

High power VCSEL systems and applications

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ABSTRACT

Easy system design, compactness and a uniform power distribution define the basic advantages of high power VCSEL systems. Full addressability in space and time add new dimensions for optimization and enable “digital photonic production”. Many thermal processes benefit from the improved control i.e. heat is applied exactly where and when it is needed. The compact VCSEL systems can be integrated into most manufacturing equipment, replacing batch processes using large furnaces and reducing energy consumption. This paper will present how recent technological development of high power VCSEL systems will extend efficiency and flexibility of thermal processes and replace not only laser systems, lamps and furnaces but enable new ways of production.

High power VCSEL systems are made from many VCSEL chips, each comprising thousands of low power VCSELs. Systems scalable in power from watts to multiple ten kilowatts and with various form factors utilize a common modular building block concept. Designs for reliable high power VCSEL arrays and systems can be developed and tested on each building block level and benefit from the low power density and excellent reliability of the VCSELs. Furthermore advanced assembly concepts aim to reduce the number of individual processes and components and make the whole system even more simple and reliable.

Keywords: Vertical-Cavity Surface-Emitting Laser, VCSEL array, High Power VCSEL System, laser heating applications, VCSEL illumination, modular high power laser system, VCSEL reliability

1. INTRODUCTION

Thermal processing of materials is one of the oldest and most important technologies in human history. The ability to cook food or to melt metal enabled mankind to modify the materials provided by nature and drove all historical waves of industrial revolution. Most of the time the required heat has been provided by fire which is still an economic but not always ecologic way. Heating by fire is a mature technology; sophisticated furnace constructions have been invented to provide temperatures well above 1000°C and dedicated gas supply allows tailoring chemical reactions during processing.

Electrically powered devices replaced the fire in more and more applications over the last century. Most electricity is still generated by burning fossil fuels and therefore an improved eco-balance is not self-evident. The major advantage of electrical heat is the ability of better control in time, space and temperature although the major heat transfer mechanism is still a complicated process i.e. a mix of conduction and radiation inside the furnace. Electrically powered furnaces became smaller and easier to integrate into the production process. Most of all goods of today have seen thermal processing and there is hardly any plant not using electrically generated heat excessively.

With the current developments in manufacturing technology electrically powered furnaces come to their limit. Miniaturization and the use of hybrid materials require an increasingly better dosage of heat. Complex manufacturing processes ask for thermal processing at many stages and therefore integrated into the process flow and applied at specific areas only rather than concentrated in a few oven steps heating up the whole product.

An additional drive for a new way of heating will come from the current trend towards “digital manufacturing” including quickly reconfigurable production that enables a fast switching between different products, or even individualized products. The ideal heat source allows spatial control, fast on-off, very compact form-factor and an ease of use allowing the integration into almost any production machine.

Heating with infrared radiation offers the advantage of good spatial control by the use of optics and the separation of heat generation and products i.e. allowing regions of the product to stay cold. Metal filaments and tungsten halogen lamps are used as infrared heat sources and similar to lighting applications represent a mature technology. This technology is currently replaced by solid state sources offering much smaller and colder radiators, simpler packaging, better reliability and possibilities for segmentation and spectral tailoring.

Solid state radiation sources are LEDs and lasers both based on compound semiconductor materials and with many similarities in device design and packaging. Besides the narrower spectrum of lasers the major difference in the application is brilliance where lasers are superior by many orders of magnitude thus enabling much faster and more localized heating than LEDs.

Powerful lasers can be demanding in terms of a well controlled environment, mounting restrictions, laser safety regulations and even the need for expert persons operating them. Driven by such higher demands the cost of laser systems in most applications is still higher than that of the traditional technologies. Removing such obstacles is the vision of high power VCSEL systems and the major goal of their further improvement in technology and design. This article describes why VCSEL technology is most suitable (section 2) and how high power systems can be configured from simple building blocks (section 3) leading to a competitive system performance (section 4). Applications in thermal processing (section 5) and beyond (section 6) are illustrated by a few examples and upcoming technological developments (section 7) are mentioned.

2. WHY VCSEL ARRAYS?

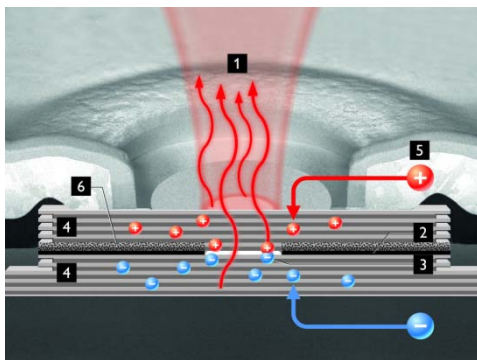


Figure 1: Illustration of a cross section through a single top emitting VCSEL superimposed to a SEM picture.

Vertical Cavity Surface Emitting Lasers (VCSELs) combine the outstanding properties of laser diodes with the ease of use and production of LEDs. Figure 1 shows the working principle of a so-called top emitting VCSEL: DBR mirrors consisting of many AlGaAs layers (4) with varying Al-content enclose an active layer (3) with multiple quantum wells. Electrons and holes are injected via the conductive DBRs and the current is confined by a high Al-content layer (6) close to the active which is partially oxidized after being exposed by mesa etching. A metallic ring contact (5) is deposited on top of the p-conducting DBR, the n-contact is made on the bottom of the GaAs substrate below. Such layer structure and the vertical emission of laser radiation (1) perpendicular to the wafer surface enable the epitaxial growth of many lasers in a single reactor process. Afterwards the wafer is structured into many individual VCSELs and metallic electrodes are evaporated. On a 3-4 inch wafer there are up to more than one million VCSELs which are fully operational on wafer level. Further details and alternative designs can be found in the literature [1].

The laser radiation is emitted with a rotationally symmetric pattern at about 20° divergence angle (full width $1/e^2$). This divergence allows a good directionality on one hand but on the other hand a lateral spreading of the emission and the mixing with neighboring sources. Combination with standard optics is straightforward.

The size of such a single VCSEL and therefore the emitted power is limited (typically 4-20μm in diameter emitting 1-

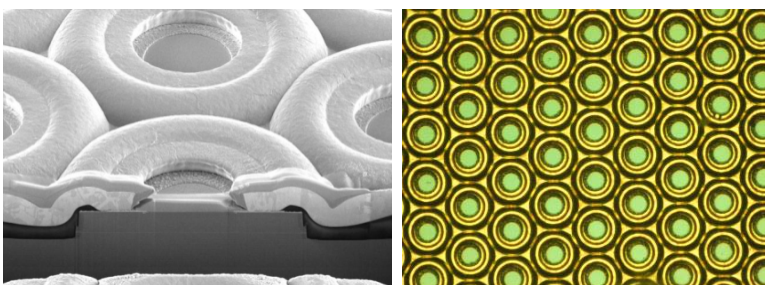


Figure 2: SEM cross section and plan view of a VCSEL array.

30mW). Scaling to larger diameters suffers from the low hole-mobility and the injection via a ring contact. Although alternative designs as e.g. larger bottom-emitters with full contact on the p-side [1] would allow about 10x larger size and power the most straightforward power scaling is using multiple apertures in an array (Figure 2).

Because the top-emitting device described above is most easily manufactured, an array using hundreds or thousands of such lasers

is again easy to manufacture with 2-5W/mm² laser emission. The individual lasers in an array share the same electrodes and are thermally connected. On the other hand they emit incoherently and independently of each other. The superimposed emission of all individual VCSELs in an array is therefore rather uniform and speckle free. Even failures of individual VCSELs do not distort the emission significantly nor do they affect their direct neighbors.

The mounting and contacting of such top-emitting VCSEL arrays is done via hard soldering of the metalized substrate backside and wire bonding to a bond pad at the front side (Figure 3, right). Similar assembly processes are used for (high power) LEDs facilitating know how and equipment for VCSEL assembly.

Single VCSELs or small arrays are already used for sensing and data-com applications since almost 20 years [1]. Several 100 Millions have been produced already [2] and the understanding of device physics and production technology is relatively mature. Although high power arrays just contain more of the same VCSELs their design poses new challenges in terms of current spreading, heat management and especially because of the key role of high electro-optical efficiency. A good overview of VCSEL array designs can be found in Chapter 8 of [1] latest state of performance in [3].

3. HIGH POWER SYSTEMS FROM MODULAR BUILDING BLOCKS

The wide variety of applications of high power VCSEL systems requires power levels ranging from just a Watt in surveillance camera illumination (see below) up to tens of kilowatts in high throughput industrial applications. An economic solution for a wide range of powers and with sufficient flexibility to adapt to specific user needs can be realized by a building block approach:



Figure 3: Assembled emitter (left) and detail of the individual chips (right).

The size of an array chip should be large enough in order to minimize individual assembly effort as well as overhead space around each chip, but small enough to limit the electrical current per chip as well as the thermo-mechanical stress due to mismatch of the coefficient of thermal expansion between GaAs and mounting materials. A chip of 2x2mm² (Figure 3, right) offers a good compromise and yields about 8W optical output if mounted on a densely populated cooler. This chip has 2205 individual VCSELs at a pitch of 40μm and with an active diameter of 8μm each.

In high power systems heat removal is the most severe design bottleneck and micro-channel water coolers are the technology of choice enabling heat densities of several hundred W/cm² at moderate temperatures. Figure 3 shows such an emitter with outer dimensions 8.6x65mm² and 56 chips soldered onto sub-mounts and on a micro-channel cooler. Chips are connected in series in strings of 28 each i.e. the emitter has two strings individually electrically connected via the pads left and right. This series connection allows limiting the current per string to e.g. 10A and in consequence reasonably small contact pins, cables and connectors can be used. The enabled individual electrical addressing opens up interesting options for tailored intensity profiles.

The emitters can be stitched along the short axis to form a heating line i.e. systems of various size and total power can be designed as illustrated in Figure 4. A photograph of the 4.8kW module is shown in Figure 5. The product has all supply lines from the back allowing using the same constructional elements in multiples of 6 emitters and ensuring the supply of cold water equally to all parts of the system. This combines the need for flexibility with the desire to have a minimum number of different parts.

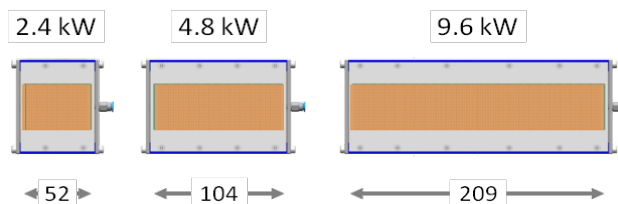


Figure 4: Power scaling of systems with the length of the emission area in mm at the bottom and laser power at the top.

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The electronic driver completing the system is based on a modular concept, too. Figure 6 shows a photograph of the smallest system supplying 6 emitters i.e. 12 zones. The

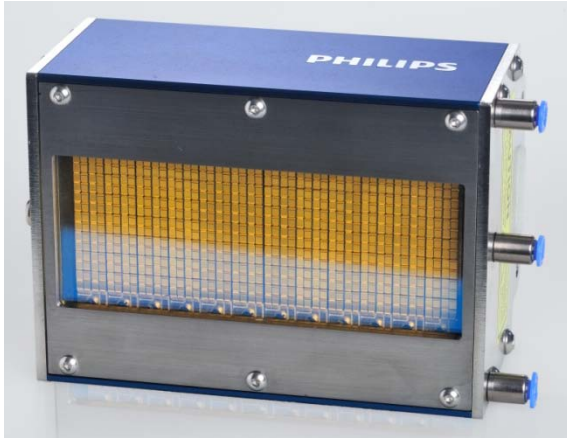


Figure 5: High power VCSEL module with 4.8kW laser power.



Figure 6: Electronic driver system for the high power VCSEL system.

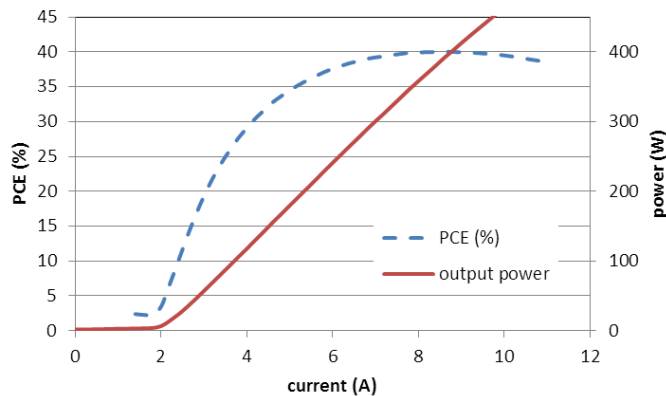


Figure 7: Output power and efficiency vs. current for a single emitter assembled with 56 chips at 808nm.

driver rack at the bottom supplies 6 emitters i.e. 2.4 kW laser output. At the top a PC and a mains supply have been mounted. More racks can be added for larger systems. Each zone can be addressed individually by setting the desired power via an industrial bus interface. This means that the power density profile along the line can be defined for each zone i.e. in steps of 4.3mm. Switching on-off or setting new power levels needs a few ms only.

As a future development a closed loop control will be added using input from a thermo-camera or a line of pyrometers or photodiodes. The primary radiation of the lasers has a narrow spectrum and can be easily filtered out in order to get a good signal to noise ratio in the pyrometric measurement. This makes the use even easier because target temperatures and temperature profiles can be set instead of laser powers. Such system will be able to adjust automatically to changing properties of the processed materials.

4. HIGH POWER VCSEL SYSTEM PERFORMANCE

Laser output and electro-optical efficiency for one emitter at 808nm wavelength are shown in Figure 7. At about 10A the power output exceeds 450W at 40% efficiency. Thermal roll-over will limit the further increase of output power beyond a current of 12A. It should be noted that the output power of a single VCSEL would be more than 2 times as high if not being part of the array and mounted on a densely populated cooler. Thermal simulations combined with spectral measurements have been used to analyze the thermal resistance [4]. The micro-channel cooler turned out to be the major thermal bottleneck i.e. the mounting surface of the cooler is already significantly hotter than the water. Array geometry has been optimized in order to work close to maximum efficiency at the operating point.

The reliability of VCSELs is known to be excellent because of the moderate power density especially on the laser output facet. Catastrophic mirror damage known from edge emitting laser diodes or similar failure modes do not occur. The dominant failure pattern is a gradual fading out of the VCSEL after a very long time. VCSELs in data-com applications have specifications equaling more than hundred thousand hours lifetime. These specifications heavily rely on accelerated life-tests with acceleration factors about 100 times at heat sink temperatures of 170°C and elevated current. Many thousand VCSELs are typically on life-test and are measured in well defined time steps up to e.g. 1500hrs. This method is based on well understood failure modes as e.g. defect migration in GaAs; it is established and relatively safe [5].

Because of the “soft” fading out of few individual VCSELs there is normally no epidemic failure of arrays i.e. even if an individual VCSEL dies early, the rest of the array stays intact and further failures

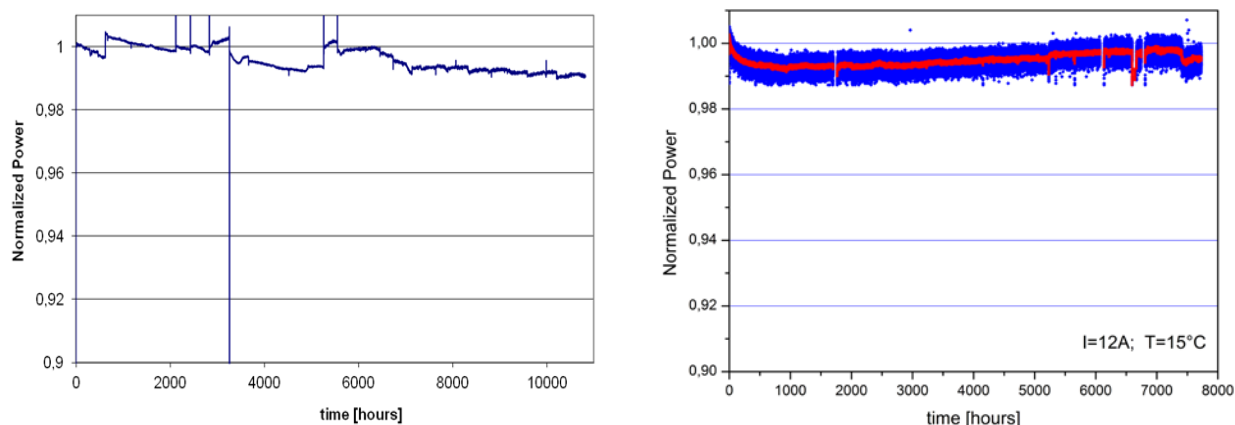


Figure 8: Reliability experiments of full emitters. Left: 1130nm wavelength at 10A. The long tests have seen some interruptions explaining the small discontinuities. Right: 980nm wavelength tested at 12A.

follow the statistics rather than suffering from side damages by neighbors. The junction temperature of the VCSEL in an array on a fully loaded emitter is about 90°C which is in the same order as e.g. data-com product specs.

For a new and hybrid product like a high power VCSEL emitter accelerated life testing is not sufficient because it is not known a priori which part will fail and what the underlying mechanism is. Therefore the final test has to be done in real time i.e. much longer and with significantly higher effort because it requires dedicated drivers and water cooling. A high number of reliability test set-ups continuously measure electro-optical properties and take photographs of all arrays automatically. Figure 8 shows measurements of the output power vs. time for two different wavelengths. Both emitters are operated at 1.2 times the nominal current with the water temperature mostly at 15°C.

The laser output variation of 1% as measured in Figure 8 is extremely small and demonstrates that no degradation has been observed in about 10000hrs. Although the potential of the VCSEL itself is allowing a much longer lifetime and the almost immeasurable degradation in the first 10000 hours is a good indication of much longer system lifetimes; hard proof has to wait for more reliability tests and simply needs more time.

5. APPLICATIONS IN THERMAL PROCESSING

5.1 Advantages of VCSEL heating

High power VCSEL systems offer more than just a new type of laser source [6,7]. They have the potential to redefine every industrial heat treatment process with high demand on process accuracy. The compact and robust systems can be easily integrated into manufacturing equipment. Figure 4 shows a close to 5kW laser system with a volume of only 0.65 liters. Integrated in a production line this system replaces a furnace with more than 1 m length. Due to the high power density and the well-defined heating zones, VCSEL systems can be more efficient than halogen lamps or electrical furnaces in many heating applications.

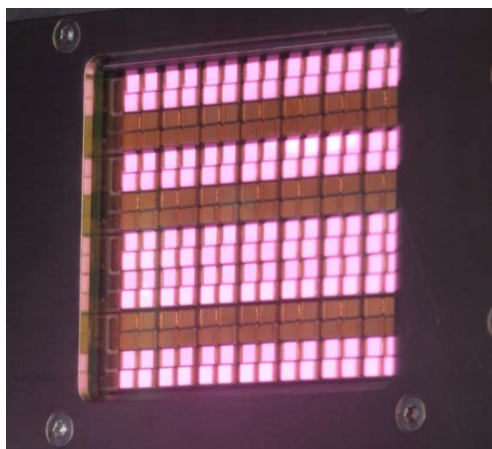


Figure 9: The high power VCSEL system of Figure 12 with independently powered zones.

The directed laser radiation of the VCSEL heating systems delivers high infrared power to a well-defined target area, exactly where it is needed, without complex reflectors, beam shaping optics or scanning units. Each point on the target is irradiated by many individual VCSELs facilitating uniformity and robustness. A uniform intensity distribution is available at a working distance between laser system and target in a range of typically 30-200mm.

VCSEL systems are powered by an electronic driver unit, containing separate driver channels to drive and control the individual heating

zones of the connected VCSEL module. In this way, each heating zone can be controlled independently by setting the current levels of each zone to its desired level from zero to full power as illustrated in Figure 9. Fast switching or pulsing is equally possible. This property enables adjustment and control not only of the total infrared heating power, but also of the power for each zone, independent from its neighboring zones. Even dynamically changing heating profiles during operation are possible, enabling an unprecedented level of control in industrial heat treatment processes.

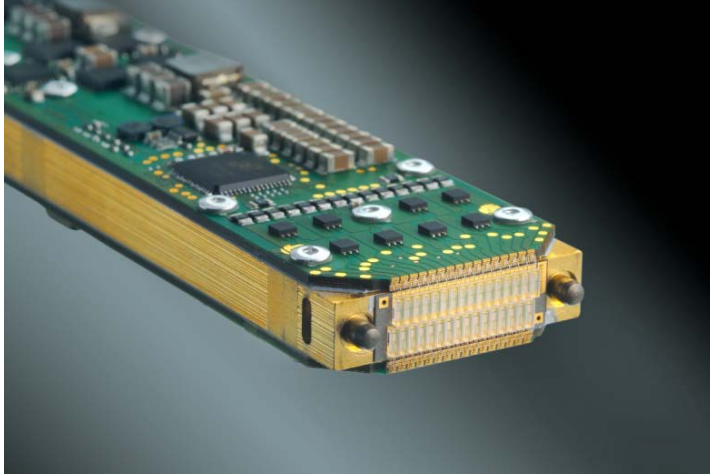


Figure 10: Photograph of an addressable module with 32 independent channels and integrated drive electronics.

can be chosen to support various printing requirements. Dynamic addressing of each individual array is done via pulse width modulation with rise times of 3-5 μ s. With such unique performance the system can be used in advanced printing applications and for material processing with a very fine spatial resolution.

5.2 Application space

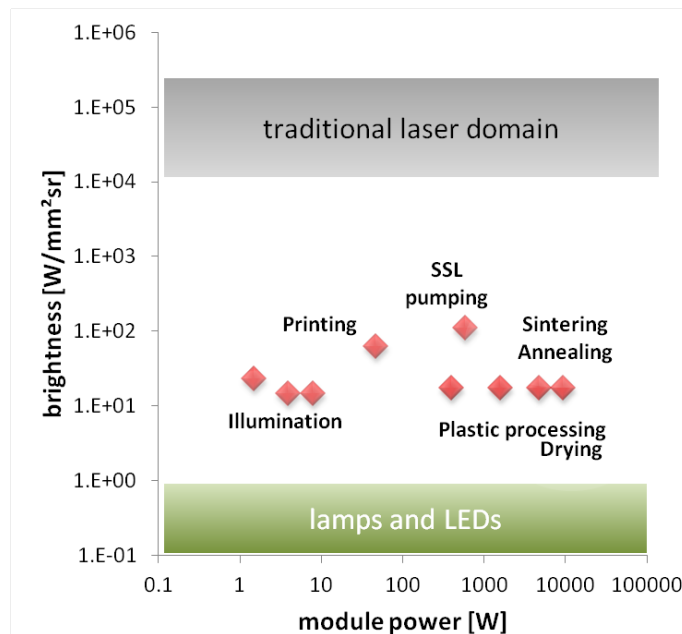


Figure 11: Various applications shown in the space of brightness and power. The red symbols represent the Philips high power VCSEL products described in this article.

High-resolution addressability in 2 dimensions at moderate power is realized in a second class of VCSEL modules as shown in Figure 10. The module is equipped with 32 VCSEL arrays at the front of the large micro-channel cooler and has 32 independently addressable drivers integrated on both sides. Each of the 32 VCSEL arrays delivers 1.5W per channel at the operating point. Micro-lens arrays on top of each VCSEL array improve the collimation and facilitate an imaging to pixels on the target. The complete module with integrated drivers is only 15.5x27.5mm² at the front and 165mm long. Several modules can be mounted next to each other in order to realize a continuous printing line.

As each pixel is illuminated by many VCSELs, the system is very reliable and the illumination pattern is uniform. Aspect ratio and intensity distribution

The heating applications described in the next section and their requirements are shown in the plot of brightness vs. optical power in Figure 11. The brightness level needed in an application is determined by the desired target temperature or temperature rise time, the speed of the production process, the wish for heating of thin layers instead of bulk material, good spatial addressing capabilities or the selective heating of stronger absorbing parts. Total power is mostly determined by the size of the treated area and high power VCSEL systems can be scaled along the horizontal axis by using just more emitters (with constant brightness). The scalable high power VCSEL systems described above can thus be found on a horizontal line in Figure 11.

Traditionally lasers are used in applications with highest requirements for brightness. The simple reason is that there was hardly any alternative, no matter how complicated or costly the traditional laser might have been. On the other hand, lamps and LEDs are rather limited in brightness to a maximum of 1W/mm²/sr. This limitation does not

allow high speed production processes or a good spatial selectivity.

The high power VCSEL systems described here offer a medium brightness level of 10-100W/mm²/sr. This is significantly more than lamps or LEDs but still low compared to lasers used for e.g. steel cutting or welding. For heating applications these medium brightness levels are ideal. They enable heat-up times from below a second to a few ten seconds which perfectly match the cycle times of many production lines. Lower brightness would resemble the slow batch processes in a furnace, higher brightness would lead to a too fast temperature increase at certain parts (e.g. the skin layer) resulting in overheating without allowing heat to be conducted to the rest of the work piece.

High power VCSEL systems are bound to change the world of thermal processing and replace traditional heat sources. Compact and affordable systems over a wide range of kW powers are needed to facilitate this change. The race for high brightness which is important on the innovation roadmap of edge emitting laser diodes is not of interest here.

5.3 Application examples

The power density of VCSEL heating modules is sufficient to melt plastic materials at high speed. Examples of related industrial processes are forming of plastic parts, and joining of parts by plastics welding or by thermally melting glues.

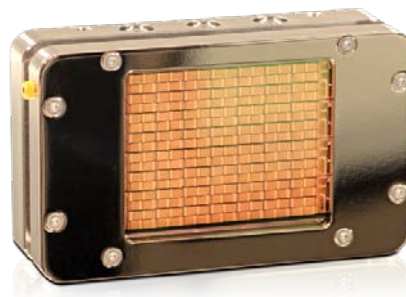
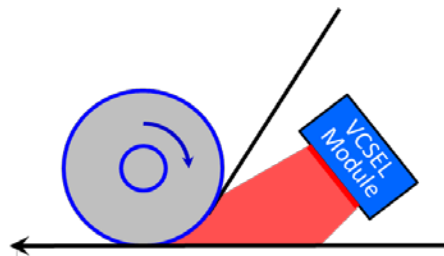


Figure 12: Illustration of a composite manufacturing process and a 50x80mm² form factor VCSEL system delivering 1.6kW laser power.

A specific field of interest is the thermal treatment needed in various composite manufacturing processes. An example is the fast carbon fiber placement process illustrated in Figure 12. Heat is applied at the laying head to attach the fibers or tapes on the

surface thereby enabling a stable build-up of the composite layers. The small laser head shown in the figure can be easily integrated into the limited available space or mounted on a robot arm.

VCSEL systems can be used for drying and curing processes of surfaces, paints, coatings and thin films. The integration of a VCSEL line heating module into an offset printing system for in-line ink drying has been described earlier [8] with special emphasis on the realized uniformity along the line of better than 1%.

In applications, where material is structurally modified at high temperature, the energy density delivered by the VCSEL heating technology enables new solutions. As an example, in solar cell manufacturing, the firing step used for metallization line sintering has been realized by VCSEL heating [6]. A first concept has been developed to integrate a VCSEL heating module in a conventional manufacturing line by mounting the module above the existing conveyer belt for the silicon wafers. Experiments were performed with a VCSEL heating module (similar but twice as long as shown in Figure 5) integrated into a Fast Firing System of Rehm Thermal Systems. The results show maximum temperatures above 900°C reached within 0.5 s, corresponding to heating rates in excess of 1000 K/s. First wafers produced with the VCSEL heating system instantly reached the benchmark performance of state-of-the-art solar cells.

As a further field of industrial heating processes, local heat treatment of steel parts with VCSEL technology is under investigation. Especially the precise spatial and temporal control of the heating profile can be beneficial, e.g. at sharp edges of a workpiece, which are difficult to treat with conventional techniques. First tests have been performed with good results: After local heat treatment of a steel sample of 1.5 mm thickness at 900°C, the crystal structure was changed as expected, forming a softened zone to facilitate the subsequent cold forming process.

6. MORE APPLICATIONS

Active illumination with near infrared is used in camera systems for surveillance and inspection [9]. It allows pictures of objects at high speed and under difficult conditions. The stable emission characteristics of a VCSEL array make it a favorable radiation source because of the efficient and easy combination with simple (zoom-) lenses avoiding the complicated optics needed for LEDs with their wide emission patterns. Furthermore the brilliance of a VCSEL array is 10-100 times higher than that of the brightest LEDs enabling focused illumination at large distance up to several hundred

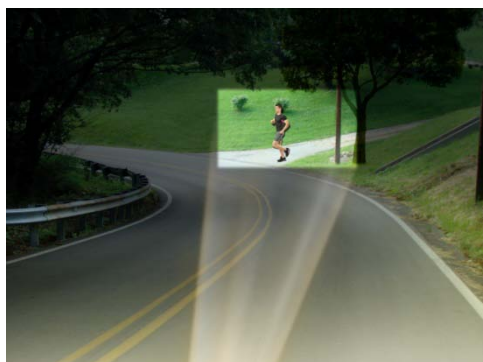
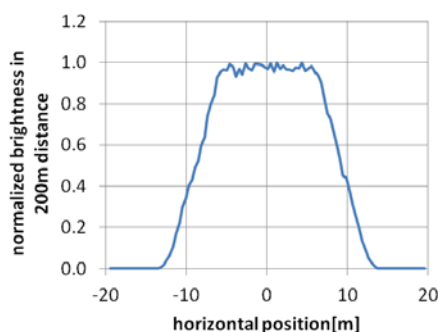


Figure 13: Illustration of the uniform illumination pattern with adapted shape allowing recognizing a person on the road. On the right a measurement of a cross section through such illumination pattern is shown.



meters. The most important advantage in this application may be the very uniform illumination of a field of interest with an aspect ratio which can be tailored to the needs of the camera. Figure 13 illustrates the use of a tailored illumination pattern and shows a measurement of a cross section on the right. The light distribution is uniform and without disturbing speckle.

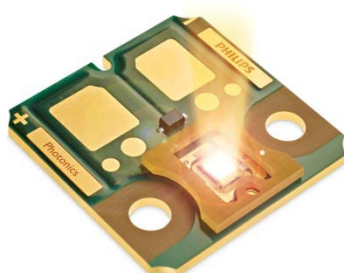


Figure 14: Photograph of an illumination product. The high power VCSEL array is emphasized by the illustrated emission cone.

Industrial inspection and consumer applications incl. 3D capabilities make a promising field for the future use of VCSEL arrays. Different technologies are used for real 3D measurements: Structured light patterns i.e. many thousand spots of light can be projected on a scene and the position of objects in space can be derived from a camera image measuring the deflection of individual points. The high brilliance of VCSELs facilitates the generation of structured light patterns.

Another technology for an unambiguous distance measurement is the so called time of flight method where light is emitted by a VCSEL and the travel time towards an object and back to a sensor is measured. The very fast switching times of VCSELs in the ns range and the well reproducible turn-on behavior enable a precise time of flight measurement.

Figure 14 shows a photograph of an illumination product where the 2x2mm² sized chip is soldered to a 20x20mm² MCPCB with a frame for lens mounting and electrical contacts. This product emits at least 4W of

laser radiation under adverse conditions (60°C heat sink temperature). Other chip sizes mounted to the same platform complete a full a range of products from 1-8W.

Besides heating and illumination high power VCSELs have interesting applications as pump sources of solid state lasers. A very compact system of only 23mm diameter (Figure 16) producing more than 500W QCW power pumps a small laser rod in the longitudinal direction and is used in a laser ignition application in combustion engines [10]. Robustness, low thermal shift of the emission wavelength and a uniform pumping pattern characterize the attractiveness of VCSELs. Transversal pumping of solid state laser rods benefits from the same VCSEL properties. Laser rods can be pumped from several sides, a building block system adaptable for a wide range of rod length and power is based on the emitter shown in Figure 15.

7. TECHNOLOGY OUTLOOK

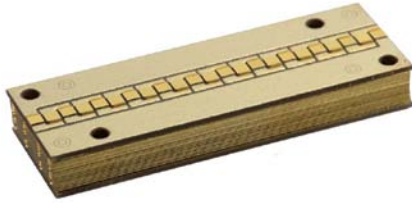


Figure 15: Single row emitter with 23 chips on the cooler delivering 200W cw laser output.

50% is almost on par with alternative solutions using edge emitters and requiring additional fiber delivery and homogenizing optics [14,15].

Next to a good efficiency, heat removal is critical in order to realize low cost systems at high packing density. There may be some freedom to improve the performance of single chips on large mounts, but a dense packing like in high power systems requires the removal of a few 100W/cm². This automatically leads to the use of micro-channel water coolers and they are key components for further developments in assembly.

The soldering of VCSEL chips is done on insulating but thermally well conducting substrates (AlN, BeO, diamond). While the last two are either toxic or expensive AlN works well in combination with hard solders like AuSn or SAC because of the well matched coefficient of thermal expansion. The soldering on an insulating surface in combination with wire-bonding allows a series connection of chips and therefore limits the required current.

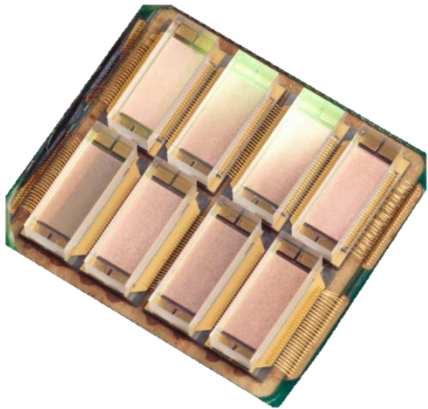


Figure 16: QCW 500W module of 23mm diameter with 8 arrays of integrated micro-lenses.

VCSEL array chips as already applied in the product shown in Figure 10 and in Figure 16 for the QCW pump module [10].

8. CONCLUSIONS

Heat treatment of materials is one of the basics of industrialization. This application field is enormous and way beyond today's application space of lasers. High power VCSEL systems provide a novel solution for exactly this wide field of heat treatment in manufacturing processes. In the course of increasing digitization of industrial processes, they provide an excellent tool, which can be easily integrated into production lines ("digital photonic production"). Tailored treatment areas with stable power uniformity can be realized without the need for additional homogenizing optics.

Addressability in time and space allows heating exactly where and when it is needed. Furthermore, addressability enables a fast reconfiguration of a production line for changing products. The building block approach described in this article supports the various applications, but is based on a manageable number of different parts. VCSEL are fundamentally LED-like devices and will eventually reach LED-like price levels, however coming with orders of magnitude higher brightness. The remaining challenge is to exploit the full advantage of this new technology by integration and validation in industrial processes.

9. ACKNOWLEDGEMENT

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