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S. Arafin, H. Jung, "Recent progress on GaSb-based electrically-pumped VCSELs for wavelengths above 4 µm," Proc. SPIE 10980, Image Sensing Technologies: Materials, Devices, Systems, and Applications VI, 109800H (13 May 2019); doi: 10.1117/12.2522418

Event: SPIE Defense + Commercial Sensing, 2019, Baltimore, Maryland, United States

# Recent progress on GaSb-based electrically-pumped VCSELs for wavelengths above 4 µm

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## ABSTRACT

This paper reports the recent progress on the development of GaSb-based vertical-cavity surface-emitting lasers (VCSELs) with a record-long emission wavelength of above 4 µm using type-II quantum wells. Mid-wave infrared (MWIR) spectral region, covering the 3-6 µm wavelength range, is technologically very interesting for enabling two major application areas such as sensing and defense/security. Among several types of diode lasers, electrically-pumped continuous-wave operating VCSELs seem to be the most attractive choice owing to their low-power consumption, inherent longitudinal single-mode emission, and simple electro-thermal wavelength tunability. The applicability of MWIR VCSELs for these two major areas are also discussed in this paper. Single-mode low-power (a few mWs) VCSEL operating at room-temperature with reasonable tunability is essential for the sensing application. For the advanced military application, high optical power (with at least a few watts), high-efficiency and high-brightness (>1 W/mm$^2$) MWIR lasers are important. Given that the MWIR wavelength regime is eye-safe and has a low-loss atmospheric window, the development of next-generation MWIR laser sources is currently in high demand.

**Keywords:** VCSEL, interband cascade laser, tunnel junction, GaSb, type-II quantum well, high efficiency, high-brightness, 2D array

## 1. INTRODUCTION

The mid-wave infrared (MWIR) spectral regime with the wavelengths ranging from 3-5 µm is highly interesting for the detection of various gaseous and biological molecules including $CH_4$, $CO_2$, $NO_2$, $SO_2$ and $O_3$[1]. These important molecules absorb and radiate much strongly with their characteristic lines in the MWIR region, making it to be a fruitful area of research from an environmental perspective. Due to the unique specificity of a molecule's spectrum, lasers in this wavelength regime have a unique advantage over ultraviolet and visible or near-IR lasers.

The greenhouse gases, for instance, $CH_4$ and $CO_2$ has absorption bands at MWIR wavelengths, which is about a few orders of magnitude stronger than the SWIR band, as shown in Fig. 1. Therefore, if a handheld and battery-operated sensing system can be developed to operate in the MWIR, then sub-ppm sensitivity can be achieved and weak fugitive emissions can be readily detected. However, MWIR lasers are relatively less mature than those operating at SWIR and they are also costly. Therefore, achieving low-cost and energy-efficient MWIR lasers is of utmost importance. Despite of the commercial availability of quantum cascade laser (QCL)-based MWIR sensors[2], QCLs are known to consume far more power than is viable for a small, handheld sensing system. Also, the device performance of QCLs near 3 µm is not satisfactory; hinting that further improvement of the MWIR system is possible. Therefore, if low-power MWIR lasers can be developed and matured, then handheld and low SWaP-C MWIR sensors can become reality and can provide far stronger performance than their SWIR and LWIR counterparts.

Among several type of semiconductor diode lasers, VCSELs are considered to be one of the ideal light sources for the development of a photonic sensor technology utilizing the detection technique, so-called tunable diode laser absorption spectroscopy (TDLAS)[3]. This is because VCSEL as a light source offer a number of attractive features. For instance, VCSEL exhibits inherently single-mode emission, consume low electrical power and provide continuous wavelength tunability, leading to photonic sensors for detecting greenhouse gases and other hydrocarbons at a time. Most importantly, selective and sensitive photonic sensors operating even at the parts-per-billion (ppb) level, being beneficial for advancing sustainable energy solutions.

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Image Sensing Technologies: Materials, Devices, Systems, and Applications VI, edited by Nibir K. Dhar,
Achyut K. Dutta, Sachidananda R. Babu, Proc. of SPIE Vol. 10980, 109800H · © 2019 SPIE
CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2522418

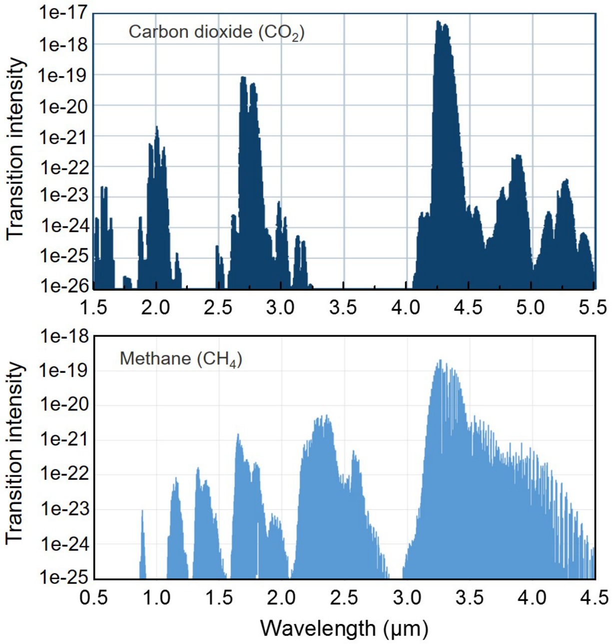

Figure 1. Infrared spectroscopic intensity of methane and carbon dioxide on semi-logarithmic scale. (www.hitran.org). The bands near 3.3 µm and 4.2 µm are approximately a few orders of magnitude stronger than that at the SWIR regime.

By moving away from the sensing area, one could also think whether VCSEL devices can enable other important functions to benefit other areas. Especially from the defense perspective, infrared against countermeasure (IRCM) and scene illumination are the two important applications that require for these lasers to scale the output to much higher powers on SWaP-C constrained platforms[4]. Unlike edge-emitters, fortunately VCSELs can be made in densely-packed two-dimensional (2D) arrays. So MWIR VCSEL arrays can be employed as a means to achieve high output power. However, phase coherence within the 2D array may be needed to obtain low beam divergence and high spectral purity.

In this paper, the recent progress on the development of GaSb-based VCSELs for emission wavelengths beyond 4 µm is presented. We first review the recent demonstrations of such laser devices of $3 \leq \lambda \leq 4$ µm made by several research groups. We then discuss the importance and significance of VCSEL research in the $\lambda > 4$ µm wavelength range. This discussion will be fully based on sensing and defense areas. In order for these lasers to be deployed in these two application areas, several aspects of VCSEL devices are also described.

## 2. REVIEW OF ANTIMONIDE VCSELS ABOVE 3 µM

Prior to discussing GaSb-VCSELs with $\lambda > 4$ µm, it is important to provide a short review of the recent demonstrations of MWIR VCSELs beyond or at 3 µm that have been developed by academia and government research lab. Because of intrinsic high efficiency, less complexity, small form factor and cost-effectiveness, electrically-pumped VCSELs are more demanding than the equivalent optically-pumped devices. Therefore, the demonstrations of only electrically-pumped devices are considered in this paper. All the electrically-pumped VCSELs at and above 3 µm reported so far are achieved by employing only the less mature GaSb material system. Andrejew *et al.* reported GaSb based VCSELs at $\lambda \approx 3$ µm which are made using type-I quantum wells (QWs)[5]. The devices operate up to 5°C continuous-wave (CW) and up to 50°C in pulsed mode. However, extending the emission wavelength beyond 3 µm requires type-II QWs as a gain medium in these devices[6]. By taking this into account, a few months later from the previous demonstration, Bewley *et al.* reported VCSELs using cascaded active region with type-II QWs, which emitted at 3.4 µm[7]. These devices were named as interband-cascade (IC) VCSELs that operate in pulsed mode at temperatures up to 70°C. Recently, the emission wavelength of VCSELs has been extended further to $\lambda \approx 4$ µm[6,8-10]. The devices operate in the CW mode up to -7°C and in the pulsed mode up to 45°C. All these research reports indicate that achieving high-performance electrically-injected VCSELs in the $\lambda = 3\text{-}6$ µm wavelength range is currently an active area of research.

## 3. ANTIMONIDE VCSELS FOR SENSING

All these three VCSEL demonstrations were aimed for the applicability into the sensing area where the devices are intended to be utilized for the sensitive detection of trace gases. Only electrically-pumped laser devices, which can be operated continuous wave at room temperature, are particularly suitable for compact and low-cost applications[3]. In general, this application require only a few mWs of optical power with single transverse mode emission and good beam quality[11]. Also a narrow optical linewidth is required to sample the gas absorption spectrum with high resolution. Mode-hop free wavelength tuning with electro-thermal tunability would also be critical to hit fundamental vibrational absorption lines of important gases. The devices with low tuning range as low as a few nanometers are enough for the detection of only one gas at a time. However, developing a micro-electro-mechanical systems (MEMS) technology platform for these device will allow us to achieve tuning range as high as 200-250 nm[12]. This could effectively probe multiple important gases with a single device by probing several spectral lines associated with methane, propane, ethane, and acetylene in the 3-6 μm region.

### 3.1 Device design

The schematic of the MWIR VCSELs is shown in Fig. 2. The design utilizes undoped epitaxial mirror and lateral intra-cavity contacting scheme as *n*-side contacts for the device. The bottom epitaxial DBR provides a high reflectivity that can be achieved only with undoped DBR layers and with sharp interfaces between the low and high refractive index materials. In other words, we will be exempt from any linear compositional grading at the hetero-interfaces between low and high-refractive index materials of the bottom mirror unlike GaSb-based SWIR VCSELs with a large-area backside *n*-contact[13, 14]. The cavity is dominated by *n*-GaSb layer which is modulation doped with doping maxima in the nodes of the optical electric field. For current injection and low-resistive ohmic contact, the intra-cavity *n*-contacts need to be formed on a highly doped and lattice matched $n^+$-InAs$_{0.91}$Sb$_{0.09}$ contact layer. This layer is positioned at the first node of the electric field after the bottom mirror to reduce the optical absorption. For the top *p*-side metal-semiconductor contacts, the same lattice-matched $n^+$-InAs$_{0.91}$Sb$_{0.09}$ contact layer can be used and placed in a node of the electric field to reduce optical losses. The top mirror is made of dielectric DBR. For top-emitting MWIR VCSELs with an episide-up configuration, this design is relatively independent of wavelength throughout the $\lambda = 3$-6 μm spectral band. As a part of the device design, there are three critical components, such as active region, highly-reflective mirrors and current aperture that will be discussed in details.

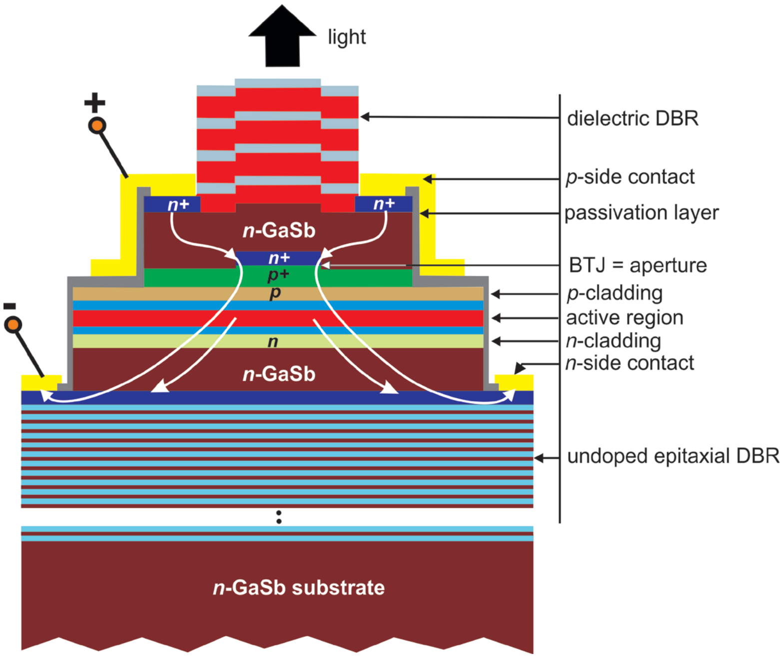

Figure 2. Schematic cross-sectional view of an epi-side up vertical-cavity surface-emitting laser. The direction of current flow is shown which is defined by the buried tunnel junction.

## 3.2 Active region

Figure 3 shows the typical type-II QWs based active region utilized in GaSb based VCSELs with $\lambda > 3$ μm. A single-stage (non-cascaded) active region was employed for the demonstration of 4 μm VCSELs, as presented in Fig. 3(a). This non-cascaded design[6] was needed due to the incorporation of the buried tunnel junction (BTJ) concept within the device. The devices comprised 8 type-II QWs in a single stage configuration, which were made of a $Ga_{0.9}In_{0.1}Sb$ hole confining QW sandwiched between two InAs electron confining QWs, as commonly used in ICLs. The photon energy is determined by the energy separation between the ground electron-state (e1) and hole-state (hh), as shown in Fig. 3(a). The photon energy corresponding to the lasing wavelength can be changed by changing the thickness of the constituent QWs. The thickness of the $Al_{0.35}GaSb$ barriers between the QWs were chosen in a way that prevent excess energy broadening of the mini-bands and allow homogeneous filling of the QWs by tunneling at the same time. On the *n*-side, InAs/AlSb super-lattice (SL) was used to gradually lower the conduction band offset from GaSb to a level suitable for electron injection into the QWs. This also effectively acts as the hole-blocking layer. On the *p*-side, lattice-matched Al-containing quaternary layer is used for hole injection and electron-blocking.

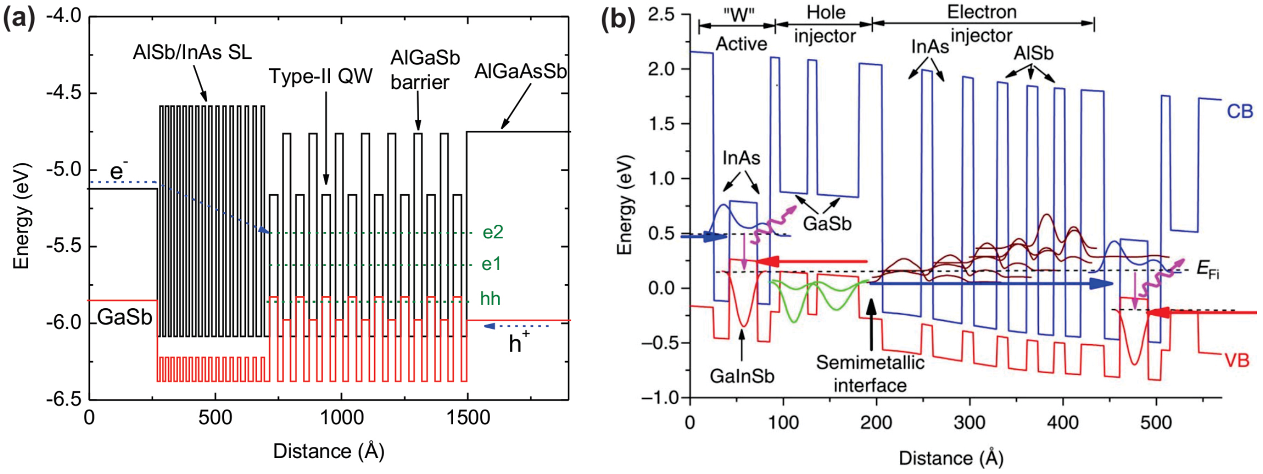

Figure 3. Band diagrams of the type-II QWs based active regions with (a) non-cascaded and (b) cascaded configurations. Figures adapted from ref[6] and ref[15].

Figure 3(b) shows the type-II QW based active region employed in 3.4 μm VCSELs[7]. This typical multi-stage (cascaded) active region, previously used for edge-emitting ICLs[16], is split into three groups of five stages, totaling 15. Such a higher stage multiplicity in these VCSEL devices assures sufficient gain to overcome the cavity loss. The three groups of active stages were separated by *n*-GaSb spacer layers that are in turn bounded by transition superlattices. The layering and right doping configurations of the active stages with carrier rebalancing are important to significantly reduce the threshold current density of the device[15].

## 3.3 Highly-reflective mirrors

Due to the $\lambda^2$- $\lambda^3$ scaling of free carrier absorption, the use of undoped epitaxial mirror is justified in the design of $\lambda > 4$ μm VCSEL, forcing to utilize intra-cavity contacts in the resonator. Thus, cavity losses should be minimized in such a low-doped cavity structure. Figure 4 shows the simulated reflection spectra of both bottom epitaxial and top dielectric distributed Bragg reflector (DBR) mirrors, where GaSb and air are considered to be the incident media, respectively. The bottom mirror consists of an approximately >15.6-μm-thick epitaxially grown (DBR) with 26-pairs of alternating undoped lattice-matched $AlAs_{0.08}Sb_{0.92}$ and GaSb layers. The peak power reflectivity is calculated to be 99.9% at 4.2 μm by considering the plane-wave approximation. The bottom dielectric DBR consists of only 5-pairs of a-ZnS and a-Ge. These two dielectric mirror materials can be deposited by e-beam evaporation. Despite of the poor thermal conductivity of these dielectric materials, the peak reflectivity of this mirror can be as high as 99.8% by considering the refractive index contract $\Delta n$ between these two materials to be approximately 2 at around 4.2 μm. The simulation was performed with the transfer matrix method and the refractive indices used for the calculation are experimentally measured by reflection spectroscopy technique[17].

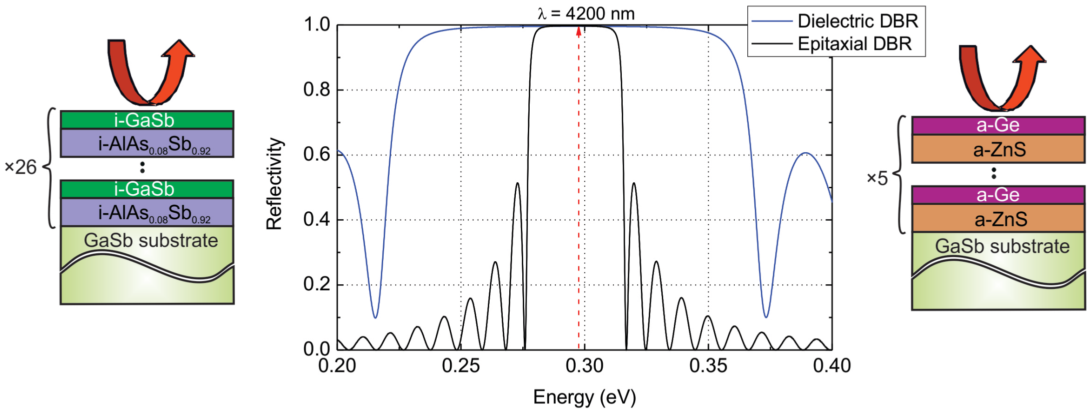

Figure 4. Simulated reflectivity spectra of a 26 pair epitaxial DBR and 5 pair dielectric DBR designed for maximum reflectivity at 4.2 µm and the results are superimposed. The structures used for these simulations are schematically shown as well.

### 3.4 Current aperture

In conventional VCSELs after being pumped from the top annular *p*-contact, uniform current distribution around the active region is a big concern. This problem can be naturally overcome by incorporating the cascaded active region. As a matter of fact, current spreading along the transverse plane (i.e. perpendicular to growth direction) is very significant in a cascaded structure with thousands of thin layers that magnify resistance anisotropy[18]. In other words, a large ratio between in-plane and vertical conductivity in the cascaded layer structure ensures excellent lateral carrier injection through metal contacts with the intra-cavity configuration. Also in general, the GaSb material system has high electron and hole mobilities[19]. This also means that the diffusion coefficients of electrons and holes in these materials will be higher compared to GaAs or InP based materials. In addition to achieving the higher roundtrip gain required for efficient lasing, cascaded active region can intrinsically benefit the device by homogeneous current distribution through this physical phenomenon. Note that this cascade VCSEL configuration is possible with IC lasers based on transverse electric (TE) polarization.

Excessive lateral current spreading in such cascaded structures also creates a problem in making current confinement of the devices. As it is known that VCSELs require an aperture close to the active region for current confinement so that only single but fundamental $LP_{01}$ transverse mode is obtained from the device. The BTJ concept has already been proven to be a successful way of confining the current at the center of GaSb-based VCSELs[13,14,17]. However, this concept cannot be applied in IC-VCSELs with a multi-stage active region. This is why a single stage active region with 8 QWs was employed while demonstrating 4 µm BTJ-VCSELs[6]. Single stage active region is acceptable after the BTJ because the carrier diffusion happens only once. However, in case of a cascaded design with many thin layers connecting QWs, the diffusion will happen at each stage. This will require aperture for the current confinement at each stage, indicating that number of epitaxial regrowth for defining the tunnel junction-based aperture will be equal to number of stages. Even monolithic aperture-VCSELs based on the selective, lateral under-etching of the tunnel-junction to define carrier confinement[20] cannot solve the problem in VCSELs with multi-stage active region. Larger devices without current aperture is not a solution since they start lasing on several higher radial and azimuthal order modes right above or even at threshold, which essentially limits their suitability in the sensing application. Most importantly, the apertureless device becomes power-hungry since they experience higher optical loss due to the interaction between top annular contact and transverse modes emerging from the resonator. Therefore, one has to think of alternative techniques for instance, proton implantation technology[21] to solve this fundamental problem.

## 4. ANTIMONIDE VCSELS FOR DEFENSE

In defense-based applications, lasers should at least provide 10 W of output power with a high brightness ($M^2 < 3$). This area also requires the high brightness source that involves minimal to no free-space optics in order to reduce the effects of shock, vibration and extreme temperature variations. Given that a single VCSEL cannot provide a watt level of output power, two-dimensional (2D) arrays of low-power VCSEL emitters will be needed, allowing us to achieve small form-factor and light-weight solutions. Unlike edge-emitters, VCSELs do not suffer from catastrophic optical damage (COD), which means VCSELs can be operated reliably at high temperatures. Despite of the fact that a VCSEL source itself has a lower conversion-efficiency than the edge-emitter source operating with a cooling unit, one could obtain a high system-level conversion efficiency by eliminating the cooling unit from the VCSEL-based high-power system. Moreover, edge-emitters cannot be fabricated as a 2D array, confirming VCSEL's benefits to establish a power scalable technology with an increased brightness and reduced thermal burden in the arrays.

Note that as opposed to sensing applications that requires choosing the emission wavelengths near or at strong absorption lines of gases, military application requires the laser wavelength that transmit through the atmosphere. Therefore, the atmospherically transparent windows of the MWIR wavelength band should be carefully selected.

### 4.1 Designing 2D array

A high-brightness 2D VCSEL array can be fabricated using thousands of small devices, as shown in Fig. 5. However, the poor transverse mode properties and lower beam quality of VCSELs restrict these devices to be used in this application area and raise the cost for beam-shaping and packaging. By using a microlens array with the same footprint as the VCSEL array, the output power from the array can then be efficiently coupled into a fiber using a simple focusing lens. For this purpose, it is important to develop small, high-efficiency single-mode devices to make high-brightness sources. Microlenses monolithically integrated on the VCSEL output window is a potential method to compress far-field divergence angles and control the mode-profile simultaneously. In fact, such integrated microlenses will be used for beam shaping and directional control to enable incoherent beam combining so that compact, high-brightness sources with low coherence noise can be made.

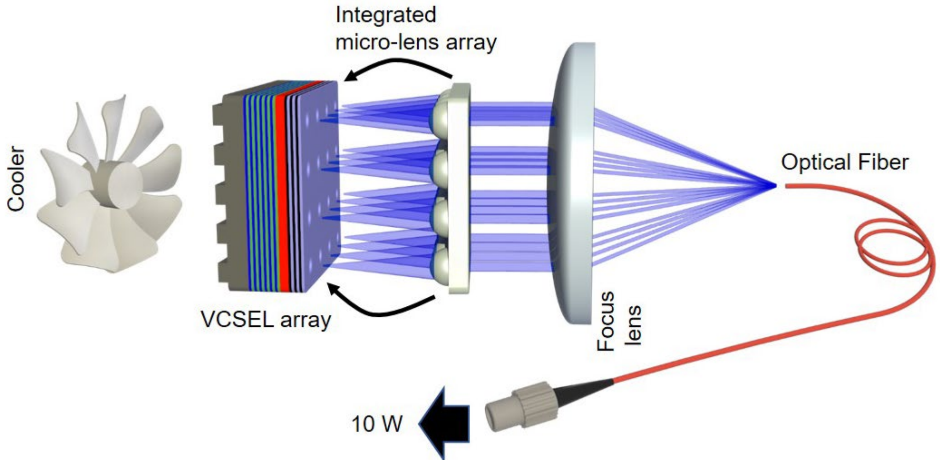

Figure 5. Schematic of a 2D VCSEL array with an integrated micro lens array to get high-power and high-brightness.

However, the integrated microlens array mentioned earlier will not make a coherent combined output with low beam divergence and high spectral purity that is required in some demanding applications. So, phased-locked VCSEL arrays is essential to achieve focused, diffraction-limited beam. Several different designs have been proposed and investigated to fabricate phase-locked VCSEL arrays. Evanescent coupling between densely packed etched air post VCSELs[22], reflectivity modulation of broad-area VCSELs[23], defect cavities within the top distributed Bragg reflector of a photonic crystal VCSELs[24] are some of the approaches adopted for making 2D phase-locked array. Coherent combining could also be obtained essentially based on the VCSELs within the array with an external cavity design, e.g. Talbot configuration[25]. Hence, almost perfect phase synchronization from VCSELs in large arrays can be obtained that make a significant leap forward in high-power laser technology.

## 5. CONCLUSIONS

We have shown that it is important to develop MWIR laser technology to make compact, high-power and high-efficiency light sources. Because of the significant and unique advantages in terms of costs, reliability and performance, VCSEL is the best candidate as a light source which could benefit both sensing and defense application areas at a time. The sensing area requires low-power single-mode VCSEL devices operating cw at room-temperature. The defense area requires high-power VCSEL arrays with high power conversion efficiency and high brightness. Many of the advantages on which low-power single VCSEL devices have built their success are preserved for high-power VCSEL arrays. These advantages primarily include low manufacturing costs, reliability and high beam quality. Therefore, it is believed that high-brightness high-power VCSEL-based modules emitting at the MWIR regime could become the next technology of choice for compact and efficient high-power semiconductor laser sources for many applications. For high-power operation, efficient heat-removal is required and therefore a junction-down, substrate side-emitting structure is preferred to improve current injection uniformity in the active region and to reduce the thermal impedance between the active region and the heat-spreader.

## ACKNOWLEDGEMENTS

The authors would like to thank Dr. Jerry Meyer at NRL, Dr. Rui Yang at the University of Oklahoma and Dr. Ganpath Veerabathran at Technical University of Munich for many helpful discussions on various technical issues mentioned in the paper.

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