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Invited Paper

Progress on high-power, high-brightness VCSELs and applications

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ABSTRACT

Vertical-cavity surface-emitting lasers (VCSELs) are attractive for many pumping and direct-diode applications due to combined advantages in low cost, high reliability, narrow and thermally stable spectrum, high power scalability, and easy system integration, etc. We report our progress on electrically pumped, GaAs-based, high-power high-brightness VCSELs and 2D arrays in the infrared wavelength range. At 976nm, over 5.5W peak CW output and 60% peak power conversion efficiency (PCE) were demonstrated with 225um oxide-confined device. For 5x5mm arrays, peak PCE of 54% & peak power of >450W at 976nm, peak PCE of 46% & peak power of >110W at 808nm were achieved respectively under QCW conditions. External cavity configuration was used to improve the VCSEL brightness. Single mode output of 280mW & 37% PCE were realized from 80um device. For large 325um device, we obtained single mode (M^2=1.1) CW output of 2.1W, corresponding to a brightness of 160MW/cm^2*sr. Three major areas of applications using such VCSELs are discussed: 1. High brightness fiber output; 2. High power, high efficiency green lasers from 2nd harmonic generation. 3.34W green output with 21.2% PCE were achieved; 3. Pumping solid state lasers for high energy pulse generation. We have demonstrated Q-switched pulses with 16.1mJ at 1064nm and 4.9mJ with 1W average power at 473nm.

Keywords: VCSEL, semiconductor laser, high power, high efficiency, high brightness, 2D array, external cavity, fiber coupling, DPSS, SHG, green, Q-switch

1. INTRODUCTION

High power high brightness semiconductor lasers are widely used in many industrial, medical, commercial and military fields either serving as the pumping sources for fiber lasers, solid state lasers or amplifiers (DPSS, EDFA, etc), gas laser (e.g. DPAL), or working as direct-diode light sources for material processing, imaging, printing, data storage, heating, and optical communication applications[1-7]. Depending on the specific application, the required output power and brightness levels are quite broad, ranging from below 1W to several kilo-watts in the near infra-red wavelength range, corresponding to a large range of brightness from several kW/cm^2*sr to GW/cm^2*sr. For example, in reference [3], relatively low brightness 808nm pump module with 31.6W output from a 400μm/0.22NA fiber (brightness of only 165kW/cm^2*sr) was used to end-pump an Nd:YAG rod laser. For fiber laser pumps or direct diode module in the material processing area (range from surface cleaning and treatment to marking, cutting, and welding), tens to kilo-watts of output are typically required out of 100um/0.1 NA, corresponding to very high brightness of MW/cm^2*sr to GW/cm^2*sr[8-10].

The high brightness semiconductor laser field is currently dominated by the edge-emitting laser technology. In the case of pumping the fiber-lasers, several 9xx nm high brightness edge-emitter-based pump chips are required, each individually collimated and aligned[2, 8] while the beam is highly asymmetric. In particular, edge-emitter technology is not suitable for 2D array fabrication and subsequent integration with other components such as 2D lens-array. While the general trend for the laser system is smaller size, higher efficiency, longer lifetime and lower cost, vertical cavity surface emitting laser (VCSEL) is very effective in meeting those goals due to its intrinsic advantageous properties in low cost manufacturing[11], high scalability to high power[12] and high reliability[13]. Some well-known advantages of VCSELs include wafer level fabrication, test and burn in, large 2D arrays fabrication[12], narrow spectrum with high thermal stability (0.065nm/C for VCSEL vs 0.3nm/C for edge emitter), immune to COMD that dominates edge emitters' failures[14], and operation at high temperatures[15]. Its circularly symmetric surface emission feature provides additional benefits of easy packaging, simple beam-shaping optics and amenable system integration. It was shown [12, 16, 17] 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. Currently VCSELs's power conversion efficiency (PCE) are ~50% at 808nm and >60% at 976nm and 1064nm[18]. Using such high performance VCSELs as building blocks, 100s to 1000s-Watts of VCSEL arrays have been constructed[18]. Those VCSEL based pumps had been successfully used for DPSS to generate Q-switched high energy pulses with high average power[19-22]. With such approach, more than

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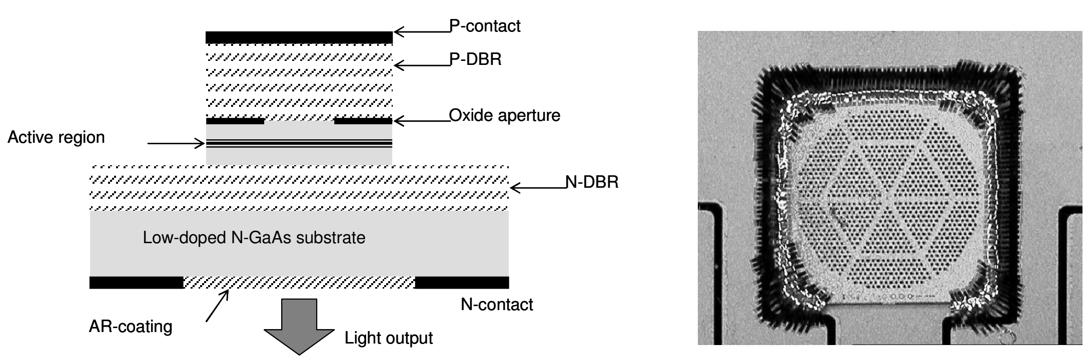
40W of power at 976nm from a 400μm/0.46NA fiber was also reported[12]; corresponding to a brightness of 48kW/cm2.sr. But it's not bright enough for applications such as fiber laser or nonlinear wavelength conversion.

To increase the VCSEL's brightness, external cavity configurations (EC-VCSEL) can be constructed to improve the beam quality[23]. In this approach, the VCSEL chip only has partial distributed bragg mirror (DBR) on one side, therefore it does not lase by itself. A flat or curved mirror is placed at some distance away (such as a few mili-meter) to boost the overall mirror reflectivity and control its mode profile. More than 10W single TEM00 mode was realized with large aperture 500um optically pumped EC-VCSELs[24]. In addition, EC-VCSEL's intra-cavity field intensity is much higher than that of outside, making it ideal for second harmonic generation (SHG) to generate high power, and high brightness lasers of visible wavelength[25-28]. EC-VCSEL can be optically pumped[29]or electrically pumped[30, 31]devices. Because the electrical pumping method is intrinsically more efficient, less complex, and scalable to 2D arrays, we focused on the development of electrically pumped EC-VCSELs. Previously, we have demonstrated single VCSEL device with 63.4% efficiency at 300mW output, and array with 56.4% efficiency at 150W output[18]. We have also reported high performance EC-VCSELs with >1W output and 86.7MW/cm^2*sr[32] in brightness. In this paper, we present our recent progress in high brightness VCSEL development. Over 2.1W single mode (M2~1.1) output under CW operation was achieved with a 325um large aperture devices, at either 976nm or 1064nm, corresponding to a brightness value of 157MW/cm^2*sr. We first review our high power self-lasing VCSELs, followed by the high brightness electrically pumped EC-VCSELs. We then discuss some of the applications using such high power, high brightness VCSELs.

2. REVIEW OF SELF-LASING VCSELS

For our self-lasing VCSELs between 780nm and 1.1um, the epitaxy materials are grown on n type GaAs substrate using MOCVD. Both p and n type distributed bragg reflectors (DBRs) are made of either C or Si doped AlGaAs layers. Quantum wells are made of strained InGaAs, InAlGaAs or AlGaAs materials targeting different wavelengths. The VCSELs can be designed for "top emission" (through the epi/air interface) for 8xx nm or "bottom emission" (through the transparent substrate) for longer wavelength such as 976nm and 1064nm. Such "junction-down" soldering is also beneficial for more efficient heat-removal. A representative bottom emitting VCSEL structure is shown in Figure 1(a). Fabrications for both top-emitting and bottom-emitting 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 that deep enough to expose the Aluminum-rich oxidation layer. The samples are then exposed to high humidity in a furnace (~400^{o}C) for the selective oxidation process[33] to form electrical and optical confinement[34 - 37]. On the substrate side, it is thinned to less than 150um thick 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. To achieve high-power operation with VCSELs, 2D arrays of single devices operating in parallel can be fabricated. 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. The finished arrays can be linear (one dimensional), triangular, rectangular, square, or any custom designed shape, which is defined by photolithography.



(a) (b)

Figure 1. (a) Schematic of bottom emitting VCSEL structure; (b) packaged 5mm VCSEL array on diamond submount.

Furthermore, the position of each individual element inside the 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 fabricated. After processing, devices are tested at wafer level to check the performance before being singulated and packaged on heat-spreading submounts such as AlN (or BeO) for low cost, low power, or diamond for high power applications. Details of the device design and fabrication can be found in References [12, 16, 18]. A packaged 5mm VCSEL array chip on diamond submount is shown in Figure 1(b).

Previously we showed 63.4% record PCE from a 976nm VCSEL with 80um aperture diameter. Such performance is scalable to larger devices. Figure 2 shows the CW LI-PCE curves of a 225um high power VCSEL at 976nm that operates under room temperature. The device peak PCE is 60% with 3.5W output. The peak power exceeds 5.5W with high PCE of 55%. Similar performance is found for 1064nm VCSELs that can utilize the same bottom emitting design. At shorter wavelength, e.g. 8xxnm, it needs to be top emitting structure due to strong substrate absorption, resulting in much smaller device diameter and output power. Our 808nm single device has close to 50% peak PCE with output of ~ 6mW, as shown in Reference [16, 18].

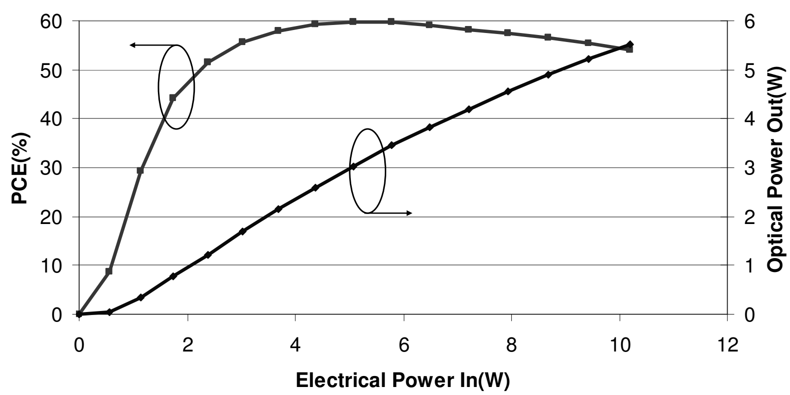


Figure 2. CW power-PCE curves for a 976nm VCSEL device with 225um diameter oxide aperture, showing peak PCE of 60% with 3.5W output at room temperature. Peak power exceeds 5.5W.

2D high power VCSEL arrays were fabricated from wafers with the same design as the single devices. For many applications such as pumping the Q-switched solid state YAG lasers, it only needs the pumps to operate under long pulse condition, or QCW. Figure3 shows the LI-PCE curves under QCW condition of 100us pulse duration and 100Hz repetition rate for 5x5mm high power VCSEL arrays at 976nm and 808nm respectively. At 976nm, while the PCE peaks at 54%, it still exceeds 50% at 450W output. At 808nm, the PCE peaks at 46% and stays above 40% with over 100W output. Other than superior single device performance, low-stress, void-free packaging approach for such large high power arrays is also critical.

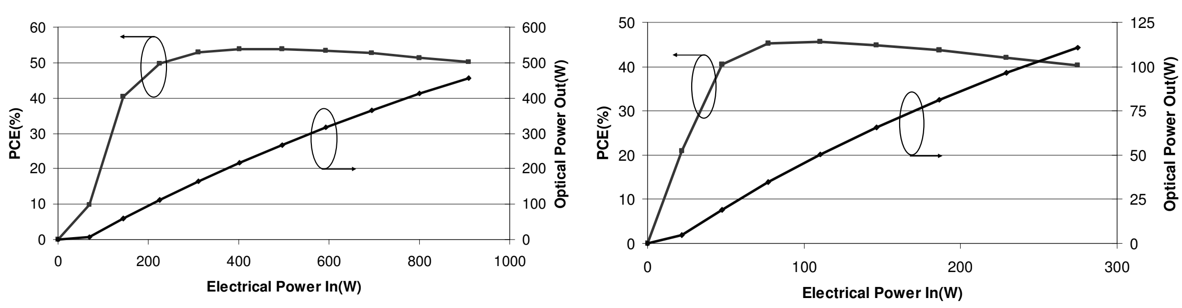


Figure 3. LI-PCE curves for (a) 5x5mm 976nm; (b) 5x5mm 808nm VCSEL arrays under QCW (100us/100 Hz)

Although those arrays have very high power, their brightness remains below 50kW/cm^2*sr. Nevertheless, as shown in section 4, they can be used for end-pumping or side-pumping many solid state lasers. As shown in Reference [32], the brightness of incoherent array cannot exceed the brightness of its individual element. For applications demanding very high brightness, we can improve the brightness of single device, e.g., achieve high power single mode operation, by the means of external cavity.

3. HIGH BRIGHTNESS EXTERNAL CAVITY VCSELS

Many applications require very high brightness (such as many MW/cm^2*sr) laser source. For VCSEL, an external cavity setup can be used to improve its single fundamental mode output, therefore the brightness. Such device structure is schematically shown in Figure 4. In this approach, the VCSEL chip is very similar to a normal self-lasing device, but has only partial DBR on the output side (OC-DBR); therefore its reflectivity is not high enough to lase by itself. It has to rely on the external output coupler (OC) that placed some distance away from the chip to provide additional reflection in order to reach lasing threshold. At the same time, fundamental mode can be selected due to diffraction loss and spatial filtering. By properly adjusting the OC distance, reflectivity and curvature, single mode lasing can be realized for even very large devices, resulting in very high power and high brightness. Because of device self-heating, there is thermal lens formed inside the chip that can help stabilizing the mode even if a flat OC is used. Obviously such flat OC approach is very desirable for large 2D external cavity VCSEL arrays. With high OC reflectivity, the intra-cavity field intensity can be much higher than that of outside, allowing efficient intra-cavity nonlinear frequency conversion. In addition, it can easily integrate with other nonlinear components to generate high energy short pulse (such as Q-switch or mode-locked lasers)[38].

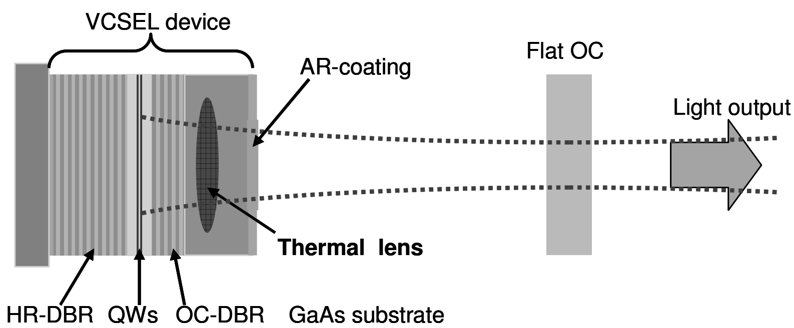


Figure 4. Schematics of an EC-VCSEL structure

For such EC-VCSELs, the performance are highly dependent on the output coupler (OC) being used because it's part of the laser resonator. We can treat the laser resonator as a coupled cavity of OC and VCSEL chip. The composite reflectivity R_tot on the output side at resonant wavelength can be shown[39] to be

$$R_{tot} := \left(\sqrt{R_{dbr}} + \frac{T_{dbr} \cdot \sqrt{R_{OC}}}{1 + \sqrt{R_{dbr} \cdot R_{OC}}} \right)^2$$

where R_OC is the OC's reflectivity, R_dbr and T_dbr are the OC-DBR's reflectivity and transmission respectively. To optimize the device performance, the OC-DBR, substrate, and OC property must be carefully considered. As the OC reflectivity is reduced, both the laser threshold and the slope efficiency will increase. To some extent, the power conversion efficiency will also increase at the same time. With more gain introduced to the structure, we are able to push OC reflectivity very low, such as <60%. Figure 5 shows the PCE vs injected current for our EC-VCSELs measured with different OC. It shows that OC reflectivity of 56% provides the best performance.

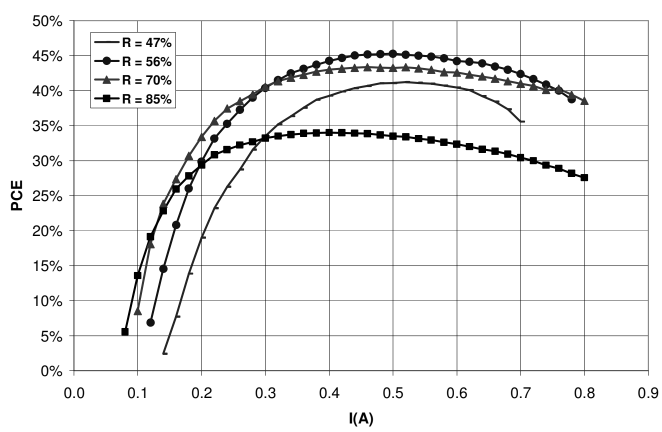


Figure 5. Output coupler (OC)'s impact on EC-VCSEL's PCE

We use electrical pumping for our EC-VCSEL approach for many reasons, including high efficiency and low cost, easy scalability, etc. Basic device structure is very similar to the self-lasing ones described in previous section. One issue with conventional large aperture oxide VCSEL is the current crowding effect, as shown in Figure 6 of the simulated vertical current distribution profiles with finite element method (FEM). It's a 200um diameter device (only showing half of the geometry due to circular symmetry). As expected, the current density is relatively flat and trend up significantly toward the apertures edge. While this does not affect much on the multi-mode performance because whatever mode reaches the lasing threshold will lase, it is not desired for high brightness VCSEL operation for two main reasons: 1st, it does not overlap well with the fundamental optical mode profile with a Gaussian-like distribution, which reduces the effectiveness of gain utilization. 2nd, single fundamental mode lasers with such current and gain profile will suffer strongly from the spatial-hole-burning (GSHB) impact, therefore limiting its high brightness operation. In addition, the joule heating related thermal distribution will follow such current profile as well, resulting in very un-desired thermal lensing and heating effect, which would be detrimental to the single mode stability and device reliability. Generally speaking, such current crowding effect is related to the lateral spreading of electrical currents, and can be relieved or improved by several means, such as introducing 'disk contact' into the device structure[ref], modifying the DBR layers' resistivity profile, or adjusting the oxidation layers thickness and location, etc. New current distributions from an improved structure with above mentioned adjustment is also shown in Figure 6. Carrier diffusion process inside the active layers is neglected here, but we believe such analysis is sufficient for the purpose of seeking design guidance. For comparison, the current profiles for both old and new structures are shown together. Obviously, the new design represents a dramatic improvement over the conventional one for which we believe should benefit the EC-VCSEL's high brightness performance.

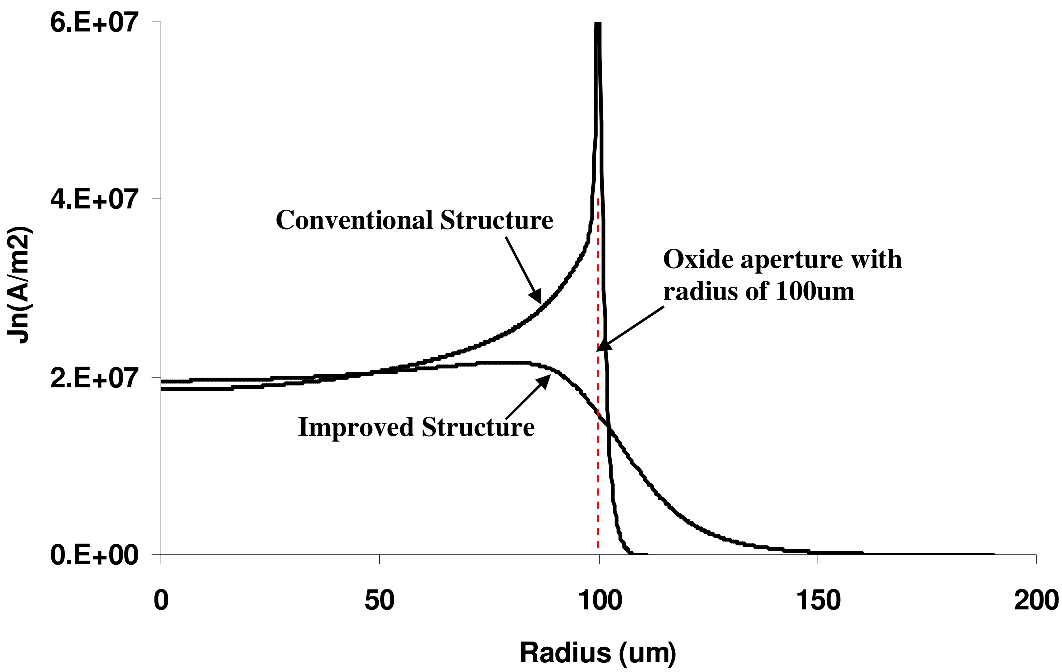


Figure 6 Simulated vertical current density profiles for 200um oxide apertures VCSEL with conventional and improved structures

Actual device performance, especially the beam quality, is also highly impacted by the chip packaging. For large aperture ECVSEL or 2D arrays under single mode operation, any cavity aberration or thermal hot spot would degrade the brightness. Therefore a low stress, flat, and void free soldering process has been developed to meet such requirement. Figure 7 shows the power and PCE curves of a 976nm EC-VCSEL with 80um oxide aperture diameter. The flat OC's reflectivity is 56%, as optimized in Figure 5. For comparison, both single mode and multi-mode performance are shown. Initially the OC was placed very close to the chip, such as <1mm. As expected it lase multi-mode with higher peak PCE of ~55%, which is quite close to the estimated self-lasing device's PCE of >63%.When the OC is moved away from the device, such as ~1.5mm from the AR coated chip surface, it lase single TEM00 mode with measured M^2 of ~1.2, peak PCE of ~37% and peak power of ~280mW. This corresponds to a brightness of ~17MW/cm^2*sr, representing a significant improvement from the multimode devices shown in Figure 2 and Figure 3. Single mode efficiency should be improved with further optimization on the EC-VCSEL design, including gain, DBR, OC and current profiles.

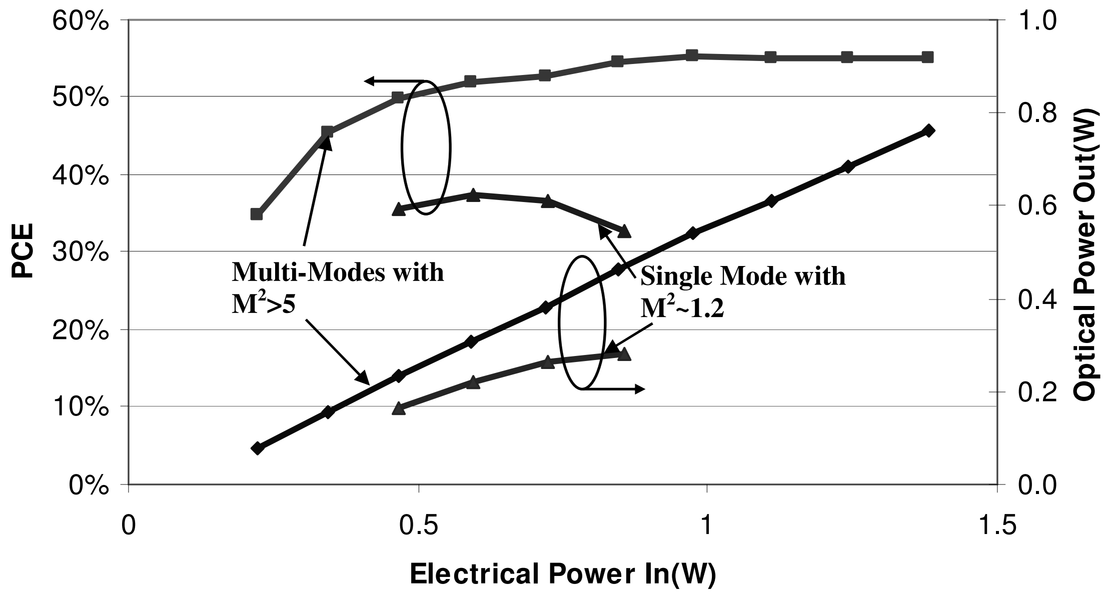


Figure 7. CW power-PCE curves for 80um EC-VCSELs operating under multi-mode and single mode conditions

For larger device, we observed much higher single mode power while the beam quality still remains excellent in a large operating range. Figure 8 shows the CW output and brightness curves for a 325um aperture diameter EC-VCSEL. It shows single mode (M^2~1.1) operation with peak power of ~ 2.1W, corresponds to a brightness of 157MW/cm^2*sr, both of which are record values for electrically pumped VCSELs. Because of the flat OC being used, performance from single EC-VCSELs can be easily scaled up to high power large 2D EC-VCSEL arrays. We have achieved over 200W single mode output from 5x5mm EC-VCSEL array.

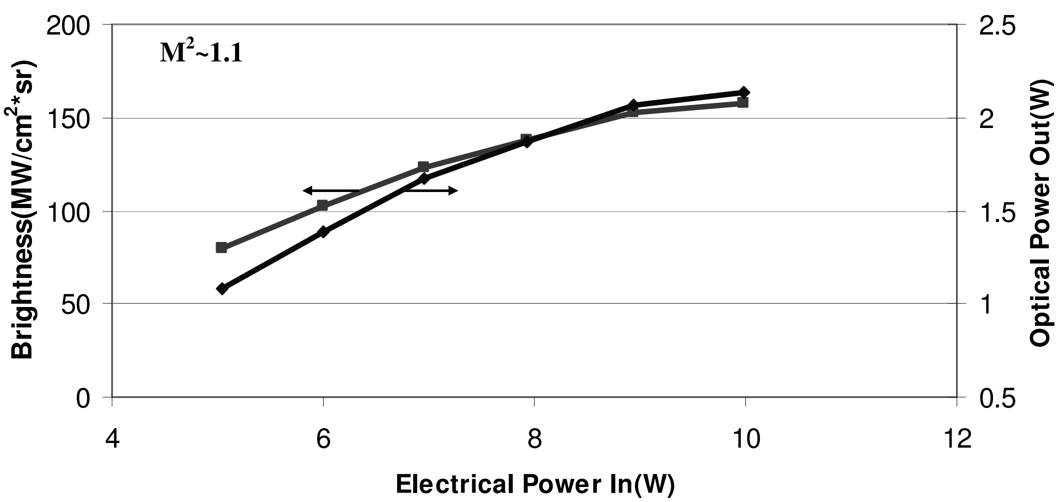


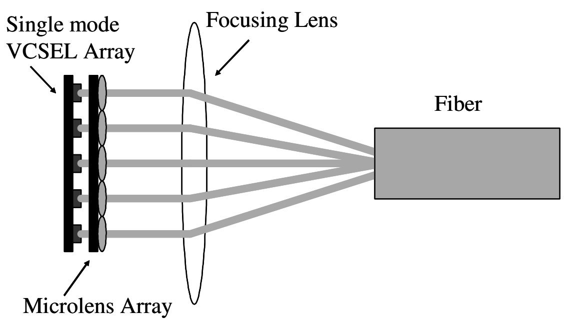
Figure 8. CW power & brightness for large EC-VCSEL with 325um aperture diameter and flat OC.

4. HIGH BRIGHTNESS VCSEL-BASED APPLICATIONS

High power VCSELs represent an attractive alternative to edge emitters for some of the pumping or direct-diode applications due to its intrinsic lower cost, higher reliability, narrower and morethermally stable spectrum, less complicated beam shaping optics and easier system integrations. In addition, the electrically pumped EC-VCSELs are also quite advantageous in applications involving 2nd harmonic wavelength conversion and high energy pulse generation with Q-switched laser, as discussed below.

4.1 High brightness fiber output

Figure 9(a) shows the high power fiber coupling setup using our high brightness 2D EC-VCSEL arrays. A large flat OC whose parameters are decided from single devices characterization is used to enable single TEM00 mode emission out of each emitter. An AR-coated microlens array is placed in front of the VCSEL array to collimate beams from each individual element and effectively fill the whole emission area. By this, the array brightness is conserved from the single emitter's brightness, which was discussed in section 3. After that, the light is being focused by a matching focusing lens before being collected by the fiber (or a solid state rod such as YAG for DPSS applications). Because the device aperture is relatively small (less than 100um), cavity length is very short (in the 1mm range). This makes the whole design very compact. Figure 9(b) shows such compact pump module, with size of 2.5x3x1.5 inch. 100W out of 100um/0.22NA fiber has been demonstrated for this setup.



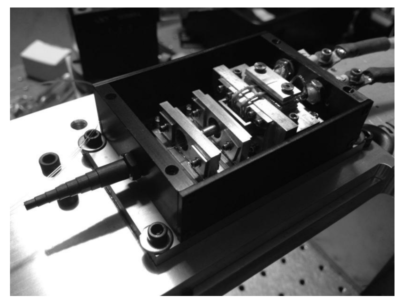
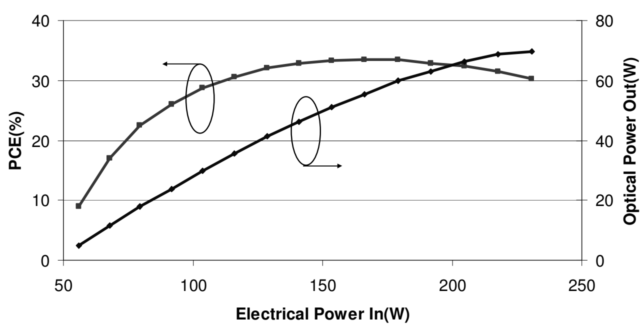


Figure 9. (a) Schematic of high brightness 2D VCSEL array coupled into fiber; (b) Actual fiber pump module with

We have fabricated 4x4mm 2D EC-VCSEL array with 60um aperture diameter and pitch of 200um. The CW output of the array under single mode operating condition is 70W, with peak conversion efficiency of ~34%. We could not directly measure the beam quality of such large high power array, but results from the single devices fabricated on the same wafer show that the M^2 is <1.5. The microlens array used in this setup has the same pitch of 60um and focal length of ~5.4mm. There are several factors limiting the fiber coupling results for this array: 1st is that the chip bowed much larger than expected, at ~ 1m in radius; 2nd is that the micro-lens used was originally designed for devices of 100um or larger, its NA does not match the VCSEL array's divergence. Those factors contribute to the less than expected fiber coupled output of close to 40W, corresponding to peak coupling efficiency of ~50%.



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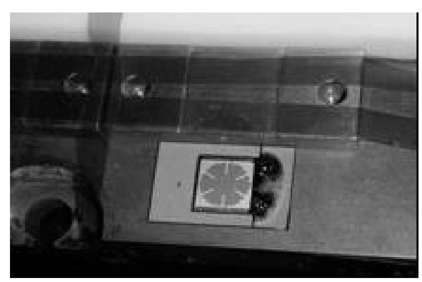


(b)

Figure 10. (a) Single mode output of 4mm array before the microlens; (b) Photograph of the 4mm array mounted on diamond submount.

4.2 High power visible laser from 2nd harmonic generation

There are strong needs for high power visible lasers (especially green laser at 532nm) for display and projection applications. Typically green laser can be obtained from: 1.direct laser diode using InGaN/GaN material; 2. 2nd harmonic generation (SHG) from 1064nm solid state laser (Nd:YAG) that pumped by 808nm diode laser; 3.SHG from 1064nm InGaAs/GaAs based semiconductor laser. Among them, the last approach using 1064nm semiconductor laser is very attractive due to its combined advantages in performance, cost, complexity and reliability. Because SHG efficiency is directly proportional to the square of field intensity, intra-cavity SHG using EC-VCSEL setup is very beneficial to improve the green laser performance. Previously we reported green laser results based on our electrically pumped EC-VCSEL with record performance of 4.7W and 18.3% PCE[40]. Compared with optical pumping, electrically pumped devices provide higher efficiency, less complexity, and lower cost. In addition, it's easier to design and fabricate 2D electrically pumped VCSEL arrays in order to scale up the power, as discussed previously.

The green laser setup using electrically pumped EC-VCSEL is shown in Figure 11. We chose MgO: PPLN crystal as the optical frequency converter. The crystal is 1mm thick, 7 mm long with a periodically poling period of 6.94 µm. The output surface of the crystal is high-reflection (HR) coated for IR and AR coated for green, while the other surface is AR coated for IR and HR coated for green. A Brewster plate is also used to stabilize the polarization of VECSEL and ensure that the polarization direction of IR beam is parallel to electric poling direction of MgO: PPLN crystal. In addition, a wavelength selective etalon is inserted into the cavity such that the IR bandwidth is reduced to around 0.2 nm which is narrower than the acceptance bandwidth of the 7 mm MgO: PPLN crystal. A plano-convex lens (focal length ~ 15 mm) is placed between the VCSEL chip and PPLN. Because of flat surface, beam waists reside on both the VCSEL chip and output surface of nonlinear crystal, with the one on chip restricted by the size of active region. By changing the position of lens between two end-mirrors of laser cavity, we can vary the beam sizes ratio of those two beam waists and actively control the actual beam size on the nonlinear optical crystal. Therefore, the IR power density could be controlled accordingly.

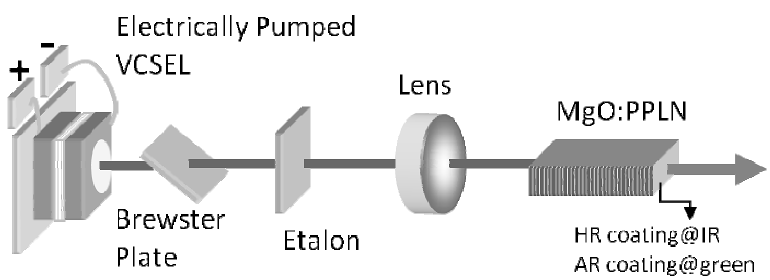
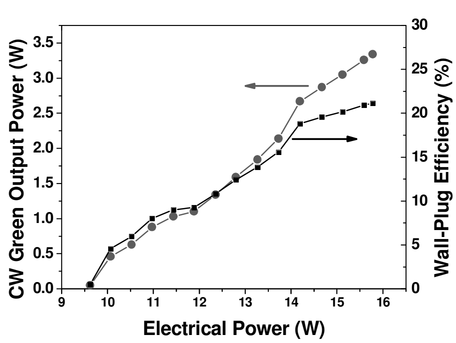
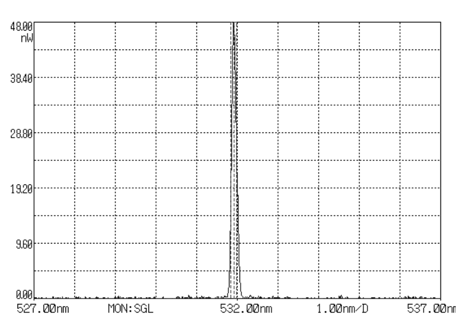


Figure 11. Green laser setup using 1064nm electrically pumped EC-VCSEL for 2nd harmonic generation.

1064nm EC-VCSELs with 440um aperture diameter was fabricated, packaged and assembled into the green laser setup. Such large laser aperture is capable of providing high intra-cavity IR power density, which is critical for improving the SHG efficiency. The measured CW green output power and wall-plug efficiency (WPE) are shown in Figure 12(a). At the input electrical power of 15.78 W, 3.34 W CW green output power is achieved, corresponding to a WPE of 21.2%. To the best of our knowledge, this is the highest value ever achieved to date by using an electrically pumped VCSEL. The center wavelength of the spectrum is at 532 nm, as shown in Figure 12(b). The measured beam quality or M^2 is around 13.



(a)



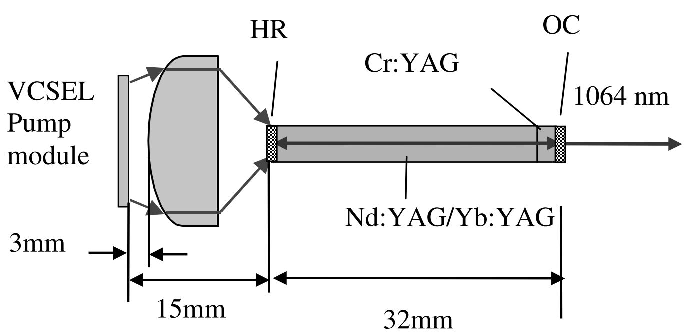
(b)

Figure 12. (a) CW green laser output and wall-plug efficiency; (b) CW spectrum showing 532nm green laser.

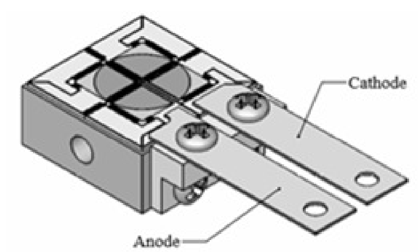
It's worthwhile to point out that, such approach of using electric pumped EC-VCSEL for direct SHG can also be used to generate other visible wavelength, such as high power blue and red lasers.

4.3 High energy pulse generation from Q-switched DPSS

High power high brightness VCSEL arrays at 808nm can be used for either end-pumping or side-pump solid state lasers. Compared with edge-emitter pumps, VCSELs have much simpler coupling optics, narrower and thermally more stable spectrum, lower cost and higher reliability. Figure 13(a) shows the setup of a monolithic Q-switched 1064nm laser end-pumped by 808nm VCSEL array. The monolithic Nd:YAG (for gain) and Cr:YAG (for Q-switch) rod was HR coated at 1064 nm but HT coated at the 808 nm pumping wavelength on the entrance side (Nd:YAG side). The exit Cr:YAG side of the crystal was coated with 50% reflection at 1064 nm therefore forming a plano output coupler. Stable laser operation results from the weak thermal lens formed in the crystal. The 808 nm VCSEL pump module is shown in Figure 13 (b). It has 4 closely spaced VCSEL arrays that together form a 9mm circular emitting area. Each array is mounted on diamond submount that mounted on a Cu heat-sink cooled by forced-air. It's capable of 800 W QCW output under the condition of 250 us pulse duration and 20 Hz repetition rate. Pumping light is focused into the 4.5 mm in diameter, 32 mm long, conductively cooled Nd:YAG and Cr:YAG rod with 10.5 mm focal length aspherical pump lens.



(a)



(b)

Figure 13. Schematic of monolithic Q-switched laser using high power 808nm VCSELs for end pumping

Figure 14 shows the Q-switched laser pulse energy and optical-to-optical conversion efficiency when both the VCSEL and YAG were not actively cooled i.e. no TEC or fan being used. The laser pulse length was measured to be 5.8ns while operated at 10 Hz. The pump power varied from 506 W to 884 W. As the pump power is reduced, it takes longer for the Q-switch to start and therefore the pump pulse duration needs to be increased. Higher losses from increased fluorescence before Q-switching lead to lower pulse energy and conversion efficiency. It is 16.1mJ at 884 W pumping and 11.5mJ at 506 W pumping.

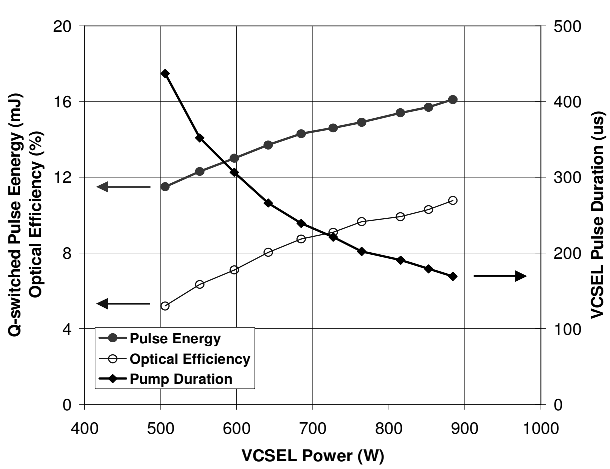
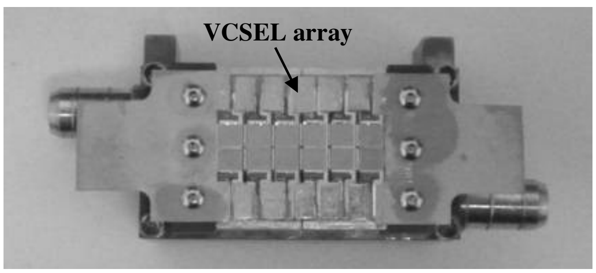
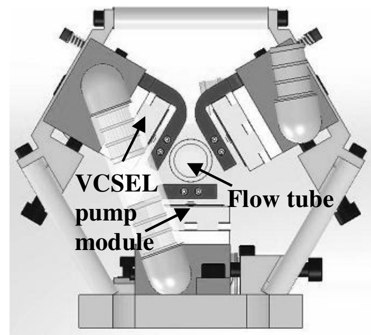


Figure 14. Q-switched pulse energy and optical to optical efficiency as a function of VCSEL pump power

High power VCSELs can also be used to generate high energy high power Q-switched blue lasers[19]. Figure 15(a) shows an 808 nm VCSEL pump module designed for side pumping an Nd:YAG laser. The module comprises twelve 3 mm VCSEL arrays arranged in a 6 x 2 layout for efficient pumping of a 20 mm long gain medium. A water cooled VCSEL side-pumped laser gain module was constructed by mounting 3 high power VCSEL pump modules at 120 degree angles with respect to each other in a rigid hexagonal structure containing a flow tube for the gain medium as shown in Fig. 15(b). A circular 2 mm or 3 mm diameter 30 mm long YAG rod with a 20 mm long Nd doped gain section was mounted in the 188 mm long flow tube. The gain medium was symmetrically side-pumped by three VCSEL pump modules operating at 200 A, corresponding to 3 kW total incident pump power. The output of each VCSEL pump module was focused onto the Nd:YAG rod by a 8 mm diameter half rod cylindrical lens. The actively Q-switched 946 nm output of the laser cavity was subsequently frequency doubled to 473 nm in an 8 mm long BBO crystal. Pulsed width at FWHM was measured at 27ns. Record blue laser performance with 4.9mJ pulse energy and >1W average power at 210Hz has been demonstrated. Details of the laser setup and performance can be found in Reference [41]. Such lasers are extensively used for optical communication field such as long range underwater detection and imaging.

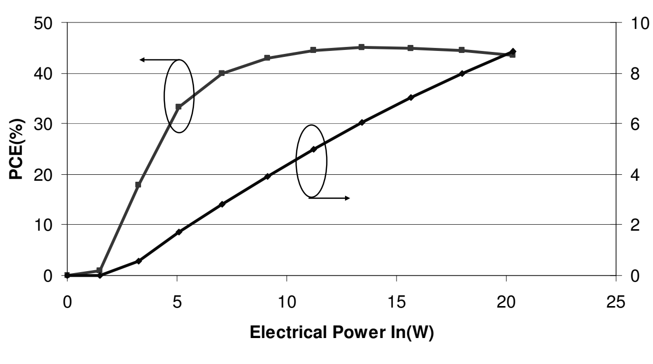




(a) (b)

Figure 15. : (a) Photograph of a VCSEL pump module comprising twelve 3 mm VCSEL arrays in a 6 x 2 layout, and (b) end-view of the flow tube in a hexagonal structure holding 3 VCSEL pump modules.

We also developed 885nm VCSELs for DPSS applications. Because of the smaller quantum defect at this wavelength, higher solid state laser efficiency can be expected. Due to the very narrow absorption bandwidth at this wavelength, high power VCSELs with very narrow and thermally stable spectrum is best suited for such applications. Figure 16 shows the QCW (100us pulse width, 1% duty cycle) power and PCE curves for 2x2mm VCSEL array lasing at 885nm.



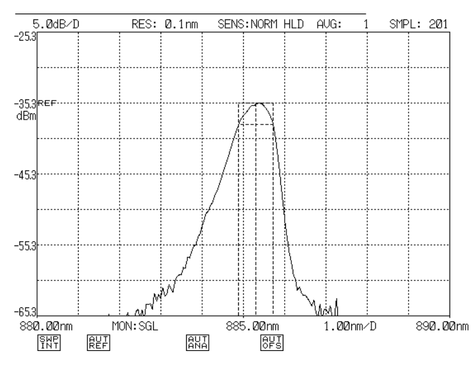


Figure 16. QCW (100us pulse width, 1% duty cycle) performance for 2x2mm 885nm VCSEL array: (a) power and PCE; (b) spectrum

5. CONCLUSIONS

We demonstrated record performance for GaAs-based, high-power high-brightness VCSELs and 2D arrays. At 976nm, over 5.5W peak output and 60% peak power conversion efficiency (PCE) were demonstrated with 225um oxide-confined device. For 5x5mm arrays, peak PCE of 54% & peak power of >450W at 976nm, peak PCE of 46%

& peak power of >110W at 808nm were achieved respectively. For EC-VCSELs, single mode output of 280mW & 37% PCE were realized from 80um device. For large 325um device, we obtained single mode (M^2=1.1) CW output of 2.1W, corresponding to a record brightness of 160MW/cm2*sr. >200W was achieved for 2D external cavity VCSEL arrays. Such high performance VCSELS can be used in three major areas of applications: 1. High brightness fiber output; 2. High power, high efficiency visible lasers via 2nd harmonic generation. 3.34W green laser with 21.2% PCE were achieved; 3. Pumping solid state lasers for high energy pulse generation. We have demonstrated Q-switched pulses with 16.1mJ at 1064nm and 4.9mJ with 1W average power at 473nm.

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