Due to the proliferation of diode lasers and optical fibers in modern optical systems, microlenses are the most important refractive micro-optical components today by far. Nearly every diode laser and optical fiber end face has at least one microlens associated with it for beam conditioning purposes. A growing number of applications also feature diode lasers and optical fibers packed in various 1-D and 2-D arrays. The natural extension of these applications is to assemble microlenses in arrays as well, for applications such as Shack-Hartmann wavefront sensing, fiber collimators/couplers in optical communications, and beam shaping in diode-laser arrays.

Properly designed and fabricated, the microlens array (MLA) can be a powerful tool for a variety of applications. Here, we present the design and fabrication of highly complex, 50-µm-deep, 100%-fill-factor MLAs for optical fiber coupling of diode-laser bars. The designs achieved laser-to-fiber coupling efficiencies of 70%.

Array Advantages
MLAs can be manufactured in a number of configurations in a variety of materials. The microlenses themselves can be spherical, aspherical, or exhibit still more complex, non-symmetric shapes. The microlenses may even vary in optical prescription throughout a single MLA.

Although MLAs often originate in photoresist, they can be transferred into other, more suitable materials by various etching and replication techniques. Simple MLAs consisting of spherical microlenses can be manufactured by a number of techniques, including photoresist reflow, gray-scale mask lithography, diamond turning, or direct laser writing. When the MLAs consist of complex lenslets with 100% fill factors, however, only a few techniques such as gray-scale mask lithography and direct laser writing provide sufficient free-form manufacturing capability.

Our direct laser write system consists of a high-precision translation stage that moves a substrate spin-coated with photoresist under a stationary write beam, which is kept in focus by a high-numerical-aperture (NA) microscope objective and a fast autofocus system (see figure 1). A 30-mW helium-cadmium laser operating at 441.6 nm generates the write beam, which can be modulated at up to 1 MHz in 1024 levels by an electro-optic modulator. The substrates are moved by an x-y translation stage that is controlled interfe-
metically, with an accuracy of 40 nm at velocities of up to 100 mm/s. Synchronization of the modulated laser beam with the translation stage permits line-by-line fabrication of arbitrary, continuous-surface-relief micro-optical components such as 100%-fill-factor aspherical microlenses, cylindrical microlenses, phase plates, and so on.

Laser writing consists of a raster-based writing process in which all lines are parallel and spaced by some nominal amount $\Delta$. Taking into account the accuracy $\varepsilon$ of the translation stage and assuming the write beam is a Gaussian beam of diameter $\phi$, we can express the local pattern written in any small area as proportional to a summation of Gaussian profiles of the form

$$\sum \exp \left( -\frac{\left( x - x_i + \varepsilon \right)^2}{\Delta^2} \right)$$  \hspace{1cm} [1]

where $x$ is the position perpendicular to the scanning direction.

Equation 1 indicates that the write process introduces low-amplitude residual lines in the optic surface, parallel to the scanning direction. These lines cause scattering, which degrades optical performance. Here, $\varepsilon_i$ represents a small, random perturbation of the $i^{th}$ line position from its nominal value, caused by the finite accuracy ($\pm 40$ nm) of the interferometrically controlled translation stage. Such accuracy, although very good at first glance, still has a strong, negative impact on the surface roughness. Care must be exercised in the choice of the line spacing $\Delta$ and beam diameter $\phi$ in order to limit the roughness, and therefore the scattering losses, to some acceptable value.

In the near-IR spectral region, a roughness of 40 nm rms introduces scattering losses of approximately 1% for a fused-silica element used in transmission. These values vary depending on the wavelength and the material considered. Elements used in reflection are significantly more sensitive to roughness. Control of surface roughness becomes even more essential for deep structures because scattering increases for given writing parameters as the square of the relief depth. Equation 1 shows that we may improve roughness by increasing $\phi$ and decreasing $\Delta$, but we do so at the detriment of the resolution and the writing time, respectively.

**Microlens Arrays in Action**

As an example of the effectiveness of direct laser writing for the generation of highly complex surface-relief structures, consider a beam-shaping system for a diode-laser bar. Diode-laser arrays are attractive, high-power laser sources because of their high conversion efficiency, high reliability, and suitability for compact packaging. Diode-laser bars typically consist of 10 to 50 equally spaced emitters roughly $1 \mu m \times 50$ to $200 \mu m$ in size, which spread over a total width usually set to 10 mm. As a consequence of such asymmetric apertures, the diode lasers emit radiation in a highly asymmetric cone of approximately $10^\circ \times 80^\circ$ full width at 1/$e^2$. We denote the long axis of a diode laser as the slow axis ($x$-axis) and the other, perpendicular axis as the fast axis ($y$-axis). The asymmetric, unconditioned beam emitted by a diode-laser array is rarely adapted to most applications, however, and requires beam conditioning and/or reshaping first.

We quantify the characteristics of a beam emitted by a diode-laser bar by the beam product parameters (BPPs)

$$BPP_{x,y} = W_i \cdot \theta_i = (\lambda/\pi)M^2$$  \hspace{1cm} [2]

where $W_i$ and $\theta_i$ represent the beam width and its divergence, respectively, along a given axis, and $M^2$ is a measure of beam quality. Note that, generally, $M^2 \geq 1$ for any beam, but the equality sign in this relation holds only for a diffraction-limited Gaussian beam. To properly condition a beam for coupling into an optical fiber, for example, we want $BPP_x = BPP_y$ in order to better match the circular aperture of the fiber. Typical values for the types of emitters listed above are $BPP_x = 10 \text{ mm} \times 175 \text{ mrad}$ and $BPP_y = 0.001 \text{ mm} \times 1400 \text{ mrad}$, which denote a poorly conditioned beam.

Clever micro-optical systems can improve these beams. In such systems, a high-NA cylindrical lens placed at a short distance from the array typically collimates the output of every emitter along the fast axis ($y$-axis). This allows us to decrease the divergence along this axis to values on the order of 0.3°. The dimension $W_i$ of the beam is then 300 µm due to the propagation up to the lens, yielding $BPP_y = 0.3 \text{ mm} \times 5 \text{ mrad}$ while $BPP_x$ remains unchanged. At this point, if the divergence values could be interchanged ($\theta_x \leftrightarrow \theta_y$), our BPPs would become $BPP_x = 10 \text{ mm} \times 5 \text{ mrad} = 50 \text{ mm mrad}$, and

![Figure 1 INO’s direct laser write system consists of a high-precision translation stage that moves a substrate spin-coated with photoresist under a stationary laser beam kept in focus by a high-numerical-aperture microscope objective and a fast autofocus system.](image-url)
are difficult to manufacture for a number of reasons. First, their surface-relief profiles consist of arbitrary, free-form structures with discontinuities. In addition, one of the MLAs is very deep, and the overall shape and roughness of both MLAs should be good in order to minimize aberrations and scattering. Finally, both MLAs must be able to sustain the high powers typical of diode-laser bars, and their fabrication method should be cost effective.

**Fabrication Challenges**

Elements manufactured by laser writing cannot be used directly in diode-laser-bar applications for two reasons. First, photoresist is a soft, low-melting-point material that cannot sustain the high powers involved in the process. Second, direct write production of MLAs is a time-consuming process that is not suited for mass production. We can solve these two difficulties simultaneously by replicating the photoresist masters in a more robust material; one might UV-emboss the structures in hybrid glass materials on host fused-silica substrates, for example. In this process, a semi-transparent mold fabricated from a photoresist master serves as the replication tool. Alignment marks generated with the MLAs of interest by laser writing may be used for the double-side replication and alignment of the MLAs together, using a modified mask aligner. This replication method offers a number of advantages, including good temperature stability of the replicated components and compatibility with conventional planar microfabrication technologies.

Direct laser writing and replication in hybrid glass provide a good solution to the problems of free-form structures and demanding damage thresholds. In addition, hybrid glass replicas are compatible with antireflection coatings. The cost effectiveness of the replication process is further enhanced by the excellent adherence of hybrid glass to fused silica, which allows dicing without risk of delamination.

Significant challenges remain, however: the demanding optical prescription and surface requirements, and, in particular, the height of the structures and their optical quality. The realization of the first MLA, with a depth of 18.5 µm, was not a major challenge. The depth of the 76-µm-deep MLA, however, significantly exceeded direct write capabilities, which typically range from 30 to 40 µm for this type of component.

Although a few positive photoresists targeted for the manufacturing of binary components can be easily spun in single or multilayer coats to thicknesses of 100 µm, such photoresists are not always suitable for gray-level exposure. Outgassing, for example, creates bubbles that can yield components of extremely poor optical quality. Consequently, we decided to maximize the thickness of photoresist films known to be free of these outgassing problems. By a careful optimization of photoresist spinning and baking procedures, we achieved maximum usable film thicknesses of around 60 µm. To safely comply with this manufacturing limit and ease fabrication, we truncated the depth of the second MLA from 76 to 50 µm. The resultant clipped, lost areas in the bottom corners of each microlens did not contribute to the beam-shaping process. The clipped areas are small, however, and produce minimal optical losses in practice.

Figure 2 Scanning electron microscope images of the beam-conditioning elements show pairs of crossed microlens arrays with a depth of 18.5 µm (top) and a depth of 50 µm (bottom). Note that the design parameters for the second MLA called for a 76 µm depth, but the truncation had a minimal effect on optical performance.

The micro-optical system was tested by coupling the output from a diode-laser bar into a 400-µm-core multimode optical fiber, achieving a coupling efficiency of 70%. These results confirm that direct laser writing can produce complex, free-form micro-optical elements, meeting the most demanding design requirements.

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**References**