USING DROP-ON-DEMAND TECHNOLOGY FOR MANUFACTURING GRIN LENSES

H.-J. Trost, S. Ayers, T. Chen, W.R. Cox, M.E. Grove, and R. Hoenigman
MicroFab Technologies, Inc., Plano, Texas, USA

Overview

Lenses with gradient index of refraction (GRIN) are used to reduce focal spot sizes and correct chromatic aberrations found in lenses made of homogeneous materials. Current production methods for GRIN lenses suffer from two main limitations: For radial and spherical gradients, ion exchange in glass preforms is used, limiting their sizes to several millimeters dictated by diffusion lengths and rates of the selected ion species. For axial gradients, plates of different indices of refraction are stacked, fused at high temperatures ($1000°C$), cored and machined [1], requiring extensive tooling adjusted for the specific parameters of the lens. Lens diameters and focal lengths of 100 mm are possible. Drop-on-demand technology allows to construct either of these GRIN variants, or even mixtures, with a simple data-driven process, providing lots of flexibility for covering a wide range of lens parameters.

Existing small GRIN lens designs address applications in optics (communications, scanning), medicine (endoscopes [2]), and some other fields compatible with the few-mm size limit. Larger size axial GRIN lenses find use in, e.g., laser beam welders [3] and slide projectors. Our work is driven by interest in fast lenses with much larger focal lengths beyond 1 m for operation in the visible and infrared ranges of the optical spectrum, and focal spot sizes in the order of 5 μm. We have worked out a detailed design for a printing machine tailored to the task of printing lenses and performed various experiments to develop suitable optical materials and to study options in the manufacturing process. This is a project in progress. The machine has yet to be built and printing of full size lenses to be begun.

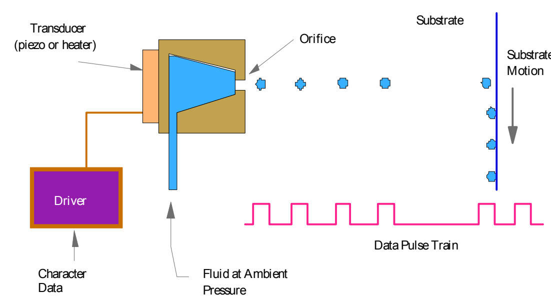

Figure 1: *Principle of drop-on-demand dispensing.*

Drop-on-Demand Printing

The most common use of drop-on-demand technology is found in ink-jet printers. The fundamental element consists of a piezoceramic cylinder fitted around a small glass tube with a narrow orifice (as is the case for the application discussed here) or a piezoceramic block with a number of fluid channels directly machined into it. The underlying principle of operation is the creation of acoustic waves in the fluid column by the piezo actuator which then, under proper shaping of the stimulating pulse to the piezo element, leads to controlled ejection of single droplets (Figure 1)[4].

A number of companies worldwide are applying this technology to many other fields that can benefit from precise dispensing of fluids in very small unit quantities. Among others, these include biotechnology and medicine, flat panel displays, adhesives, optical microlenses and solder bump bonding. This list is ordered roughly in terms of the fluid temperature needed

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to sustain drop-on-demand dispensing. Optical materials usually require temperatures in the order of $150°C$ for direct dispensing. We have years of experience with high-temperature dispensing [5, 6] and are applying that technique here as well (Figure 2).

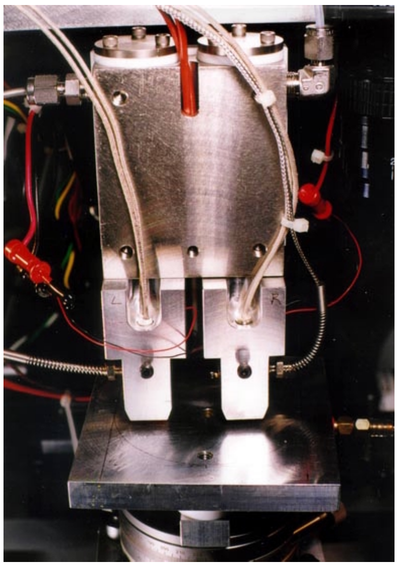

Figure 2: *Heated dual print head.*

Technical Implementation

We build our print stations with the dispensing head held in a fixed position and the substrate being moved to produce the desired pattern. By convention, the substrate (glass for experiments, glass, silicon and other substrates for custom applications), moves horizontally in the x-y plane. A third stage, usually moving vertically (z axis), positions the print head or heads closely above the substrate. It also supports a downward looking camera that can be used to survey printed patterns without relocating the substrate off of the motion table.

Large lenses cannot be created simply by piling up droplets in a single position, expecting spreading on the surface to take care of the sizing of the lens and surface tension of the fluid to assure the proper shape. Therefore, we have added a precision rotational stage on top of the x-y table to allow building up lenses ring by ring for a layer, and then, through raising the print head, layer by layer for its full shape (Figure 3). The x and y stages then serve mainly to provide the centering of the rings and the selection of the print head.

The optics field in general demands a variety of fluids to be dispensed with precisions down to 1-3 μm (3 std. dev.). To date, we have accomplished a relative placement accuracy of better than 2 μm (1 std. dev.) in arrays of microlenses [7]. It appears that this result is dominated by the properties of the motion system and the currently used software corrections.

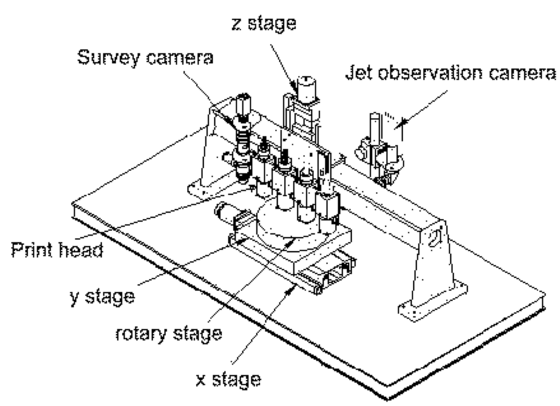

Figure 3: *GRIN lens printer concept.*

For small lenses of diameters in the order of 300-330 μm, we have achieved errors on diameter of less than 0.6%, and on focal length (also around 300-330 μm) of less than 1.1% (both 1 std.dev.). These are indicators of the good control over drop sizes and surface effects.

Requiring a focal spot size of 5 μm at a focal length of 1 m for a thin 100 mm diameter plano-convex lens implies that the droplet placement be clearly better than 5 μm so that the local radius and center of curvature are maintained within that limit across the whole lens area. We are aiming at positioning in the x-y plane to better than 1 μm and along the perimeter of every circle of better than 5 μm. Our current design calls for air-bearing x and y stages and a direct drive rotary stage.

The desired variation of the index of refraction is accomplished by using different fluids. Our machine is laid out to support four fluids in separate heads on the machine (Figure 3). Because of the ring-by-ring and layer-by-layer construction, we can implement both radial and axial gradients at the same time.

Printing GRIN Lenses

Various of our projects in the optics sector are centered around creating small lenses on flat substrates like glass plates or on the ends of fibers. The former are useful for building massively parallel optical switches while the latter include, e.g., efficient and stable couplings for single fibers. The basic lens is spherical, coming about quite naturally when one or a few droplets are dispensed at a fixed location. The drop-on-demand technology does allow us to also make quite odd-shaped lenses, e.g., hemielliptical or even nearly-square based ones.

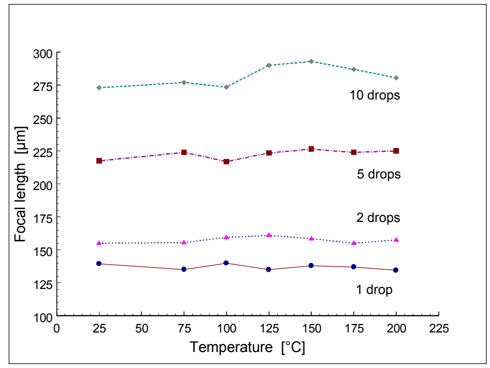

Figure 4: *Focal length vs baking temperature for different lens sizes (numbers of droplets)*

Once printed, the optical material is cured by exposure to ample heat or UV light. For small lenses, the curing process is quite uncritical in terms of maintaining a specified focal length; e.g., a wide variation of the baking temperature will affect the focal length only to within a very few percent (Figure 4). This also implies that the lenses remain unaffected by large temperature variations in their operating environment.

The basic printing strategies are quite simple, as shown in Figures 5 and 6. The time needed to produce a single lens is not small, however. Assuming a dispense droplet rate of up to about 1 kHz, spacings of 120 μm between rings, between droplets around a ring and between layers, 100 mm lens diameter and 2 mm lens thickness, we will need about 6 hours for a single lens. The thickness and diameter match a plano-convex lens with 1 m focal length and a refractive index of n˜1.4. The 120 μm spacings correspond to droplets of 2 nL volume or 135 μm diameter which are large for our dispensing devices but we have reliably produced droplets of tin-lead solder of this size before.

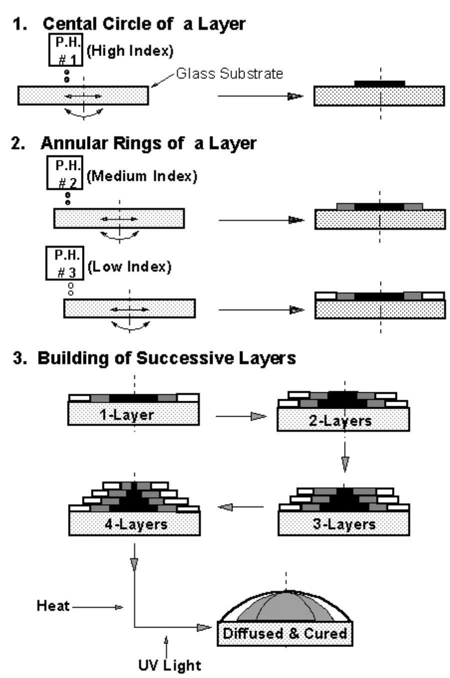

Figure 5: *Process steps for radial GRIN lenses.*

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Beyond the machine construction and tuning, the optical materials require attention as well. Although we are able to operate our dispensers at temperatures up to over $300°C$, many materials are not available to us due to their much higher melting temperatures. We are developing optical adhesives in-house which can be dispensed at 100-150$°C$ and provide different indices of refraction. Curing is accomplished by UV exposure, which is applied only a the every end of the manufacturing processes (Figure 5). This provides for the opportunity to allow diffusion to occur at the interface between the different optical materials and also avoids the formation of reflective or absorptive skins in that area.

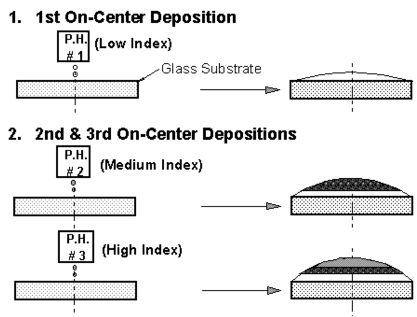

Figure 6: *Printing steps for axial GRIN lenses.*

We can test the material properties by printing small lenses on an existing print station. The example in Figure 7 shows effectively a measurement of the difference in index of refraction for two materials. The slopes (2.5, 3.0) can be converted into indices of refraction (1.4, 1.333) using the thin-lens approximation. As the approximation is not quite appropriate, the absolute sizes of the indices are inaccurate but their difference (0.067) is expected to be close to reality.

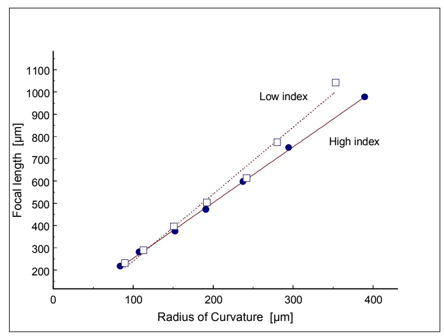

Figure 7: *Focal length vs. radius of curvature for small lenses with different indices of refraction.*

Summary

Drop-on-demand technology offers new avenues in the development and production of macroscopic optically corrected lenses. The primary benefit is the avoidance of mechanical tool making and setting dependent on lens parameters and added flexibility in the design, allowing to combine radial and axial gradient approaches.

Acknowledgements

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