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Fabrication of micro-optics by microjet printing

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ABSTRACT

Microjet printing methods are being utilized for data-driven fabrication of micro-optical elements such as refractive lenslet arrays, multimode waveguides and microlenses deposited onto the tips of optical fibers. Materials used for microjet printing of micro-optics to date have included optical adhesives and index-tuned thermoplastic formulations dispensed at temperatures up to 200°C onto optical substrates and components. By varying such process parameters as numbers and locations of deposited microdroplets, print head temperature and orifice size, and target substrate temperature and surface wetability, arrays of spherical and cylindrical plano-convex microlenses have been fabricated with dimensions ranging from 80 μm to 1 mm to precision levels of just a few microns, along with multimode channel waveguides. Optical performance data such as lenslet f/#'s and far-field diffraction patterns are presented, along with beam-steering agility data obtained with an optical telescope system assembled from microlens arrays printed by this process.

Keywords: refractive micro-optics, microlens arrays, optical waveguides, micro-jetting

1. INTRODUCTION

Micro-optics, as an enabling technology for applications that cannot be addressed with conventional optics, is growing in importance for a wide range of state-of-the-art optical systems. Binary, or diffractive micro-optics have been developed for applications such as laser diode beam shaping,[1] beam splitting[2] and fill factor enhancement for focal plane imaging.[3] However, refractive microlenses offer an attractive, low- cost alternative in the case of short wavelength ($\lambda<1\,\mu m$) systems requiring relatively high speed (< f/4) lenslets[4], e.g. in applications such as microlenses for increasing the efficiency of detector arrays[5] or imaging arrays for facsimile machines.[6] A commonly used method for fabricating refractive microlens arrays has involved the melting of photolithographically formed cylinders of photoresist,[7] where varying lenslet speed has been accomplished by preshaping of the cylinders by lateral mask translations[8] or laser machining.[9]

We are developing a new, low-cost technique for fabricating fast refractive microlenses and micro-optical interconnects derived from ink-jet printing technology. We have utilized this technology for the direct printing of optical materials in liquid form onto optical substrates and components to form plano-convex spherical or cylindrical microlenses and multimode channel waveguides. This method could offer both cost and flexibility advantages over photoresist cylinder melting processes in certain applications by enabling data-driven, in situ fabrication of micro-optical elements. For example, microlenses of differing sizes and speeds may be formed directly on an optical device, or on a substrate in an array at predetermined locations, as final value-added steps for system performance enhancement.

Here we first outline how an inkjet printing method may be applied for the fabrication of refractive micro-optics, what process control parameters it provides and what considerations are involved in optical materials selection. Then we will present typical physical and optical performance data for various types of printed micro-optical elements, including spherical and cylindrical lenslet arrays and multimode waveguides. Finally, we will provide data demonstrating the performance of printed lenslet arrays in a beam-steering system.

2. THE MICROJET PRINTING METHOD FOR MICRO-OPTICS FABRICATION

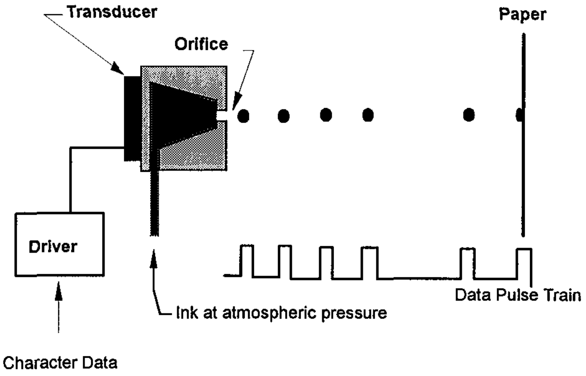

Figure 1. Schematic of a drop-on-demand inkjet printing system.

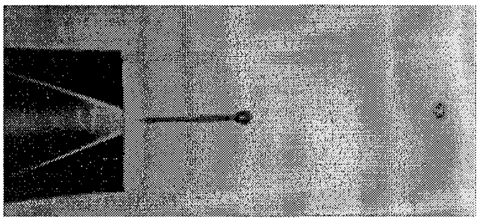

Figure 2. Generation of 50 μm droplets of ethylene glycol at 2 kHz by a drop-on-demand "microjet" device with a 50 μm orifice, where stroboscopically illuminated image is superposition of 2000 droplets.

Our micro-optics fabrication technique is based upon "drop-on-demand" (DOD) inkjet printing, where a volumetric change in fluid within a print head is induced by the application of a voltage pulse to a piezoelectric transducer coupled to the fluid. This volumetric change causes pressure/velocity transients to occur in the fluid, and these are directed so as produce a drop that issues from an orifice.[10] In this type of printing system, depicted schematically in Figure 1, a voltage pulse is applied only when a drop is desired, as distinguished from the "continuous" type where the printhead produces a continuous stream of charged droplets which are directed to the target by deflection plates.[11] Since such a system is data-driven, single droplets or bursts of droplets ejected at frequencies up to 5kHz may be printed at predetermined locations. The DOD microdroplet formation process is seen in the photograph of Figure 2 which shows a print head tip generating 50 μm diameter droplets under stroboscopic illumination at 2 kHz. In addition to traditional inkjet printing, this "microjetting" method has also been used previously for such unconventional applications such as dispensing liquid solder for microelectronic packaging.[12,13]

If the ink and paper of this inkjet system are replaced by an optical material and an optical substrate or component, respectively, and the system is provided with additional capabilities such as dispensing at elevated temperatures, it becomes a highly versatile tool for in situ micro-optics fabrication. The minimum feature size which may be printed is determined by both the volume of the smallest ejectable microdroplet, as controlled by printhead orifice diameter, and the degree of wetability of the substrate surface to the printed material. Single or multiple droplets printed onto a flat substrate spread and coalesce to form plano-convex elements upon solidification and/or curing. Hemispherical lenslets of differing diameters and speeds are formed by varying the number of droplets per substrate site, the substrate surface condition and the type and/or solidification rate of the optical material used. Other types of micro-optical structures, such as cylindrical lenslets, microlens arrays and optical interconnects, may be printed by translating the substrate in the plane perpendicular to the jet and controlling its temperature.

3. EXPERIMENTAL METHODS

3.1. Micro-optical material selection

Formulations of optical materials for microjet printing of micro-optics must satisfy two primary requirements. Firstly, after solidification and curing they should provide both the optical and physical properties needed for the particular application. Secondly, they must be reducible in viscosity below about 20 cps, by either heating or mixing with a solvent, in order to be readily printable by this method. Solvents are often employed for spin coating of photoresist onto substrates, for example, for subsequent microlens formation by polymer island melting. However, evaporation of solvent from microjetted droplets during solidification can cause size and shape distortion in printed features, so solvent-free materials dispensed at elevated temperatures are inherently preferable for microjet printing.

The types of micro-optical materials for which we have developed microjet printing processes to date include a variety of thermoplastics, such as index-tuned "meltmounts" and hydrocarbon resins dispensed at 100-200 °C, along with uv-curing optical adhesives microjetted at room temperature.

3.2. Micro-optics printing processes

A schematic of our micro-optics printing station is pictured in Figure 3. The microjet printhead, along with a 5 µm mesh stainless steel filter, is contained within a heating shell which is connected to a stainless steel heated fluid reservoir. All of the microjet printing parameters are set via the computer which controls both the function generator that provides the printhead drive waveform and the XY-stage motion. A pulse generator, triggered by the function generator, drives an LED positioned below the printhead orifice to provide stroboscopic illumination of the superimposed images of the ejected microdroplets during pre-printing microjetting parameter optimization. The fluid reservoir, printhead and target substrate are independently temperature-regulated in order to control fluid viscosity at the orifice and printed microdroplet solidification rate.

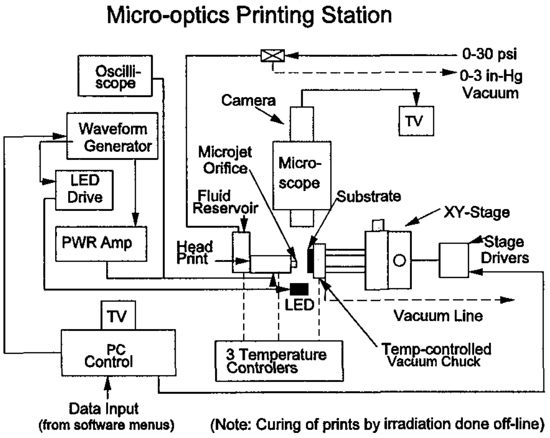

Figure 3. Schematic of micro-optics-jet printing station

The micro-optics printing process involves: (i) adjusting printhead temperature (up to 240°C) and drive waveform parameters to achieve stable microdroplet formation with the particular optical material to be printed, (ii) setting the substrate surface condition and temperature for optimal micro-optical element formation , then (iii) specifying the specific pattern of print sites and the number of microdroplets to be printed per site. Here substrate cleaning is obviously important and its surface may or may not be treated with a low-wetting coating to inhibit or encourage, respectively, droplet spreading and coalescence prior to solidification.

4. EXPERIMENTAL RESULTS

4.1. Microlenses

Plano-convex spherical microlenses have been fabricated by microjetting microdroplets of either optical adhesive material at room temperature or optical thermoplastic formulations at elevated temperature onto substrates such as glass slides, silicon wafers and the tips of optical fibers, and then solidifying the droplets by uv-curing or cooling, respectively. Here lenslet diameters are determined primarily by the size and number of microdroplets deposited, and the speed of a microlens of a given diameter depends on the droplet surface tension and wetability of the substrate to the material being printed. This is illustrated in Figure 4 for microlenses of low-index (n_D=1.53) optical adhesive, high-index (n_D=1.704) thermoplastic

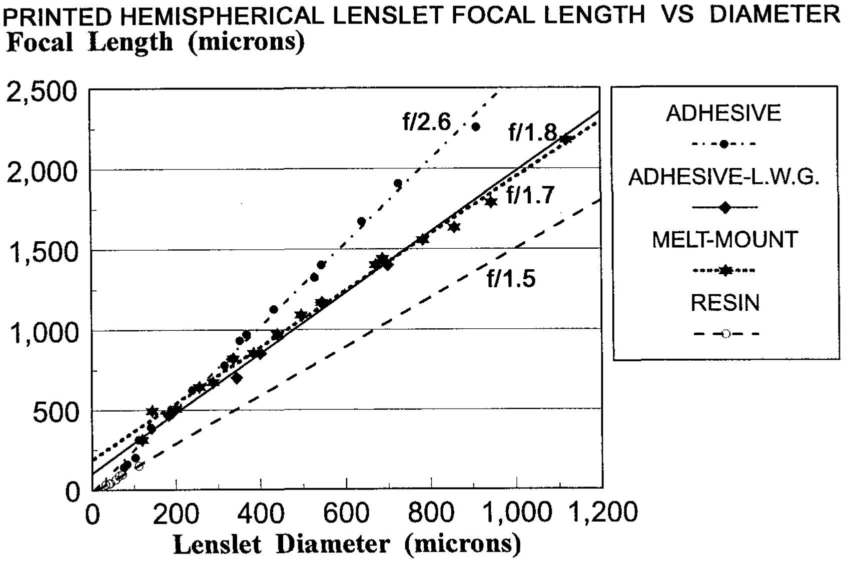

Figure 4. Variation of microlens f/# & focal length with diameter, material and substrate condition for: optical adhesive printed at 25°C onto virgin & low-wetting surfaces and meltmount & resin at 145°C & 200°C, resp.

"meltmount" material, and high-melting-point resin, dispensed at 25°C, 145°C and 200°C, respectively. All of these lenslets were printing onto virgin (untreated) glass slides except for one set of the solvent-bearing adhesive microlenses where the glass was pre-treated-for-low wetting. In all cases focal length varies linearly with diameter, whereas lenslet speed, as determined by line slope, varies independently of diameter with lenslet material and substrate surface condition. Here lenslet speeds are seen to variable by nearly a factor-of-two over the range f/1.5 - f/2.6 by changing the microjetted material and substrate surface preparation, e.g., a 30% increase in speed can be obtained with the optical adhesive by reducing the wetability of the glass.

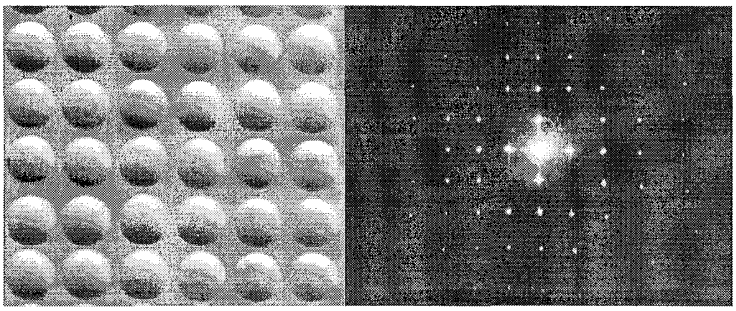

Figure 5. Optical micrograph and diffraction pattern of 100 μm diameter plano-convex microlenses on 125 μm centers, microjet printed with optical adhesive onto low-wetting glass.

Part of a typical array of such microlenses, along with its far-field-diffraction pattern under back-illumination with collimated light, is shown in Figure 5. Here a 50 x 50 array of 107 μm diameter lenslets on 125 μm centers was printed onto a glass substrate treated with a silicone formulation for low surface wetting, by dispensing 50 μm droplets of a 2/1 mixture of Norland Products #71 optical adhesive and acetone at room temperature and then curing the structure under uv illumination. Microscopic measurements at 100X of lenslets selected at random over the entire array area indicated a standard deviation in diameter of 2 μm. The uniformity and clarity of the diffraction pattern indicates good lenslet formation, optical quality and placement for this array.

Hemispherical lenslets have also been printed directly onto the polished tips of optical fibers by the microjetting process, where diameter is constrained by the fiber width and the lenslet radius of curvature may be tailored over a wide range by varying the number of deposited microdroplets. The range of lenslet speeds which may be achieved for a given fiber in this way is illustrated in Figure 6, which shows four 300 μm fibers, one with only a polished tip and three with printed lenslets. By increasing the number of 57 μm deposited droplets from 100 to 200 a lenslet radius of curvature range of 150-300 μm was achieved for this particular fiber

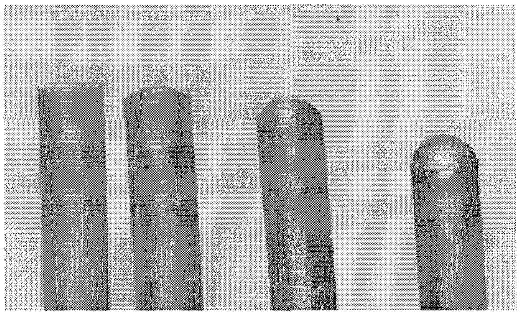

Figure 6. 300 μm core diameter optical fibers without (far left) and with microjet printed lenslets with radius of curvature decreasing (toward right) from 300 μm to 150 μm.

Plano-convex cylindrical microlenses have been fabricated from the meltmount formulations by placing adjacent microdroplets at spacings which enable them to coalesce into a single elliptical droplet prior to solidification. Part of a 20 x 30 array of cylindrical microlenses with corresponding diffraction pattern are pictured in Figure 7. Each lenslet was formed by microjetting four each 50 μm droplets of 1.704 index meltmount at 145°C onto a glass substrate maintained at 45°C, at droplet-to-droplet spacings of 75 μm. These 304 μm x 196 μm microlenses are very reproducible, varying in major and minor axis dimension over the entire array by standard deviations of less than 4 μm. The overall size and length/width aspect ratio of these elliptical lenslets, along with placement positions, may be tailored to match a particular application or add value to an electro-optical device, e.g., to increase the efficiency of coupling the output of edge-emitting diode laser arrays to an optical fiber or the end of a

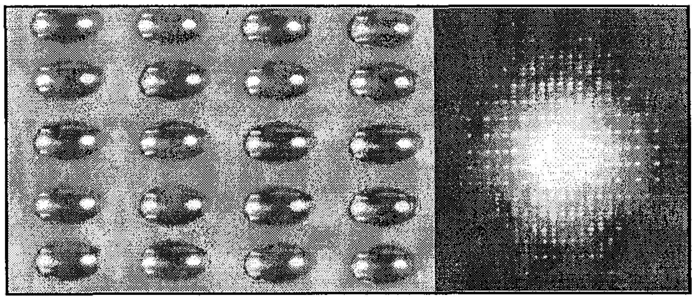

Figure 7. Hemi-cylindrical thermoplastic microlenses, 304 μm x 196 μm, printed at 145°C onto 45°C glass substrate, along with the diffraction pattern from 20x20 lenslet array.

solid-state laser rod, by varying the printing process parameters. Again, the regularity and uniformity of the far-field diffraction pattern attests to the overall good optical quality of this particular array.

4.2 Waveguides

Channel waveguides of the ridge configuration with cylindrical cross-section have been microjet printed for potential applications such as multimode board-to-board, backplane interconnects. An example of such a structure is given in Figure 8, which shows part of an array of 18 mm long, 134 µm wide cylindrical waveguides of high-index (n_D=1.704) meltmount on glass slides (n_D=1.53). Each waveguide was formed by dispensing 250 each 50 µm droplets at 145°C onto a 45°C glass substrate on 75 µm centers, where they coalesced prior to solidification to form very uniform and straight lines. This waveguide printing process is similar to that used for elliptical microlens fabrication and gave a standard deviation in width over the length of all ten waveguides of about 2 µm.

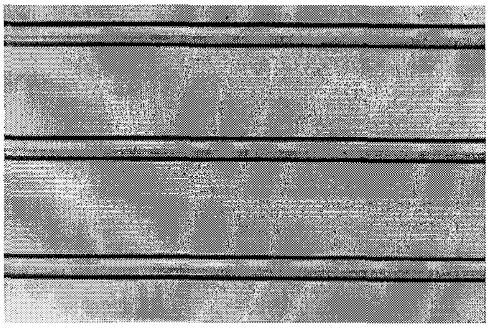

Figure 8. Hemi-cylindrical ridge waveguides, 134µm in width on 625µm centers, fabricated by microjet printing of a high-index (n_D = 1.704) optical thermoplastic material at 145°C onto a glass substrate.

4.3 Beam steering

It has been noted recently that the small sizes and short focal lengths achievable with microlenses can be utilized for agile beam steering, i.e., large angular changes in beam propagation direction can arise from very small displacements in lenslet position[14,15] As a demonstration of this property of micro-optics we built a telescope with microjet-printed refractive microlens arrays, using the experimental setup pictured schematically in Figure 9, and measured scan angle as a function of de-centering of one array relative to the other. A HeNe laser beam was expanded by a factor of 30 and recollimated using a standard Galilean telescope. A micropositioner was utilized to set the spacing of two arrays, oriented face-to-face, equal to the sum of their focal lengths and to translate the second relative to the first in the transverse plane. Steering "agility" was obtained by measuring the displacement of the center of the far-field pattern as a function of array translation.

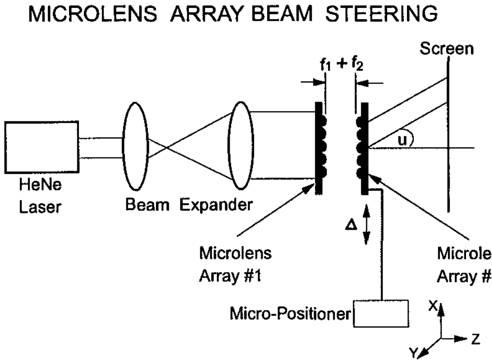

Figure 9. Beam steering by moving one microlens array relative (x-y) to another, with arrays positioned (z) at the sum of their focal lengths.

The arrays consisted of 20 x 20 spherical plano-convex lenslets, printed with uv-curing optical adhesive on 700 µm centers onto low-wetting glass substrates. The lenses of the first array in the optical path were 530 µm in diameter and had a focal length of 720 µm. Two arrays were used in the scanner position having lenslet diameter & focal length of 530 µm & 800 µm and 440 µm & 540 µm, respectively. The data for these two configurations, shown in Figure 10, are seen to follow the expected governing relationship among the scan angle *u*, the focal length *f2* of the decentered array and the decenter distance Δ:

$$\tan(u)=\frac{\Delta}{f2}$$

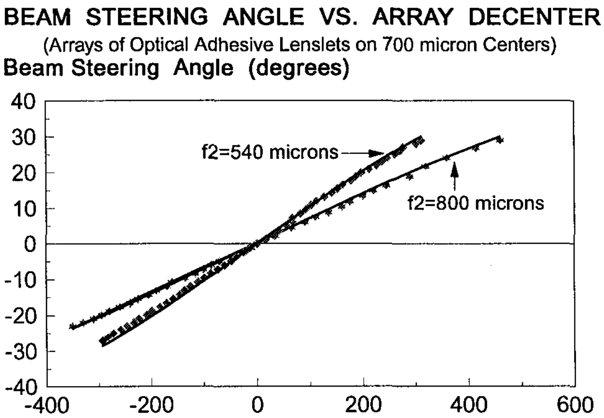

Figure 10. Beam steering angle as a function of array decenter distance for two printed microlens arrays and two focal lengths for the second array.

Here it can be seen that an array of fast (f/1.2) 500 µm focal length lenses decentered by only 100 µm produces a scan angle of 11 degrees and that a total scan of about 40 degrees was achieved with a nearly linear relationship between steering angle and array decenter.

5. CONCLUSIONS

We have demonstrated the viability of a microjet printing method for the fabrication of refractive micro-optical elements such as spherical and cylindrical microlens arrays, lenslets printed onto the tips of optical fibers and multimode channel waveguides. The potential advantages of this approach for certain applications include low cost (no photolithographic masks, minimal usage of optical materials), manufacturing flexibility (data-driven), in situ, non-planer processing (direct writing, non-contact) and the ability to create new micro-optical structures (e.g., arrays of lenslets of differing shapes and speeds in same array) which cannot be accomplished readily by conventional methods. The current limitations of this "micro-optics jetting" technology, primarily minimum feature size and limitations in material selection, can be reduced with further printhead system and optical materials development efforts.

6. ACKNOWLEDGEMENTS

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