

Commercial VCSELs reach 0.1 W cw output power

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ABSTRACT

Following the success in fiber based DataCom, VCSELs start to conquer additional market shares in a variety of other applications like free space optics (FSO), lighting, printing, and sensing. U-L-M photonics presents a new family of commercial high power VCSELs emitting powers of up to 50 mW cw at RT based on top-emitting technology. The devices are available at 850 nm emission wavelength. All devices can be operated passively cooled and provide modulation bandwidths of up to 1 GHz. Wallplug efficiencies are in excess of 25 %. Even higher output power of 250 mW cw from a 80 μm active diameter bottom-emitting VCSEL operating at 980 nm has already been obtained although just being passively cooled. Further power up scaling is achieved by arrangement of multiple VCSELs in 2D arrays. For the first time we demonstrate cw output power of 10 Watt cw at RT from compact monolithic VCSEL module of 14 mm^2 chip area. Transfer of the technology to other wavelengths, e.g. 808 nm and 945 nm, is presented, too, and shows perspectives towards homogeneous optical pumping of solid state lasers. Almost identical device performance levels can be presented for the entire wavelength span. All discussed results are based on highest quality epitaxy optimized for maximum intrinsic efficiency and differential slope efficiency. Oxide confinement is used for current constriction that provides most efficient electrical pumping of the active area. In combination with advanced mounting techniques all mentioned aspects sum up to allow for cost effective VCSEL products in the medium and high power laser regime. The circular output beam in addition to simple heat sinking offers attractive solutions for advanced system integration.

Keywords: Commercial VCSELs, high output power, 2D arrays, FSO, optical pumping

INTRODUCTION

Since more than 10 years high power VCSELs have been under development in the scientific community. Single devices achieving output powers up to several 100 mW [1, 2] and 2D arrays reaching the Watt regime [3, 4] have already been published. The introduction of wet oxidized current apertures and therefore availability of highly efficient devices has played a key role for the evolution of high power devices. VCSEL technology was focused on fiber based DataCom for the past years, but now for the first time high power VCSELs experience increasing demand from several applications. Requirements in free space optical DataCom (FSO) perfectly fit to the characteristics that can be provided by highly efficient, large area 850 nm VCSELs. This will be discussed in detail in the following sections. Based on the well known technology of standard DataCom VCSELs these devices have been developed and qualified within short time and are already in production. Looking at the technological possibilities that have been realized during this development work, many more promising applications come into focus. IR illumination e.g. for night vision systems, direct laser treatment in medicine, and large scale high power VCSEL arrays for printing are within the scope of this technology. Even more challenging is the competition with conventional optical pump sources for highest optical powers towards the kW regime. The absolute maximum power per mm^2 chip area in VCSEL technology ($\sim 1 \text{ W}/\text{mm}^2$) is getting close to the values provided by commercial laser bars ($\sim 3 \text{ W}/\text{mm}^2$). Although edge emitting lasers will always benefit from approximately factor 2 higher electro-optical efficiencies, VCSEL technology might compensate this drawback by more accurate wavelength tuning, small spectral width, and reduced temperature dependence of the emission wavelength. The optical-optical efficiency will of course not entirely compensate the mentioned factor of 2, but for special use in solid state laser pumping, where e.g. homogeneous power density across certain areas is required, VCSEL technology might successfully compete with other solutions. In the latter sections of this paper we present results of record high output powers from 2D VCSEL arrays that demonstrate the promising capabilities of VCSEL technology in the high power laser regime.

HIGHLY EFFICIENT 850 NM TOP-EMITTER

The devices described in the following sections are based on MBE grown wafers. Optimization of doping profiles, material composition graduation and number of Bragg layer pairs in the upper and lower mirror is necessary to find the

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perfect balance of threshold current densities, slope efficiencies, kink voltages, and series resistances in order to obtain highly efficient devices. Using wet oxidation for current confinement offers both, most efficient current constriction and flexibility of defining active diameters. The definition of power levels for the high power VCSELs described in the following is done by increasing the active area of the laser without changing the epitaxial layer structure.

Fig. 1 shows the 4 members of U-L-M photonics' high power 850 nm VCSEL family ULM850-XX-TT-HYYYYY. Target output powers are 6, 12, 24, and 48 mW cw from chip format or TO package and 3, 6, 12, 24 mW coupled into the optical fiber (125 μ m/NA 0.37), respectively. In Fig. 1a LIV characteristics of a 10 μ m active diameter VCSEL are presented. Above threshold current, which is less than 1 mA, slope efficiency of 0.9 W/A is obtained. At 8 mA laser current, which is 8 times the threshold current, the targeted optical output power of 6 mW is reached. According conversion efficiency is as high as 31 %, based also on the low voltage drop of 2.4 V. LIV characteristics presented in Fig. 1b belong to a 14 μ m active diameter VCSEL. Threshold current is 3 mA, slope efficiency again is calculated to 0.9 W/A. Output power of 12 mW at operation point is reached at 16 mA, or 5 times threshold current. Corresponding wallplug efficiency is 35 %.

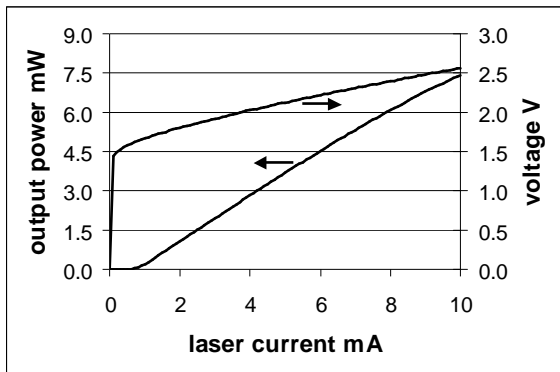


Fig. 1a: LIV characteristics of a 10 μ m active diameter VCSEL at RT. 6 mW cw output power is reached at 8 mA.

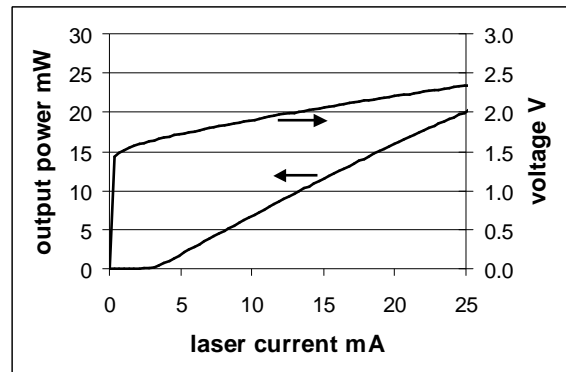


Fig. 1b: LIV characteristics of a 14 μ m active diameter VCSEL at RT. 12 mW cw output power is obtained at 16 mA.

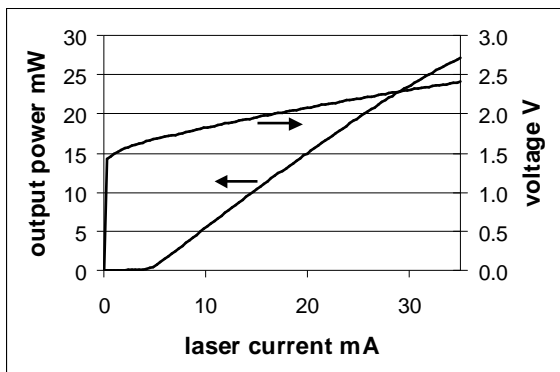


Fig. 1c: LIV characteristics of a 25 μ m active diameter VCSEL at RT. At 31 mA the specified power of 24 mW is reached.

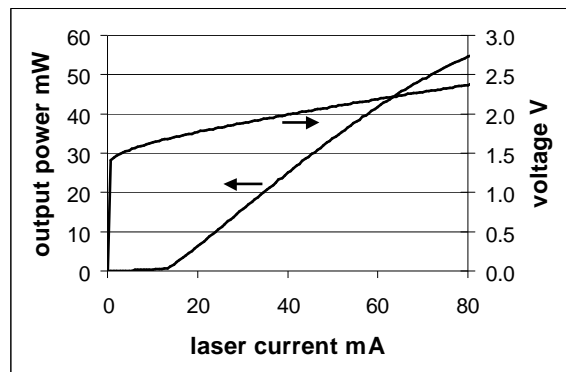


Fig. 1d: LIV characteristics of a 50 μ m active diameter VCSEL at RT. For the targeted 48 mW cw output power 63 mA have to be applied.

Further increase of the active diameter to 25 μ m results in 5 mA threshold current and still high slope efficiency of 0.9 W/A at room temperature. The target output power is 24 mW which is reached at 6 times the threshold current at 31 mA. Conversion efficiency is 33 %. For the largest active diameter of 50 μ m Fig. 1d shows LIV characteristics with output powers in excess of 50 mW. The target value of 48 mW is already reached at 63 mA which is approx 5 times the threshold current. Slope efficiency again amounts to 0.9 W/A. Due to the high conversion efficiency of 34 %, the device can be operated without active cooling in a TO56 can as long as reasonable thermal contact to a heatsink is provided. Due to the oxide layer that provides current confinement, current crowding effects have to be considered. Especially for

large active diameters and top-side emission geometry rather strong side lobes in the farfield patterns occur. Fig. 2a indicates that high order transversal modes are preferred in a 25 μm active diameter VCSEL by the inhomogeneous current density distribution and thus ring shaped emission dominates the farfield pattern for all laser currents. Peak-to-valley-ratio along the cross-section is about 1:5 from maximum at the side lobes to minimum at the axis of the emission profile. The $1/e^2$ full width angle is dependent on the laser current and increases from 25° at 10 mA to 34° at 40 mA as can be seen in Fig. 2b. The numerical aperture for the 25 μm device is $\text{NA}=0.29$.

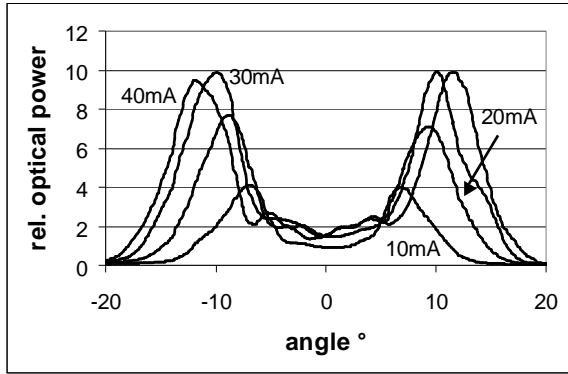


Fig. 2a: Farfield intensity profile of a 25 μm active diameter VCSEL

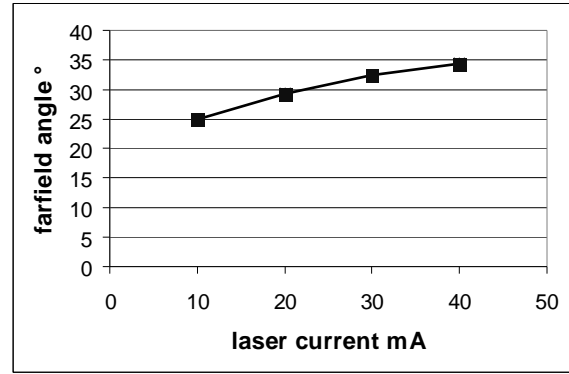


Fig. 2b: Full width $1/e^2$ farfield angle versus current of a 25 μm active diameter VCSEL

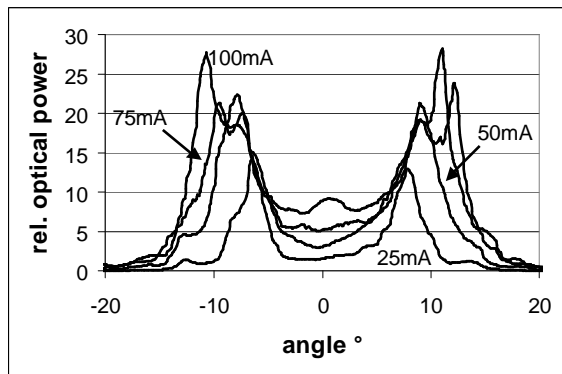


Fig. 2c: Farfield intensity profile of a 50 μm active diameter VCSEL

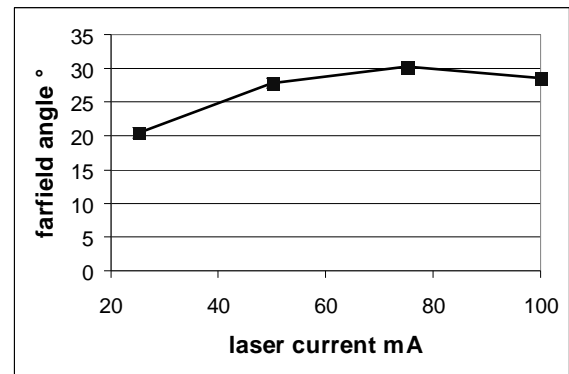


Fig. 2d: Full width $1/e^2$ farfield angle versus current of a 50 μm active diameter VCSEL

In Fig. 2c the presented intensity profile of the large area 50 μm diameter VCSEL is not much different from the smaller 25 μm diameter device. Both numbers, maximum farfield angle and peak-to-valley ratio is comparable. Only the less smooth shape of the side lobes indicates that the number of individual modes is higher which all contribute to the overall power. The maximum farfield angle versus laser current plotted in Fig. 2d increases to about 30° for currents close to thermal roll-over. For high power laser diodes it is important to operate them without active cooling. Due to the high conversion efficiency of the presented devices and thus small internal heating, operation at high ambient temperatures is possible. Fig. 3a shows LI characteristics of a 14 μm active diameter devices where ambient temperature is changed from -5°C up to $+100^\circ\text{C}$. As can be seen in Fig. 3c, the corresponding slope efficiency is decreasing from 1.0 W/A down to 0.65 W/A for -5°C and $+100^\circ\text{C}$, respectively. At $+100^\circ\text{C}$ still more than 5 mW optical output power can be obtained at 12 mA laser current. The threshold current dependence versus ambient temperature, plotted in Fig 3e, shows nice parabolic behavior. The minimum threshold current observed at 40°C indicates perfect matching of gain and resonance wavelength at that particular ambient temperature. Larger devices, e.g. the 50 μm active diameter device presented in Fig. 3b, show stronger effects on LI characteristics with changing temperature. Whereas output powers of 40 mW are still reached at temperatures up to 40°C , maximum output power decreases with further increasing temperatures. Anyway, at 70°C maximum still output power of 15 mW is observed. The slope efficiency drops from 0.9 W/A at $+15^\circ\text{C}$ down to 0.6 W/A at $+70^\circ\text{C}$ as can be seen in Fig. 3d. There are two reasons for the disadvantageous

characteristics of this large device compared to the smaller one. First, large active area VCSELs suffer from relatively high thermal resistances due to the only inversely linear decrease of thermal resistance with active diameter [5], but more than linear (but not squared) increase of dissipated power with increasing active diameter [4]. As a second effect, the spectral relation of gain peak and resonance wavelength of the epitaxially grown wafer used to produce this large area device is not optimized for high temperature operation. In Fig. 3f the threshold current is plotted versus temperature and has not reached its minimum value even at low temperature of +15°C. Therefore this device is not well suited for high temperature operation.

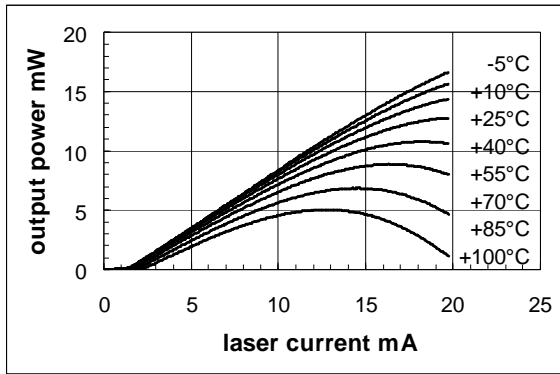


Fig. 3a: LI characteristics of a 14 μm active diameter VCSEL for temperatures from -5°C up to 100°C

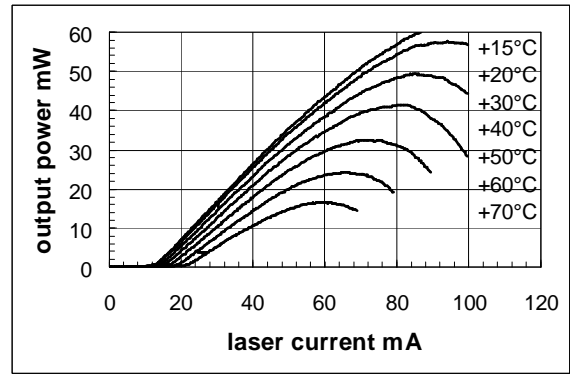


Fig. 3b: LI characteristics of a 50 μm active diameter VCSEL for temperatures from 15°C up to 70°C

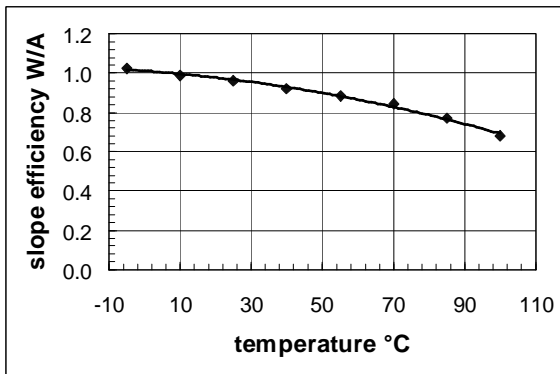


Fig. 3c: Slope efficiency of a 14 μm active diameter VCSEL versus ambient temperature.

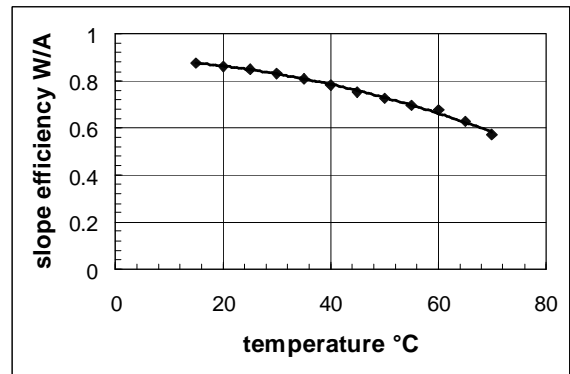


Fig. 3d: Slope efficiency of a 50 μm active diameter VCSEL versus ambient temperature.

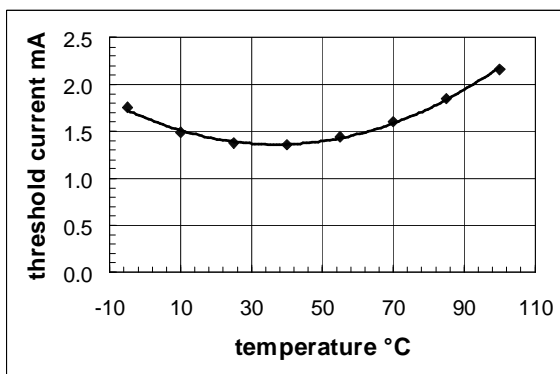


Fig. 3e: Threshold current variation versus ambient temperature for a 14 μm active diameter VCSEL.

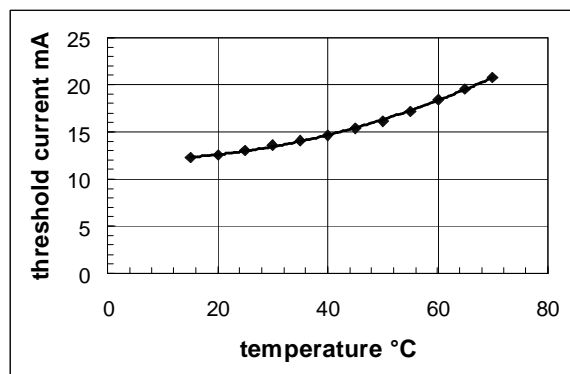


Fig. 3f: Threshold current variation versus ambient temperature for a 50 μm active diameter VCSEL.

LARGE AREA VCSELS IN FSMA RECEPTACLE FOR FSO

Free space optical point-to-point data links are among the first applications of high power VCSELS. Requirements include power levels up to 24 mW, high speed modulation of several 100 MHz and homogeneous emission profiles in the farfield. Expanded need for data rates up to 1 or 2.5 Gbps is expected in near future. Whereas output power and speed is supported by the introduced VCSELS, the disadvantageous ring shaped farfield distribution of the presented devices must be homogenized by the use of optical fibers where modal intermixing in the optical fiber results in a rather homogeneous emission pattern from the fiber end surface. Fig. 4a shows the chip design of U-L-M photonics' high power VCSEL chips. The emission area is centered in the $250 \times 350 \mu\text{m}^2$ chip area. Both contacts are attainable from the top side and allow for variable arrangement of VCSEL, monitor photodiode, common n or common p configuration when mounted into the TO56 can. Illustration can be seen in Fig. 4b. Finally the TO56 can is adjusted into a FSMA receptacle, shown in Fig 4c, where coupling efficiencies of minimum 50 % can be guaranteed.



Fig. 4a: Chip design of high power VCSELS from U-L-M photonics. Chip area $250 \times 350 \mu\text{m}^2$.

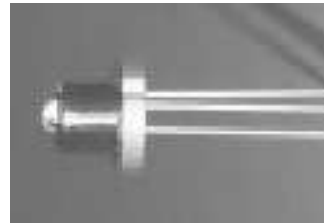


Fig. 4b: TO56 package with ball lens cap.

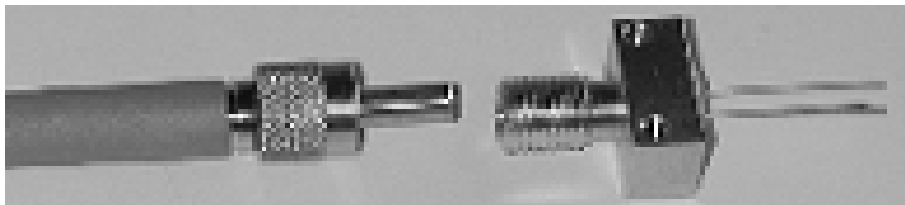


Fig. 4c: FSMA receptacle with $125 \mu\text{m}/\text{NA } 0.37$ fiber.

Fig. 5a presents results from a fiber coupled $25 \mu\text{m}$ VCSEL, where LIV characteristics confirm the good coupling efficiencies. In this case coupling efficiency is better than 70 %. The specified 12 mW fiber coupled power is reached at 21 mA. The same technology can of course be used for $200 \mu\text{m}$ fiber core diameters. Coupling efficiency is then further increased to values around 90 % which has already been demonstrated. Using $62.5 \mu\text{m}$ core diameter fibers is also possible but demands for more accurate alignment, especially for the large area devices. Anyway, coupling efficiencies of 30 to 50 % have already been achieved.

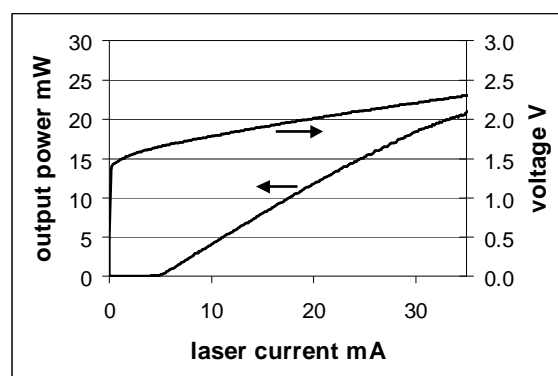


Fig. 5a: LIV characteristics of $25 \mu\text{m}$ active diameter VCSEL coupled into $125 \mu\text{m}/\text{NA } 0.37$ fiber

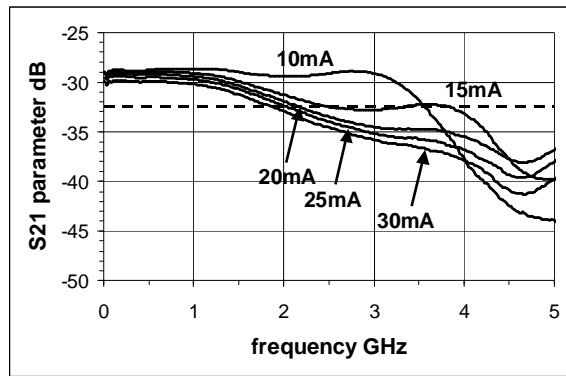


Fig. 5b: S21 parameter of 25 μm VCSEL. Small modulation bandwidth (3dB down) is larger than 1 GHz for all laser currents up to 30 mA.

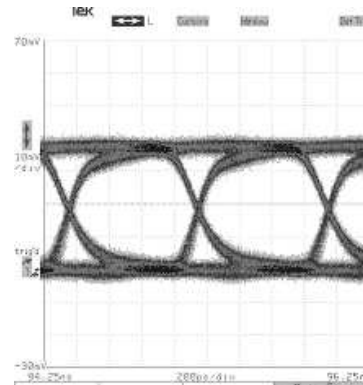


Fig. 5c: Eye diagram at 1.25 Gbps of fiber coupled 25 μm active diameter VCSEL.

Small modulation response from a 25 μm active diameter VCSEL is presented in Fig. 5b. For all operation currents from 10 mA up to 30 mA, the 3 dB modulation frequency is larger than 1 GHz. Data transmission experiments at 1.25 Gbps have been carried out and the obtained eye diagram presented in Fig. 5c clearly indicates that even such high data rates can be provided.

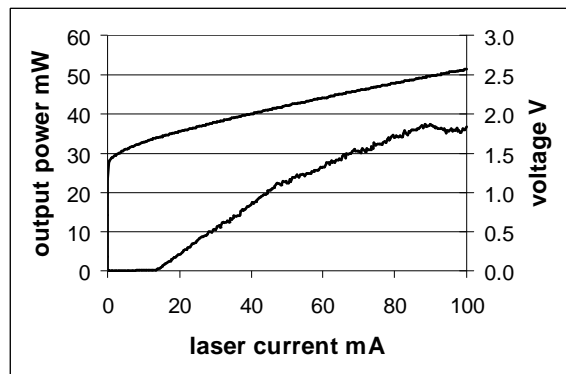


Fig. 6a: LIV characteristics of 50 μm active diameter VCSEL coupled into 125 μm /NA 0.37 fiber

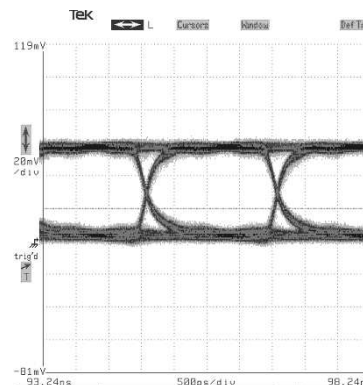


Fig. 6b: Eye diagram of 50 μm active diameter VCSEL at 500 Mbps data rate.

Fiber coupling of the 50 μm diameter VCSEL is more demanding and the LIV characteristics in Fig. 6a are influenced by modal losses at the ball lens and the subsequent fiber coupling. Anyway, maximum fiber coupled power is as high as 35 mW at room temperature, the specified 24 mW are reached at 55 mA laser current. Due to electrical parasitics of the laser diode, like the built in capacitance, the speed of such large devices is reduced. Nice eye diagrams can be obtained up to 500 Mbps, but 1 Gbps seems to be the upper limit that can be achieved for such power levels today.

980 NM BOTTOM-EMITTER

For top-emitting VCSELs up scaling of output power for single devices is only possible when increasing the active diameter. By changing the resonator design to bottom-emitting VCSEL structure more advanced heat removal through the top DBR is possible. Mounting the VCSELs junction down on appropriate heat sinks results in significantly reduction of the thermal resistance and thus strong increase in output power. The schematic drawing in Fig. 7a illustrates the main advantages of bottom-emitting resonator design. Heat removal from the top p-type DBR is improved due to efficient heat spreading directly from the semiconductor/heat sink interface. The full size p-type contact in addition allows for more homogeneous current injection into the active area. The current crowding effects at the current aperture are not totally compensated but significantly reduced, which results in a more homogeneous farfield pattern [4].

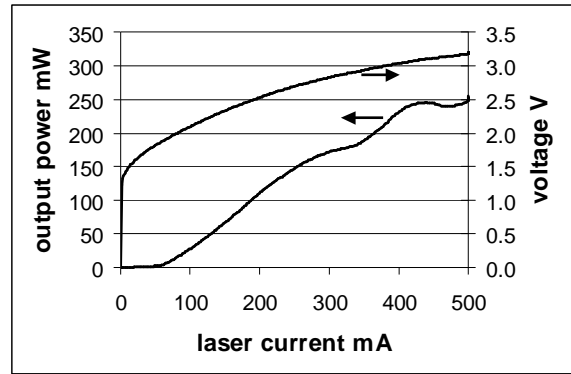
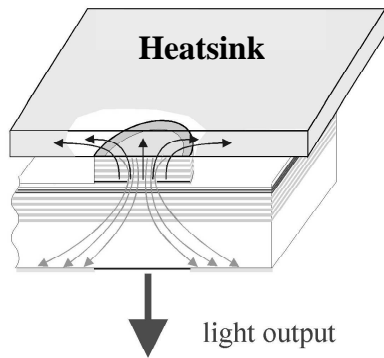


Fig. 7a: Junction down mounted bottom-emitting VCSEL. Improved heat removal as well as improved current density distribution is realized. Fig. 7b: LIV characteristics of a 80 μm active diameter 980 nm bottom-emitting VCSEL.

Because of fundamental absorption of wavelengths below 900 nm, we focus on 980 nm emission wavelength for the demonstration of high output powers from bottom-emitting structures. The LIV characteristics presented in Fig. 7b are taken from a 80 μm active diameter bottom-emitting VCSEL which was soldered onto a TO56 header. The device is not actively cooled, just good thermal contact to an external passive heat sink is provided. Maximum output power is measured to 250 mW at 450 mA laser current. The slope efficiency is 0.6 W/A. The variation in the LI curve at high laser currents is due to non-optimized AR coating of the emission window on the substrate and therefore interference effects into the resonator cannot be avoided.

980 NM BOTTOM-EMITTING LARGE ARRAY

Output powers in the Watt regime can be achieved with extremely large active diameter VCSELs [3], but the performance of such devices is not acceptable for any application. 2D array arrangements seem much more promising to provide high powers at high efficiencies still from compact monolithic chips. We have manufactured an array of 224 individual bottom-emitting VCSELs, 30 μm active diameter each. The pitch between centers of the elements is 250 μm , as shown in Fig. 8a. Total chip area is 14 mm². All elements are soldered in parallel onto a water cooled heat sink which is operated at 18°C. The resulting LIV characteristics presented in Fig. 8b shows output power of 10 W at 22.5 A module current. Slope efficiency is 0.6 W/A. At a module current of 11 A and according voltage drop of 2.2 V the output power amounts to 6 W cw. The resulting wallplug efficiency is 22 %. To our knowledge this is the highest cw output power from monolithic VCSEL arrays operated at RT so far.

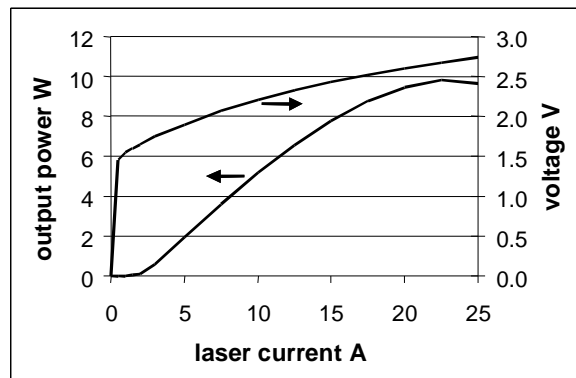
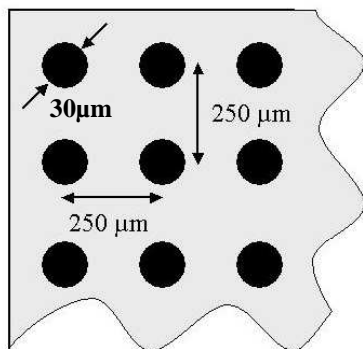


Fig. 8a: The 224 elements of the 2D VCSEL array are arranged with a pitch of 250 μm in both directions. Active diameter is 30 μm for each element.

Fig. 8b: LIV characteristics of a 224 element VCSEL array with active diameter of 30 μm each. The arrays is mounted on a water cooled submount and is operated at 18°C.

OUTLOOK: SPECIFIC HIGH POWER OPTICAL PUMP MODULE

2D VCSEL arrays could be used for homogeneous large area solid state laser pumping, e.g. Nd:YAG, or direct laser treatment. For solid state laser pumping accurate wavelength and small spectral width of the emitted light is required. Fig. 9 shows two examples of 25 μm aperture VCSELs that emit at 808 \pm 1 nm and 945 \pm 1 nm with electro-optical performances comparable to the previously discussed 850 nm VCSELs. Output powers well above 20 mW at laser currents around 35 mA are presented, conversion efficiencies at 20 mW are above 25 % for both devices. The slight variations in the LI characteristics of the 945 nm VCSEL is due to residual back reflections from the substrate/air interface. Highly absorbing metal film or AR coating could avoid this effect.

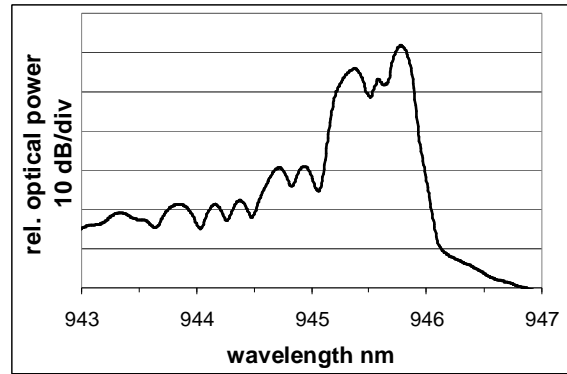
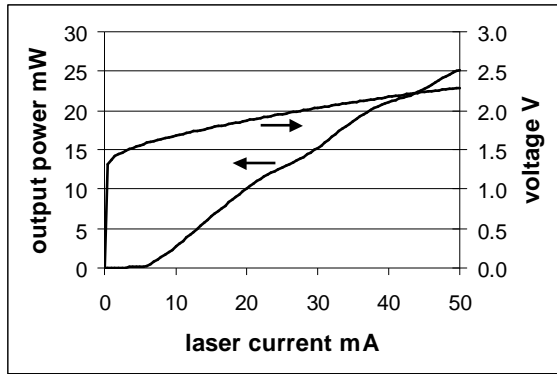


Fig. 9a: LIV characteristics of a 25 μm aperture VCSEL emitting at 945 nm.

Fig. 9b: Optical spectrum at 20 mW output power of a 25 μm active diameter VCSEL centered at 945 nm. Spectral width is 1 nm (10 dB down).

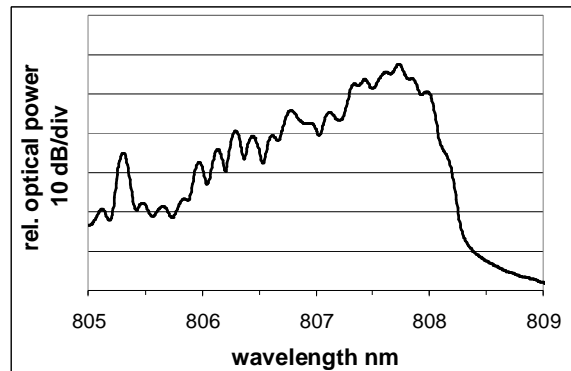
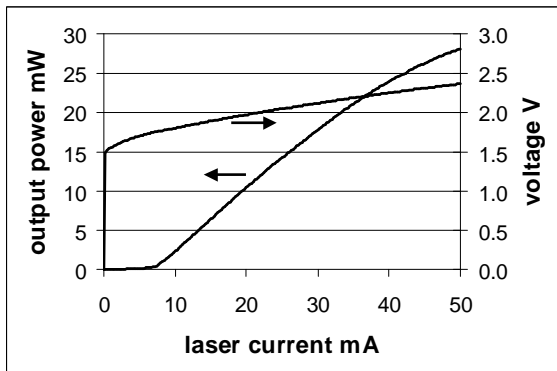


Fig. 9c: LIV characteristics of a 25 μm aperture VCSEL emitting at 808 nm.

Fig. 9d: Optical spectrum at 20 mW output power of a 25 μm active diameter VCSEL centered at 808 nm. Spectral width is 1 nm (10 dB down).

High efficiency and thus high power individual VCSELs and the advanced mounting technology presented for the 2D arrays in combination with the substrate replacing process introduced in [6] can be seen as the technological basis for advanced optical pump modules at specific wavelengths between 780 and 1000 nm. Individually addressable areas of such 2D arrays provide further functionality.

SUMMARY

We have presented a family of high power 850 nm VCSEL products that emit 6, 12, 24, and 48 mW from 10, 14, 25, and 50 μm active diameter, respectively. Data rates up to 1 Gbps are demonstrated and an advanced fiber coupling solution by FSMA receptical is provided optionally. According coupling efficiencies are in excess of 50 %. These power levels are well suited e.g. for FSO applications, where high power, high speed and homogenized farfield emission from fiber end surfaces is required.

CW output power of 250 mW from a single VCSEL is demonstrated from a 80 μm aperture device emitting at 980 nm. Using junction-down mounting technology heat removal is improved and thus output power is increased significantly.

Two-dimensional arrangement of 224 devices of 30 μm active diameter each and 250 μm pitch from center to center results in 10 W cw output power from a 14 cm^2 chip area. To our knowledge this is the highest cw output power at room temperature reported for a monolithic VCSEL array so far.

High power 25 μm aperture VCSELs of 808 nm and 945 nm wavelength have also been demonstrated. At both wavelengths, which are of interest for optical pumping of solid state lasers, comparably high performance levels to 850 nm VCSELs are presented. In combination with already discussed array arrangements, mounting technologies, and substrate replacing technologies, prospective high power optical pump sources are foreseen.

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