

Integrated high power VCSEL systems

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ABSTRACT

High power VCSEL systems are a novel laser source used for thermal treatment in industrial manufacturing. These systems will be applied in many applications, which have not used a laser source before. This is enabled by the unique combination of efficiency, compactness and robustness. High power VCSEL system technology encompasses elements far beyond the VCSEL chip itself: i.e. heat sinks, bonding technology and integrated optics. This paper discusses the optimization of these components and processes specifically for building high-power laser systems with VCSEL arrays. New approaches help to eliminate components and process steps and make the system more robust and easier to manufacture.

New cooler concepts with integrated electrical and mechanical interfaces have been investigated and offer advantages for high power system design.

The bonding process of chips on sub-mounts and coolers has been studied extensively and for a variety of solder materials. High quality of the interfaces as well as good reliability under normal operation and thermal cycling have been realized. A viable alternative to soldering is silver sintering. The very positive results which have been achieved with a variety of technologies indicate the robustness of the VCSEL chips and their suitability for high power systems.

Beam shaping micro-optics can be integrated on the VCSEL chip in a wafer scale process by replication of lenses in a polymer layer. The performance of VCSEL arrays with integrated collimation lenses has been positively evaluated and the integrated chips are fully compatible with all further assembly steps.

The integrated high power systems make the application even easier and more robust. New examples in laser material processing and pumping of solid state lasers are presented.

1. INTRODUCTION

High power VCSEL systems have been successfully demonstrated in applications for thermal treatment in manufacturing [1]. Compactness and robustness of the VCSEL systems facilitate the integration into the production equipment. First products have entered the market and the next step is to mass-produce and to simplify all processes.

In the context of the technology project VORTEIL subsidized by the German Federal Ministry of Education and Research (BMBF) under contract FKZ 13N12470 relevant steps in the production process have been investigated in detail and have been improved. The technologies presented in this paper can be summarized under the headline “integration” i.e. offering the same or better functionality with fewer parts and production steps. Based on these results the next generation of high power VCSEL systems will achieve improved performance with simplified and robust production technology.

High power VCSEL systems are based on a building block approach, which has been described in detail earlier [2]. One chip of 2x2mm² has 2205 individual lasers at a pitch of 40µm and each

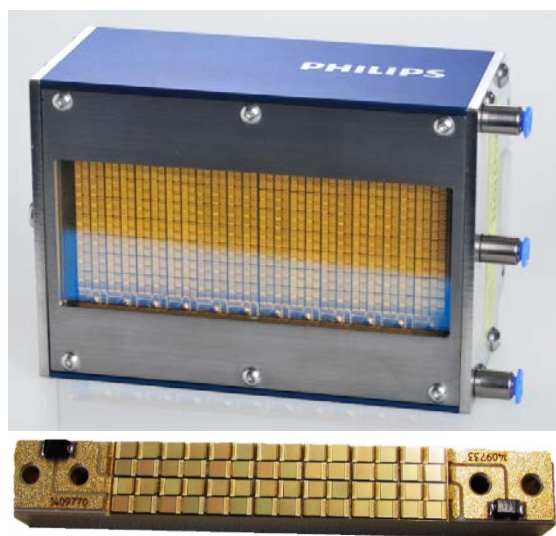


Figure 1: High power VCSEL module with 4.8kW laser power on top and the basic building block “emitter” below.

with an active diameter of 8 μ m. One chip yields about 8W optical output and 56 chips are used in one so called “emitter” (Figure 1, bottom). 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 temperature gradients. Chips are electrically connected in strings of 28, i.e. one emitter has two strings that are each connected in series. This series connection allows limiting the current per string to 13A and as a consequence reasonably small contact pins, cables and connectors can be used. The emitters can be stitched along the short axis to form heating lines of various size and power.

An example of a 5kW system comprising 12 emitters is shown in Figure 1. Thanks to the low current and integrated mechanical features the system volume is below one liter.

2. INTEGRATION

The goal of integration is optimum performance from the simplest VCSEL system with fewest materials and manufacturing steps involved. Such a system is more robust and more cost effective. On the other hand it is desirable to use standard processes as much as possible and to leverage e.g. the large LED supply industry. Therefore integration should not generate and enforce very specific processes.

Integration has been improved on several levels in high power VCSEL systems. Micro-channel coolers have been developed which do not only offer a better heat removal (more heat out of the same area) but also integrate mechanical and electrical contacts allowing easy mounting i.e. they are designed for manufacturability.

Chip assembly on sub-mounts and coolers is the next level of integration and of high importance. The large number of VCSEL chips used in a high power systems requires simple and high yielding assembly processes.

Individually mounting micro-optics on each chip requires a similar effort as the chip assembly itself. Therefore wafer level integration of optics as presented below is very beneficial in terms of cost and simplicity. Integrated micro-optics can be used in many applications, which benefit from the about ten times higher brightness.

The following sections step by step describe these new technologies and show experimental results. The combination of all technology steps in new products will be realized soon after.

3. MICRO-CHANNEL COOLER

The emitters as shown in Figure 1 are the core of the building block approach. Depending on the desired power level and geometry of a total system a number of such emitters is mounted on a water distribution means and further built into a housing. In order to facilitate this mounting and to avoid weak links like the soldering of thick cables the cooler structure is designed for mechanical fixation and electrical contacting in single bolts. Each string of 28 chips is connected to the electrical terminals at one end of the cooler. Therefore two zones per emitter can be addressed independently by the in total 4 connections. The maximum current of 13A allows for compact standard connectors.

The inner structure of the micro-channel cooler has been optimized for the high power VCSEL application by Rogers Germany [3]. The flow inside the structure is arranged vertically as shown in Figure 2. The advantages are a uniform

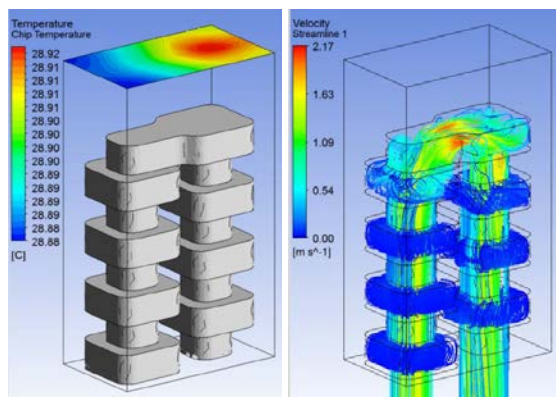


Figure 2: Simulation of temperature and flow in the new cooler structure.

temperature at the surface of the cooler instead of a gradient with increasing temperature along lateral flow direction. In addition the thermal resistance of the cooler structure has been lowered significantly by the new design to $R_{thA}=0,125K*cm^2/W$. With typical values reported later in this article the optical output of an emitter is more than 400W and the dissipated heat equals 600W. The cooling surface is about 320mm² thus resulting in a temperature increase of 23K above the water temperature. With this excellent heat removal capability the VCSELs can be safely operated in the region of good efficiency and lifetime.

4. ASSEMBLY TECHNOLOGY

VCSEL chips are assembled on an insulating carrier in order to separate neighboring chips electrically and to connect all chips in series. Thermally well conducting substrates like AlN are used with a coefficient of thermal expansion close to GaAs. Major requirements on the solder interface are:

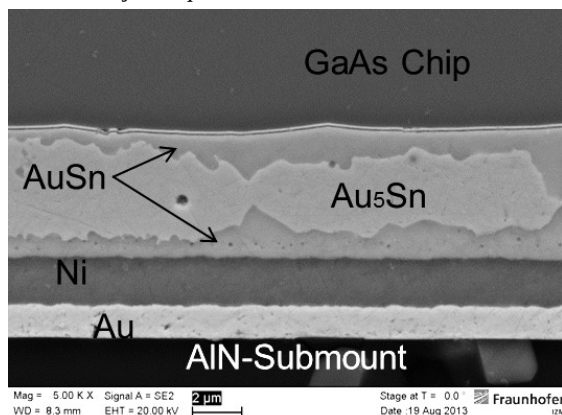


Figure 3: Cross section of AuSn solder interface.

- Low thermal resistance to minimize temperature drop across the interface in order to get maximum power per area out.
- The interface has to survive many thermal stress cycles in operation and storage. Typically 125/25/-55 °C are applied and especially at -55°C the mechanical stress is maximum compared to the solidification temperature of the solder.
- The required equipment should be widely available and used in semiconductor manufacturing.
- At least for the combination with wafer-level micro-lenses the process temperature should be as low as possible.

Various assembly technologies have been investigated in the context of the German subsidy project VORTEIL and all results shown in this section have been achieved by the Fraunhofer Institute IZM in Berlin [4]. AuSn solder is stable against thermal cycling but needs a high temperature solder process on non-standard equipment. SAC solder is standard in the semiconductor industry but has a much lower resistance against thermal cycling. Silver sintering can combine good resistance with a standard process at low temperature.

4.1 Soldering with AuSn

AuSn is commonly used as “hard-solder” in laser diode assembly. The method requires a vacuum oven and relatively high solder temperature above 300°C. The solder interface can be thin (low thermal resistance) and serve as a high quality low porosity interconnect. Thermal cycling (1000 times 125/25/-55 °C) reveals excellent reliability of the solder joint. AuSn soldering is therefore the method of choice for a first level soldering, in case that the sub-mount plus chip has to be assembled on a second level e.g. a micro-channel cooler.

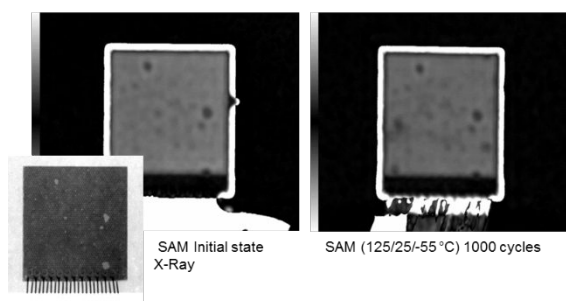


Figure 4: X-ray (lower left) and scanning acoustic microscopy (SAM) photos before (left) and after (right) thermal cycling.

Figure 3 shows a cross section of an AuSn solder interface incl. an analysis of the metallic compounds. Figure 4 shows images of the complete chip by x-ray and by scanning acoustic microscopy. No voids and no reliability issues have been detected after soldering nor after thermal cycling. Actual test results with VCSEL chips in operation show a very good reliability, all life-tests presented in this article use AuSn as a first level VCSEL array solder.

4.2 Soldering with SAC

SAC soldering using paste or preforms is widely used in the semiconductor industry and therefore many assembly facilities are in place. The lower process temperature reduces the stress on the devices and the lower temperature is advantageous for the wafer-level micro-optics, described later on. Typical thicknesses of the interface are 25-50 μm which are significantly larger than those used for AuSn. The increase in thermal resistance is acceptable on system level, however chip tilt in the solder bed may become critical. Therefore it has been explored to use Ni-spacers (25μm size balls) in the solder preform. Figure 5 shows a cross section through a soldered chip. Some voids in the solder are visible but size and volume contribution are acceptable i.e. do not negatively affect the quality of the solder interface.



Figure 5: Cross section of SAC solder interface.

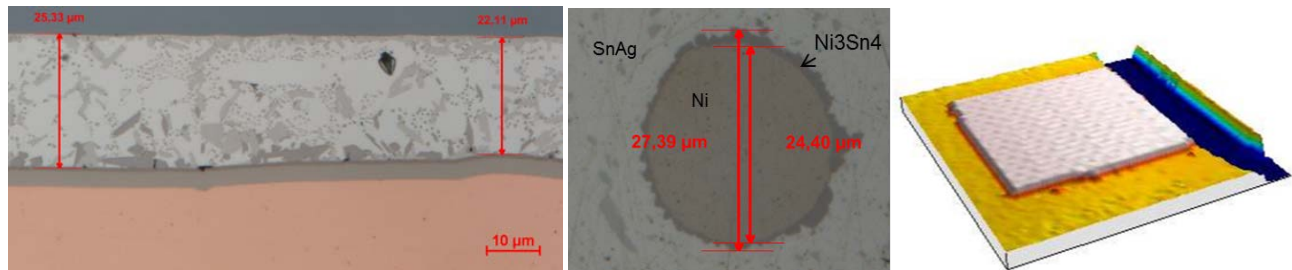


Figure 6: Detail of a cross section through a SAC solder interface (left), a Ni-spacer in the preform (middle) and a 3D profile of the soldered chip (right).

Figure 6 shows details of the interface including a measurement of the thickness of the interface layer and on the right a 3D profile of the soldered chip. As expected the thickness is kept constant at 25µm by the Ni-spacers embedded in the solder preforms and no tilt is observed. The spacers are not visible in the cross sections as only a tiny fraction of spacers is used. Figure 6 (middle) shows a spacer in the pre-form.

4.3 Silver Sintering

An attractive new bonding method is Ag-sintering. It needs screen printing of paste as well as pick and place equipment. The methods used are both pressure-less and with pressure but the larger the size of the sintered areas the more pressure is required. The adhesion to chip and sub-mount is very good and so is the reliability of the sintered layer against thermal cycling (>>1000 times 125/25/-55 °C). Figure 7 shows cross sections through the silver sinter interface and illustrates the

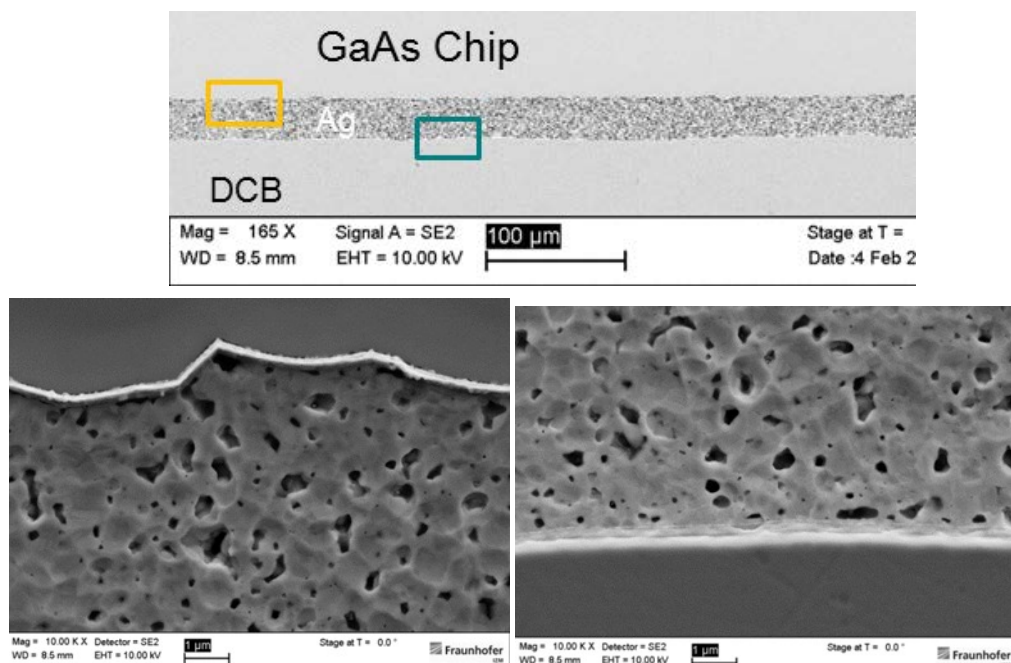


Figure 7: Cross section through a silver sinter interface at low (top) and high (bottom) magnification.

good density, which can be achieved. The method is especially interesting in combination with the integrated micro-lenses because of the low process temperature.

5. WAFER-LEVEL MICRO-LENSES

Micro-lens arrays with a pitch identical to that of the VCSEL array improve the collimation of the VCSEL emission and preserve the brightness in arrays. Thus collimation with a micro-lens array can reduce the divergence angle at best by the factor $(pitch/active\ diameter)-1$ (e.g. $40\mu m$ pitch, $8\mu m$ active diameter can be improved by a maximum factor 4) as has been described before together with a method for the integration of micro-lenses on wafer scale on the flat backside of the substrate for bottom emitters [5]. A discrete assembly of micro-lens arrays on posts and above top-emitting VCSEL array chips has been applied as well [6]. Each placement needs 6 axis adjustment plus time to cure the glue which could sum up

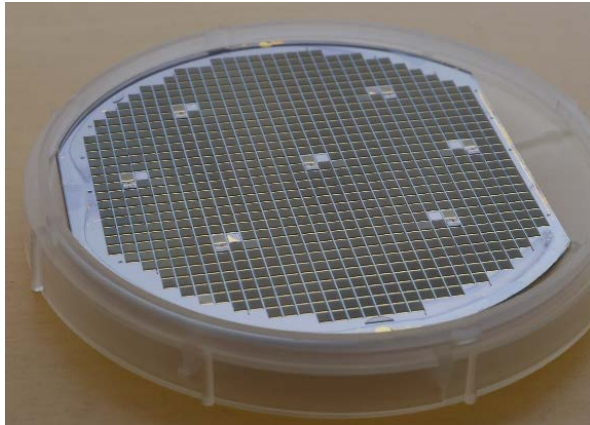


Figure 8: 3" wafer with polymer micro-lenses produced on wafer.

to minutes per array. It is therefore highly desirable to enable wafer scale micro-lens arrays i.e. making thousands at a time.

Top-emitting VCSEL arrays as used in this article have clear advantages in terms of simple manufacturing and assembly with standard processes. However their bumpy topography makes the integration of micro-lens arrays on wafer level a new challenge. A new process based on on-wafer replication of micro-lenses in a polymer layer has been investigated by the Fraunhofer Institute IOF [7] to produce full VCSEL wafers with integrated micro-lenses on top.

Figure 8 shows a 3" VCSEL wafer with polymer micro-lenses produced on wafer level. The micro-lens facets are on top of an about $120\mu m$ high pedestal and cover the front side of the chip as shown in more detail in Figure 9. The array described in this article has a pitch of the mesas of $40\mu m$ with $8\mu m$ active diameter. One array of $2 \times 2 mm^2$ has 2205 individual mesas. The divergence angle (full width $1/e^2$) of the VCSEL is maximum 20° . In order to capture most of the light and to realize a good collimation we designed a distance between VCSEL and micro-lens of $120\mu m$ (in polymer) and a radius of curvature of the lens of $42\mu m$. The replication process generates very accurate micro-lens shapes with rms-deviations typically smaller than $20 nm$.

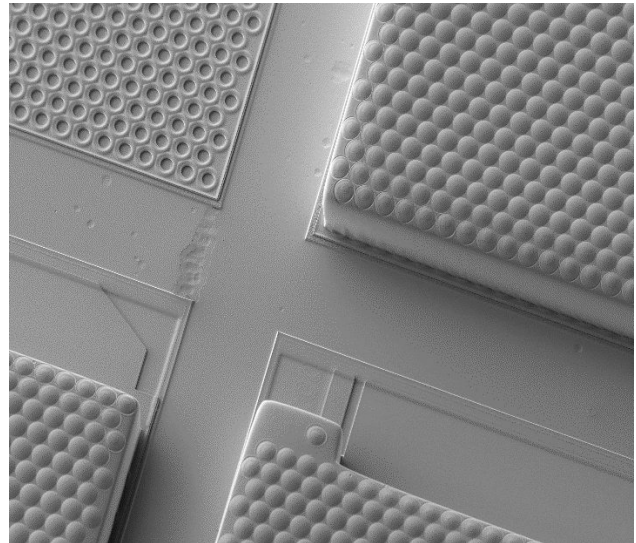


Figure 9: SEM photo of a wafer with VCSEL arrays and integrated micro-lenses. The top left array has no lenses for comparison.

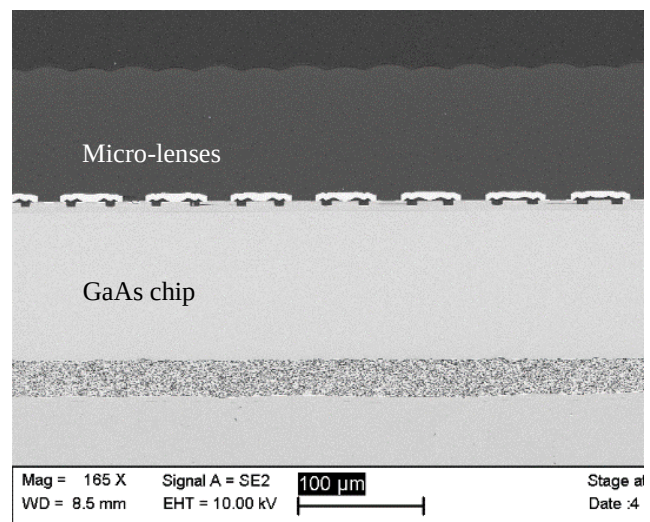


Figure 10: Cross section through a VCSEL chip with micro-lenses on top, which has been Ag-sintered to a DCB.

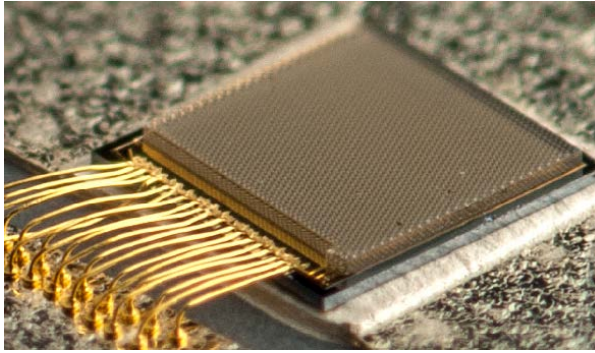


Figure 11: 2x2mm² VCSEL array chip with integrated micro-lenses.

For the subsequent processes like sawing of the GaAs wafer and especially for the wire bonding of the assembled chip it is important not to cover sawing lanes and bond pads with polymer. Figure 9 shows that almost perfectly perpendicular side-walls in the polymer were obtained. For illustrative purposes the top left array has not been covered with micro-lenses.

Figure 10 shows a cross section through the VCSEL chip structure with the micro-lenses on top. The chip has been Ag-sintered to a DCB. The photograph illustrates the relatively small pitch of the structure compared to the thickness of the lenses, the chip and the sinter layer. Ag-sintering is the bonding method of choice because of the low process temperature. High temperatures would lead to more stress caused by the large difference in the coefficient of thermal expansion and could

cause delamination of the polymer and the VCSEL array chip.

Figure 11 shows a photograph of the assembled chip with integrated micro-lenses. It has been sintered to the DCB and wire bonded. This configuration is used in single array products in e.g. illumination applications [8]. The optical performance tests described below are using this set-up.

Figure 12 (left) shows a camera measurement of the emitted far field image using an array with 2205 individual mesas with micro-lenses on the chip. The divergence angle is reduced to a full angle at $1/e^2$ of 6° , which is a factor of 3.3 smaller than the 20° for the array without micro-lenses. The brightness of such a chip is ten times higher than without micro-lenses.

As a further performance test of the micro-lenses the amount of scattered and refracted light outside the primary cone has been measured in Figure 12 (right). A large laser power-meter has been positioned directly in front of and in a distance of 25cm from the chip corresponding to a full angle of 11.4° . 92% of the light has been measured inside this angle. This is considered to be a reasonable value in view of the uncoated interface to the air and the fact that light emitted under large angles will not hit the associated micro-lens but can be bend outwards.

We conclude that the process of on wafer integrated polymer micro-lenses is feasible and shows a good performance. The

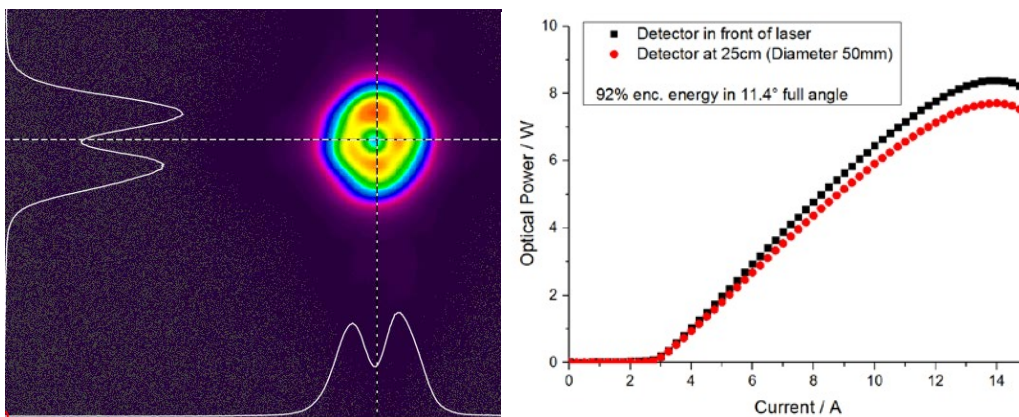


Figure 12: Measurement of the far-field of a 2x2mm² VCSEL chip with integrated micro-lenses and of the optical power at two different positions of the detector.

chip with on wafer micro-lenses is compatible with all further production steps and is currently investigated on emitter level. The significant increase in brightness can be leveraged in many high power applications. Faster heat-up can be one advantage but a larger free working distance is interesting as well.

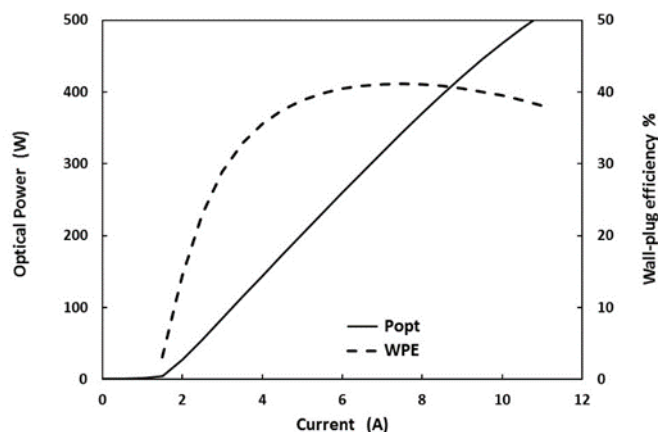


Figure 13: Output power and efficiency vs. current for a single emitter assembled with 56 chips at 808nm.

rely on accelerated life-tests with acceleration factors about 100 times at heat sink temperatures of 170°C and elevated current. The method is based on well understood failure modes as e.g. defect migration in GaAs; it is widely established and relatively safe [10]. 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 alone 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 high power drivers and water cooling. Eight reliability test set-ups continuously measure electro-optical properties and take photographs of all arrays automatically. Figure 14 shows measurements of the normalized 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. Small discontinuities are related to e.g. a move of the equipment and recalibration of the emitter performance on a reference measurement set-up afterwards.

The laser output variations as measured in Figure 14 are extremely small and it can be concluded that no degradation has been observed in almost 20000hrs. Although the VCSEL itself is allowing a much longer lifetime and the almost immeasurable degradation in the first 20000 hours is a good indication of long system lifetimes; hard proof has to wait for more reliability tests and simply needs more time. The results shown in Figure 14 are in some part based on the predecessor

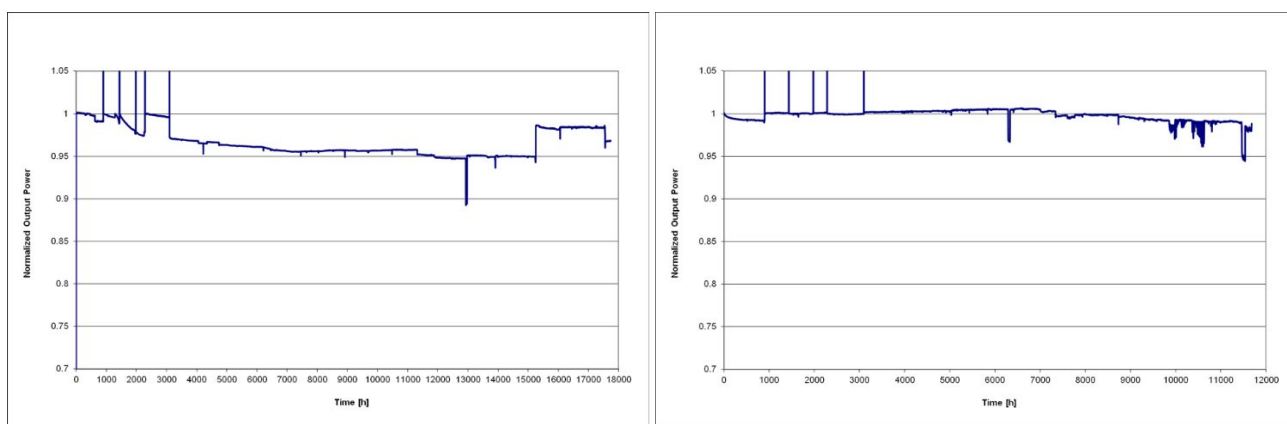


Figure 14: Reliability experiments of full emitters. Left: 1130nm wavelength at 10A. Right: 980nm wavelength tested at 12A. The long tests have seen some interruptions in facilities explaining the small discontinuities.

6. PERFORMANCE AND RELIABILITY

Laser output and electro-optical efficiency of an emitter are shown in Figure 13. Slightly below 10A the power output exceeds 450W at 40% efficiency. Thermal simulations combined with spectral measurements have been used in the past to analyze the thermal resistance [9]. The micro-channel cooler was identified to be the major thermal bottleneck which determines the point of roll-over. This underlines the relevance of the improvements on the cooler as described above.

The reliability of VCSELs is known to be excellent because of the moderate power density especially on the laser output facet. The dominant failure pattern is a gradual fading out of the VCSEL after a very long time. VCSELs in data-com applications have specifications corresponding to more than hundred thousand hours lifetime. These specifications heavily

technology as only for those the really long test times are available. Further experiments with the new technologies are ongoing and e.g. the new cooler structure already survived 8000h at two times the nominal water flux.

7. APPLICATIONS

Thermal treatment may be by far the most frequent process used in manufacturing, but only at a few places lasers could make an inroad. For thermal treatment homogeneous illumination of large areas at a lower brightness, and accurate temporal as well as spatial control of the power is required. This is complicated for conventional high-power lasers, while VCSEL arrays inherently have these capabilities.

High power VCSEL systems have been successfully tested in metal softening and hardening, in the treatment of solar cells [11], curing of coatings, activation of glues and drying of ink [12]. All these applications benefit from the good uniformity without the need for complicated optical set-ups and the compactness of the systems. The power density of VCSEL heating modules is ideal to melt plastic materials at high speed, already without the micro-lenses described in the preceding



Figure 15: Welding of fiber-reinforced thermoplastic tapes with a VCSEL heating module. Left: Schematic. Middle: Integration on the automated tape-laying robot. Right: Close up of module and press wheel.

paragraph. The benefit of better collimation or higher brightness can be exploited by a larger working distance or will enable new processes with new materials.

7.1 Fiber-reinforced tape welding

For weight saving, while maintaining or improving mechanical strength, fiber-reinforced composite materials are nowadays being used in aerospace production and more recently finding applications in the automotive industry. Welding of tapes of carbon fibers embedded in a thermoplastic matrix is using automated placement of tapes on a mold. During placement the tape is also welded to the surface of the previous layer, by melting both surfaces before pressing them together (see Figure 15 left). It allows producing parts at the location where they are needed, eliminating transportation costs.

Figure 15 shows a 1.6 kW VCSEL heating module, containing four emitters, integrated in a tape-laying robot. This work has been performed in cooperation with Fraunhofer IPT [13] under German subsidy contract 13N13477. The orientation of the module is such that its radiation is directed into the wedge formed by the tape and the substrate. In this way both surfaces are melted before they are pressed together by the press wheel. The orientation of the emitters within the module is such that the power can be varied over the width of the tape, such that for instance during curved motion, where the outer radius has a higher speed, this can be compensated by a higher power.

7.2 Edge banding of furniture panels

Figure 16 shows a high power VCSEL system in a professional, high-speed woodworking machine. Laminated particle board is widely used in the woodworking industry for making desktops or cabinet doors. The edges are usually finished with a plastic band that is conventionally glued to these edges. This always leaves a visible seam between the edge band and the laminated surface, which over time collects dirt and induces delamination due to moisture entering the seam. An improvement is seamless edge banding using a laser to melt the band to the panel edge and simultaneously to the surface laminate, significantly improving the appearance and making it immune for deterioration by moisture.



Figure 16: High power VCSEL product in a woodworking machine. Left: High power VCSEL system. Middle: Integration of the flat module into the equipment below the red hood. Right: Illustration of the process.

The flat VCSEL system is fully integrated into the machine i.e. the VCSEL system is covered by the red hood in Figure 16. Direct illumination of the edge band from a short distance is used in order to realize the most compact system. Thanks to the huge number of individual VCSELs, the illumination is very uniform and robust to variations among individual VCSELs. An external connection is made for cooling water and to the electronic driver module by standard power cables. The process is illustrated on the right of Figure 16. The incoming edge-band is heated by the two groups of VCSEL emitters thus enabling a high throughput. By the addressable zones in the module the system can be adapted to different panel size and the process can be optimized. The successful application of a product in the harsh environment of woodworking workshops demonstrates the robustness of VCSEL systems. Traditional laser systems have been used in furniture edging in the past. Those used a separate laser cabinet linked to the production equipment via a fiber plus optics or a laser scanner i.e. a more complicated configuration.

7.3 Solar-cell manufacturing

A key step in photovoltaic solar cell manufacturing is the fast firing of metallization lines. This is conventionally done in large belt ovens as shown in Figure 17 (left). The metal lines, which are screen-printed on polycrystalline Si wafers, are dried in the first section of the oven at around 500 °C. In the fast firing section of the oven, the temperature is ramped to above 800 °C, to alloy the metal with Si and are, while exiting the system, cooled down to ambient temperatures. The ramp rate is limited to 130 °C/s due to the limited power density of the used halogen lamps.

To investigate potential advantages for improved process control and cell efficiency, the fast firing sections in this oven were set also at 500 °C, such that a flat thermal profile is provided over the entire length of the oven. Close to the exit, a 9.6 kW 808 nm VCSEL module, containing 24 emitters was mounted for fast firing (see Figure 17 right). Experiments were done varying the power and the belt speed.

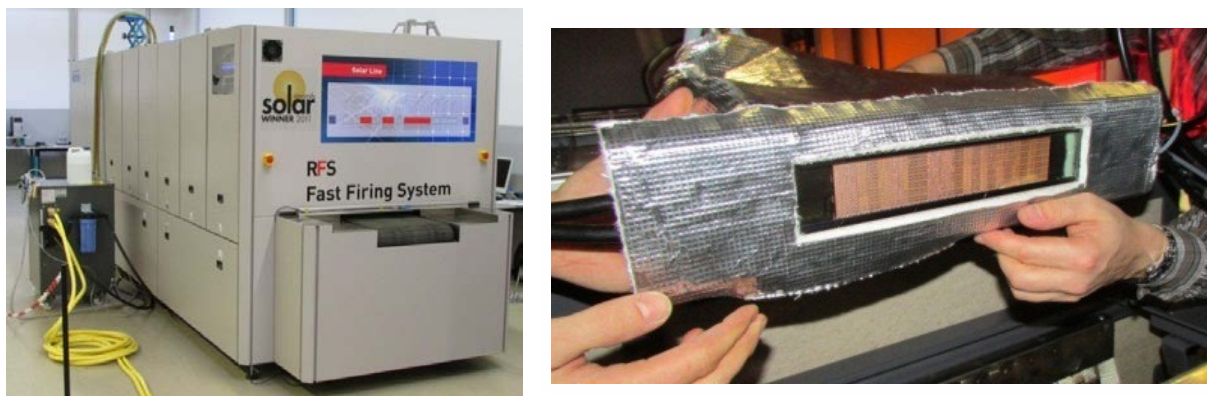


Figure 17: A belt oven of Rehman Thermal Systems GmbH, for fast firing of solar cells (left) and the 9.6 kW 808 nm VCSEL module mounted inside this oven close to the exit.

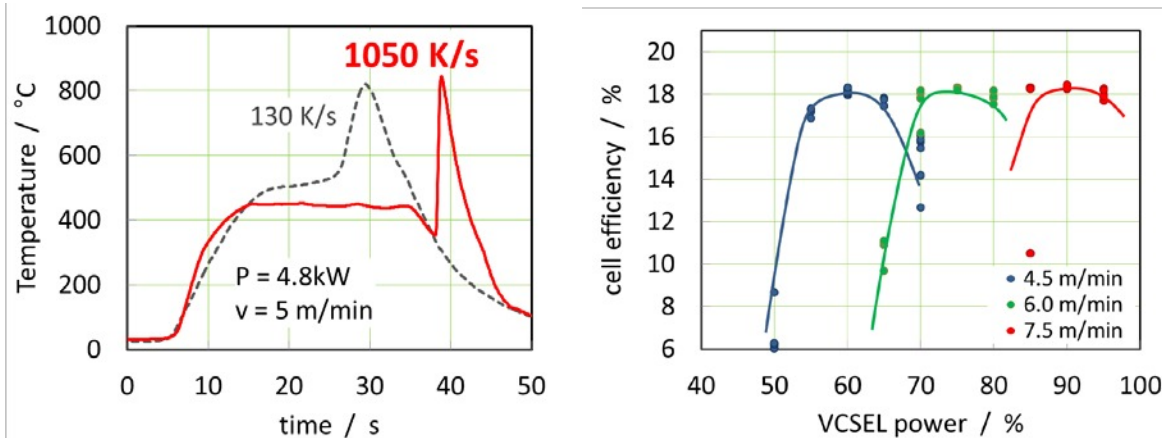


Figure 18: Left: Normal temperature profile in a fast firing oven (black dashed) and using VCSEL module (solid red). Right: Cell efficiencies as a function of belt speed and relative VCSEL power, as measured by Fraunhofer ISE [14].

The resulting temperature profile is shown in Figure 18 (left), indicating that the ramp rate can be increased by an order of magnitude using the VCSEL module. The cell efficiencies as a function of belt speed and power setting are shown in Figure 18 (right). For every belt speed up to the highest value of 7.5 m/s a plateau in the efficiency is found of 18.5%, which equals the best result achieved with conventional firing. This provides the potential for lower production spread and opens up the possibility of very compact machine concepts.

VCSEL heating may also replace belt ovens for other applications like firing of thick films for passive components- and electronic circuits and printed electronics.

7.4 Line modules and solid state laser pumping

High power VCSELs can be applied as pump source for solid-state lasers. Laser rods are surrounded by VCSEL pump modules and are pumped from several sides. The configuration is similar as used for lamps in the past, more and more recently for edge-emitting laser pump modules. The advantage of lasers over lamps is the significantly better spectral match and therefore higher system efficiency. Compared to edge emitters VCSEL modules offer a reduced spectral shift with temperature, a better uniformity and a much more robust design.



Figure 19: Single row emitter with 23 chips on the improved cooler delivering 200W cw laser output.

A building block system adaptable for a wide range of rod length and power is based on the emitter shown in Figure 19. It is 50mm long and can be stitched almost seamlessly in the long direction. The 23 VCSEL chips deliver 200W CW output power and more in QCW operation. All technological improvements described in this article are currently combined in these emitters.

Next to rod pumping this module can be used for thermal processing of lines and contours. Especially using the integrated micro-lenses and additional optics very thin lines of approximately 0.2 mm width can be irradiated.

8. CONCLUSIONS

High power VCSEL systems provide a novel solution for the wide field of heat treatment in manufacturing processes. The building block approach supports various applications with a manageable number of different parts. With improved mechanical design of coolers, a proper choice of the assembly process and with on-wafer integrated micro-lenses, the number of manufacturing steps is significantly reduced, while the performance of high power VCSEL systems is further improved by these new technologies.

VCSEL-based heating systems are compact, robust and easy to integrate and can be offered at significantly lower cost than conventional laser systems. VCSEL arrays are now finding their first inroads into industrial applications and have been designed-in into commercially available production machines.

9. ACKNOWLEDGEMENT

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