50C degree. Its peak PCE is ~55.3% with ~700mW output. We believe that with further device optimization, VCSEL efficiency can be improved to be close to that of edge emitters (currently >70%[16]). In addition, such technology can be transferred to other wavelengths as well.

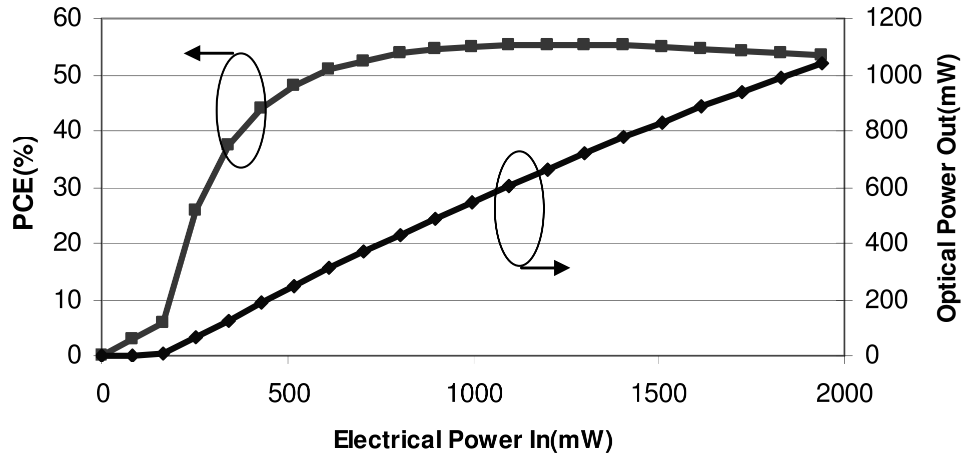


Figure 9. CW power-PCE curves at 50C for 976nm VCSEL with 100um diameter oxide aperture, showing >55% efficiency.

3.3 VCSEL array results

With proper array design, VCSEL array performance should be very close to that of singles. Based on single devices discussed earlier, we built various high power 2D VCSEL arrays to meet specific applications. Figure 10 shows the power and PCE curves for a 2x10mm VCSEL array at 976nm. It has peak efficiency of 56.4% at output power of ~150W. For such high power large size arrays, process and packaging are a little bit more challenging than single devices. For example, when the array elements are very close to each other, thermal and electrical cross talks will dominate. Also, Au plating in Figure 7 need to be >>5um to ensure uniform current injections. In addition, chip stress & bow control, as well as soldering process will all contribute to the performance.

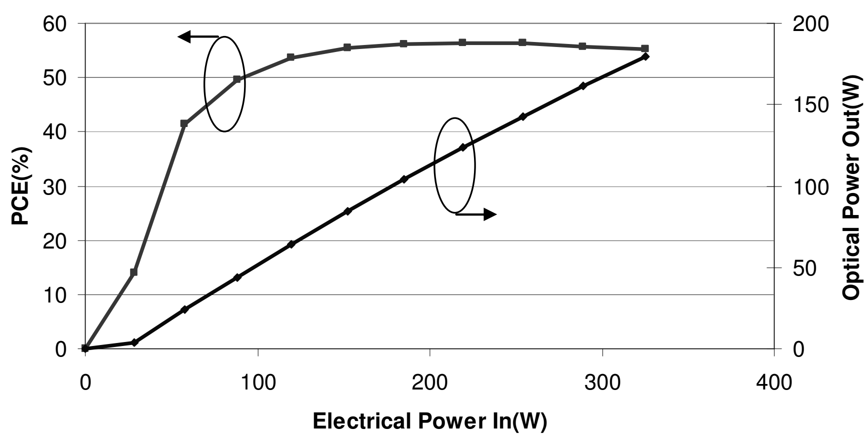


Figure 10. Power-PCE curves for $20mm^2$ array at 976nm with peak efficiency of 56.4%.

For high-power top-emitting arrays at 808nm, it's beneficial to remove the substrate for efficient heat removal. Detailed fabrication steps and device characteristics for such 'ultra-thin' arrays were discussed in details in Reference [2]. For 2x2mm array, peak PCE of ~43% was achieved with 7W output power. It's also possible to keep the substrate for smaller arrays with a few Watts output power or arrays operate under pulse. This represents a 'simpler' alternative in terms of wafer process and chip packaging. Figure 11 shows the CW LI-PCE curves for a 2x2mm array at 808nm with 100um thick substrate, mounted on BeO submount. The peak PCE is ~42% with 6W output, which is quite comparable to the performance of ultra-thin arrays.

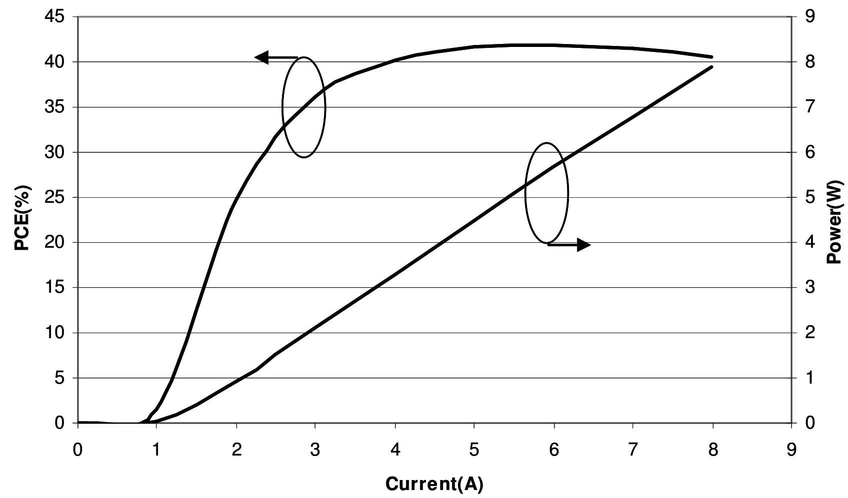


Figure 11. LI-PCE curves for 2x2mm 808nm VCSEL array with 100um thick substrate.

4. VCSEL-BASED ILLUMINATORS

Our VCSEL based illuminators for short to mid range surveillance applications were discussed in details in Reference [2]. Figure 12 shows the typical design and performance of such illuminators covering <500m of illumination range with a few Watts of CW output. No optics is used with its intrinsic 20 degree divergence, and it's fully portable.

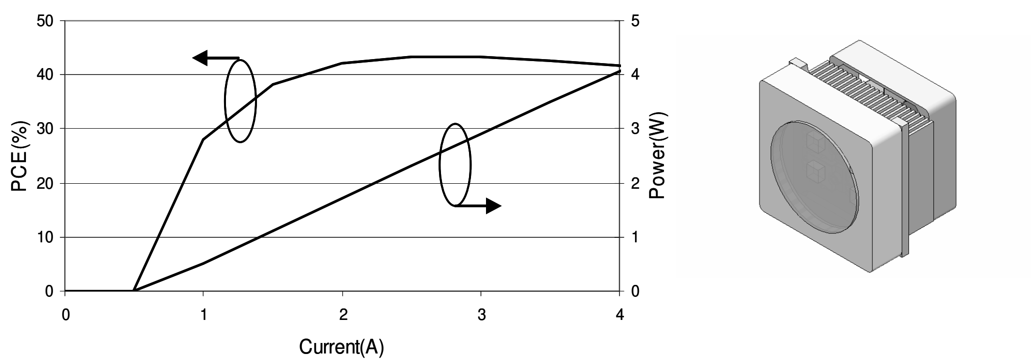


Figure 12. Typical low power VCSEL illuminator and its performance at 808nm.

Recently we expanded our illuminator portfolio by extending the wavelength to 1064nm and increase the output power level to over 100 kiloWatts. The basic building blocks of such high power illuminators are from high performance

VCSELs discussed in previous sections. Generally speaking most of the advanced features including spectrum, far-field, efficiency, beam quality and reliability are retained when scaling up the size for high power illuminators by connecting more VCSEL chips and modules together. However careful design at both chip and module levels must be carried out in order to optimize and balance the overall performance, reliability and cost.

Figure 13 is a portable high power illuminator at 808nm with CW output of 70-120W and adjustable beam divergence of 20-80 degree. It does not need liquid cooling and is cooled by base plate and a small fan. The user friendly design includes green and red LED light on the front panel to indicate power and laser being on or off.

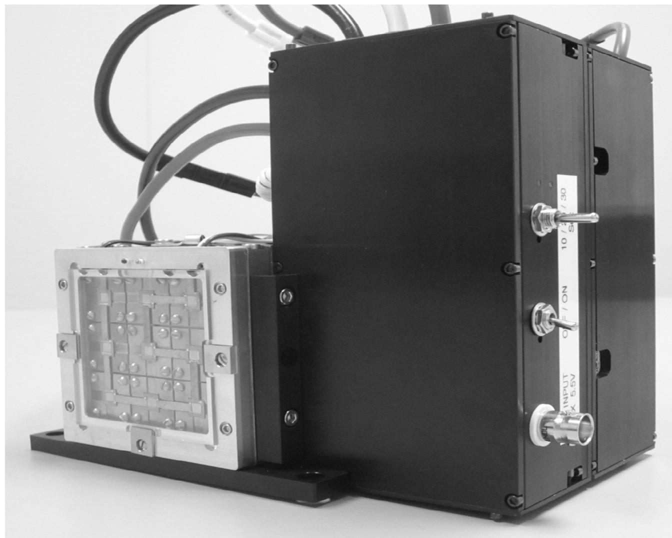
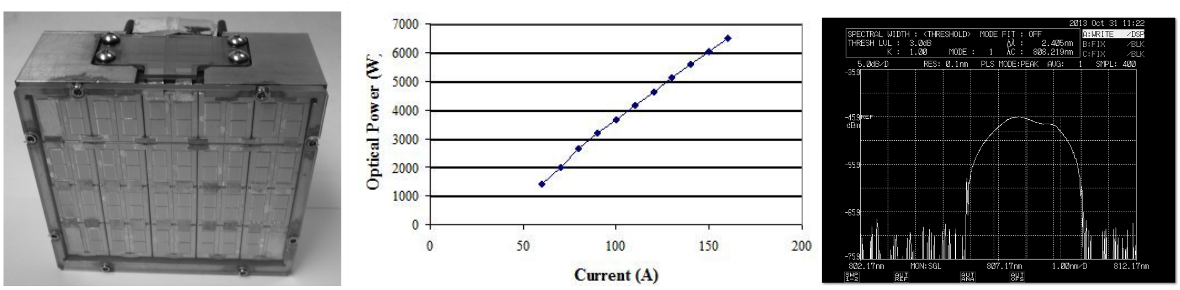


Figure 13. Portable 70-120W 808nm illuminator with adjustable divergence of 20-80 degree.

Figure 14(a) shows a 5 kiloWatts 808nm illuminator that is being used for various military and commercial applications. It has 20x 250W units connected together in series. It’s driven by a single power supply with a compact size of approximate 4x5x2”. Its output power and spectrum are shown in Figure 14(b) and (c). Because the array chips were selected from different wafers, the spectrum is slightly wide at ~4nm.



(a) (b) (c)

Figure 14. 5kiloWatt illuminator at 808nm: (a) design; (b) power; and (c) spectrum.

Figure 15 shows a 300W flare illuminator’s design and illumination patterns at 808nm. As shown in Figure 15(a), VCSEL chips are mounted at an angle so that they emit at different directions. This results in a lens free design with 140° beam divergence. Therefore the illuminator can cover a range of 1.5km diameter at altitude of 1000-3000 feet. As shown in Figure 15(c), the illumination pattern is very uniform at such working distance. It’s also battery powered with compact size of 2.75x16”. Typical operation duration for the battery is 3 min under CW.

(a) (b) (c)

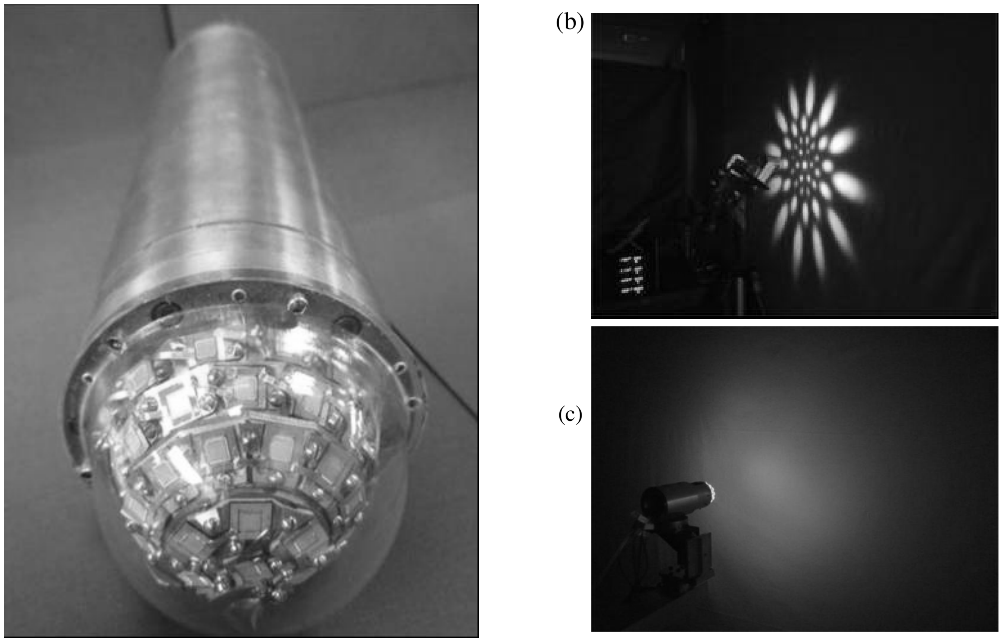


Figure 15. 300W flare illuminator’s (a) design; (b) multi-beam illumination pattern at very close distance; and (c) uniform illumination pattern at working distance.

By connecting more modules together, we are able to construct very high power illuminators. Figure 16 shows our 100kW illuminator at 1064nm. It has 8x 16kW modules mounted on a movable mount. Each module consists of 60 high performance VCSEL arrays that are capable of delivering >300W output. The whole system is also very compact and cooled by fans, with physical width and height of ~22.5x22.5”. Such high power illuminator can be used for very long distance (such as a few kilometers) illuminations.

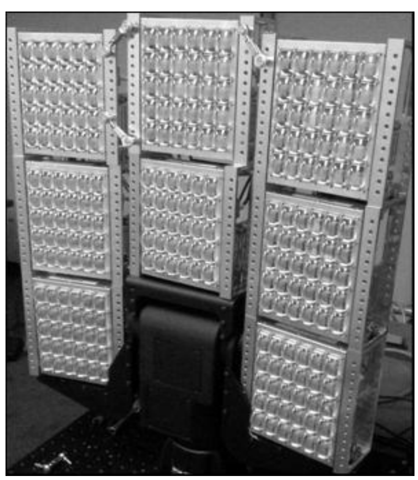


Figure 16. 100kW VCSEL based illuminator at 1064nm.

5. CONCLUSIONS

When being used for IR illuminator, VCSELs offer many advantageous properties such as symmetric circular beam with low divergence, speckle free image, improved eye-safety, low manufacturing cost and high reliability. With the optimization of device structure, epitaxy growth and fabrication, we achieved power conversion efficiency of 63.4% at 1064nm, a record high value for any type VCSELs. We also demonstrated >55% PCE at 50C, and >56% PCE for 2x10mm 2D array. At 808nm, it's preferred to remove the substrate for efficient heat removal. For the simpler alternative that has 100um substrate un-removed, we demonstrated 42% PCE with 6W output from 2x2mm 808nm array mounted on BeO submount. Using those high performance VCSELs as building blocks, we are able to construct very high power IR illuminators at 808nm, 976nm, and 1064nm, with output powers up to 100 kiloWatts.

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