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Efficient vertical-cavity surface-emitting lasers for infrared illumination applications

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ABSTRACT

Infrared illumination is used in the commercial and defense markets for surveillance and security, for high-speed imaging, and for military covert operations. Vertical-cavity surface-emitting lasers (VCSELs) are an attractive candidate for IR illumination applications as they offer advantageous properties such as efficiency, intrinsically low diverging circular beam, low-cost manufacturing, narrow emission spectrum, and high reliability. VCSELs can also operate at high temperatures, thereby meeting the harsh environmental requirements of many illuminators. The efficiency and brightness of these VCSELs also reduce the requirements of the power supply compared to, for example, an LED approach. We present results on VCSEL arrays for illumination applications, as well as results on VCSEL-based illumination experiments. These VCSELs are used in illuminators emitting from a few Watts up to several hundred Watts. The emission of these VCSEL-based illuminators is speckle-free with no interference patterns. Infra-red illumination at up to 1,600ft (500m) from the source has been demonstrated using VCSEL-based illumination, without any optics.

Keywords: Semiconductor lasers, vertical-cavity surface-emitting lasers (VCSELs), 808nm, 976nm, high efficiency, high-power, 2D array, reliability, infrared illumination, infrared imaging, speckle-free.

1. INTRODUCTION

In infrared illumination, an infrared light source is used to illuminate a scene (generally under low-visibility conditions) while a charge-coupled device (CCD) or InGaAs-based camera (depending on the wavelength) is used to capture the resulting image. Infrared illumination has a wide range of applications such as surveillance (industrial & military), covert operations (military), detection (sensing), and imaging. For surveillance applications, infrared illumination can be used to monitor highly sensitive areas such as rail-road tracks or oil pipelines. For military applications, invisible infrared illumination can be used to covertly reveal enemy presence and locations under night-time conditions. Infrared illumination coupled with a gated detection system can be used to image events masked by explosions, dust clouds, or other adverse conditions. Finally, infrared illumination can be used as an efficient means for 3D imaging and 3D location mapping and sensing. This has applications in console gaming, and 3D dental and medical imaging.

Traditional thermal imaging systems tend to suffer from high costs, a limited spectral range, and poor image contrast. There is an increasing need for compact and efficient illumination systems. Low-cost is also a requirement for some applications. Using separate illumination source and camera enables increased flexibility in performance and/or cost optimization. For example, different wavelengths can be used for the illumination source depending on the application.

The illumination source employs different technologies, ranging from lamps to semiconductor light emitting diodes (LEDs) or 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 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 main wavelengths of interest for illumination are around 808nm, 976m, 1064nm, and 1550nm. The 808nm region offers the best responsivity for a CCD camera and is compatible with Gen-III night vision goggles. As a result, it

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is one of the most popular wavelengths for illumination. However it has two main drawbacks: it is not considered eye-safe (depending on the power level) and the human eye is generally able to detect it (as a red glow), making it unsuitable for covert applications. The 976nm region offers a good responsivity with a Silicon detector and can also be used with an InGaAs-based camera, albeit with a lower responsivity. While still not considered eye-safe, it cannot be detected by the human eye and is therefore suitable for covert applications. The 1064nm region offers a much better responsivity with an InGaAs-based camera, is considered a covert wavelength, and offers some improvement regarding 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.

For illumination, power levels of interest range from a few hundred milli-Watts to several hundreds of Watts. The low-power range (<1W) is generally used for imaging and short-range security surveillance (<200m). The medium-power range (1~100W) is used mainly for long-range illumination (>200m). The high-power range (~100W to kW-level) is used for very long-range illumination as well as some military covert operations, and illumination through obstacles (dust-clouds, explosions).

It was recently shown [1, 2] that semiconductor vertical-cavity surface-emitting lasers (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 Watts to several hundred Watts, while keeping the power conversion efficiency (PCE) at high levels (typically >40%). These high-power, high-efficiency VCSEL sources preserve many of the advantages present in a single VCSEL device, such as low-cost manufacturing [3], high reliability [4], and operation at high temperatures [5]. In addition, such high-power VCSEL arrays emit in a spectrally narrow beam (full-width at half-maximum typically <2nm) and in an intrinsically circular, narrow divergence uniform beam (numerical aperture typically between 0.15 and 0.20) without the need for optics. As such, VCSEL arrays offer much potential as a light source for illumination and related applications [6].

In this paper we present results on VCSEL-based illuminators, at the 808nm and 976nm emission wavelengths, and for different power levels. First, we briefly review the VCSEL array structure and fabrication. We then present the main device characteristics, followed by results on VCSEL-based illuminators. In particular, speckle measurement data is presented demonstrating the VCSEL array's superior performance (near speckle-free) compared to other light sources, resulting in better image quality.

2. DEVICE STRUCTURE AND FABRICATION

The basic building blocks of VCSEL-based illuminators are 2D VCSEL arrays. Depending on the power level required, arrays range from ~1mm x 1mm to ~6mm x 6mm in size and contain from a few hundred to a few 10,000's of elements connected in parallel. The VCSEL-based illuminators contain single or multiple arrays, depending on the power level required and the application.

Epitaxial VCSEL materials designed to lase around 808nm and 976nm were grown on GaAs substrate using MOCVD. For current and optical confinement, the selective oxidation process [7] is used to create an aperture near the active region to improve performance [8]. In the case of the 808nm material, the growth starts with an etch-stop layer to facilitate substrate removal for processing of arrays as explained below. Following the etch-stop layer is a highly doped N-GaAs layer that is used for the N-contact of the arrays. Then, an AlGaAs N-type high-reflectivity distributed Bragg reflector (DBR) follows. The active region consists of InAlGaAs strained quantum wells designed for 808nm emission, and is followed by P-type DBR output mirror, whose reflectivity is optimized for maximum PCE [1, 9]. A high-Aluminum content layer is placed near the first pair of the P-DBR to later form the oxide aperture. The placement and design of the aperture is critical to minimize optical losses [10, 11] and current spreading [12]. Band-gap engineering (including modulation doping) is used to design low-resistivity DBRs with low-absorption losses [13]. The epitaxy of the 976nm material is similar, but designed for substrate emission and "junction down" mounting for efficient heat removal [1]: the N-DBR is designed as the output mirror, while the P-DBR is designed as the high-reflecting mirror. For the active region, strained InGaAs quantum wells are used.

For high-power operation, efficient heat-removal is required [1]. However, unlike 976nm high-power VCSEL arrays, a junction-down, bottom-emitting (substrate-emission) configuration is not possible for 808nm, because of the excessive GaAs substrate absorption at that wavelength. Furthermore, a top-emitting configuration with the GaAs substrate still present (even if thinned down) would add excessive thermal impedance. Therefore, in the case of 808nm VCSEL arrays, the GaAs substrate needs to be removed [2]. First, the epitaxial side of the sample is fully processed. The sample is then bonded onto a sacrificial carrier using a special bonding agent. The GaAs substrate is removed using a selective wet-etch. The etch-stop layer is then removed using another selective wet-etch, thus exposing the N+ GaAs contact layer. At this stage, the sample is only 10microns thick. Patterned N-metal pads are evaporated onto the N+ GaAs contact layer. Alloying temperature is minimized to avoid affecting the bonding agent, while still providing an Ohmic contact. These bonding pads are then plated with Gold. The individual arrays are cleaved, with each array still attached to its individual sacrificial carrier. Each array/carrier assembly is then soldered to a high-conductivity submount (such as diamond). The sacrificial carrier is removed and the array-on-submount assembly is cleaned. Finally, the array is wire-bonded and tested. Figure 1 shows a schematic of the cross-section of a packaged 808nm VCSEL array.

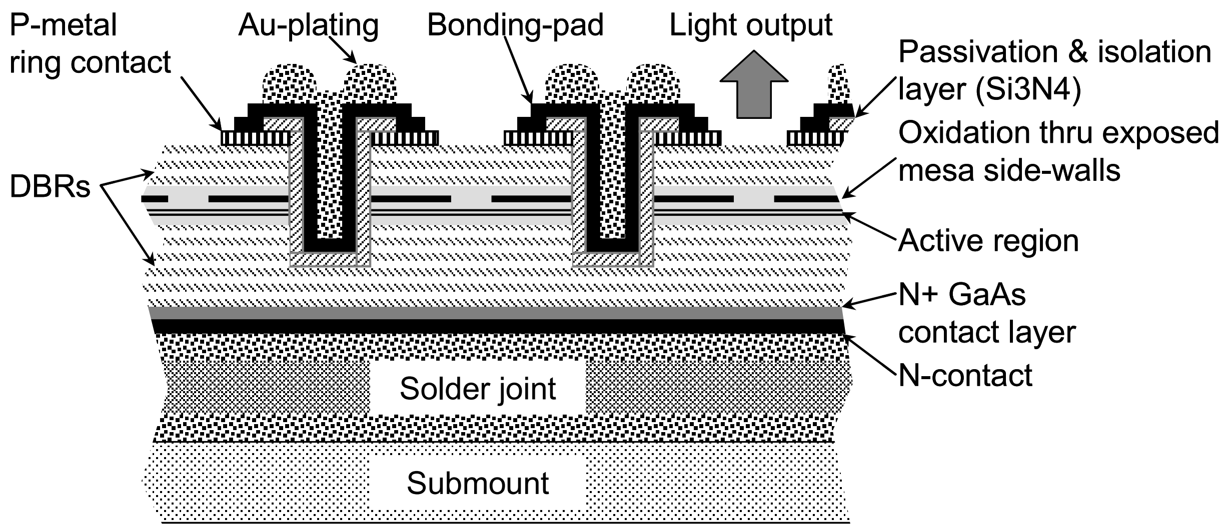

Fig. 1. Cross section schematic of a packaged 808nm 2D VCSEL array. The GaAs substrate is completely removed during processing, thus considerably reducing the thermal impedance of the array and enabling higher operating output powers.

Depending on the illumination application, different size arrays have been fabricated at 808nm and 976nm, ranging from 2mm x 2mm to 5mm x 5mm. Also, depending on the power output requirement, the arrays are packaged either on BeO (low power) or diamond (high power).

3. DEVICE CHARACTERISTICS

Results for high-power VCSEL 808nm and 976nm arrays packaged on diamond submounts have been presented in detail elsewhere [1, 2]. Power levels exceeding 200W were demonstrated. For low-power illumination applications, and where cost is a concern, we developed Watt-level VCSEL array modules packaged on BeO instead of diamond. While BeO's thermal conductivity is much less than that of diamond (~200W/m-K vs. ~1,500W/m-K), its cost is also significantly less. Figure 2(a) shows a photograph of a fully packaged 2mm x 2mm 808nm VCSEL array. The VCSEL array contains a few hundred multi-mode devices connected in parallel. The VCSEL chip is soldered on BeO, and then attached on a copper carrier with leads. The module can then easily be mounted on a heat-sink/fan for heat-removal.

The continuous-wave (CW) characteristics (L-I-V) of this module are shown in Figure 2(b). The threshold current, slope efficiency, and resistance are 1.32A, 1.1W/A, and 44Ω, respectively. A maximum power conversion efficiency (PCE) of 43% is achieved at an output power of 7W (8A drive current). This module is designed to operate CW between 3 and 7W.

The spectral and beam characteristics of this module at 7W output power are shown in Figure 3. The spectral full-width at half-maximum remains low (<0.5nm), making this type of device useful when used in conjunction with a narrow-band-filter-equipped camera for image noise reduction and for elimination of unwanted light. The far-field intensity distribution is circular and uniform, with a profile shape somewhere in between that of a Gaussian and a top-hat. Such distribution is well-suited for uniform illumination. The beam divergence corresponds to a numerical aperture (N.A.) of ~0.17 (approximately 20^o full-angle 1/e^2 divergence). This module could therefore be used "as is" without the need for additional optics. In cases where the divergence needs to be reduced or increased, a simple, low-cost lens can be used.

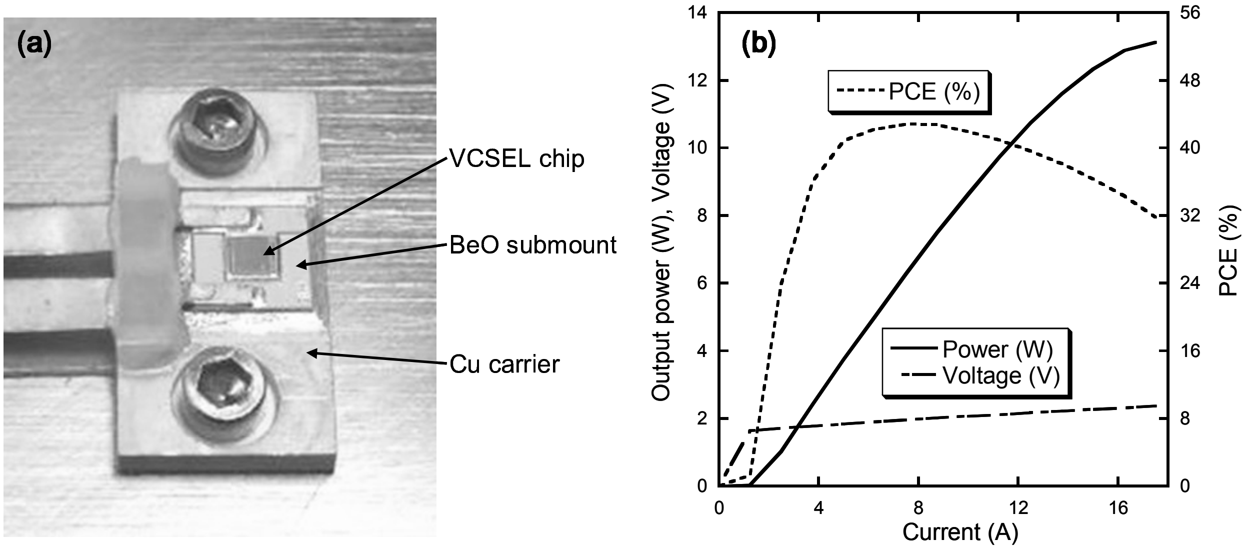

Fig. 2. (a) Photograph of a packaged 2mm x 2mm 808nm 2D VCSEL array, and (b) CW L-I-V characteristics. A maximum PCE of 43% is achieved at a CW output power of 7W.

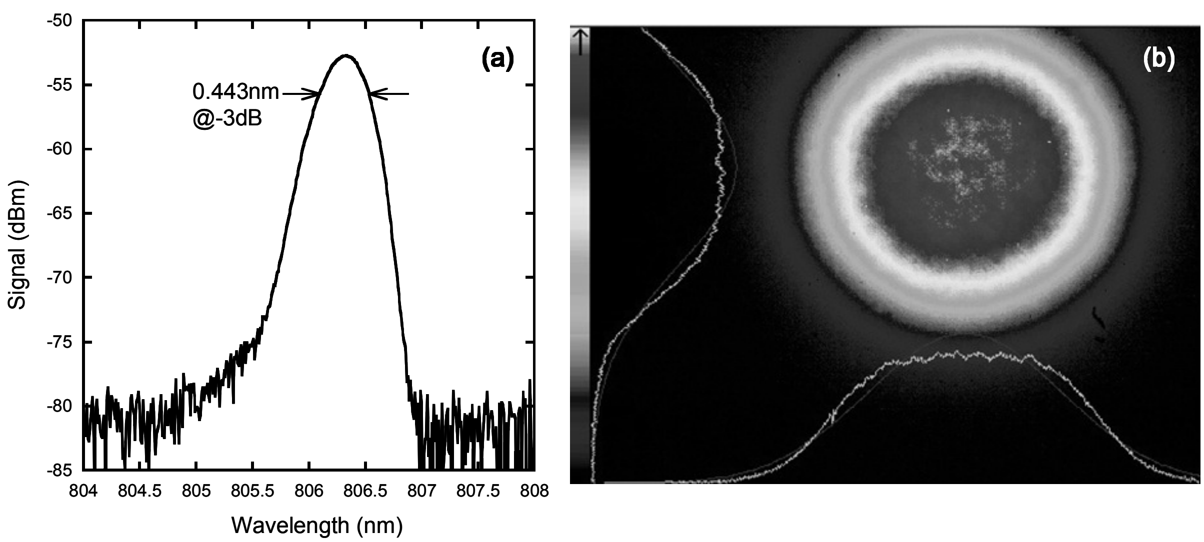

Fig. 3. (a) Spectrum and (b) far-field intensity distribution at an out put power of 7W, for the 2mm x 2mm VCSEL module shown in Figure 2. The spectral FWHM is <0.5nm and the far-field divergence corresponds to a 0.17 N.A.

These characteristics highlight some basic key advantages of VCSELs as an illumination source compared to other semiconductor technologies. Compared to light emitting diodes, VCSELs offer similar manufacturing costs, greatly increased power conversion efficiency, much narrower spectrum, and much narrower beam divergence. Compared to edge-emitting lasers, VCSELs offer lower manufacturing costs (both at the chip and packaging levels), comparable power conversion efficiency, narrower spectrum, and circular, symmetric low-diverging beam. In addition, VCSELs offer improved reliability over edge-emitting lasers. The main reason is that VCSELs are not subject to catastrophic optical damage (COD) [14]. As a result, VCSELs can more readily operate at high temperatures [5], thereby meeting some of the harsh environmental requirements in some illumination applications (such as oil pipeline surveillance in deserts).

For illumination applications requiring higher powers, such as long-range illumination (>200m), modules comprising several VCSEL arrays have been developed. As an example, Figure 4(a) shows a photograph of a 3 x 3 module, emitting around 808nm, with the nine arrays connected in series to reduce the operating current requirements. Such a module is designed to operate CW at 300W while requiring only 67A of drive current (Fig. 4(b)).

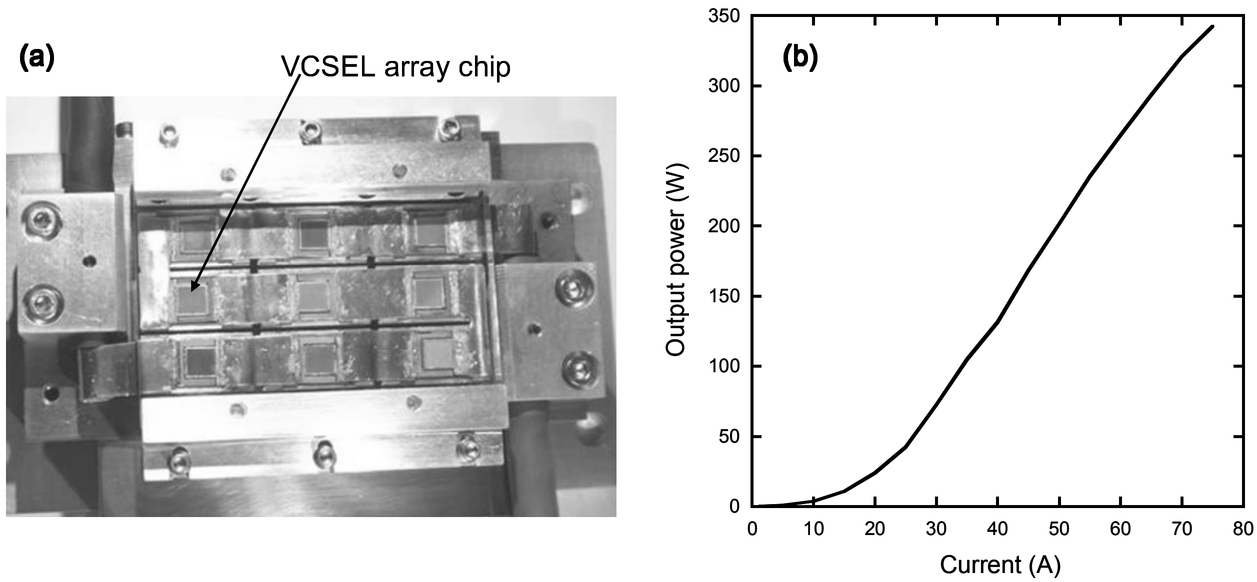

Fig. 4. (a) Photograph of a high-power 3 x 3 array module and (b) CW L-I characteristic. This module is design for >300W CW operation. The nine arrays are connected in series to reduce the operating current requirements.

As far as the output beam properties, generally only the far-field characteristics are important for illumination considerations and as such, this high-power module does not require any optics as its far-field intensity distribution is similar to that shown in Fig. 3(b).

Typically, the size and power density of the illumination source are not so much of an issue. Therefore module power can be easily scaled up by connecting more arrays together and the arrays can be spaced apart for better heat management.

4. VCSEL-BASED ILLUMINATORS

Several types of VCSEL-based illuminators at the 808nm and 976nm wavelengths were developed depending on the end application.

For short range surveillance applications, we developed compact, Watt-class illuminator modules at 808nm and 976nm. Such a module is shown in Figure 5(a). It uses a VCSEL source similar to the one shown in Figure 2 combined with a simple heat-sink/fan architecture for heat-removal. No optics are used and the illuminator emits in the VCSEL's intrinsic divergence of ~20^o (full angle, $1/e^2$). Such modules are designed for a 1~3W CW output power range over a wide range of temperatures. Furthermore, their small size and weight allows them to be used in portable units.

At the other end of the spectrum, Figure 5(b) shows a 976nm kW-class illuminator. This illuminator uses nine high-power VCSEL arrays emitting more than 120W CW each and requires water-cooling. This type of illuminator is used in military application for detection through adverse conditions such as explosions or dust clouds. Unlike most types of illuminators where the far field radiation is used for illumination, this type of illuminator overlaps magnified images of the sources at a certain distance away (several tens of meters) so that a specific area (1~2 meters in diameter) is illuminated with maximum intensity. Nine large lenses in front of each array can be individually adjusted along different directions so as to adjust the magnified images of each array. The VCSEL arrays used have a very large number of elements (10,000's), so that the projected images, when overlapped, create a very uniform, "top-hat" intensity distribution with no pixelation effect.

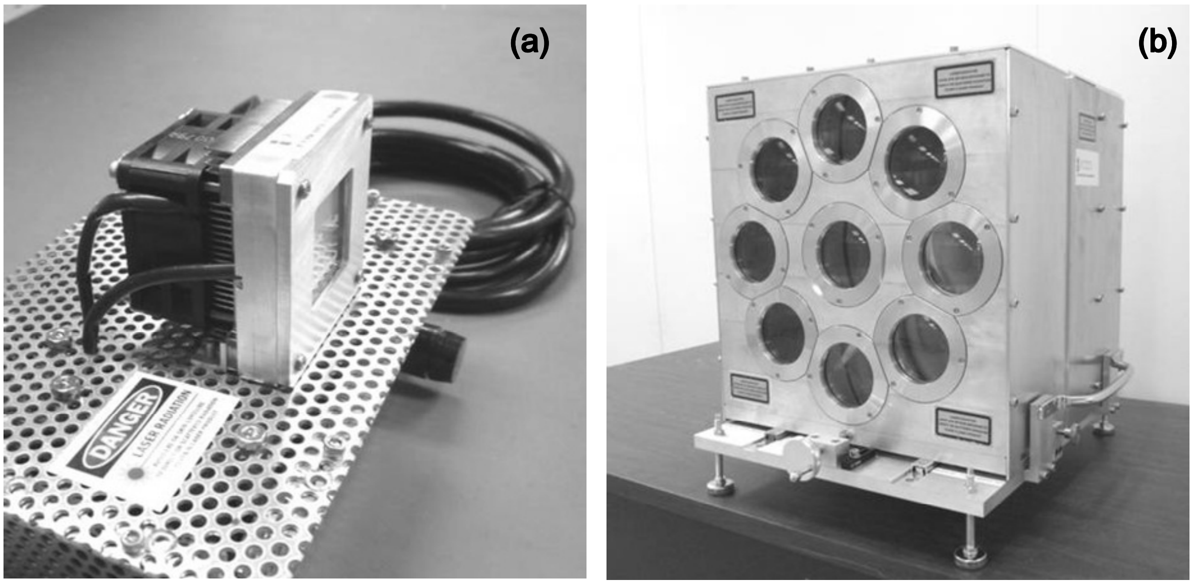

Fig. 5. Photographs of (a) a Watt-level illuminator for short range surveillance (1~3W output at 808nm and 976nm) and (b) a kW-class illuminator for military detection applications (1kW output at 976nm).

The following video still (Fig. 6) shows a scene illuminated with the compact Watt-class illuminator discussed previously and captured by an InGaAs camera from Goodrich ISR (formerly Sensors Unlimited). The illumination power is 2~3W, at 976nm. The resulting image is clear, with no interference patterns or speckle.

Fig. 6. Night-time image under 2~3W VCSEL-based illumination at 976nm. An InGaAs-based camera was used to capture the image.

For longer illumination ranges (>200m), 100-Watt-level VCSEL-based illuminators at 808nm were developed. The following image (Fig. 7(a)) shows an aerial view of the illumination test zone with the illuminator location ("source") and with specific landmarks at 190m (car) and 532m (high-voltage transmission tower). Figure 7(b) shows the resulting night-time image captured with a CCD camera for an illumination power of ~140W at 808nm.

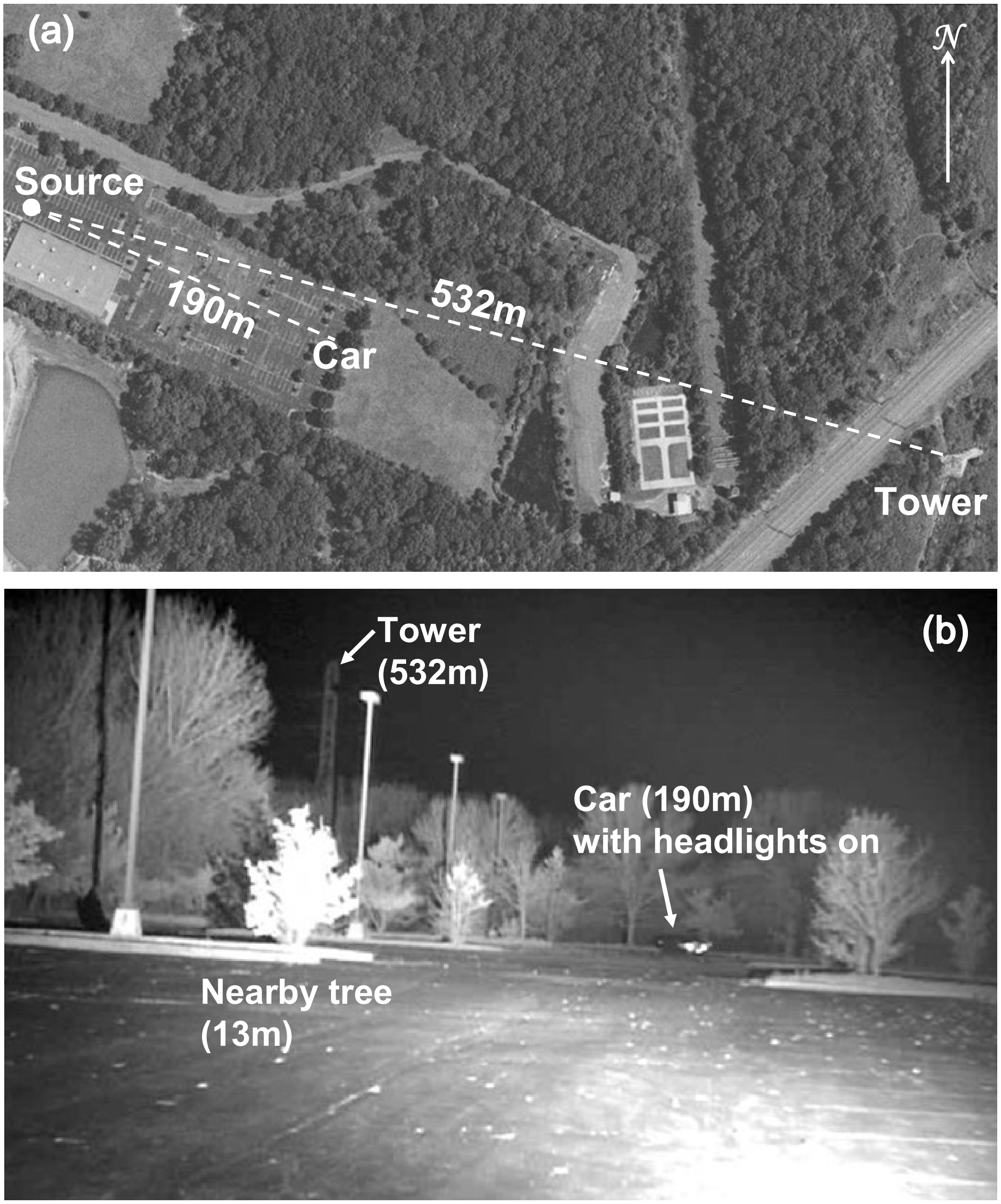

Fig. 7. (a) Aerial view of the test zone for high-power night-time illumination. (b) Image capture using a CCD camera of the illuminated zone, under ~140W VCSEL illumination at 808nm. A narrow filter was used on the camera. The filter transmission at the illumination wavelength was approximately 30%, resulting in an effective illumination power of ~42W.

The CCD camera was equipped with a generic Thorlabs 50%-transmission narrow-band filter (~10nm FWHM) centered around 811nm to reject parasitic light (such as visible light). As a result, even though the car had the high-beams on, it can still clearly be identified. Because of some wavelength misalignment between the source and the narrow-band filter, it is estimated that the filter transmission at the source wavelength is around 30%, such that the effective illumination power is only 42W. Still, objects as far as 500m (the high-voltage transmission tower) can be identified. The image is clear with no interference pattern or speckle.

To better understand the improved image quality using VCSEL-based illuminators, an experiment was undertaken at SRI International to quantify the speckle of different light source. Four different light sources were compared: an edge-emitter laser (EE) with a diffuser, an edge-emitter laser without diffuser, an LED, and a 2D VCSEL array from Princeton Optronics. The test set-up is shown in Figure 8. The speckle is measured by sampling the illumination with a pinhole. The pinhole/photo-detector scans the power along a line several meters from the source. The results are shown in Figure 9.

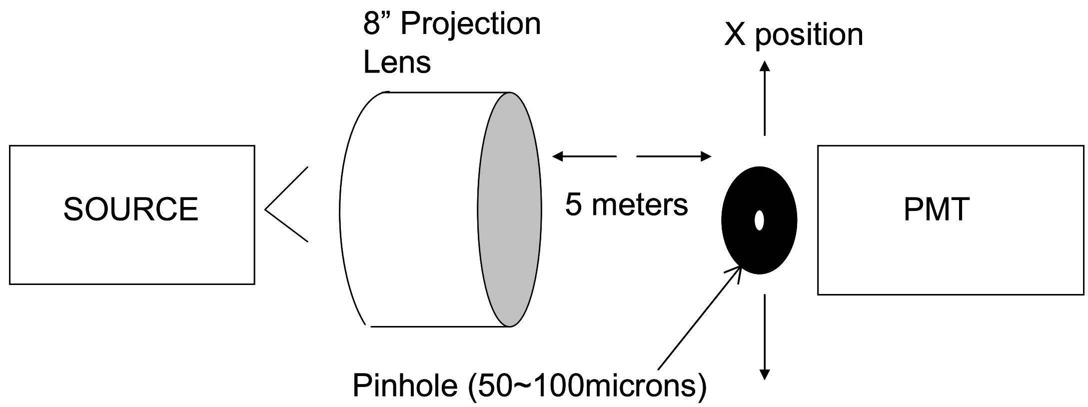

Fig. 8. Speckle measurement test set-up.

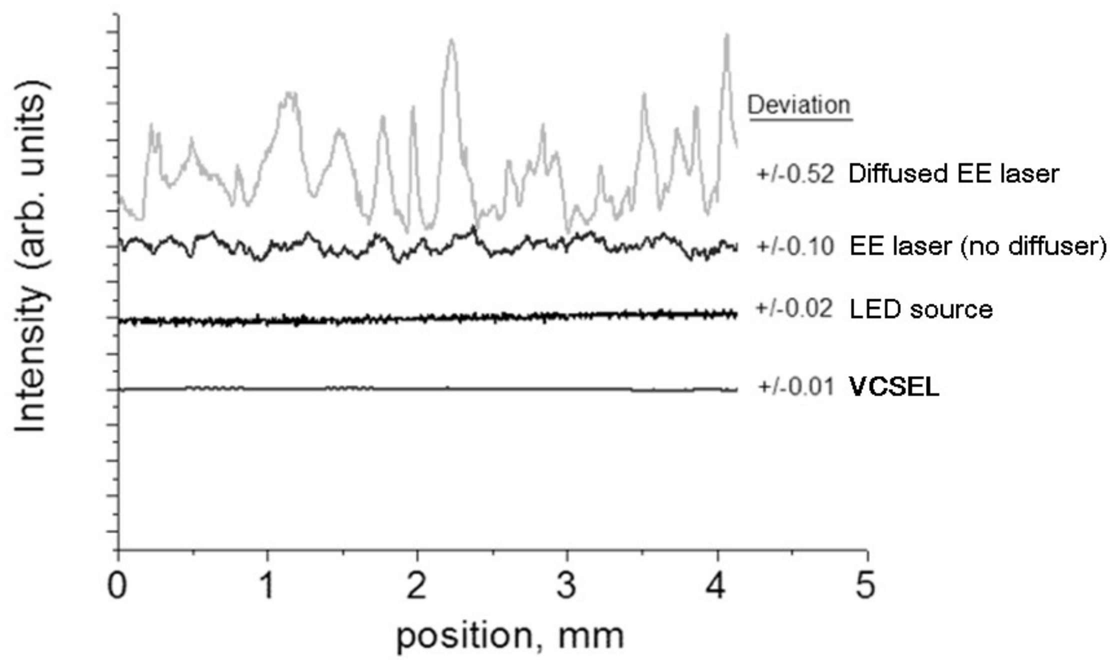

Fig. 9. Speckle measurement results for different illumination sources. The VCSEL 2D array source yields the lowest intensity variation.

The 2D VCSEL array shows the best performance (even over the LED source) and is virtually speckle-free.

5. CONCLUSIONS

A variety of illumination results using high-power, high-efficiency 2D VCSEL arrays has been presented, at 808nm and 976nm, and for different illumination output power levels ranging from a few Watts to several hundred Watts. It was shown that high-power VCSEL arrays can be packaged on low-cost BeO and still maintain high CW output power (up to 13W) and high power conversion efficiency at operating power (43% at 7W), making this an attractive solution for compact, Watt-level illuminators. For long-range illuminators, we demonstrated night-time visibility up to 500m with a filter-equipped CCD camera and an illumination output power of 140W at 808nm. Furthermore, we believe that an optimization of the filter would reduce the illumination output power requirement down to ~42W. These results were obtained in an "optics-free" configuration, using the natural divergence of the VCSEL array.

Compared to light emitting diodes, VCSELs offer similar manufacturing costs, greatly increased power conversion efficiency, much narrower spectrum, and much narrower beam divergence. Compared to edge-emitting lasers, VCSELs offer lower manufacturing costs (both at the chip and packaging levels), comparable power conversion efficiency, narrower spectrum, improved reliability, high-temperature operation, and circular, symmetric low-diverging beam.

Finally, VCSEL-based illuminators offer very good, speckle-free image quality.

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