New markets for VCSELs: pulsed operation of high power devices

Martin Grabherr*, Michael Miller, Dieter Wiedenmann, Roland Jäger, Roger King
U-L-M photonics GmbH, Albert-Einstein-Allee 45, 89081 Ulm, Germany
U-L-M photonics GmbH is fully owned by PHILIPS and will be renamed as PHILIPS PHOTONICS in 2007

ABSTRACT

Driving basic VCSEL technology in the '90, datacom has been the first volume market for various VCSEL products. The downturn in 2001 can be regarded as a point in time, when engineers both from VCSEL manufacturers and non-datacom users started to identify VCSEL technology as a very promising laser source platform for many other applications. Dedicated spectroscopy laser sources based on VCSEL technology, e.g. for oxygen sensing [1], have proven their competitiveness in industrial applications. The most prosepective consumer market of human-machine-interfaces like laser mice has shown the huge potential of the VCSEL technology in low costs, high volume applications, even given extreme technical performance specifications [2]. Just as a consequence, VCSELs are now penetrating into the next potential volume markets, where unique properties of this technology is requested: High power pulsed laser applications, where low cost is a key factor for market entry. In this paper we discuss a suitable semiconductor technology platform, assembly solutions, selected applications and their market potential as well as performance and reliability data. From small footprint of 0.3 mm² and 0.11 mm² peak output powers of 0.7 W and more than 6 W at 850 nm wavelength are shown at 30 µs and 30 ns pulse widths, respectively.

Keywords: automotive, high power, pulsed, LIDAR, reliability

INTRODUCTION

Whereas most VCSEL applications like datacom, laser mice, spectroscopy or optical encoders request output powers in the 0.5 to 10 mW regime, VCSEL arrays can also deliver power levels up to several W in cw [3] and several 10 W in pulse mode. In comparison to state of the art edge emitting lasers, VCSELs suffer from increased serial resistance and thus limited wallplug efficiency, especially at operating points far above threshold. Whereas VCSELs achieve a maximum wallplug efficiency of around 50 % at around 3 times threshold current with strongly decreasing value at higher operating current [4], edge-emitting lasers reach more than 60 % along a wide operating current range [5]. Therefore VCSELs can not compete with edge emitting lasers in terms of sheer cw output power. When it comes to pulsed operation with pulse length smaller than 1 µs and/or duty cycles of less than 5 % the situation looks different. Due to their benefits in simple mounting, advantageous beam shape and robustness, VCSELs outperform edge-emitting lasers for various applications. While high brightness LEDs also claim assembly and robustness as plus on their side, wide spectral width, large thermal spectral shift, worse emission profile and limited modulation speed clearly disqualify LEDs for several applications when comparing with VCSELs.

Table 1 presents a comparison of major parameters for high brightness LED, edge-emitting laser, and VCSEL.

As a conclusion, VCSELs appear to combine the advantageous of LEDs and edge-emitting lasers perfectly, if conversion efficiency is not regarded as major criterion.

Up to now VCSELs have not been regarded being competitive in high power applications. In the following paragraphs performance characteristics as well as reliability results will be discussed showing the potential of VCSEL technology also the high power segment.

---

*martin.grabherr@ulm-photonics.de; phone +49 731 550194-011; fax +49 731 550194-026; www.ulm-photonics.de

	LED	Edge-emitting laser	VCSEL
efficiency	+	++	+
absolute power cw	o	++	o
modulation speed	-	+	++
beam shape	-	+	++
chip costs	++	o	+
packaging costs	++	-	++
spectral width	-	+	++
spectral shift	-	-	++

Table 1: Comparison of semiconductor light sources regarding main characteristics.

APPLICATIONS

Potential applications for short pulse lasers are in the field of safety systems, e.g. in automobiles, or surveillance, e.g. in industrial environments. As examples, object detection in the surroundings of a car (pre-crash sensing or park assistant), distance measurement to cars in front of you (distance warning or adaptive cruise control) [6], and intelligent lighting solutions for camera based image processing systems will be discussed in the following.

Power requirements for object detection in short distances are output powers around 1 W and pulse lengths of several 10µs. Within the rather long pulse, high frequency modulation can be applied to the output power for special data computing.

Much shorter pulses are required for time of flight systems like they are used, e.g. in LIDAR applications. Pulse lengths as short as 10 ns and output powers of up to 100 W allow for spatial resolution of several 10 cm and a distance coverage of up to 200 m, respectively.

Using VCSEL technology for illumination, small spectral width, fast modulation and the given by nature fact of a distributed light source, improves the performance of camera based imaging systems in terms of dynamic range, and in case of a 3D camera system based on PMD (Photonics Mixer Device) technology [7], also spatial resolution.

Based on a common technological platform, VCSEL array design provides the freedom to address the above mentioned different specifications. As a main design parameter, thermal management determines the required footprint of the chip as well as the ratio of active area to chip area.

In all applications VCSEL arrays can be designed according to the thermal boundary conditions and due to their modular assembly potential output powers are easily scalable. Especially for automotive applications reliability aspects are of highest concern. Details of intermediate results are presented later in the paper.

Laser baser sensors are in direct competition to RADAR based solutions. Besides minor performance differentiation laser based systems offer a much less expensive solution which opens markets also in mid class cars. Volumes in this market segment are in the order of 10 million systems per year, requiring multiple lasers per system.

FABRICATION: EPITAXY AND PROCESSING

High quality epitaxial layer stacks are crucial for achieving high slope efficiency and reasonable voltage drops. As minimum threshold currents are not as important as slope efficiency because of the high operating current in multiples of threshold current, the design of the DBR stacks needs to address minimum absorption and a most aggressive outcoupling ratio for the two DBRs.

Using selective oxidation technique for current confinement, high internal efficiency is achieved. The active diameters for top emitting devices is chosen to be 10 to 50 µm, depending on further system requirements like farfield characteristics and thermal boundary conditions. Scalability of output power is given by 2 dimensional arrangements of individual emitters. All emitters are connected by a common anode on epitaxial side and a common cathode either on the substrate or also placed on the chip top side. This configuration offers most flexibility for modular combination of chips, e.g. when being connected in series for better matching of high operation voltages as can be found in automotive electrical systems. In case emitters need to be placed extremely close to each other, as shown in Fig. 1, dry etching is used to separate the mesa and expose the confinement layer.

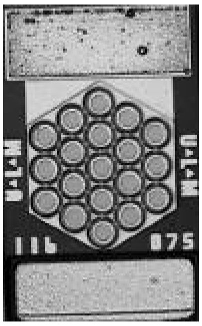

Fig.1: Example of chip layout. Both electrodes are on top side, 19 emitters are closely spaced in the center of the chip. The chip is designed for more than 100 mW cw output power at 850 nm.

The results discussed in the following are based on two other designs that provide even higher output powers at pulsed operation. The main parameters for these designs are given in Table 2.

	Design A	Design B
Footprint mm²	0.30	0.11
Emission area	0.014	0.0072
Addressed pulse length	10 µs	10 ns
Duty cycle	1:100	1:100, 1:1000
Package	Ceramic SMD	PCB

Table 2: Design parameters of two VCSEL arrays, “design A” and “design B”, that are under investigation.

The VCSEL chips can be mounted similar to LEDs either on standard SMD platforms or directly chip on board (COB). Thus, assembly is most simple and cost effective.

CW, PULSED LIV AND FARFIELD PERFORMANCE

In Fig. 1 LIV data of a “design A” laser diode emitting at 850 nm are depicted. Threshold current is 140 mA, corresponding to 1 kA/cm² threshold current density. Slope efficiency of 0.8 W/A results in an output power of 200 mW at 400 mA. Conversion efficiency at this operation point is 23 %. Above 400 mA thermal rollover is dominating the performance and output power is thermally limited to below 250 mW.

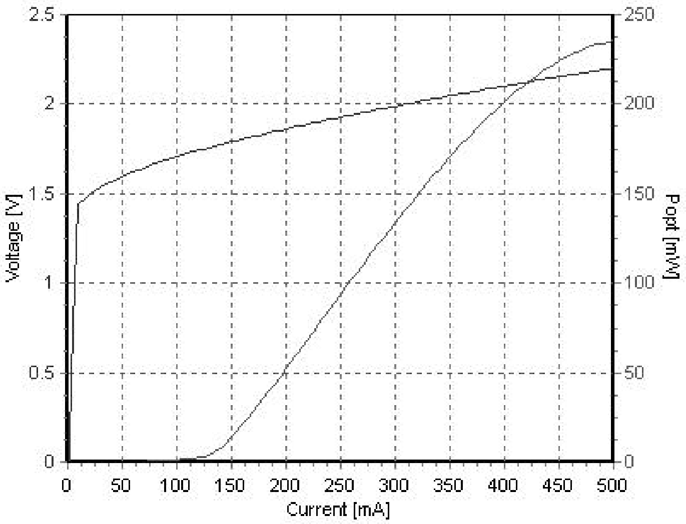

Fig. 2: Cw LIV characteristics of a "design A" laser diode, measured on wafer (no heat sink)

When operating the device in pulse mode (voltage driver), higher output powers can be achieved. Fig. 3 shows LI characteristics for different duty cycles, but constant pulse width of 30 µs. Current is measured as a voltage drop at a resistor connected in series, output power is measured by a fast photodiode for pulse shape control and a calibrated integrating detector for absolute power. For duty cycles of less than 1:50, the influence of average joule heating is negligible and the peak output power is limited by the self heating during the individual pulse to around 0.8 W. With increasing duty cycle, 1:10 and 1:5, peak output power is decreasing to 0.56 and 0.37 W, respectively. Constant threshold current and slope efficiency for currents less than 0.5 A again indicates that peak power is only limited by average heating, but is limited by pulse width as soon as average heating is negligible.

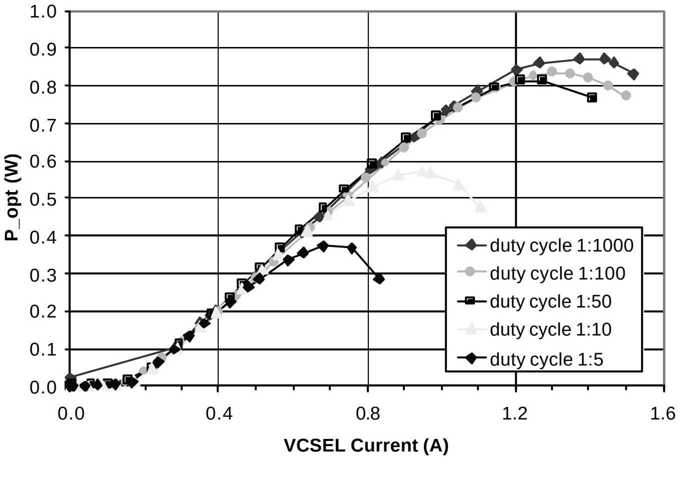

Fig.3: Pulsed LI characteristics for various duty cylces of a "design A" laserdiode, mounted on ceramic SMD platform.

In order to investigate on the influence of pulse width, achievable peak output power has been measured versus applied pulse width. For the experiment the repetition rate has been kept constant at 5 Hz. When reducing the pulse width, the laser peak current has been increased until the self heating during the pulse caused a 3 dB drop in output power, as indicated in the inset of Fig. 4. Down to about 100 µs pulse length, which corresponds to a duty cycle of 1:2000, the peak power is increasing steadily, but going to even smaller pulse widths towards 1µs, peak output power is drastically increasing due to reduced temperature increase inside the semiconductor device during the pulse. 10 µs seems to be the thermally characteristic time for the heat transport from the laser chip to the SMD package.

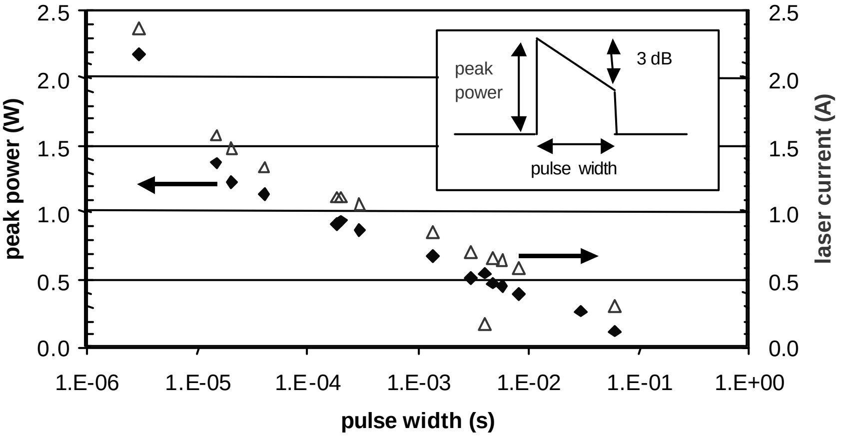

Fig. 4: Peak output power versus pulse width at constant repetition rate of 5 Hz. Laser current is tuned at 3 dB drop of power during pulse length (see inset).

For even shorter pulses, much higher peak output powers are expected. VCSELs of “design B” are designed for short pulse operation around 10 ns pulse width and small duty cycles of less than 5 %. Their active area to chip area ratio is as high as 1:15. Since thermal effects, average joule heating as well as significant temperature increase during the pulse, can be neglected, current and carrier densities as well as electrical parasitics might be the limiting factors for the maximum peak power. In Fig. 5 the average optical power versus average laser current is depicted. Both values must be multiplied by a factor of 1000 in order to correspond with the pulse characteristics since they have been measured as average values at a duty cycle of 1:1000. For comparison, the cw LI characteristics are included, but can hardly be seen in the graph. A zoom in graph is showing the actual values in the inset. Threshold current is 0.2 A, slope efficiency is 0.73 W/A, and maximum peak power of 7.0 W is reached at 12.5 A peak current. Applied voltage amounts to 14 V. The according current density at maximum peak power is as high as 175 kA/cm².

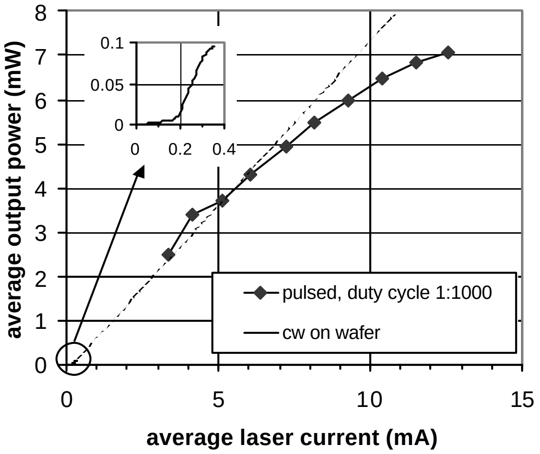

Fig. 5: LI characteristics of pulse operation at 30 ns pulse width for a “design B” laser diode. Duty cycle is 0.1 %, operation temperature is 25°C. LI characteristics of cw operation on wafer are seen in the lower left corner for comparison.

In contrast to cw operated large area VCSELs, the farfield characteristics shown in Fig. 6 present a nice axis centered pattern of low divergence. FWHM is only 15°.

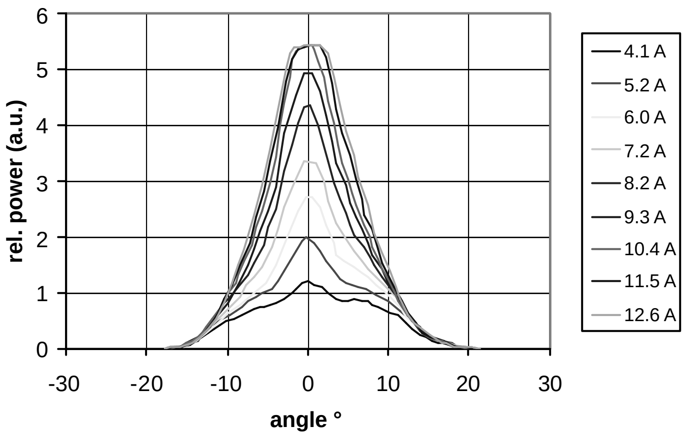

Fig 6: Farfield pattern of a "design B" VCSEL array, 30 ns pulse width with 1 % duty cycle at RT.

THERMAL ASPECTS OF OUTPUT PERFORMANCE

Especially for automotive applications, temperature behavior of the laser diodes are of high interest. Wide temperature ranges have to be addressed. Peak output power and laser current versus ambient temperature for laser diodes under test are shown in Fig. 7. At constant applied voltage, the laser current is increasing by 1.5 dB due to decreasing series resistance of the laser structure with increasing temperature. The detuning of the VCSEL cavity with respect to the peak gain wavelength is homogenizing the temperature performance at low temperatures, since increasing threshold current, increasing slope efficiency and increasing laser current result in only a small increase of output power, showing a maximum around room temperature. At higher temperatures, both, increasing threshold current and decreasing slope efficiency are disadvantageous. The increasing laser current is partly compensating these effects and the power drop at 105°C ambient temperature is less than 1.5 dB compared to maximum value.

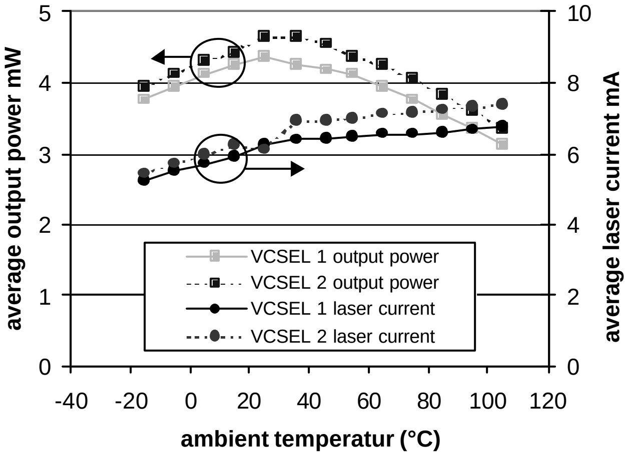

Fig. 7: Temperature dependence of peak current and peak output power versus temperature at constant applied voltage. The output peak power is homogenized due to increased laser current and reduced slope efficiency with increasing temperature.

RELIABILITY

In the past reliability testing of VCSELs has mostly been focussed on cw or qcw operation. Especially operation at extremely high current densities in short pulses has to be evaluated in order to prove the abilty of VCSELs for the discussed applications. In Fig. 8 peak output power versus test time is plotted for “design B” VCSELs. Accelerated aging is achieved by increased ambient temperature of 130°C. The pulse width is 30 ns, duty cycle is 1 %. The laser current amounts to 7.2 A. The output power is measured frequently after cooling down to room temperature. The two groups of power levels are due to electrical parasitics on the test board. After 1900 h no failure is observed and no significant power degradation is detected, even at the corresponding current densities of 83 kA/cm².

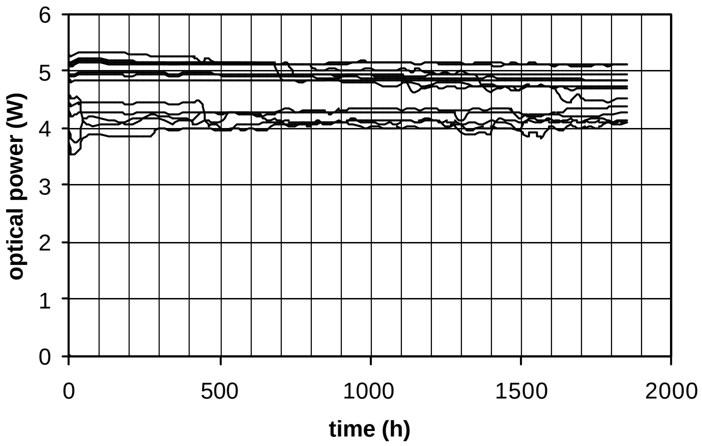

Fig. 8: Peak output power at RT and constant peak voltage of “design B” laser diodes under accelerated lifetime testing. The acceleration temperature is 130 °C ambient, applied voltage is 10 V. Pulse length is 30 ns, duty cycle is 1 %. No failure, defined as 2 dB power drop, observed after more than 1800 h of operation of 13 lasers.

Further tests on wear out have been started. Table 3 gives an overview on test ensembles of both, “design A” and “design B” devices. Ambient temperatures range from 43 °C to 170°C, ensemble size is 12 to 15 devices. Out of the total of 141 devices under test, only one device failed. In this case it has not yet been evaluated, if the VCSEL or the electronics failed.

Design	Pulse mode	Peak current A	Peak power W	Heat sink °C	Test time h	# devices	# failures
A	30/3000 µs	1.0	0.3	85	320	14	0
A	30/3000 µs	1.0	0.3	43	2800	14	0
A	30/3000 µs	1.0	0.3	100	2300	14	0
B	30/3000 ns	4.6	3.5	70	2400	15	0
B	30/3000 ns	5.7	4.3	105	2200	14	0
B	30/3000 ns	8.3	5.5	105	1900	12	0
B	30/3000 ns	7.2	5.0	130	1900	13	0
B	30/3000 ns	6.9	5.0	150	1900	15	0
B	30/3000 ns	6.8	4.9	170	1900	15	0
B	30/3000 ns	14.7	7.5	130	300	15	1 (150 h)

Table 3: Overview of ongoing ALT test of both designs, “A“ and “B”. At ambient temperatures of up to 170 °C only one device failed, which was operated at extreme voltage conditions of 16 V applied voltage.

Although MTTF and activation energy values can not be derived from the data before a majority of devices has failed, there is a good chance that the activation energy of the failure mechanism will not significantly differ from the value of 0.7 eV known for cw or qcw operation. In this case, worst case estimates for the MTTF at 85 °C ambient temperature, derived from the arrhenius plot given in Fig. 9, are in range of 10E5 hours and thus well above the minimum requirement of about 20 thousand hours, indicated by the dashed lines.

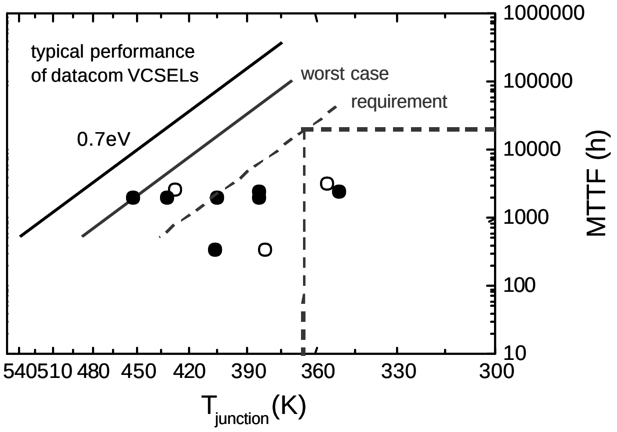

Fig 9: Arrhenius plot of the intermediate reliability data, MTTF versus junction temperature, of pulsed high power VCSEL arrays. Open dots are representing “design A” ensembles, closed dots represent “design B”. So far, no ensemble failed and thus the dots indicate the worst case scenario. For comparison, the typical cw reliability data of datacom VCSELs is included, showing an usual 0.7 eV activation energy. Dashed lines are indicating minimum requirements for automotive applications.

SUMMARY

Small footprint VCSEL arrays provide output powers in pulsed operation of 0.8 W at 30µs pulses and up to 6 W at 30 ns pulses, respectively. In combination with the advantageous circular symmetric and low divergent farfield and a most simple assembly technique, those devices qualify for many cost sensitive applications, e.g. in automotive or industrial laser sensing systems. Intermediate reliability testing shows promising results even for highest applied current densities of 175 kA/cm². MTTF at RT of more than 10E5 h is expected.

Target markets are LIDAR applications in automotive and industrial as well as intelligent lighting systems for camera based object detection and recognition, where high volume, high performance but low cost illumination solutions are key elements.

REFERENCES

[1] M. Grabherr, et al., “Fabrication and performance of tuneable single-mode VCSELs emitting in the 750 to 1000 nm range”, *Proceedings SPIE*, 3757-17, 2005.

[2] D. Wiedenmann, et al., “High volume production of single-mode VCSELs”, *Proceedings SPIE*, 6132-2, 2006.

[3] M. Grabherr, et al., “High power VCSELs – single devices and densely packed arrays“, *IEEE J. Selected Topics Quantum Electron.*, vol. 5, pp. 495-502, 1999.

[4] B. Weigl, et al., “High performance oxide-confined GaAs VCSELs”, IEEE JSTQE, vol. 3, no. 2, pp. 409-415, 1997

[5] D. Botez, et al., “66 % cw wallplug efficiency from Al-free 0.98 µm emitting diode laser”, *Electron. Lett.*, vol. 32, pp. 2012-2013, 1996.

[6] www.tierone.com/accmtrpr.html

[7] Z. Xu, et al., “Smart pixel - photonic mixer device (PMD)”, www.pmdtec.com/inhalt/download/documents/paper_4.pdf