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Research Article

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Optical components and optical systems for VCSEL diode laser systems

Abstract: High power vertical-cavity surface-emitting laser (VCSEL) arrays can be used as a versatile illumination and heating source. They are widely scalable in power and offer a robust and economic solution for many new applications with moderate brightness requirements. The use of VCSEL arrays for high power laser diode applications enables multiple benefits: full wafer level production of VCSELs including combination with micro-optics; assembly technologies allowing large synergy with LED assembly thus profiting from the fast development in solid state lighting; outstanding reliability and a modular approach on all levels. With the use of μ-lenses, the described optical principle of near field imaging and superpositioning of many thousands of VCSELs gives perfect control over intensity distribution and is inherently robust. With a slightly modified approach, lines of any desired length can be built from modules of 1-cm length and are therefore scalable for a wide range of applications.

Keywords: high power VCSEL system; μ-lens arrays; vertical-cavity surface-emitting laser (VCSEL) arrays.

OCIS codes: 140.3300; 140.7260.

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1 Introduction

Vertical-cavity surface-emitting laser (VCSEL) arrays offer a way to scale the low power of single VCSELs towards systems in the kilowatt range [1, 2]. Beyond established applications in sensing and data-com this will open a new market for applications of VCSELs namely 'high power VCSEL systems'. The known good properties of VCSELs such as completely wafer-scale manufacturing, outstanding reliability, and ease of assembly will also be beneficial in these new applications. In particular, potential for robust and low cost solutions will enable mass applications which cannot be addressed by current price levels of traditional laser systems. In addition, the round and low divergent beams (NA <0.2) allow the use of cost-efficient optical systems. Furthermore, high power VCSEL systems can exploit good optical properties of VCSELs to tailor intensity distributions to the needs of an application [3].

High power VCSEL systems offer brightness levels of <100 W/mm^2 ster or using micro-optics of up to 1000 W/mm^2 ster. Therefore, most applications will be based on thermal processes or pumping of solid state lasers. The advantage of laser systems (e.g., compared with a traditional oven) is much higher selectivity, which enables new processes and helps safe energy or material. Such selectivity can be enabled by the small spectrum of the laser (i.e., tailored to the absorption of the material in the application), by the brightness allowing for short heating times (i.e., selectively heating the part of the material absorbing most) or by a structured illumination pattern.

Combination of special beam characteristics of VCSELs with suitable optics enables tailored illumination patterns, and needed optical concepts and optical systems are described in this article.

2 General types of optics in VCSEL modules

Most high power VCSEL modules consist of several semiconductor chips, with a dimension of 1 to 10 mm^2, containing several tens to thousands of individual VCSEL lasers (the 'VCSEL array') soldered to a common heat sink, forming a submodule. Several of these submodules are then packed together to the complete module. One example is shown in Section 4. The optical systems of most high power VCSEL systems are composed of three types of optics.

2.1 Microlens arrays

Microlens arrays with one μ-lens per VCSEL can be used to collimate the beam of each laser [4], thus closing unavoidable gaps between VCSELs and increasing the brightness of the VCSEL array by factor $[(CA\text{-}D)/D]^2$, with CA being clear aperture of the individual μ-lens and D being active diameter of the individual VCSEL. Owing to low NA of VCSELs in the order of 0.2 and below, usually spherical μ-lenses are sufficient. The focal length f depends on VCSEL divergence angle θ, VCSEL dimension D, and VCSEL pitch p with $f=(p\text{-}D)/(2 \tan \theta)$ and is typically in the order of 50 μm to 1 mm, for a typical VCSEL pitch p of 30 μm–600 μm. In addition, integration of this μ-lenses in the semiconductor chip have been shown [5, 6].

2.2 One collimation/imaging lens per chip

The next class is a lens to collimate the beam of a complete VCSEL array with typical dimensions of 0.5 mm upto 5 mm. NA of the lens needs to be equal or larger than NA of the VCSEL array with a clear aperture ideally at least three times as large as the VCSEL array dimension. In most cases, the lenses have focal lengths of 10 mm to 30 mm and f-numbers in the range of f/1.5 to f/3. Sometimes, also a direct image of the plane of the VCSEL array to the working plane is desired. This enlarges the needed clear aperture and often a correction for the Petzval curvature is needed, because VCSEL array size is comparable to the focal length of the optical system. Also, compact multilens objectives known from cell phone cameras can be used, as chip size is similar to the size of the CCD chip in these cameras.

2.3 Macroscopic optics

The third type are large-scale optics, which shape the beam of a submodule or the complete VCSEL module, which can be some cm in size, but also up to 1 m (one example is given below). Often the optic is used to focus the beam in one or both directions in the working plane. Striving for the highest intensities results in a large NA of the laser beam, therefore aspherical lenses or multiple lens optics are required in this class.

A second option is imaging of the laser module consisting of, for example, individually addressable lasers or addressable arrays. In this case, usually the most complex optical systems are needed, which are, for example, corrected for astigmatism, coma, and/or a flat Petzval curvature of the focal plane.

3 Tailored intensity distributions with VCSEL modules

To increase power and decrease modulation of intensity profile, the near fields of several VCSELs can be superimposed by a simple optic consisting of a microlens per VCSEL and a common lens. Figure 1 shows several VCSELs integrated to an array on a semiconductor substrate and several of these arrays assembled on a heat sink. Each lens collimates the beam of one VCSEL and transposes its near field to the far field. The beams of all VCSELs superimpose in the far field or, as shown in Figure 1, in the focal plane of the field lens. In the working plane, we obtain superimposed images of individual VCSELs with a magnification or demagnification given by the ratio of focal length of the microlens and the field lens. It was shown that VCSELs with homogeneous and robust near fields of very different shapes can be easily realized, to obtain tailored beams in the working plane [3]. In addition, the laser beam is basically speckle-free as several

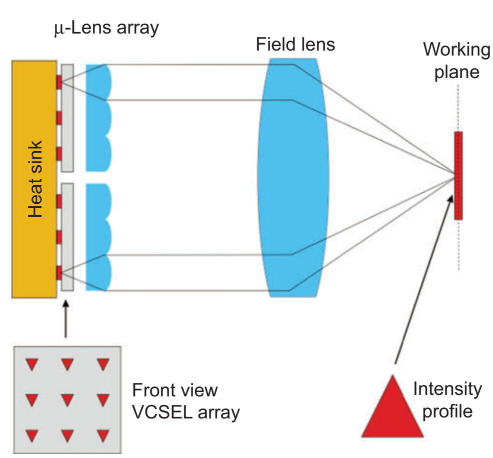

Figure 1 Schematic drawing of the optical concept.
The red areas mark the emission areas of the individual VCSELs in an array. The emission of each VCSEL is collimated by a microlens and a field lens superimposes the inverted images of all near fields in the working plane.

hundreds or thousands of lasers are overlapped incoherently in the beam.

Figure 2 shows the measured far fields of two different VCSEL arrays collimated by a commercially available microlens array from Süss Microoptics (Hauterive, Switzerland). The center-to-center distance is 100 μm for the lens array as well as for the VCSEL array. The radius of curvature of the lenslets is 120 μm and the distance to the lasers is 260 μm. The 8×8 bottom-emitting VCSELs of the first array have a quadratic shape with 20 μm side length, giving a quadratic top-hat profile with a full divergence angle of $2\theta'=6°$ for the collimated beam of the full array. The second array consists of VCSELs with the same shape but a side length of 40 μm, leading to a full divergence angle of $2\theta'=12°$ for the quadratic top-hat profile of the collimated beam.

Adding a spherical or aspherical lens with the focal length f, square-shaped top-hat intensity profiles can be realized in the backfocal plane of the lens and the side length of the beam is given by $2\theta' f$. With this method, also round or rectangular top-hat beams have been realized and even some very uncommon profiles such as a triangle [3].

4 VCSEL module for a uniform line illumination

4.1 Requirements

A uniform line illumination can be used in many applications, for example, heating, drying, or soldering. A high power VCSEL system with a scalable and very homogeneous line focus for the drying of the ink in an offset printing machine was realized by a special μ-lens array [7]. Printing applications pose highest demands on uniformity due to the sensitivity of the eye to any regular patterns. Variation of the intensity integrated in the direction of the line (y-direction) should be within ±5% over the whole line profile and even smaller gradients below 1% per mm are allowed, even in the unlikely event of failing lasers.

4.2 Lens design

The simplest approach for creating a line focus is to use a densely packed, rectangular VCSEL module with one

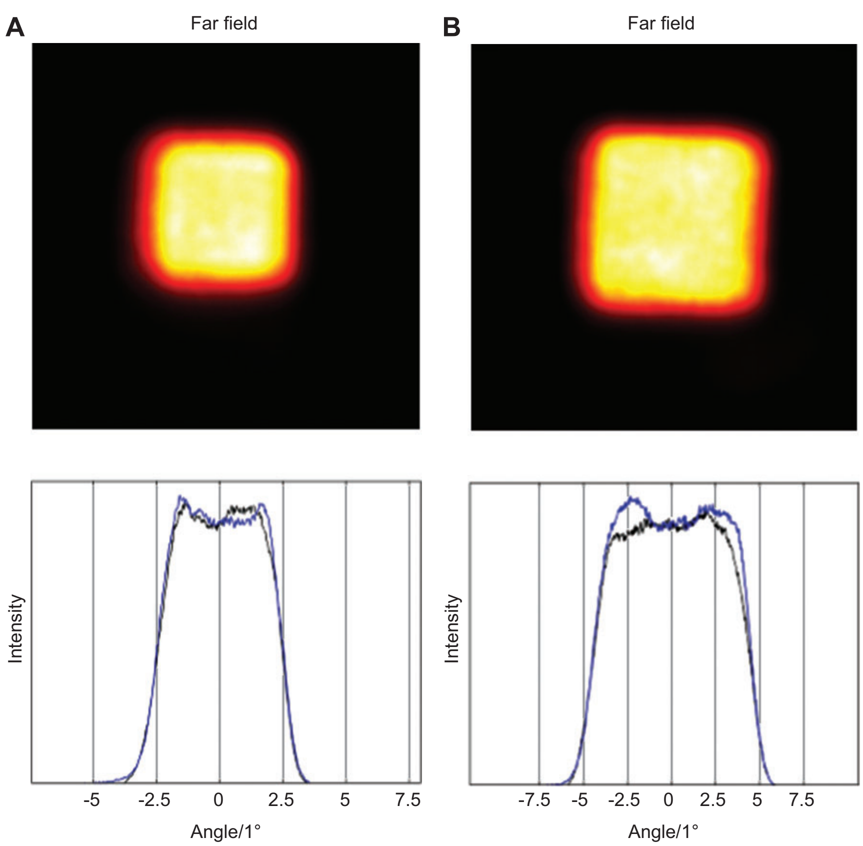

Figure 2 Measured far fields of VCSEL arrays after collimation with the microlens array.
Panel (A) shows the far field of a collimated 8×8 VCSEL array with quadratic apertures with 20 μm side length. In panel (B) the side length is 40 μm.

dimension being equal to the desired length of the line L and focus the radiation down to the desired line width W with a cylinder lens. To achieve a higher brightness, microlenses in front of each VCSEL can collimate the beams and increase the brightness of the complete module. By contrast, to achieve good homogeneity in the direction along the line, a large divergence angle in this direction is desired, to ensure a good intermixing of many lasers, thus averaging out gaps between the laser sources, intensity variations, or individual failures.

The line thickness $D=d*f_2/f_1$ is determined by the dimension of an individual VCSEL in the y-direction d, the focal length f_1 of the microlens and the focal lens f_2 of the cylindrical lens (see Figure 3). The focal length f_2 should be as small as possible to obtain a narrow line, but not smaller than the required working distance $l_{WD}<f_2$. The focal length of the microlenses is limited by the divergence θ of the VCSELs and the microlens diameter a, which ideally equals pitch p between individual VCSELs. To achieve a narrow line and a large working distance at the same time, the dimension of the VCSEL d should be small and pitch p between VCSELs should be large, to allow a long focal length f_1. To achieve high intensity in the focus, several VCSELs are superimposed in the y-direction.

In the direction along the line (x-direction) the situation is completely different. To obtain a homogeneous and robust intensity profile, it is desirable to overlap the radiation of as many lasers as possible in each point on the laser line. Therefore, a large divergence angle θ_x is desirable after the microlens array, which means a large dimension l of the VCSEL and a short focal length. The dimensions of the VCSEL in both directions can be different, as indicated in Figure 3. As the divergence angle after the microlens θ depends on the ratio of the VCSEL dimension and the focal length, the divergence angles can be different for both directions. In the y-direction $\theta_y=d/f_1$ should be small, to allow focusing on a small line with a large working distance, whereas $\theta_x=l/f_1$ should be large for a strong overlap of the individual laser beams in the x-direction.

The desired working distance determines the focal length f_2 of the cylinder lens. The line width D then gives the ratio d/f_1 or d/p. For a given pitch or diameter of the microlens, the other dimension l of the VCSEL is made as large as possible, such that the radiation fills the complete aperture of the microlens in the x-direction. In addition, a rectangular shape allows better current injection and cooling, compared with a round or square shape [8].

The system can be optimized by using a microlens with an elliptical or rectangular aperture, allowing a different pitch of the lasers for both directions, as shown in Figure 4. Thus, it is possible to have a large aperture a_x in combination with a large l of the VCSEL and a small aperture a_y combined with a small d of the VCSEL. Pitch p_y in the y-direction can be smaller, which leads to a higher power density of the laser module. In addition, Figure 4 illustrates the future idea of integration of the microlenses on the substrate of the VCSEL chips described below.

4.3 Optimum VCSEL shape

To further increase homogeneity, depth of focus, and alignment tolerances, the shape of the VCSELs can be altered from a rectangular shape to a shape which gives an integrated intensity profile with less steep shoulders instead of a top-hat profile. This shape can be, for example, a parallelogram, a trapezoid, a triangle, a hexagon, or a rhombus. The wider the shoulder of the intensity profile, the larger are the alignment tolerances and the depth of focus z_{DOF}. An illustration for these considerations is shown in Figure 5 where potential misalignment from chip to chip is depicted in the lower half. Whereas rectangular shapes shown on the left side can lead to strong variations of the integrated intensity, when misaligned,

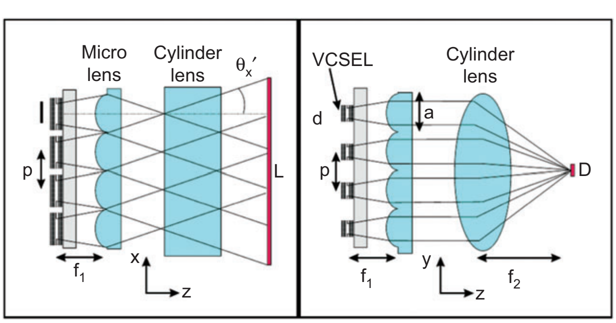

Figure 3 General concept with rectangular VCSELs.
(Left) view in the x-z-plane, (right) view in the y-z-plane.

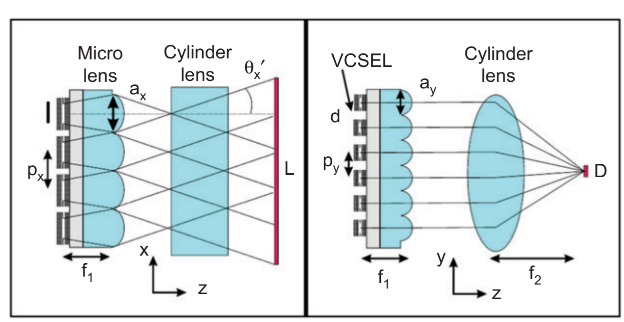

Figure 4 Schematic drawing of a VCSEL module with microlenses with an elliptical aperture.
(Left) view in the x-z-plane, (right) view in the y-z-plane.

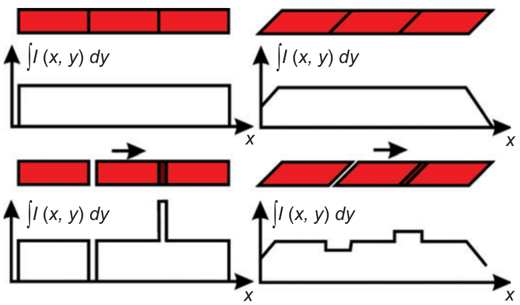

Figure 5 Influence of VCSEL shape on intensity profiles.

the parallelogram shaped intensity profiles result in lower variations as shown on the right side of Figure 5.

4.4 Designed for modularity

The system is designed in a modular way. Therefore, a component or process used on a small scale is just replicated many times to build the full system. This is of huge benefit in mass manufacturing of such products. A fully assembled cooler including power supply is 1 cm wide and therefore systems can be made in any length being an integer multiple.

However, gaps in between these modules could introduce irregularities in intensity profile, which disturb homogeneity. Therefore, gap pitch g (or in other words the center-to-center pitch of VCSEL arrays) should be matched to the size in x-direction of the intensity profile of an individual laser in the working plane, which is approximately given by the divergence angle after microlens θ_x and distance S between the laser and the working plane as shown in Figure 6. For length $l' = \tan(\theta_x) * S$, gap pitch g should be l'/N with N being any integer number. As condition $g = l'$ is only fulfilled exactly in the working plane, the intensity profile will become more inhomogeneous with increasing distance from the working plane.

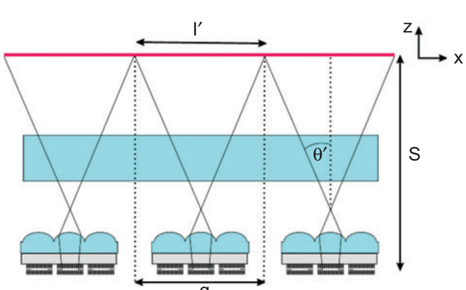

Figure 6 Intensity variations from gaps between laser modules can be avoided, if gap pitch g is matched to the size of image l′.

4.5 VCSEL array

Electrically pumped 995-nm bottom-emitting VCSEL arrays consist of 2×4 lasers on a 1.1×1.1 mm chip. The active shape of the individual VCSELs is a parallelogram with a base side length of l=320 µm, a height of d =20 µm, and an internal angle of 18°. The pitch between the lasers is p_x=600 µm in the x-direction and p_y=250 µm in the y-direction. A schematic drawing of the VCSEL chip is shown in the upper right corner of Figure 7.

VCSEL arrays (4×3) are soldered on a 200-µm thick aluminum nitride submount to insulate them from a water-cooled heat sink and enable an electrical connection between VCSEL arrays. To achieve high power density and good homogeneity in the x-direction, the distribution of the lasers needs to be dense and symmetrical in this direction, therefore a design with the bond pads in the middle of the lower and upper edges is chosen. In addition, support structures for the microlens array are implemented in the form of spacers in the corners of the submount. A schematic drawing of a submount with 12 VCSEL arrays is shown in the lower left corner of Figure 7.

4.6 Microlens array

The specially designed microlens array with asymmetrical rectangular apertures of 600×250 µm to match the pitch of the VCSELs is shown in Figure 8. For production reasons, the clear aperture of the lenses is 10 µm smaller in both dimensions. The lenses have a plano-convex shape with the curved side pointing away from the lasers and designed with an aspherical profile to minimize spherical aberrations at large angles. As the VCSELs are designed to have a divergence angle of 11° and below, the lenses have to be in a distance of 1.08 mm to the VCSELs. The shape of the lenses is optimized using ZEMAX (Redmond, WA, USA), resulting in a radius of curvature of 440±10 µm and a conic constant of k=1.1±0.05. The resulting divergence angles of the collimated beam are θ_x=21° and θ_y=1.2°, respectively. The glass thickness of the lens array is fixed at 900±5 µm, such that the laser beams are collimated when the lens array is glued on the support structure having the same thickness as the semiconductor substrate of VCSEL arrays (plus 10 µm glue thickness). This facilitates mounting of the lenses. The lens array is AR-coated on both sides (R<0.5% for wavelength from 950 to 1050 nm). Figure 8 shows the (still) hybrid assembly of microlens arrays on the submodule.

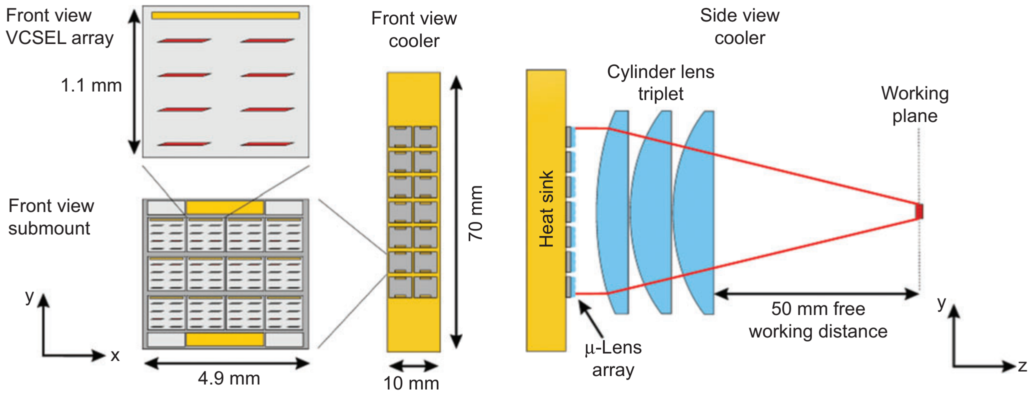

Figure 7 Schematic drawing of the line module and its components.

4.7 Complete submodule

Micro-channel coolers are chosen as the heat sink and each cooler forms one so-called submodule of 1 cm width and operated by its own power supply. Thus, the line could be scaled in the x-direction in steps of the width of one submodule. To reach the required 150 W/cm line length, at least 14 submounts are needed per cooler forming an emission area of 10×35 mm. The total number of lasers in one submodule is 2*4*4*3*2*7=1344, which results in an expected output power of 201.6 W, thus fulfilling the requirement of 150 W/cm. A fully mounted cooler is shown in Figure 8.

4.8 Cylinder lens

The focal length of the cylinder lens is determined by the desired line width D of <3.5 mm and the divergence angle θ_y, thus $f_2 * D = 2\,\theta_y$[rad] <83.6 mm. By contrast, the free working distance should be larger than 30 mm, which means the focal length had to be larger than approximately 40 mm. The radial height of the lens has to be significantly larger than 35 mm (the width on the cooler populated with VCSELs) and should be as long in x-direction as the full module (or at least an integer multiple of the cooler length to deal with potential gaps as discussed above).

A lens triplet consisting of plano-convex lenses is designed as a good compromise between cost and mounting complexity on the one hand and low spherical aberrations and a narrow line on the other hand. All three lenses have a side length of 300 mm and a height of 50 mm with the curved side facing the lasers as shown in Figure 8. Two of the three lenses are designed to have the same radius of curvature, thus only two different types are necessary. The optimum radii of curvature have been calculated with ZEMAX to be 130 mm, 67 mm, and 67 mm, with the large ROC lens facing the laser module, followed by the two small ROC lenses. The lens triplet has a combined focal length of 61 mm and a free working distance of 50 mm.

5 Technology outlook: wafer level integration of µ-optics

Microlens arrays with one microlens per individual VCSEL are mandatory for the optical concept used in this work. However, active alignment of many arrays and

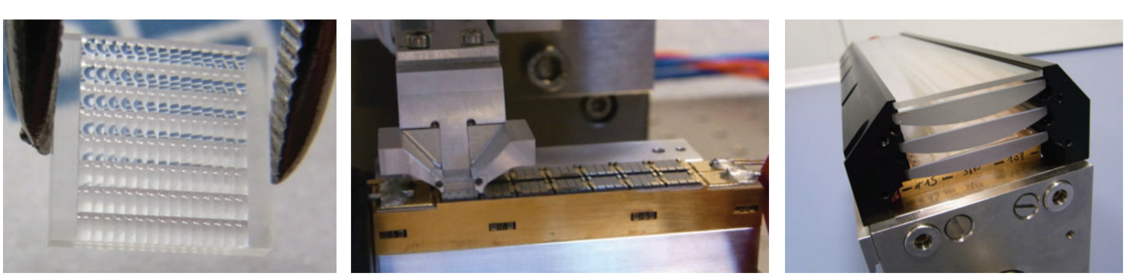

Figure 8 Microlens array with rectangular shape of lenslets (left), placement of microlens arrays (center), and finished module with cylinder lenses (right).

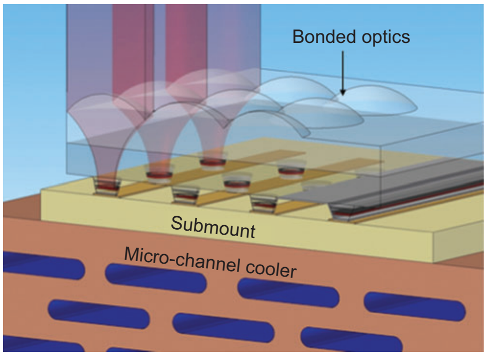

Figure 9 Illustration of a bottom-emitting VCSEL array with a microlens array bonded to the substrate side.

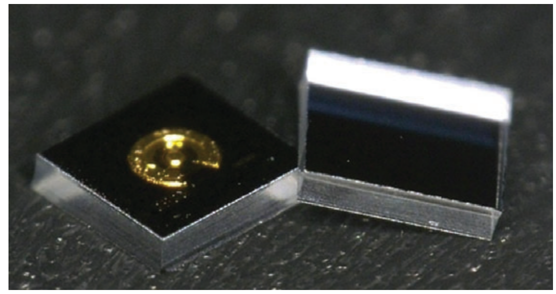

Figure 10 Photograph of single bottom emitter (substrate removed) glued to glass.
The active area is in the center surrounded by a large, horseshoe shaped n-contact.

mechanical fixation on the submounts increases cost and has the largest impact on production tolerances. The benefit of integrated microlenses on wafer level is therefore huge and will be exploited in future. Figure 9 illustrates the concept of a microlens array bonded on wafer level to the substrate side of the VCSEL wafer after the epitaxial side has been processed in a way enabling contacts of both polarities. The individual chips can be separated by sawing the compound stack of GaAs and glass.

Dedicated technology development is required to bring this idea into practical production. Production of 3″ (7.62 cm) and 4″ (10.16 cm) optical microlens wafers by replication molding on glass with an expansion coefficient close to that of GaAs is currently under development. The alignment of both wafers on a mask aligner is done via alignment marks. Obviously, only one alignment is needed for thousands of optical elements.

In parallel, a process is developed to glue glass wafers on the substrate side of GaAs wafers and to separate chips. This process optionally includes substrate removal to reduce losses. Figure 10 shows a photograph of a single bottom emitter of which the substrate has been removed by etching towards an etch stop layer and has been replaced by a flat glass wafer. In a next step, a replicated wafer with microlens arrays instead of the flat glass wafer will be used.

6 Conclusions

High power VCSEL arrays can be used as a versatile illumination and heating source. They are widely scalable in power and offer a robust and economic solution for many new applications with moderate brightness requirements. The combination with micro-optics enables tailored intensity distributions, such as robust, speckle-free top-hat beams, and highly uniform line illuminators. A further improvement will be addressed by wafer level integration of microlenses reducing the need for accurate adjustment to just one step at the wafer level. Extensive discussion of the optical concept opens the scene for adapted specifications to address many new applications.

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Gero Heusler studied physics at the University of Heidelberg and received his PhD at Freie Universität Berlin in 1999. He started his career in Philips Research developing various light sources including lasers. Currently, he is working as Project Manager in Philips Lighting and is responsible for various projects in the field of high power VCSEL applications.

Michael Miller studied Physics at the University of Ulm and received his Diploma in 1997. He was a member of the Optoelectronics Department at the University of Ulm in the Prof. Ebeling group working on high power VCSEL where he obtained his PhD in 2002. Currently, he is working in the Research and Development Department of Philips Technologie GmbH, U-L-M Photonics as Project Manager in the field of high power VCSEL.

Holger Mönch joined Philips Research in 1991 following his PhD in high energy physics at RWTH Aachen University. He has been working on various high brightness and highly efficient light sources and their application in optical systems. As a Research Fellow, he is now responsible for research on lasers and their application in projection systems, material processing, and optical sensors. His current research interests include the integration of semiconductors and optics, the design of advanced VCSEL structures, and new applications for optoelectronic systems.