High-power vertical-cavity surface-emitting arrays

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ABSTRACT

We present record output power levels (a few hundred Watts) in continuous-wave (CW) and quasi-CW (QCW) from 2D vertical-cavity surface-emitting laser (VCSEL) arrays, corresponding to power densities exceeding 1kW/cm^2 in CW and 3.5kW/cm^2 in QCW. These VCSEL arrays emit around 975nm with narrow spectral width (<1nm) and excellent wavelength stability (<0.07nm/K). Peak power conversion efficiency of properly designed arrays exceeds 50%. Additional features of these arrays include emission in a circular, low-diverging beam, and reliable high-temperature operation. These arrays can also be operated reliably in short pulses (<200nsec) at many times their roll-over CW current, making them useful for high-energy applications. VCSEL arrays with 2.2kW peak output power operating under 100nsec pulse-width have been demonstrated.

Keywords: Semiconductor lasers, vertical-cavity surface-emitting lasers (VCSELs), high efficiency, high-power, 2D array, pumping, solid-state laser, brightness, reliability, high-energy.

1. INTRODUCTION

Compact and robust high-power semiconductor lasers are needed in a variety of applications, foremost among them the pumping of solid-state and fiber lasers. Currently, the dominant technology is that of edge-emitter semiconductor lasers. However, this technology has several drawbacks such as poor intrinsic beam-profile and spectral properties, and generally low array reliability. In addition, scaling up of the output power requires complex and costly assembly of edge-emitting bars into stacks. The vertical-cavity surface-emitting laser technology (VCSEL) presents an attractive alternative as a high-power semiconductor laser source (several hundred Watts), because it can be easily processed in 2D arrays to scale up the power [1].

We recently demonstrated more than 230W of continuous-wave (CW) output power from a VCSEL 2D array (~0.22cm^2 array area), corresponding to more than 1kW/cm^2 power density. We also demonstrated 100W from quasi-CW (QCW) small arrays (~0.028cm^2 array area), corresponding to more than 3.5kW/cm^2 power density. These CW and QCW power density levels are comparable to that of edge-emitters.

Ironically, VCSELs' rise to fame originated in "low-power" (sub-milliwatt) applications. VCSELs were invented in the mid-80's and quickly gained a reputation as a superior technology for short-reach telecom applications such as fibre-channel, Ethernet and intra-systems links. Then, within the first two years of their commercial availability (mid-90's), VCSELs became the technology of choice for low-power enterprise and datacom applications, effectively displacing edge-emitters. This success was mainly due to the VCSEL's lower manufacturing costs and higher reliability compared to edge-emitters [2,3].

This paper will first review the VCSEL technology, and then present our main results on high-power, high-efficiency 2D VCSEL arrays. Finally, results and applications for high-brightness and high-energy (mJ-level) VCSEL arrays will be presented.

2. VCSEL TECHNOLOGY

VCSEL fabrication is similar to the well-established silicon integrated-circuit (IC) planar processing, resulting in a low-cost technology [4]. In the case of a VCSEL, the mirrors and active region are sequentially stacked along the epitaxial growth direction (Fig. 1). The mirrors are distributed Bragg reflectors (DBR) formed of alternating high and low

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refractive index quarter-wavelength layers. As a result, the light oscillates perpendicular to the layers and escapes through the top (or bottom) of the device in a circular, low-diverging beam.

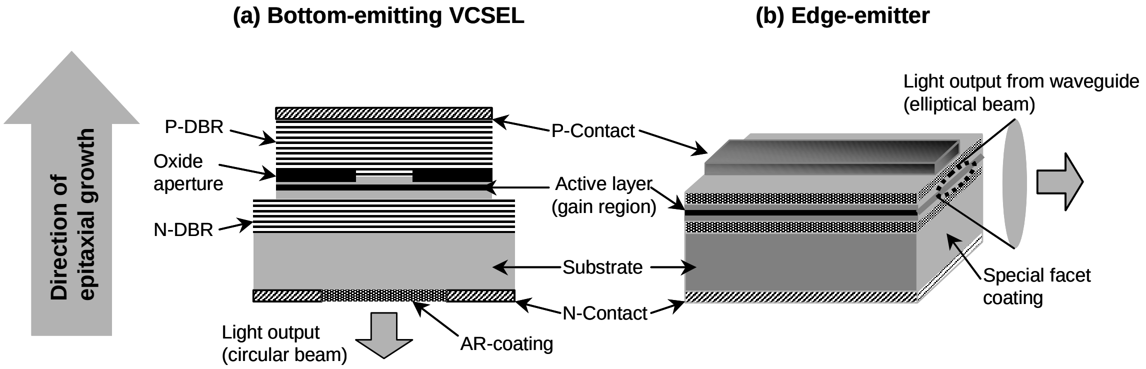

Fig. 1. (a) Schematic of the selectively oxidized, bottom-emitting 976nm semiconductor VCSEL structure, and (b) comparison to an edge-emitter lasser.

The VCSEL wafer then goes through etching and metallization steps to form the electrical contacts. Current and/or optical confinement is typically achieved through either selective-oxidation of an aluminum-rich layer, ion-implantation, or even both for certain applications. The selective oxidation process [5] has improved VCSEL performance dramatically[6], with devices achieving over 50% power conversion efficiencies (PCE) [7]. The VCSELs can be designed for "top-emission" (at the epitaxial/air interface) or "bottom-emission" (through the transparent substrate) in cases where "junction-down" soldering is required for more efficient heat-sinking, for example [8]. After processing, the wafer goes to test where individual chips are characterized on a pass-fail basis. Finally, the wafer is diced and the chips are binned for either higher-level assembly (very high yield, typically >95%) or scrap. The wafer can be diced into single-devices or arrays of single-devices effectively connected in parallel. The arrays can be linear (1D), rectangular or square (2D). Furthermore, since the position of the individual elements in a VCSEL array is defined by photolithography, this permits arbitrary design layouts of the elements with placement accuracy at the micron level. Depending on the application, VCSEL 2D arrays can contain from a few hundred to several thousands of single devices (Fig. 2). Since VCSELs are grown, processed and tested while still in the wafer form, there is significant economy of scale resulting from the ability to conduct parallel device processing, whereby equipment utilization and yields are maximized and set-up times and labor content are minimized.

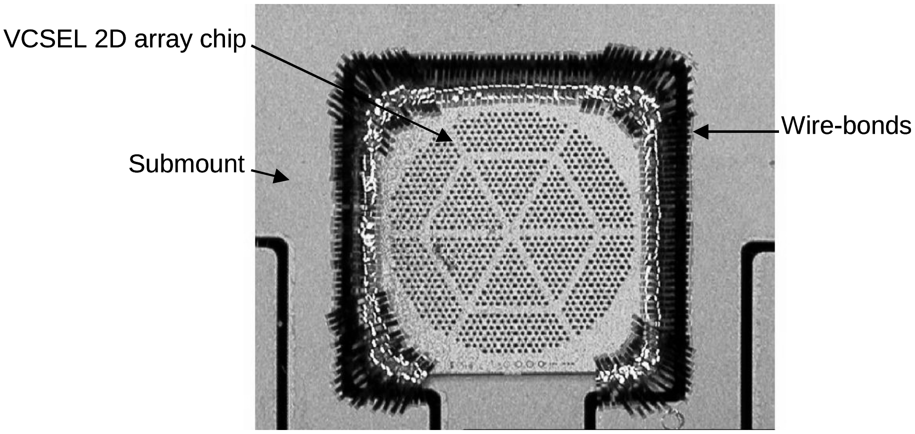

Fig. 2. Schematic of a packaged 2D VCSEL array with a few hundred single-emitter driven in parallel. The chip is approximately 5mm x 5mm.

Since the VCSEL resonant cavity is defined by a wavelength-thick cavity sandwiched between two distributed Bragg reflectors (DBRs), devices emit in a single longitudinal mode and the emission wavelength is inherently stable (~0.065nm/K), without the need for additional wavelength stabilization schemes or external optics, as is the case for edge-emitters. Furthermore, thanks to advances in growth and packaging technologies, the emission wavelength is very uniform across large VCSEL 2D arrays, resulting in spectral widths of ~0.8nm. This wavelength stability and narrow spectral width is useful in pumping applications, for example, where the medium has a narrow absorption band.

One of the main applications of semiconductor high-power lasers includes the pumping of solid-state lasers. It is well known that the degradation of these edge-emitting lasers is dominated by catastrophic optical damage (COD) at the emission facet [9]. The COD is due to the high optical power density produced at the surface of the edge-emitter. Vertical-cavity surface-emitting lasers (VCSELs) on the other hand are not subject to COD, since the gain region is embedded in the epitaxial structure (Fig. 1) and it 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 [10] depending on the operating power, whereas for VCSELs the FIT rate is on the order of 10 or less [11,12]. This advantage provides at least a 50 times longer useful life for a system using VCSEL pumps. This also means that VCSELs can be operated very reliably at high temperatures. We have operated a large number of VCSELs at 80^{o}C for extended periods of time and found no degradation. Others have operated VCSELs at much higher temperatures [13]. This advantage is significant because the requirements for refrigeration are much less for VCSELs, resulting in a more compact laser system with overall higher efficiency.

3. HIGH-POWER, HIGH-EFFICIENCY VCSEL ARRAYS

Processing of 2D VCSEL arrays is similar to that of single devices. There are a few more processing steps such as Plating of the n- and p-contacts for uniform current distribution within the array. We found that our selective oxidation process was extremely uniform within an array and from array to array within the same sample. Thus, we believe the selective oxidation process is well suited for VCSEL arrays even larger than 5mm x 5mm and for the production of these arrays.

These arrays are tested at the wafer level (before cleaving and separation) to check for performance and excessive "dead pixels" for example. After cleaving and sorting, individual arrays are soldered onto metallized high-thermal-conductivity submounts such as diamond or BeO. For packaging on diamond submount, the plating thickness is optimized and an appropriate solder is chosen to account for the CTE mismatch with GaAs. Then, the chip-on-submount can be packaged onto a micro-channel cooler to increase the heat removal capacity, especially for CW operation.

For properly designed arrays, there is little drop in PCE from the single device results. Figure 3 shows a ~5mm x 5mm VCSEL array chip fully packaged on a micro-channel-cooler and the LIV characteristics of a high-efficiency array. This array achieves a maximum PCE of 51% (similar to a single device) at a CW output power of 13W.

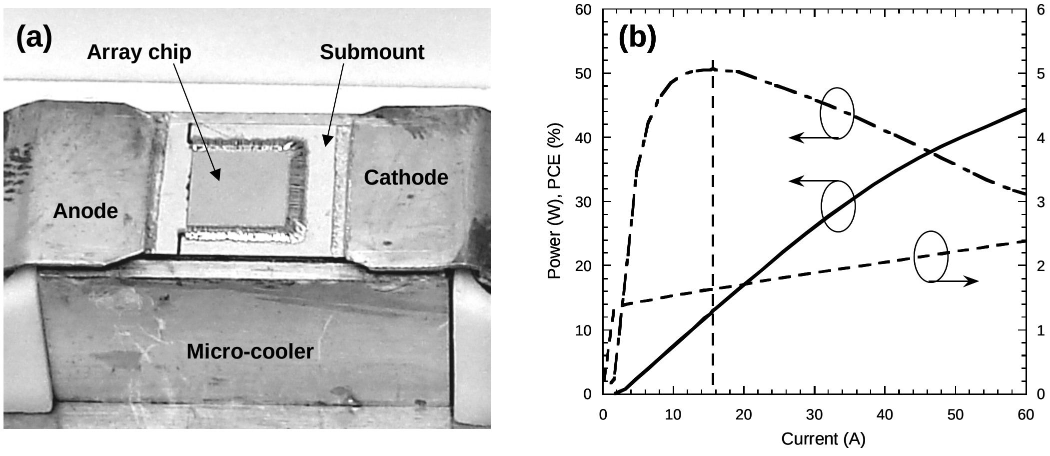

Fig. 3. (a) Picture of a fully packaged 2D VCSEL array on micro-cooler and (b) CW LIV characteristics. This array achieves a maximum PCE of 51% for an output power of 13W at 16A.

For higher power and power density, arrays with more closely spaced elements were fabricated for CW and QCW operation. The results are shown in Figure 4. The CW array has an emission area of ~0.22cm^2 and was operated under constant heat-sink temperature (15^{o}C). A record 231W output power was reached at a 320A drive current, limited by thermal roll-over, corresponding to a power density of 1kW/cm^2. This array has a peak conversion efficiency >44%. The QCW chip is smaller (0.028cm^2 area) and was designed to operate in the 100~125A window. The chip-on-submount was not packaged on a micro-channel-cooler. Instead, it was tested directly on a TEC-controlled stage maintained at 20^{o}C. A QCW power of 100W is achieved at 125A, corresponding to a record 3.5kW/cm^2 power density.

The wavelength spectrum and intensity far-field profile were measured at 100A for the 230W array and the results are shown in Figure 5. The far-field beam is circular, with a quasi-top-hat profile. The 1/e^2 full-width divergence angle is 17^o. Since such beam characteristics can be achieved without any optics, VCSEL arrays present a cost-effective solution for end-pumping applications. The spectral full-width half-maximum (FWHM) is only 0.8nm, about five times less than the spectral width of edge-emitter bars or stacks (typically in the 3 to 5nm range). We also measured the wavelength shift as a function of the heat-sink temperature to be 0.065nm/K, identical to the value for single devices. This value is five times less than that of edge-emitters (typically 0.33nm/K). Therefore, similarly to single-devices, high-power VCSEL arrays benefit from an intrinsic narrow spectrum and stable emission wavelength. This is useful for many pumping applications where the medium has a narrow absorption band.

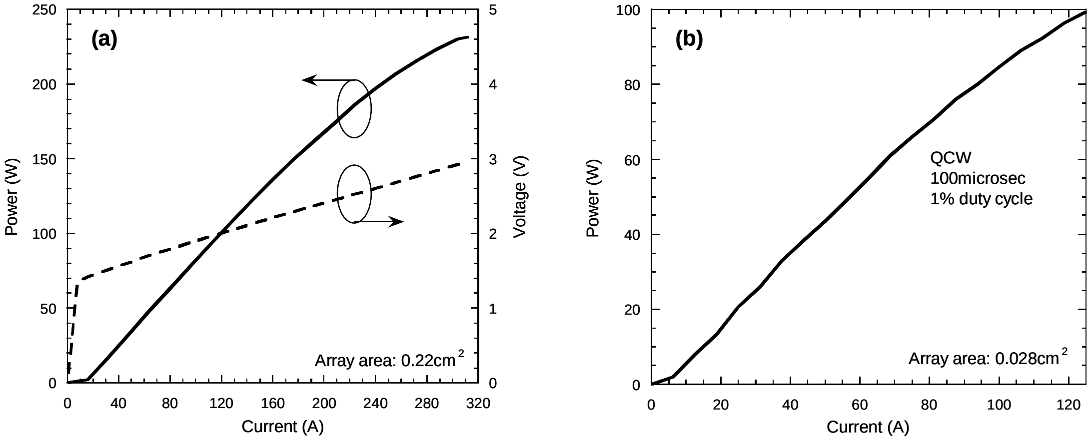

Fig. 4. (a) High-power VCSEL array achieving 231W of CW output power at 320A. (b) High-power density QCW VCSEL array. At 125A, the output power is 100W, corresponding to a 3.5kW/cm^2 power density.

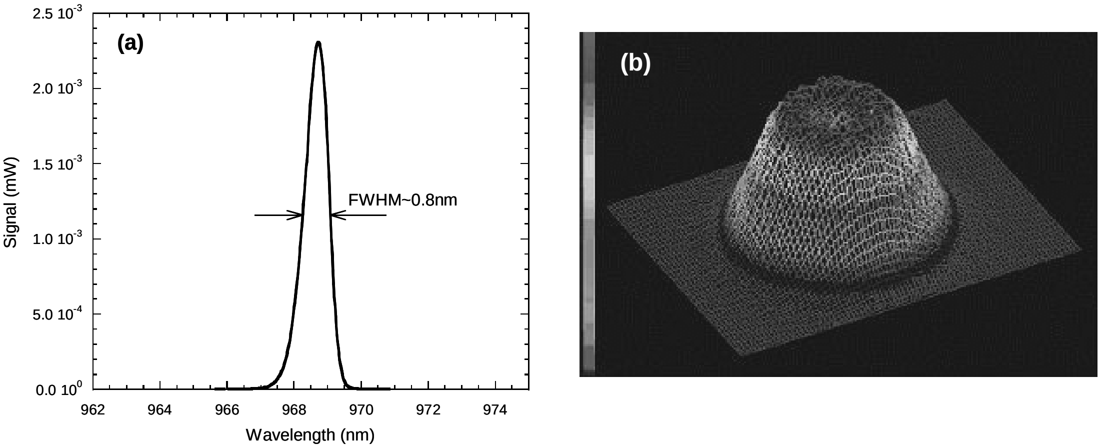

Fig. 5. (a) Wavelength spectrum and (b) far-field intensity distribution at a 100W output power (120A) from the 231W array.

Initial reliability results (a few thousands hours) show very little degradation for these arrays, in agreement with previous work [14] in which the authors reported more than 10,000 operating hours for a smaller array.

4. HIGH-BRIGHTNESS VCSEL ARRAYS

Certain applications, such as fiber lasers, require that the pump light be fiber-coupled. In this case, a high brightness source is required. In the case of VCSELs, a high-brightness 2D array can be fabricated using thousands of small devices operating in single-mode (the theory behind this approach will be presented elsewhere). Then, by using a micro-lens array with the same footprint as the VCSEL array, the output power from the array can be efficiently coupled into a fiber using a simple focusing lens (Fig. 6).

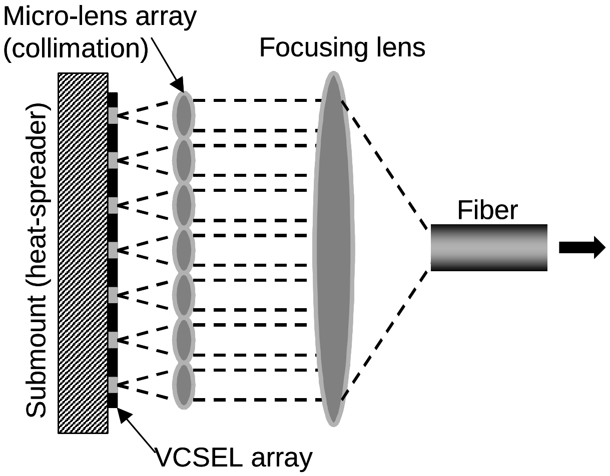

Fig. 6. Schematic of the high-brightness VCSEL array fiber-coupling scheme.

Fiber-coupled pump modules were built at 976nm for fiber laser pumping applications. Figure 7 shows a completed module and the corresponding fiber-out power versus current characteristic. The fiber used has a 400µm-diameter core and a 0.46 numerical aperture (NA). Maximum fiber-out power is 40W. Such high-power modules are useful for fiber-lasers because they avoid the need of multiple lower-power edge-emitter pump modules.

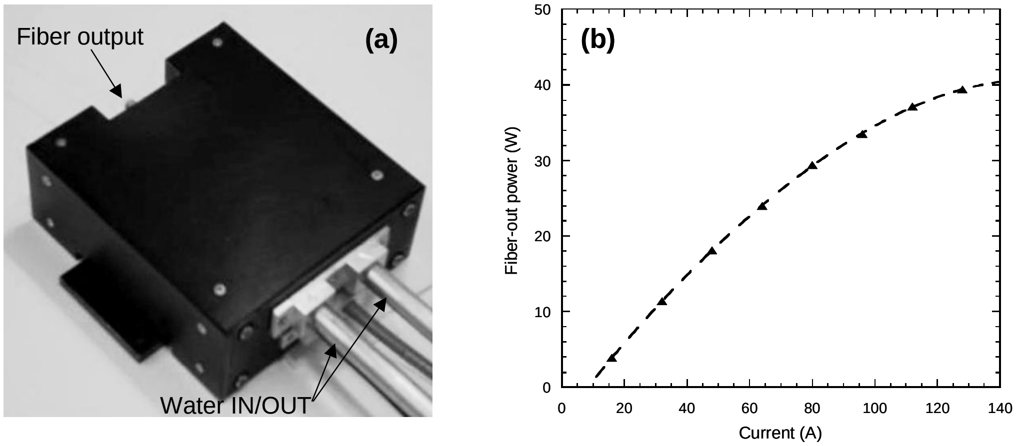

Fig. 7. (a) Picture of the completed high-brightness fiber-coupled VCSEL pump module. The fiber has a 400µm-diameter core and a 0.46 numerical aperture. (b) Fiber-out power characteristics.

5. HIGH-ENERGY VCSEL ARRAYS

5.1 VCSEL-based active Q-switch

There is increased interest from the military for a compact range finder to equip the individual soldier, thus providing him with a light-weight tool for high-precision targeting engagements. One of the main components of this micro-laser-range-finder (μLRF) is the saturable absorber Cr-doped YAG (Cr^{4+}:YAG) Q-switch [15]. This Q-switch is passive. However, a pulse-coded signal would be desired for these range finder applications. This means that the Q-switch needs to be actively turned on and off and thus a series of non-evenly-spaced pulses can be sent. This way other signals and jamming can be discriminated against.

For this purpose, we developed high-energy 5mm x 5mm VCSEL arrays and a power supply for 100nsec pulses to pump the Cr crystal. These arrays have an output energy of 220μJ at a 2kA current, corresponding to a record peak power of 2.2kW as shown in Figure 8. The fully assembled active Q-switch is shown in Figure 9.

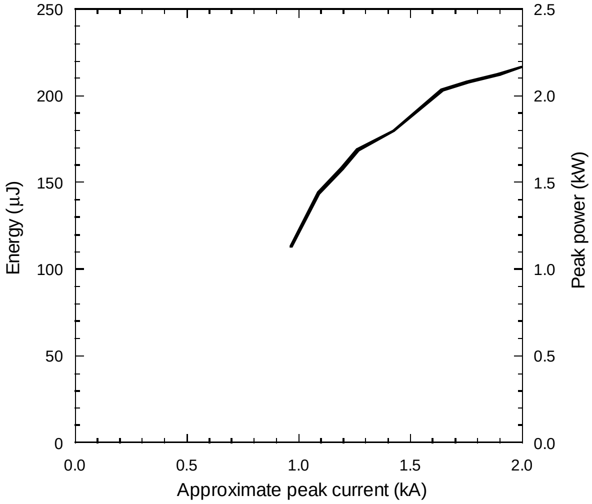

Fig. 8. Energy and peak-power vs. current (100nsec pulse-width) for a 5mm x 5mm 2D VCSEL array chip.

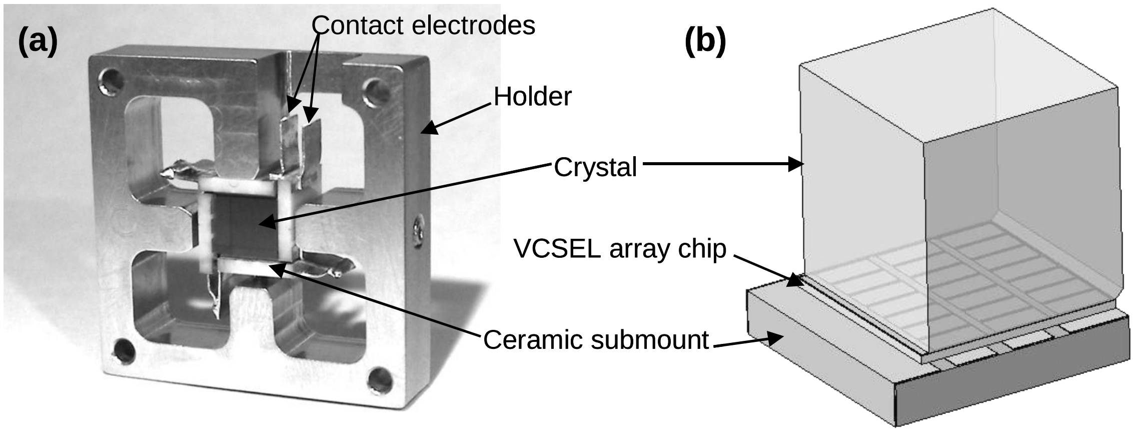

Fig. 9. (a) Fully assembled VCSEL-based active Q-switch module, and (b) detail showing the crystal with one of four VCSEL chip against the bottom facet.

The main advantage of VCSELs is that since they are not subject to COD, they do not fail when operated at many times their roll-over CW current, at such high output energies. Also, their unique geometry and properties allow for direct assembly against the crystal facets, without the need for coupling optics or isolators. The detail in Fig. 9(b) shows how one of the VCSEL array chip is directly pressed against one of the crystal facet that is anti-reflection coated at 980nm. In fact, the crystal is held in place by the pressure of all four VCSEL chips against its facets. The four VCSEL arrays provide a combined energy of close to 1mJ into the crystal, thus providing a means to actively control the Q-switch.

5.2 Short pulse VCSEL array modules

For designator and beacon applications for military applications, we developed large modules of VCSEL arrays operated under very short pulses (20~100nsec). The module (Fig. 10) comprises 64 VCSEL arrays connected in series. Each array is 5mm x 5mm and mounted on a removable individual carrier for easy replacement in case it fails. The module is approximately 5cm x 5cm. To operate this module, a custom power source delivering a peak current of 1.5kA with a pulse width of 30nsec was developed. For this first generation module, non-optimized VCSEL arrays delivering 20µJ at 1.5kA (30nsec pulse) were used, for a module-total of 1.28mJ. However, these numbers were limited by the power supply.

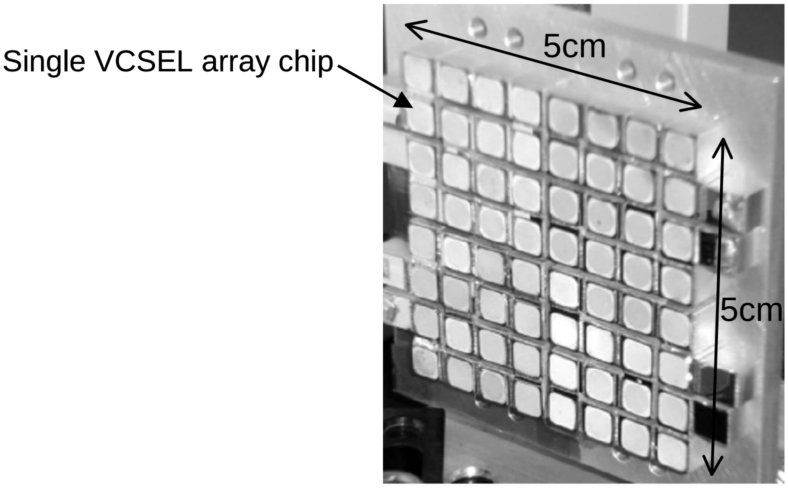

Fig. 10. Picture of short-pulse array module for designator and beacon applications.

Using the new arrays presented in Section 5.1 (220µJ in 100nsec pulse) a new 8x8 module has recently been fabricated. The module could not be measured at its peak output with all arrays connected in series because of the voltage limitations of the power supply. However, preliminary tests at lower currents and voltages showed that, proportionally, the module should deliver ~14mJ at its peak output (~2kA current) with an adequate power supply.

For designator applications, low divergence is required and the high-brightness technology discussed in Section 4 is used. The beam divergence for designator applications from the existing arrays is about 24mrad (half angle). High-energy large arrays such as shown in Fig. 10 with narrow divergence can be made for designator applications with this technology. For our new arrays this number is being reduced to 8mrad. For beacon applications, where low-divergence is not required, the module can be used as-is. Higher-energy arrays are being developed.

6. CONCLUSIONS

Compact and efficient high-power semiconductor laser sources using the VCSEL technology have been developed for many applications. These lasers have many advantages such as low manufacturing costs, reliability, high-temperature operation, intrinsic spectral stability and beam quality. For end-pumping applications, these 2D arrays can potentially be assembled directly against the facets of the doped medium, without the need for optics or isolators.

These 2D VCSEL arrays can also operate under short pulses (<200nsec) at many times their roll-over CW current without any COD-induced failure, making them a reliable laser source for high-energy applications such as designator, beacon, and active Q-switch. Arrays with a record peak power of 2.2kW under 100nsec pulse have been demonstrated. Also, modules delivering 1.28mJ (30nsec pulse) have been demonstrated and modules for 14mJ output (100nsec pulse) have been fabricated.

Although the conversion efficiency of VCSELs has improved significantly in recent years (~51%), it still lags behind that of edge-emitters (55~60% for commercial products). Still, since VCSELs can operate reliably at high temperature, the overall system efficiency could be higher using VCSELs since a refrigeration apparatus would not be needed.

Because of their significant and unique advantages in terms of costs, reliability, and performance VCSELs could become the next technology of choice for compact and efficient high-power semiconductor laser sources in many applications.

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REFERENCES

[1] L. A. D'Asaro, J-F. Seurin, and J. D. Wynn, "High-power, high efficiency VCSELs pursue the goal", Photonics Spectra, **February**, 62-66 (2005).

[2] N. M. Margalit, S. Z. Zhang, and J. E. Bowers, "Vertical cavity lasers for telecom applications," IEEE Communications Magazine, **May**, 164-170 (1997).

[3] K. S. Giboney, L. B. Aronson, and B. E. Lemoff, "The ideal light source for datanets," IEEE Spectrum, **35**(2), 43-53 (1998).

[4] K. D. Choquette and H. Q. Hou, "Vertical-cavity surface-emitting lasers: moving from research to manufacturing," Proc. IEEE, **85**(11), 1730-1739 (1997).

[5] J. M. Dallesasse, N. Holonyak, Jr., A. R. Sugg, T. A. Richard, and N. El-Zein, "Hydrolyzation oxidation of $Al_xGa_{1-x}As$-AlAs-GaAs quantum well heterostructures and superlattices," Appl. Phys. Lett., **57**(26), 2844-2846 (1990).

[6] D. L. Huffaker, D. G. Deppe, K. Kumar, and T. J. Rogers, "Native-oxide defined ring contact for low threshold vertical-cavity lasers," Appl. Phys. Lett., **65**(1), 97-99 (1994).

[7] K. L. Lear, K. D. Choquette, R. P. Schneider, Jr., S. P. Kilcoyne, and K. M. Geib, "Selectively oxidized vertical cavity surface emitting lasers with 50% power conversion efficiency," Electron. Lett., **31**(3), 208-209 (1995).

[8] M. Grabherr, R. Jäger, M. Miller, C. Thalmaier, J. Herlein, R. Michalzik, and K. J. Ebeling, "Bottom-emitting VCSEL's for high-CW optical output power," IEEE Photon. Technol. Lett., **10**(8), 1061-1063 (1998).

[9] A. Moser and E. E. Latta, "Arrhenius parameters for the rate process leading to catastrophic optical damage of AlGaAs-GaAs laser facets," J. Appl. Phys., **71**(10), 4848-4853 (1992).

[10] H.-U. Pfeiffer, S. Arlt, M. Jacob, C. S. Harder, I. D. Jung, F. Wilson, and T. Oldroyd, "Reliability of 980nm pump lasers for submarine, long-haul terrestrial, and low cost metro applications," Optical Fiber Communication Conference and Exhibit, OFC 2002, 483-484 (2002).

[11] J. A. Tatum, A. Clark, J. K. Guenter, R. A. Hawthorne III, and R. H. Johnson, "Commercialization of Honeywell's VCSEL technology," Proc. SPIE, **3946**, 2-13 (2000).

[12] U-L-M photonics, GmbH, "VCSEL Chip Products Reliability Report," (October 2005).

[13] R. A. Morgan, M. K. Hibbs-Brenner, T. M. Marta, R. A. Walterson, S. Bounnak, E. L. Kalweit, and J. A. Lehman, "200°C, 96-nm wavelength range, continuous-wave lasing from unbonded GaAs MOVPE-grown vertical cavity surface-emitting lasers," IEEE Photon. Technol. Lett., **7**(5), 441-443 (1995).

[14] M. Miller, M. Grabherr, R. Jager, and K. J. Ebeling, "High-power VCSEL arrays for emission in the watt regime at room temperature," IEEE Photon. Technol. Lett., **13**(3), 173-175 (2001).

[15] J. E. Nettleton, B. W. Schilling, D. N. Barr, and J. S. Lei, "Monoblock laser for a low-cost, eyesafe, microlaser range finder," Appl. Optics, **39**(15), 2428-2432 (2000).