Monolithic Micro-Optics for Single Mode Diode Bars

Collimation Module with ultra fine structures opens up new markets for diode laser manufacturers

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Diode lasers are characterized by their compact design, high efficiency, long maintenance intervals and a long service life. However, their brightness and beam quality are not yet sufficient for some applications – for example in material processing or medical technology. Thanks to their large number of single emitters, single-mode diode bars have the potential to generate high levels of output power, but they are not yet widely used. Micro-optics allow the brightness of diode lasers to be significantly increased by collimation of the emitted light. This opens up new applications, while at the same time providing laser manufacturers with benefits in terms of cost.

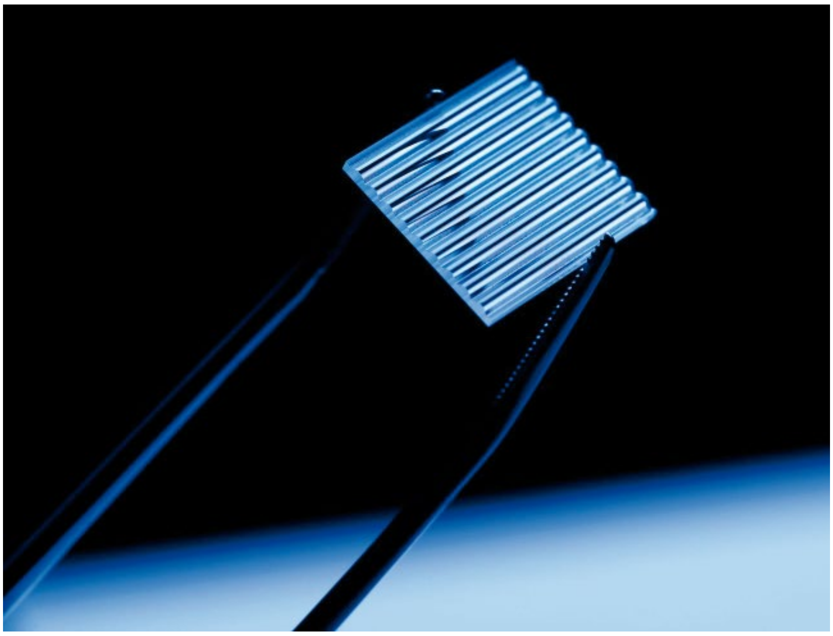

Fig. 1 The new C-SMDB monolithic cylindrical lens array from Ingeneric for single-mode diode bars achieves exceptionally high collimation quality. (Source: Ingeneric)

Single-mode diode laser bars are an arrangement of individual single-mode emitters within a certain area. Their advantage in comparison to a broad area emitter is the good beam quality in the fast and the slow axis. Their disadvantage is the low power output due to the small emitter width. For a powerful and efficient light source, a large number of emitters must be positioned on a bar. As a consequence, the pitch between the emitters is small (<50 µm). To use the advantage of the single mode characteristic, the light of each emitter must be collimated individually which results in small structures.

The path to implementation of new applications involves compact, monolithic micro-optics with ultra-fine structures, precisely adapted to the requirements of single-mode diode lasers. This calls for production methods that enable the required accuracy to be achieved reliably and with a high level of reproducibility. The example of the C-SMDB, the collimation module for single-mode diode lasers, demonstrates that perfect coordination of the light source and optics can achieve optimum results.

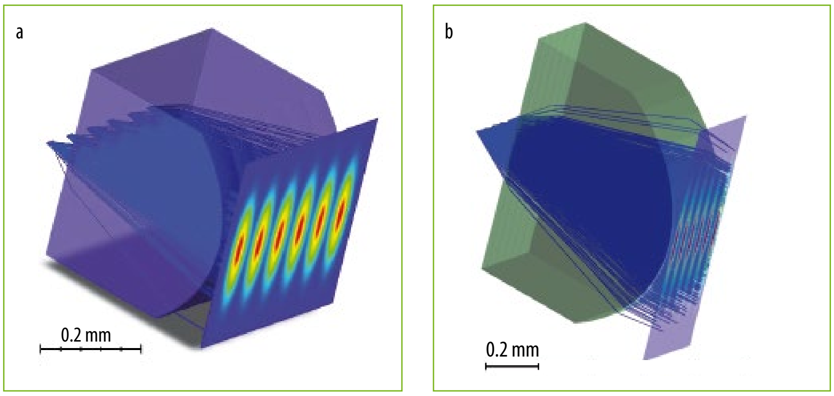

Fig. 2 Monolithic aspherical microlens array (pl-cx; a); and monolithic biconical microlens array (cx-cx; b); (Source: Ingeneric)

Challenging specifications

In principle two options can be used to collimate the light of the emitters – a plano-convex aspherical approach and a double-sided biconical one. Both have advantages and disadvantages which need to be considered for the choice of the design. The design of the lenses presumes a numerical aperture *NA* of 0.1

and 0.6 for the two axes with a pitch of 48 µm.

The advantages of the aspherical microlens array optics are the plano-convex (pl-cx) lens approach and the moderate aspect ratio (Fig. 2a). This is beneficial for manufacturing of the part. However, the design results in a low effective focal length EFL (~190 µm) and back focal length BFL (~30 µm) with a small center thickness CT (~170 µm). Especially the short BFL might be a challenge for the lensing process. The position accuracy of the bar on the heat sink or overhanging solder deposits in combination with a tolerance for the center thickness of the lens might also be critical for the production process. Moreover, the lens is very small and handling during the lensing process is challenging, too. In addition, the small EFL results in a small radius of curvature with an aspherical shape and a large *NA*. Manufacturing such optics is therefore challenging.

In comparison, the double-sided biconical approach (Fig. 2b) avoids these disadvantages. With an EFL of ~600 µm for the fast axis and an EFL of 190 µm for the slow axis, a BFL of ~183 µm and a CT of ~700 µm, this design is more robust. However, the design is not diffraction-limited because even crossed cylinders with perfect shape cause aberrations.

Additionally, the effect of a misalignment of the two surfaces must be considered. This can be derived from a tolerance analysis. Fig. 3 shows an analysis of the effect of a misalignment (angle error) of the two surfaces on the divergence of the fast and the slow axis. It is obvious that the effect is stronger for the fast axis and minor for the slow axis. In addition, a tilt error smaller than 0.2° has a minor effect on an increase in the divergence. A typical achievable tolerance is 0.02°. As a consequence, the would-be disadvantage of the double-sided approach is not an issue.

More critical is a pitch error in the lens array to collimate the slow axis (Fig. 4). Even a small error results in a significant increase in the divergence because of the large number of emitters. Therefore a simulation was carried out with only five emitters instead of two hundred and the pitch was changed accordingly to reduce the simulation time.

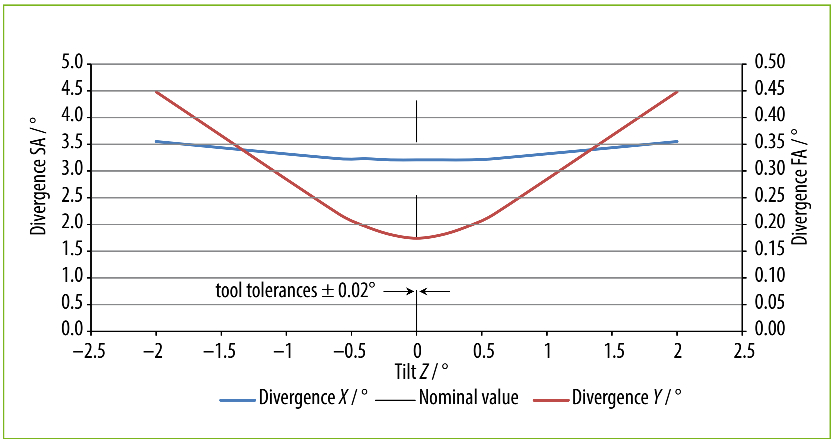

Fig. 3 A misalignment of the two surfaces (angle error) on the divergence of the fast and the slow axis smaller than 0.2° has a minor effect on an increase in the divergence. A typical achievable tolerance is 0.02°. (Source: Ingeneric)

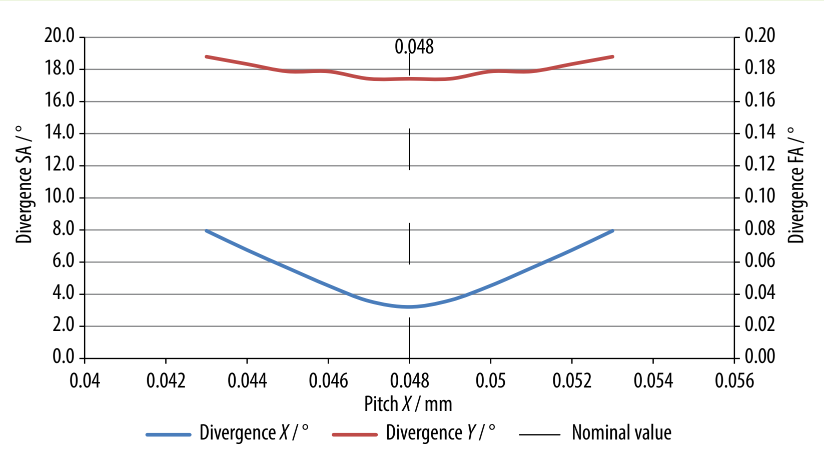

Fig. 4 The pitch error of the lens array to collimate the slow axis is more critical: Even a small error results in a significant increase in the divergence because of the large number of emitters. (Source: Ingeneric)

Company

INGENERIC
Aachen, Germany

Founded in 2001 in Aachen, INGENERIC develops and manufactures high-precision micro-optical components for high-power applications, along with optical and laser systems such as fiber couplers, homogenizers and collimation modules for science, medicine and measurement technology.
Today, INGENERIC is one of the few manufacturers in Europe to develop and manufacture glass micro-optics for beam shaping in semiconductor diode lasers according to the individual specifications of its international customers. The company handles the entire process chain from the lens design and the development of prototypes through to the small-batch production and serial manufacture.
INGENERIC also produces high-power laser systems. For the HiLASE or XFEL project, for example, INGENERIC supplied a number of high-energy lasers delivering ten pulses per second with an energy of 250 Joules, an average power output of 2.5 kW, and an extremely homogeneous top-hat beam profile with an amplitude contrast of less than 7 %.

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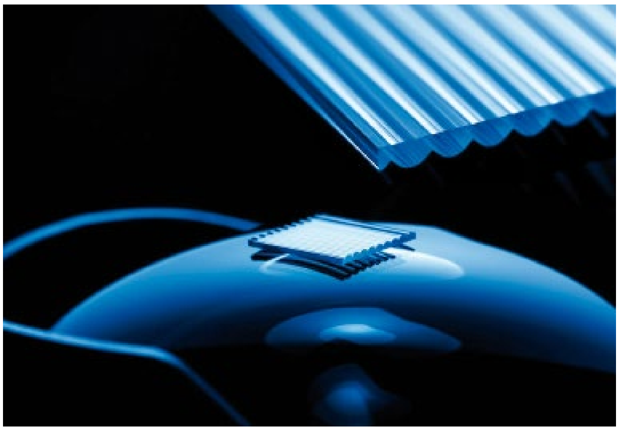

Fig. 5 The array works on two sides: The inlet side collimates the slow axis, while the outlet side collimates the fast axis of the emitted light. (Source: Ingeneric)

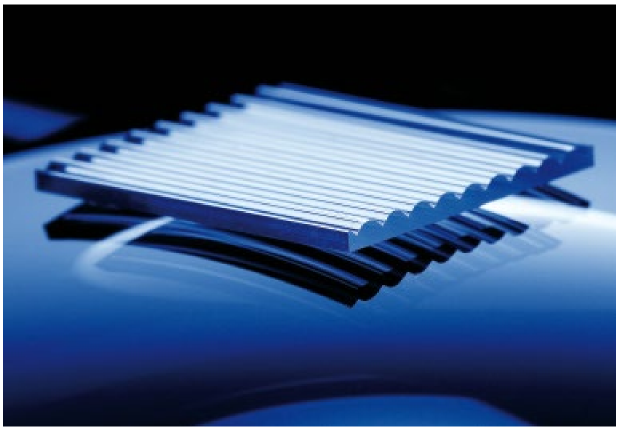

Fig. 6 The new array consists of two hundred lens elements with a pitch of 48 µm. (Source: Ingeneric)

The effect is significant for the slow axis collimation. Based on these results, the specification for the pitch error is < 1 µm for the complete diode bar (~ 10 mm). As a consequence, the specification for the emitter to emitter pitch is <0.005 µm. Of course, there are other critical parameters for the lens, like form accuracy of the lens curvatures which should be <0.150 µm or the center thickness of the optics.

Besides that, the diode has a significant influence on the result, too. Especially an increase in emitter size and divergence results in a higher divergence and beam size after the collimation module. Considering the possible variations of the diode parameters, the trade-offs of the different designs and influence of the tolerances, the biconical approach is the favored one for the collimation of single-mode diode laser bars.

High brightness with microlens arrays

Two-dimensional lens arrays can be manufactured using etching methods or precision glass molding, for example. Etching is normally preferred where a very large number of lenses has to be produced on a limited area, for example 10 × 10 mm. With glass molding, fewer lens elements are possible on a comparable area. However, it offers considerably greater flexibility in terms of the use of different glass materials and manufacturing micro-optics with a higher numerical aperture, greater pitch, and better radius accuracy and repeatability. For this reason, Ingeneric uses this method to produce the collimation optics for single-mode diode lasers and for other micro-optics in its product range.

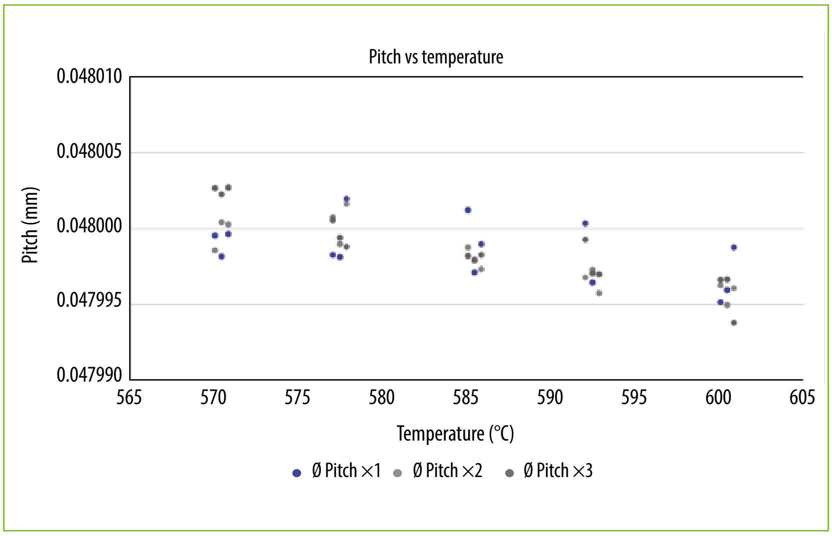

Fig. 7 Dependence of achieved pitch error on process temperature (Source: Ingeneric)

In glass molding, high refractive index glass takes on the precise shape of the molding tool. Producing the molds with sub-micron precision yields exceptionally high accuracy and reproducibility in production of the arrays (Fig. 5 and Fig. 6). This enables micro-optics to be reliably produced with minimal transition zones, maximum filling factors and minimal pitch errors, even in large volumes.

In comparison to other molding processes, the precision glass molding technology is an isothermal process. Heating and cooling of the glass material is executed in the molding machine which guarantees precise and distortion-free parts. During the molding process, precise guidance of the two tools ensures that the relative alignment of the two surfaces with one another is exactly maintained.

One specific aspect of the process needs to be considered. Since molding is a high temperature process, shrinkage and expansion appear during the heating and cooling of the parts. That effect depends on the different thermal expansion values of the materials and is considered during the design of the parts.

Excellent results

A key parameter for assessing the quality of the optics is collimation of the fast axis. The collimation has been tested with a test diode that measures the divergence after the lens in the fast axis. Of course, the result depends on the parameters of the used diode. For this test, a diode at 940 nm with 46.5° (FW

95 %) and a diode bar smile of 0.2 µm (according to the datasheet) have been used. Taking these values into consideration, a theoretical value of 2.32 mrad (FW 95 %) after collimation should be achievable, without considering the smile value of the diode bar.

It is obvious that the collimation is close to the theoretical value which hints at the very good accuracy of the lens curvature. In addition, the measurement of several lenses demonstrates the high reproducibility of the lenses, which is a characteristic advantage of the used manufacturing technology. The measured smile of around 0.2 µm is essentially the smile of the diode bar.

As shown in the simulation, the pitch of the optics is an important parameter for the performance of the C-SMDB. Fig. 7 demonstrates the dependence of the pitch on the chosen process temperature. The understanding of that specific process behavior, taking it into consideration in the design of the tools, and the selection of the appropriate process parameters are essential to achieve the required specification. The test by analogy shows that it is possible to achieve the critical specifications for that module.

Finally, a test in the application allows the overall performance of the module to be evaluated. The module was used to collimate a single-mode diode laser bar. After collimation, wavelength beam combining (WBC) was used, which is the spatial and directional superposition of many independent external-cavity diode lasers. The angle-to-wavelength conversion property is achieved by external diffraction gratings which provide feedback to each emitter in an array, via a series of lenses, at different wavelengths. The laser resonator is formed between the highly reflective coated back facet of the emitter and the output coupler. In theory, for a single-mode diode laser bar, the superposition of all emitters is possible with $M^2 = 1$.

With that approach a stabilized single-mode diode laser bar with 100 W output power and $M^2 = 2$ for the fast and slow axes was achieved in preliminary tests, which is a very good result. Further evaluation and results will follow.

Summary

The example of the C-SMDB collimation optics shows that monolithic micro-optics adapted to the properties of the diode bars significantly increase the brightness and beam quality of single-mode high-power diode lasers. For production, Ingeneric uses the precision glass molding method, which meets stringent requirements with regard to accuracy and process reliability.

An optical simulation demonstrated that the approach using a monolithic, double-sided micro-optical system with two 90° offset cylindrical lenses achieves the required accuracy – particularly in terms of the precise relative alignment of the two lens elements with one another.

With a wavelength beam combining approach, the stabilized diode laser bar achieved 100 W output power and $M^2 = 2$ for the fast and slow axes in preliminary tests.

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Stefan Hambücker studied mechanical engineering at the University of Aachen with a focus on advanced manufacturing technology conferring of a doctorate by the Fraunhofer IPT. In 2001, he established Ingeneric with a mission to develop, manufacture and sell micro-optics for high power applications. He is managing partner, responsible for product development, sales and administration.

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