

VCSEL ARRAYS EXPANDING THE RANGE OF HIGH-POWER LASER SYSTEMS AND APPLICATIONS

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Abstract

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.

Because of their fast switching capability and low power dissipation, vertical-cavity surface emitting laser-diodes (VCSELs) have been widely used for datacom and sensing applications. By forming large-area arrays with hundreds of VCSELs per mm², their use can be further expanded to high-power applications. In this way power densities of several W/mm² are achieved, making VCSEL arrays an ideal solution for many heating applications, ranging from melting and welding of plastics and laminates to curing, drying and sintering of coatings.

A turn-key system concept has been developed allowing fast and easy configuring systems to the specifications of the applications. The compact and robust system can be built directly into the manufacturing equipment, thus making expensive fibers and homogenizing optics superfluous. These systems are now finding their first inroads into industrial applications and have been designed-in into commercially available production machines.

Introduction

For the manufacturing of numerous industrial and consumer products, thermal processes are being used. Traditional ways for coupling the energy for heating into the work piece encompass burners, hot air blowers, convection ovens, micro-waves, induction heating and halogen lamps. All these methods have their merits and

are probably there to stay for specific applications but in general they heat and switch slowly. Because they heat slowly they need to be bulky for sufficient throughput. Because they switch slowly, the dosing is inaccurate. Furthermore, these methods often suffer from inhomogeneous spatial dosing.

Edge-emitting laser diodes and diode-pumped solid-state lasers have superior brightness compared to conventional radiative heat sources, but for many heating applications the power density is too high and the treated area too small. By optical means this power can be diluted to homogeneously heat larger areas, but this requires complex optics, making such systems bulky, vulnerable and expensive [1].

Like LEDs are nowadays replacing incandescent- and gas-discharge lamps for general lighting purposes, significantly increasing their efficiency and reliability, VCSELs will provide the future lamps for heating. Both manufacturing as well as assembly of VCSEL heat sources have many similarities with those of LEDs, providing cost advantages.

Without optical means they provide a very homogeneous illumination that can in principle be scaled to arbitrary areas. Because they can directly illuminate the work piece they are very compact, eliminating the need of fiber-coupled systems. Both in time, as well as spatially, the power can be controlled accurately and their narrow bandwidth allows tailoring it to the absorption spectrum of the treated material. The inherent robustness of VCSELs and use of standard LED assembly methods provide systems with high reliability, resistant against harsh workshop conditions [2,3,4].

High-power VCSEL array systems

VCSEL are produced with standard semiconductor wafer processing methods- and equipment, involving lithography, wet- or reactive-ion etching and metal- and dielectric deposition. Unlike edge-emitting lasers-diodes, their manufacturing is completed after wafer

processing is finished. They can be tested and binned by probe testing on wafer level, such that after dicing, the good dice can be selected for the subsequent assembly process. Assembly involves standard semiconductor assembly processes- and equipment, for pick-and-place, die attach and wire bonding.

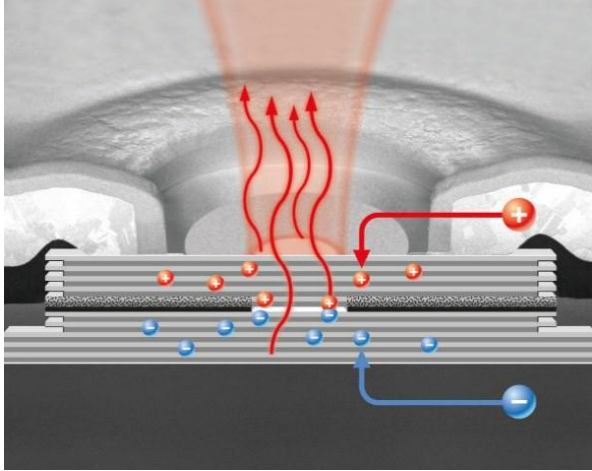


Figure 1 Schematic cross section of a VCSEL

Figure 1 shows a schematic cross-section of the active area of a single VCSEL. The active layer, consisting of multiple quantum wells, is situated between epitaxially grown so-called distributed Bragg reflectors, abbreviated DBR mirrors. These mirrors consist of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ multi-layers with alternating low and high Al content and, hence, alternating magnitude of the refractive index. The lower mirrors are doped n-type and the upper mirrors p-type, which also allows to use these mirrors as leads for the electrical current. Close to the quantum-well region a so-called current confinement layer is grown, which consists of an $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer with $x \approx 1$. After etching so-called mesas, isolating the p-doped areas from each other, this layer is exposed and during a selective oxidation it is transferred into an isolating Al_2O_3 layer, except for the central region. The width of the isolating region is determined by the oxidation time- and temperature and the Al content. The cathode contact is made by a metallic contact to the highly n-type doped substrate, either on the backside of the wafer or the front-side and the anode contact is provide by a ring-shaped metal contact on top of the p-type DBR mirror. For high-power arrays, the cathode is usually made on the backside of the wafer by a blanket deposition and the p-contact is enforced with a thick electroplated Au layer for adequate distribution of the current over the array. Depending on the mesa and aperture dimensions, the optical output power per VCSEL amounts 1 to 10 mW. The wave-length can be varied by tuning the resonance frequency of the cavity and emission spectrum of the

quantum wells between 700 and 1200 nm, but for high-efficiency, wavelengths should be restricted to the range of 800 to 1100 nm. By packing up to 600 VCSELs per mm^2 in an array, as depicted in Figure 2, optical power densities of several W/mm^2 can be achieved.

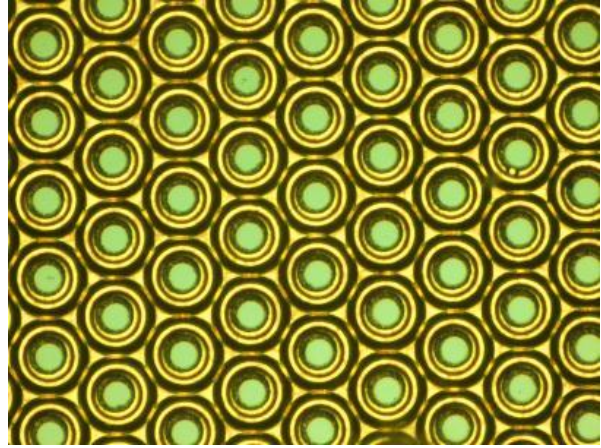


Figure 2 Top view of VCSEL array

In the array in this figure, the VCSEL are hexagonally packed at $40 \mu\text{m}$ pitch, such that a VCSEL array chip with dimensions of $1.8 \times 2.0 \text{ mm}^2$, including the bonding pad area, contains 2205 individual VCSELs. At an output power around 4 mW per VCSEL, output powers of 8 – 10 W per chip are obtained.



Figure 3 VCSEL array emitter containing 28 VCSEL array chips, with each 2205 individual VCSELs

Larger arrays can be formed by assembling multiple array chips next to each other, forming so-called emitters. The emitter shown in Figure 3 contains 28 array chips of $1.8 \times 2.0 \text{ mm}^2$. The chips are soldered on ceramic sub-mounts with high thermal conductance and these sub-mounts are soldered on a NiAu plated copper cooling structure. The 28 chips are divided in two “zones” of 14 chips, which are contacted in series by wire-bonding from the anode bonding pad on the chip to the solder pad of the next chip. A board on either end of the emitter is used for electrically connecting one zone to the power-supply connectors. Bolts for mechanically fixating the emitters to these connectors and the housing also serve for electrically contacting the boards to the connectors. The emitting area of such an emitter is $8.5 \times 41 \text{ mm}$, divided up in two addressable zones of each $2.2 \times 41 \text{ mm}^2$. One emitter can deliver a total optical output power of $> 400 \text{ W}$.

Even larger arrays are formed by placing multiple emitters next to each other. An example where 12 emitters forming a 4.8 kW module is shown in Figure 4.



Figure 4 A 4.8 kW VCSEL module containing 12 emitters with 24 individually addressable zones



Figure 5 Power supply for 12 channels of 6 VCSEL emitters

The housing is not hermetically sealed but instead an inlet is provided for purge gas, to prevent condensation on the water-cooled emitters. Additional purge gas inlets are available to provide a flow parallel to the

outside of the cover window, to prevent vapours from heating the work piece polluting this window. Per block of 6 emitters there is a water in- and outlet on the backside of the module and space for connecting two power-cable plugs.

The power supply shown in Figure 5 is configured to be able to drive up to 12 channels of one such block of 6 emitters. An EtherCAT® industrial bus interface enables software control of the power. Within 1 ms it can switch from zero to maximum power.

Modules of infinite length and power could be realized in this manner but in practicality it should be limited to about 1 m length and 50 kW optical power.

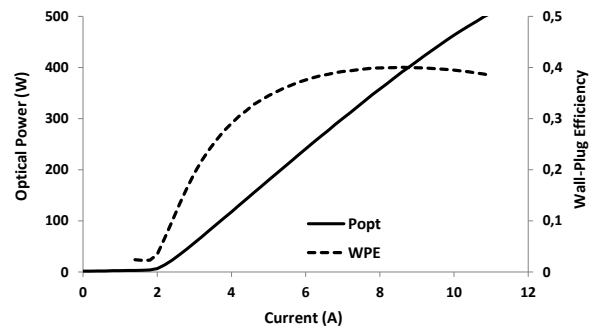


Figure 6 Optical output power and wall-plug efficiency of an 808 nm VCSEL array emitter

The optical output power and wall-plug efficiency of an 808 nm wavelength VCSEL array emitter is shown in Figure 6. At a current of about 9A an output power of 400 W, corresponding to 115 W/cm², is achieved at an electrical to optical efficiency of about 40%.

The near-field of the VCSEL emitters, as shown in Figure 7, displays a very homogeneous illumination. At larger distance the existing ripple is further evened out, but at the cost of a reduction of the average power density.

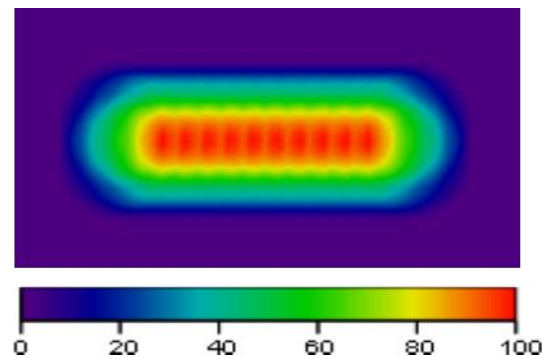


Figure 7 Near-field of VCSEL emitter at a distance of 30 mm from the VCSEL surface

Advantages of high power VCSEL arrays

As compared to conventional heating methods, VCSEL arrays offer a number of advantages. The power density of $>100\text{W}/\text{cm}^2$ allows increased process speed.

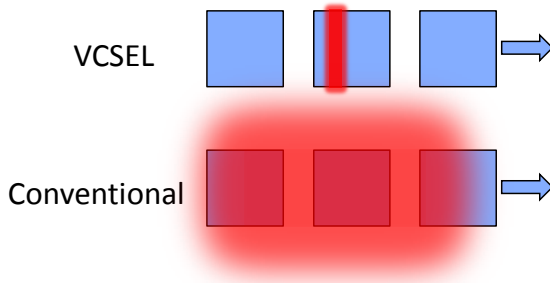


Figure 8 Schematic heat pattern for VCSEL heating vs. a conventional belt oven

In Figure 8, it is sketched how material is flowing through a conventional belt oven. Due to the low rate of energy transfer, it needs to stay a long time in the oven and therefore these ovens need to be made long enough for sufficient throughput. In contrast, the VCSEL system dimensions can remain a fraction of that of the work piece, because of its high power density. The low divergence of the VCSEL illumination, combined with the fast switching speed, allows to heat only when and where it is needed, which allows dimming spatially and over time, to only heat the work piece and not its surrounding. The narrow spectrum as compared to halogen lamps is stable when dimming, allowing accurate process control and can be chosen to overlap with maxima in the absorption spectrum of the material, to increase the overall energy efficiency of the process. The inherent high life-time of solid state devices of $>> 10,000$ hrs. offers low maintenance- and operational costs.

Conventional edge-emitting diode-lasers are able to provide similar advantages. However, their elliptical beam characteristics and high power density requires either expensive, bulky, fragile optics or scanner systems, for diluting and homogenizing the power [1]. Because of their circular far field and homogenization by overlapping radiation of a larger number of individual VCSELs, VCSEL arrays offer homogeneous illumination without optics and can be placed directly in the vicinity of the work piece. They are robust against back reflection, are compact and easy to integrate and because of their simplicity a factor of 2-5 cheaper than comparable edge-emitter diode laser systems.

The division of the emitting area in addressable zones and fast switching within milliseconds, allows spatial control of the heating profile, as depicted in Figure 9.

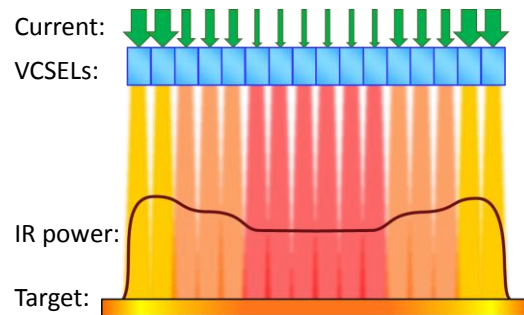


Figure 9 Spatial heating-profile control by addressable zones

This can be used e.g. to compensate for increased heat conduction at the edges of a work piece and can be adjusted dynamically in case of irregular shapes or non-linear movement of the material. When integrated with an arrays of thermal sensors, closed-loop control of the generated heating patterns is possible.

In roll-to-roll processes photonic curing and thermal treatment is used on surface layers, metallization lines, coatings and glues. Here the addressability of the VCSEL heating systems can be used to generate dynamic heat patterns with structured pulsed light, as schematically depicted in Figure 10.

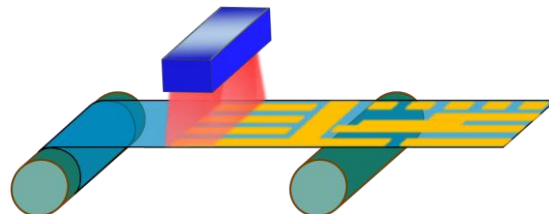


Figure 10 Generation of dynamic heat patterns with structured pulsed light

Pixelated heating systems

While the area heating systems are addressable, the smallest dimension of the addressable zones is $2.2 \times 41 \text{ mm}^2$, due to connecting 14 chips of $1.8 \times 2.0 \text{ mm}^2$ in series. This is sufficient for most purposes but for some applications this is still too coarse. Using smaller chips that are individually addressable, so-called pixelated heating modules can be made with VCSEL arrays. As for every channel two current leads are needed, that need to carry several Amperes, the biggest challenge for finer pixelation is determined by finding space for the contacting area and the volume of the current leads. In order to alleviate this challenge, the driver electronics has been integrated in the module such that for every module with 32 channels, one pair of supply cables and a signal cable is needed, as seen in Figure 11.

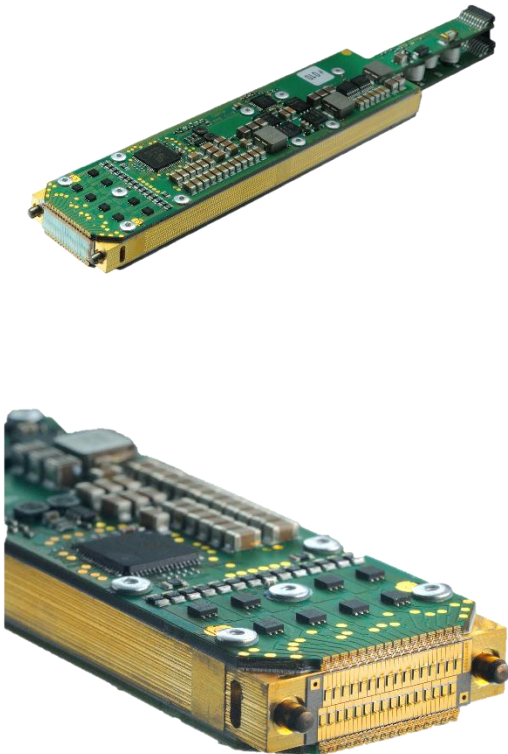


Figure 11 Pixelated heating system with 32-channels of 1.5 W output power

The emitting area of each VCSEL array is $0.5 \times 0.7 \text{ mm}^2$, delivering 1.5 W of optical power. By the use of micro-lens arrays and secondary optics, these dimensions can be de-magnified by a factor of up to five, resulting in $100 \times 140 \text{ }\mu\text{m}^2$ pixels with a power

density of $> 10^4 \text{ W/cm}^2$ and a pitch of $100 \text{ }\mu\text{m}$ (250 DPI) [5,6].

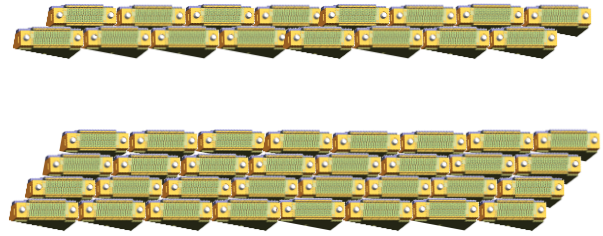


Figure 12 Two-dimensional stacking of pixelated heating modules to form a continuous line, in the top picture without de-magnification and in the bottom picture for a demagnification of a factor of two.

By stacking the module in a two-dimensional patterns a pixelated heating line can be generated as schematically shown in Figure 12. In the top picture no de-magnification is used and the modules are positioned such that in the horizontal direction, the right edge of the last pixel of the first module is aligned with the left edge of first pixel of the next module. When material is moving perpendicularly to this line in the vertical direction, the offset of the pixels in the vertical direction is compensated by a delay in the time that they are switched on.

By placing micro-lens arrays in front of every VCSEL array and using one secondary lens per module, the near-field of each VCSEL array can be projected on the work piece, de-magnified by a factor of up to five. In the bottom picture in Figure 12, a de-magnification by a factor of two is assumed. Here the modules are arranged in cascades of four modules. After de-magnification, within one cascade, the right edge of last pixel of the first module is aligned with the left edge of the first pixel of the next module. And the right edge of the last pixel of the first cascade is aligned with the left edge of the first pixel of the next cascade. Obviously, by this de-magnification by a factor of two, the power density per pixel is increased by a factor of four.

These massive parallel pixelated VCSEL heating systems can be used to significantly increase the throughput of applications where currently galvanic laser scanners are used, as long as a power density of $10^2 - 10^4 \text{ W/cm}^2$ is sufficient for these applications. Instead of scanning one laser over a two-dimensional area, the line is moved linearly over the material and multiple individual VCSEL arrays are switched on in parallel when needed. Especially when the area fraction that needs to be heated is high, increases in throughput by a factor of 10 - 100 can be achieved.

Applications

Application of VCSEL-based heating systems has been investigated in the areas of steel hardening- and weakening, curing of coatings, activation of glues, plastic welding and drying of ink [2,3,4,5]. In this paper two applications with a high potential for large scale industrial applications and one that has recently been designed-in into commercially available industrial scale manufacturing equipment are discussed.

Carbon 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. Currently most parts are being made with thermoset matrix material. Layers of epoxy-pre-impregnated weaves of fibers are placed and pressed on top of each other on a mold and are subsequently cured in large autoclaves at several bars pressure and at temperatures up to 400 °C. These autoclaves are expensive and their throughput is poor. Welding of tapes of carbon fibers embedded in a thermoplastic matrix can eliminate the need of such autoclaves. Using automated placement, tapes are laid on a mold but during placement also welded to the surface of the previous layer, by melting both surfaces before pressing them together (see Figure 13). In this manner treatment in an autoclave can be eliminated. It also allows producing parts at the location where they are needed, eliminating transportation costs.

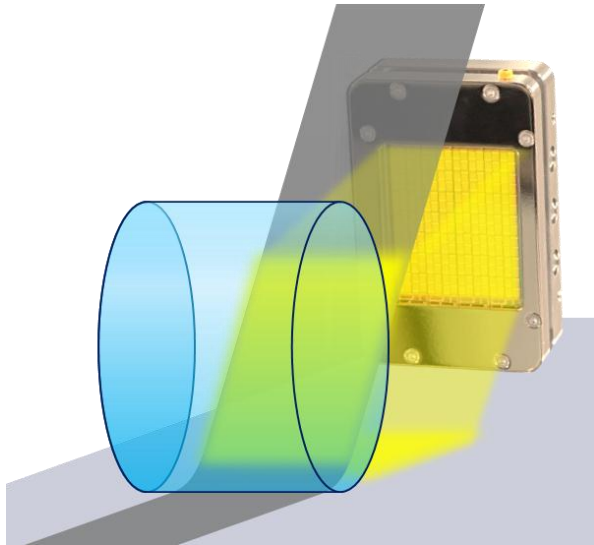


Figure 13 Welding of fiber-reinforced thermoplastic tapes with a VCSEL heating module

For sufficient throughput, a sufficiently high power density is needed and therefore the power is often supplied by a fiber-coupled diode-laser. Because of their compactness and robustness, VCSEL heating modules can be directly integrated in such tape welding heads but offer the additional advantage that the spatial heating pattern can be adjusted dynamically offering, in addition to cost advantages, improved process control and, hence, improved quality of welding.

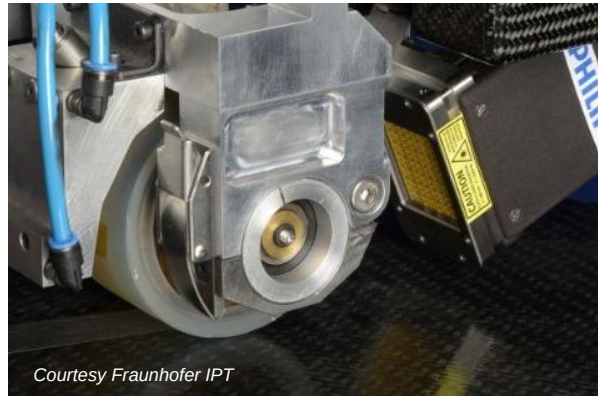


Figure 14 VCSEL heating module integrated in automated tape-laying robot (top) and close up of the module and press wheel (bottom)

Figure 14 shows a 1.6 kW VCSEL heating module, containing four emitters, integrated in a tape-laying robot. 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.

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 15 (top). 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 subsequently, while exiting the system, ramped 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 also set 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 15 bottom). Experiments were done varying the power and the belt speed.

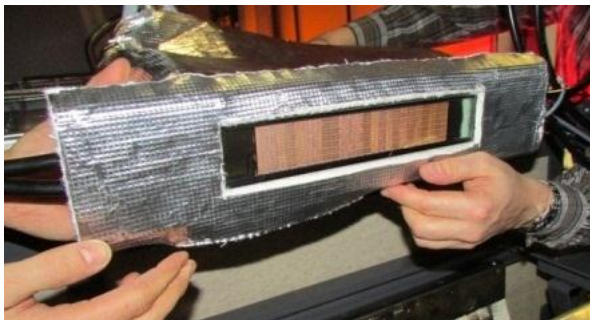


Figure 15 A belt oven of Rehms Thermal Systems GmbH, for fast firing of solar cells (top) and the 9.6 kW 808 nm VCSEL module mounted inside this oven close to the exit

The resulting temperature profile is shown in Figure 16, indicating that the ramp rate can be increased by an order of magnitude using the VCSEL module.

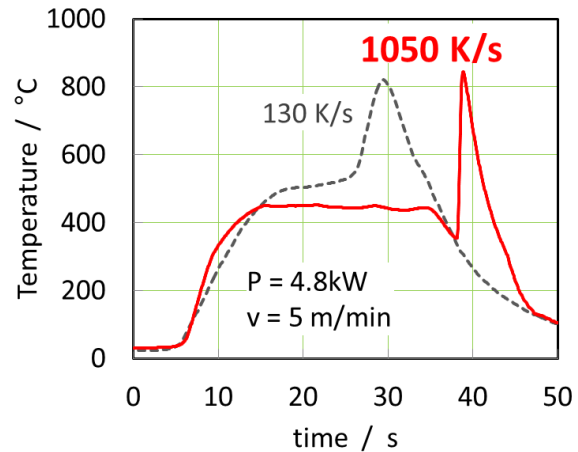


Figure 16 Normal temperature profile in a fast firing oven (black dashed) and using VCSEL module (solid red)

The cell efficiencies as a function of belt speed and power setting are shown in Figure 17. 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.

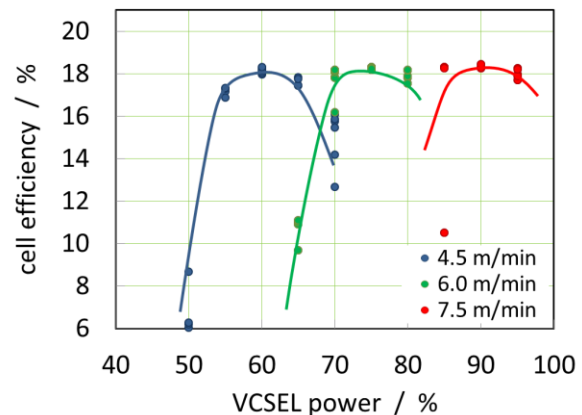


Figure 17 Cell efficiencies as a function of belt speed and relative VCSEL power, as measured by Fraunhofer ISE

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

Edge banding of furniture panels

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. The lasers systems employed for these applications are either scanning the wedge between the board and the band or fiber-coupled diode lasers with optics systems to create a stripe-like illumination in this wedge. These systems are expensive and bulky, limiting their use to the top segment of these machines, which is only attainable for large industrial furniture makers.

In order to also offer seamless edge banding for the much larger volume of smaller machines for small- and medium size workshops, hot-air blowers have been extensively investigated as an alternative. These attempts have so far not been successful as the required quality could not be obtained. Besides, they are extremely noisy and consume a lot of energy, as most of the heat goes to the environment, creating unattractive or even unacceptable working conditions.

As shown in Figure 18, a VCSEL-based heating module, denoted IMALUX, was developed and integrated in a low-end edge-banding machine for small and medium-size workshops. The edge band is directly heated by the VCSEL module, which is so compact that it can be placed on the machine, next to the existing gluing module, such that flexibly the machine can switch between gluing and seamless edge banding. While the quality is equal to that of the significantly more expensive fiber-coupled laser systems, the energy consumption is a factor of four lower than that of comparable hot air systems.



Figure 18 IMALUX direct laser system on through-feed machine from IMA Klessmann GmbH for small and medium-size workshops

The electronically adjustable heating zones of the VCSEL modules enables flexibly adjusting the width of the heated area for different panel thicknesses.

Conclusions

VCSEL arrays expand the use of VCSEL beyond the traditional areas of datacom and sensing, while expanding the range of high-power lasers and laser applications into thermal treatments in industrial manufacturing processes. VCSEL arrays have a high power density enabling fast processing, can accurately control the dose spatially as well as in time, and are scalable to almost any power level. 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.

Acknowledgments

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