Invited Paper

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Micro-jet Printing of Refractive Microlenses

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1. Introduction

The technology for fabricating micro-optical elements for low cost optical interconnects by micro-jet (ink-jet) printing has been under development for over two years [1,2]. This data-driven method of micro-optics fabrication offers the benefits of low cost, flexibility and *in-situ*, non-contact processing. These features can be used to advantage in applications where increasing the efficiency of optical power coupling as a value-added step is a goal, and they provide unique capabilities for rapid prototyping and customization of microlens arrays. Here we present our latest results in developing this Optics-Jet technology for applications such as collimation of the outputs of LEDs and diode lasers, as well as for increasing the efficiency of focusing of GRIN lenses [3]. Data on printed microlens optical characteristics will be shown, as well as their performance in collimation and astigmatism reduction of optical sources.

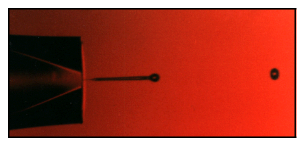

Figure 1. *Generation of 50μm droplets at 2 kHz.*

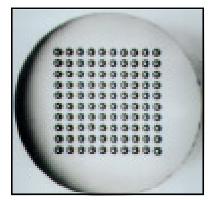

Figure 2. *10x10 array of 220μm diameter micro-lenses printed onto 5mm GRIN lens.*

2. Microlens Printing Method

In "drop-on-demand" microjet printing a single droplet is ejected from the print head every time its piezoelectric actuator is pulsed, producing droplets with precise volumetric control at rates up to 5 kHz, as illustrated in the photograph of Figure 1. To fabricate a microlens by this method, a print head with 30-60 μm orifice diameter is used to deposit at 165°C similarly sized droplets of UV-curing optical material onto the target site which is typically held at 40°C. An example of microlenses formed in this way is the array pictured in Figure 2 of 220 μm diameter lenslets printed directly onto one end of a 5 mm diameter GRIN lens for reduction of optical insertion loss. For a given optical material, device orifice size and substrate, the diameter and focal length of a printed lenslet are logarithmic functions of the number of deposited droplets, as seen in the data of Figure 3. The speed of a printed microlens for a given mass of deposited material is a function of the degree of spreading which occurs on the substrate prior to solidification which, in turn, is controlled by the viscosity level of the material and the degree to which it wets the substrate surface. For polymeric optical materials deposited onto a silanized glass substrate, microlens speed remains relatively constant over a wide range of diameters.

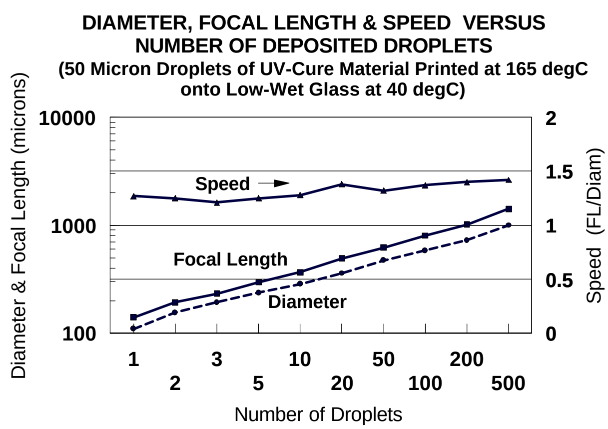

Figure 3. *Variation of printed hemispherical microlens geometry with number of deposited droplets.*

3. Printed Microlens Optical Characteristics and Reproducibility

The optical imaging quality of printed hemispherical microlenses was assessed by measuring the

Modulation Transfer Function (MTF). The measurement system, which utilizes a virtual point source of 665 nm to illuminate the convex surface of the lenslet under test and a 100x microscope objective to project the focused light onto a CCD camera, is capable of measuring microlenses with diameters in the 100 µm - 50 mm range. Measured MTF data for a printed 110 µm diameter microlens with speed of f/1.25, given in Figure 4 along with the those for an ideal (diffraction-limited) lenslet of the same speed, show an identical cutoff spatial frequency (1,200 1p/mm). The Strehl Ratio, obtained from the ratio of integrated areas under the measured and theoretical curves, is 0.71, indicating that the printed microlens produces relatively little spherical aberration in this measurement configuration. To determine the reproducibility of printing a microlens, a microscope system is used to measure diameters and focal lengths of individual microlenses within variously configured arrays. Focal length data for a 10 x 10 array of 495 µm diameter microlenses printed onto low-wet-coated glass on 750 µm centers are

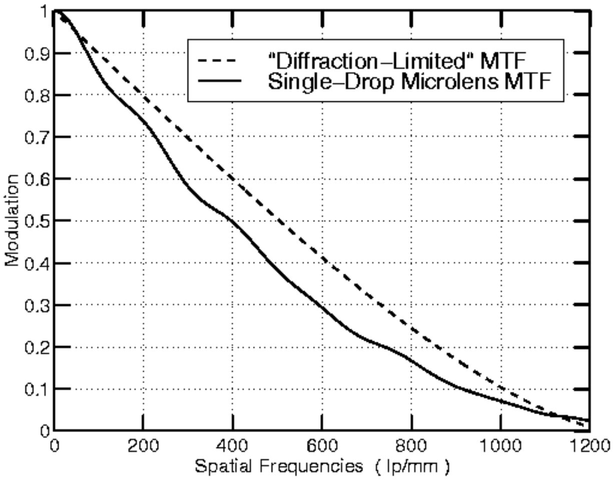

Figure 4. *Modulation transfer function for an f/1.25 microlens printed with one 50µm drop of UV-curing optical material (solid curve), compared to ideal, diffraction-limited case (dashed curve) at same f/#.*

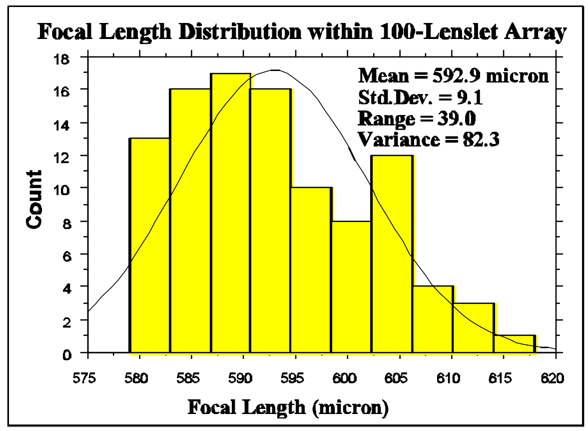

Figure 5. *Distribution of focal lengths of 100 each 0.5 µm diameter microlenses printed in 10x10 array on 750 µm centers, showing a typical standard deviation from the average value of 1.5%.*

given in Figure 5. The standard deviations from the average values of focal length and diameter within such arrays are on the order of 1.5% and 1%, respectively, which are within the measurement errors and sufficient for many array optical interconnect applications. Microlens placement accuracy depends primarily on the accuracy of the substrate stages and the distance between print head orifice and substrate surface. At a typical printing distance of 1 mm, our R&D system can place microlenses with an accuracy ≤ 2 µm.

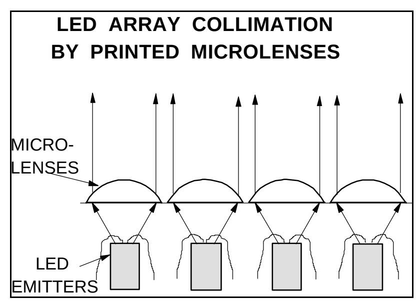

Figure 6. *Geometry for LED array collimation by printed microlenses.*

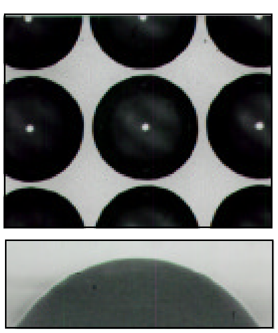

Figure 7. *Array of 355 µm diameter micro-lenses printed on 375 µm centers, shown in substrate plane (top) and in profile (bottom).*

4. Microlens Printing for LED and Diode Laser Collimation

The printing of plano/convex microlenses for source collimation is currently being explored in several areas, including hemispherical microlenses for LED and VCSEL (smart pixel) arrays and hemi-elliptical lenslets for edge-emitting diode laser arrays. For the LED array case, a microlens is printed directly above each emitter with back focal length adjusted to be at the effective emitting point, as indicated in Figure 6. Here the lenslets are printed either onto a thin glass substrate positioned above the emitters or onto a flat surface established by dispensing and curing of the same or similar material on and around the emitters to the requisite height. A typical configuration suitable for display light sourcing, and for which collimation performance data will be presented, is an array of

15 x 15 each 250 µm square LEDs on 375 µm pitch, with an array of 355 µm diameter, f/1.22 microlenses printed at the same pitch as shown in the photos of Figure 7. Data illustrating the use of printed microlenses for VCSEL array collimation will also be presented, with emitter/lenslet pitches down to 250 µm.

The objective of our work with high power edge-emitting diode laser arrays is to increase efficiency of coupling into optical fibers. The suitability of our printed microlenses for high power applications has been demonstrated by post-cure baking experiments where no measurable change in focal length occurred after exposure to temperatures up to 200°C. Collimation of an edge-emitting diode laser emitter by a printed microlens requires a slight ellipticity in lenslet shape, in order to correct for astigmatism and bring the rapidly (~40°) and more slowly (~10°) diverging planes of light into collimation at the same z-axis plane. These hemi-elliptical microlenses are printed along the bar direction by depositing a line of droplets of optical material , which join by cohesion prior to curing, and adjusting the number and spacing of the droplets to control lenslet size and ellipticity. An example of a series of microlenses of differing degrees of ellipticity is given in Figure 8, where six 60 µm droplets were printed at adjacent sites to form each lenslet, with increasing site spacing for successive lenslets. The variations with deposition site spacing of the major and minor axis lengths and corresponding "slow" and "fast" focal lengths of the microlenses pictured in Figure 8 are plotted in Figure 9. Increasing site spacing effectively increase the ratios of both major/minor axes and slow/fast focal lengths, providing the capability for tuning printed microlens properties for a wide range of diode laser configurations. In practice, the degree of ellipticity required may be quite small, e.g., on the order of 1.001 to correct an astigmatism of 5 µm.

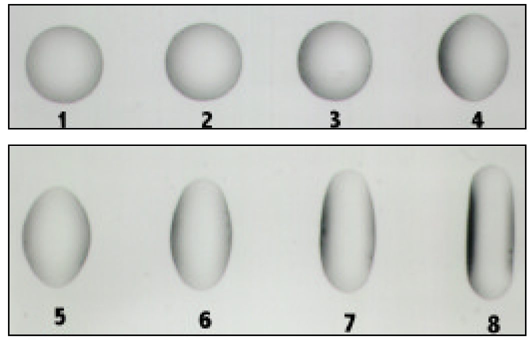

Figure 8. *Hemi-elliptical microlenses printed with 6 each 60 µm droplets on site spacings increasing by 10 µm from #1 to #8 (100X mag).*

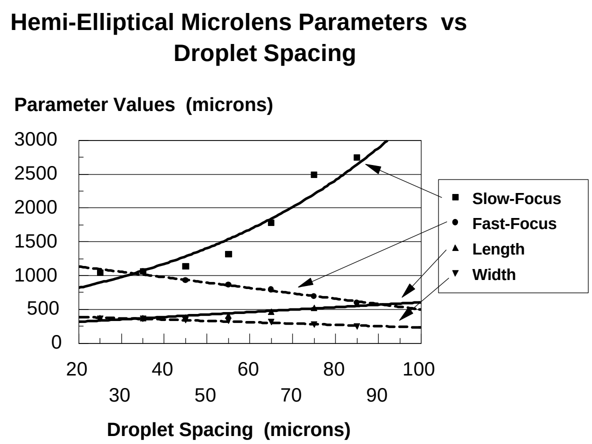

Figure 9. *Variation with droplet spacing of focal lengths and dimensions of hemi-elliptical microlenses of Fig. 8.*

5. Conclusions

Practical applications of this micro-optics printing technology are rapidly emerging in diverse and important areas of optoelectronics manufacturing where the associated benefits of cost reduction and flexibility can provide a competitive edge. As capabilities continue to develop for both improving further the accuracies of the processes for micro-optics printing and reducing the element sizes which can be fabricated, the potential application areas will be expected to expand from LED and diode laser beam shaping to new arenas such as display and sensor manufacturing.

Acknowledgments

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References

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[3] V. Baukens, A. Goulet, H. Thienpont, I. Veretennicoff, W.R. Cox and C. Guan, “GRIN-lens based optical interconnection systems for planes of micro-emitters and detectors: microlens arrays improve transmission efficiency,” *OSA Diffractive Optics and Micro-Optics Topical Meeting*, Kailua-Kona, Hawaii, June, 1998.