Microjet Printing for Low Cost Optical Interconnects

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Abstract

Drop-on-demand microjet printing methods are being developed for the formation of optical interconnections. Microdroplets of optical polymeric materials, 25-50µm in diameter, are dispensed at temperatures up to 220°C onto optical substrates and components, in order to create precisely placed & formed micro-optical elements 40-1,000µm in size. Micro-optical elements fabricated in this way include arrays of spherical and anamorphic microlenses, lenslets on the tips of optical fibers, optical waveguides and fiber-to-fiber optical interconnects. Advantages of the microjet printing method for micro-optics manufacture include: <u>low cost</u> (e.g., no photomasks and low material usage); <u>flexible and automated</u> (e.g., custom microlens arrays for diode laser array coupling into optical fibers); and <u>in situ, non-planar processing</u> (e.g., direct deposit of microlenses and waveguides onto flat, curved or flexible optical substrates as a value-added processing step).

Key words: micro-optics, microjet printing, optical interconnects, waveguides

Introduction

The continued evolution of information transmission and processing systems will increasingly rely on advanced micro-optical interconnect technologies to connect optically the various pieces of optoelectronic systems, in order to resolve bottlenecks resulting from high circuit density, multiple pin-outs, high data and processing rates, etc. Capabilities are evolving for fabricating practical optical interconnects, in the form of micro-optical waveguides [1], fibers and free-space interconnects [2], between instrument back-planes, printed circuit boards (PCB's) and electro-optic components within boards. The critical issues for optical interconnects are utilization of materials and processes compatible with electronic circuit board processing and low cost manufacturing through passive optical alignment procedures.[3]

This evolution in micro-optical interconnect technologies is being fueled by the development of new interconnect fabrication processes utilizing organic polymeric materials, which offer significant advantages over the traditional inorganic materials in both electro-optical properties and ease of fabrication. Polymers are currently considered to be the leading practical material for optoelectronic device and component fabrication, primarily by virtue of their large optical nonlinearities; mechanical, chemical, thermal and optical stability; sub-picosecond response times; very low absorption and scattering losses in waveguides; and the lack of restrictions on the types of substrates onto which they may be deposited.[4]

Microjet printing of polymeric micro-optical interconnects, as a non-contact, data-driven process, potentially could provide both significant reductions in costs and increases in the flexibility of manufacturing of optoelectronic packages and interconnect components, in addition to enabling new optical-interconnect device configurations. This paper will review developments to date in this new technology.

Micro-optics Printing Methods

In "drop-on-demand" (DOD) microjet printing of micro-optical elements a microdroplet of polymeric material is dispensed, at a typical velocity of 1-2 m/s, from an unpressurized print head orifice in response to an applied voltage pulse, as pictured in Figure 1. Upon striking an optical substrate the droplet spreads, coalesces with other droplets and is solidified to form a microlens or waveguide segment of the desired dimensional and optical characteristics.[5]

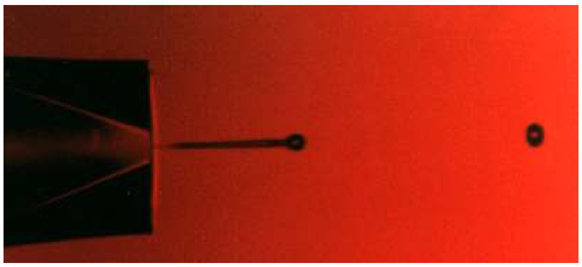

Figure 1. Two-second exposure of generation of 50µm droplets of fluid at 2 kHz by a DOD microjet device with 50µm orifice (where clarity of stroboscopically illuminated superimposed image of 2000 droplets illustrates precision of droplet formation process).

A schematic of our micro-optics printing station is pictured in Figure 2. The microjet print head is contained within a heating shell which is connected to a heated fluid reservoir. Most of the microjet printing parameters are set via the computer which controls both the function generator that provides the print head drive waveform and the XY-stage motion. A pulse generator, triggered by the function generator, drives an LED positioned below the print head orifice to enable viewing of the ejected microdroplets. The fluid reservoir, print head and target substrate are independently temperature-regulated in order to control fluid viscosity at the orifice and printed microdroplet solidification rate. The station is inclosed within a class 100 clean air bench for control of airborne contamination and is exhausted to contain any heated polymer fumes.

The micro-optics printing process involves: (i) adjusting print head temperature (up to 220°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 prior to coalescence and solidification.

Formulations of polymeric optical materials for microjet printing of micro-optics must satisfy three 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 free of solvents, and, thirdly, be reducible in viscosity to about 20 centipoise by heating (without material degradation). The types of micro-optical materials for which we have developed for microjet printing to date include a variety of optical thermoplastics and hydrocarbon resins dispensed at 100-220 °C, along with a variety of uv-curing optical resins dispensed at temperatures up to 150°C. These materials cover a range in index of refraction (n_D) from 1.5 to 1.7, have optical transmissions in excess of 95%/cm at wavelengths above 750 nm, and, in some cases, exhibit cured thermal stability up to 200°C.

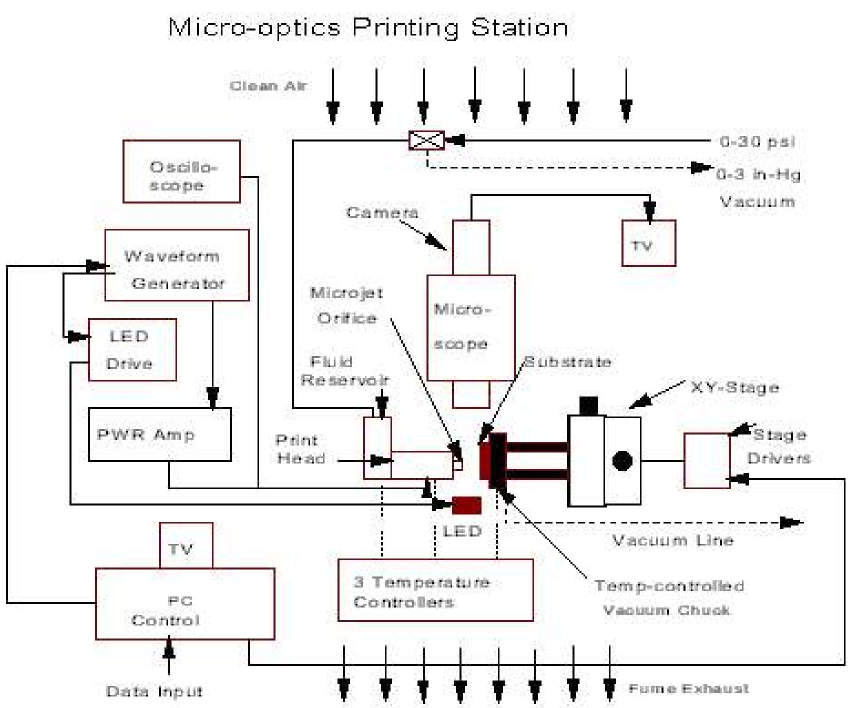

Figure 2. Schematic of micro-optics printing station.

Free-Space Optical Interconnects:

--- Circular Microlenses

The microjet printing of microlenses with circular substrate footprints involves deposition and *in-situ* solidification of one or more appropriately sized microdroplets at each target substrate site. For example, as illustrated in the SEM photos of Figure 3 for uv-curing resin lenslets, relatively high fill-factor arrays of hemispherical microlenses may be printed for focusing or imaging applications.

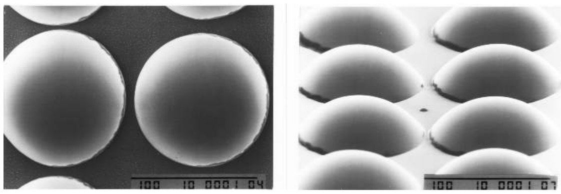

Figure 3. Array of 100µm diameter hemispherical plano-convex microlenses printed on 125µm centers.

One example of the flexibility in microlens fabrication provided by the microjet printing process is illustrated in Figure 4. Here a high-temperature optical thermoplastic material is used to print microlenses of differing radii of curvature at equal volume by varying the temperature differential between print head and substrate. This flexibility of fine tuning the aspect ratio, and, hence, lenslet speed, without changing volume, could be used to advantage in several optoelectronic manufacturing applications. For example, appropriately sized microlenses with curvatures fine tuned for specific focal requirements could be printed directly onto LED's, as a low-cost alternative manufacturing process to the currently utilized method of manually gluing of glass spheres.

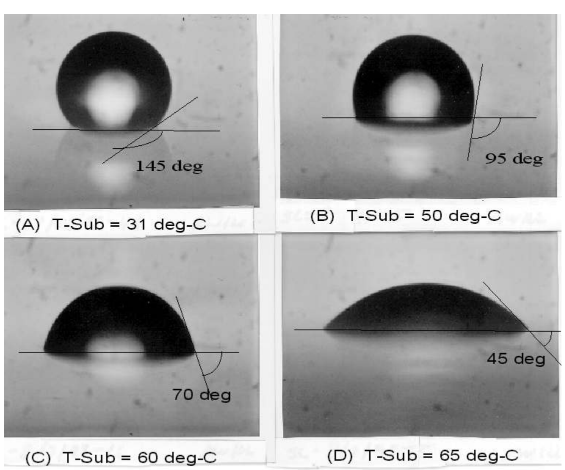

Figure 4. Variation of surface contact angle with substrate temperature for microlenses printed at 215°C with 5 each 50µm droplets of thermoplastic.

Another example of microlens printing flexibility is provided by the utilization of intervening, in-situ, uv-spot cures to achieve quasi-hyperbolic configurations. Figure 5 compares two microlenses printed with a total of 25 microdroplets of uv-curing optical resin. Applying flashes of uv irradiation *during* printing increases the viscosity of the material sufficiently to enable building up of a taller structure (5A) with a nearly hyperbolic shape, as opposed to the flatter lenslet (5B) obtained by printing all 25 droplets before any uv-exposure. Such high aspect ratio microlenses could potentially be printed directly onto the emitter cavities of vertical-cavity surface-emitting lasers (VCSEL) to focus the outputs into optical fibers.

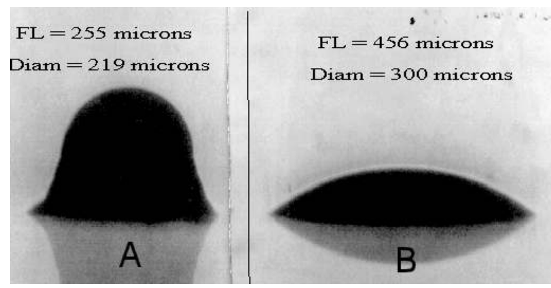

Figure 5. Hyperbolic profile microlens (A) printed by uv-spot-curing after each of 5 depositions of 5 each 40µm droplets, compared to microlens (B) printed by curing after deposition of all 25 droplets.

Spherical microlenses may also be printed directly onto the tips of optical fibers, as illustrated in Figure 6, in order to increase their effective numerical apertures for receiving light from sources such as diode lasers. Here the edge of the fiber tip constrains the deposited material, enabling control over printed lenslet curvature and, consequently, of fiber acceptance angle, according to number and size of deposited microdroplets. [6]

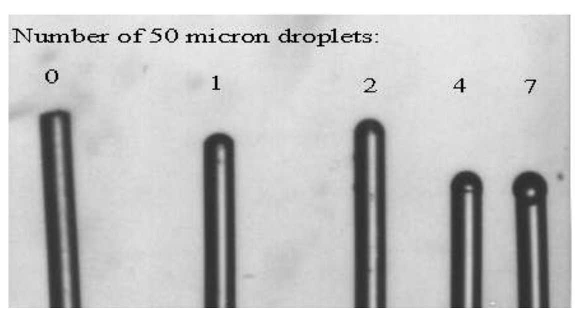

Figure 6. 140µm diameter optical fibers with microlenses of differing radii of curvature microjet printed onto their tips.

Free-Space Optical Interconnects:
--- Anamorphic Microlenses

Non-circular or "anamorphic" microlenses which can be microjet printed for free-space interconnect applications include those with elliptical, square and rectangular substrate footprints. Lenslets with these configuration are printed by a somewhat different process, whereby sequential microdroplets of optical material are deposited at adjacent sites such that they coalesce smoothly during solidification.[7]

Hemi-elliptical microlenses are printed by depositing microdroplets at elevated temperatures along a line on a temperature controlled substrate and adjusting their spacing to achieve the desired geometry. An array of four such lenslets, each printed with six 35µm droplets of optical thermoplastic at 150°C onto 30°C glass on 40µm centers, is pictured at three different heights above the substrate in Figure 7. Here collimated illumination from behind the substrate is first brought to a horizontal line focus in the "fast"focal plane, due to the lenslet curvature about its minor axis, and then to a vertical line focus in the "slow" focal plane, due to the major axis curvature. (Lenslet speed, f/#, is the ratio of focal length to aperture, here the length or width along the appropriate radius of curvature.)

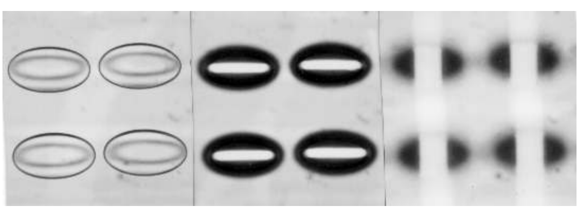

Figure 7. **Four each hemi-elliptical microlenses, 284µm X 146µm X 20µm high, viewed in substrate plane (left), "fast" (f/1.5) focal plane (middle) and "slow" (f/3.2) focal plane (right).**

The data of Figure 8 illustrate how the "slow" focal length of such microlenses may be adjusted over a wide range while keeping the "fast" focus relatively constant. This capability for independently fine-tuning optical parameters while printing each lenslet at exact, predetermined source locations, should render printed hemi-elliptical microlenses as the ideal choice for collimating the anisotropically diverging outputs from edge-emitting diode laser arrays for coupling into optical fibers.

As the droplet spacing is increased during deposition of optical material along a line, a point is reached where the curvature along the major axis flattens and hemi-elliptical microlenses become

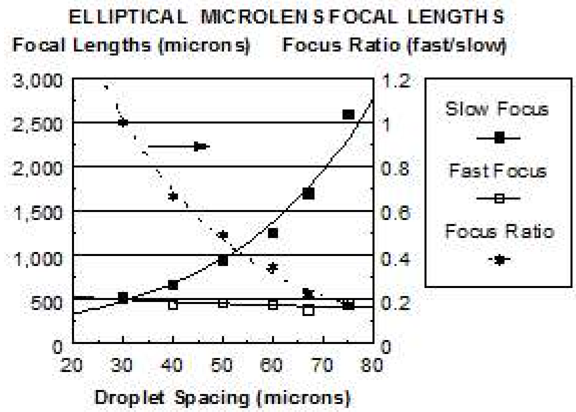

Figure 8 Variation of hemi-elliptical microlens focal lengths and focal length ratio with spacing of 6 deposited 60 µm droplets.

cylindrical, having only a single focal plane, as illustrated in the Figure 9. Arrays of such cylindrical microlenses may be printed for interconnect applications such as single-axis collimation or focussing of diode laser arrays. By extending to two dimensions the deposition of adjacent droplets nearly square or rectangular shaped microlenses may be printed, as illustrated in Figure 10, for a variety of light detector efficiency enhancement applications.

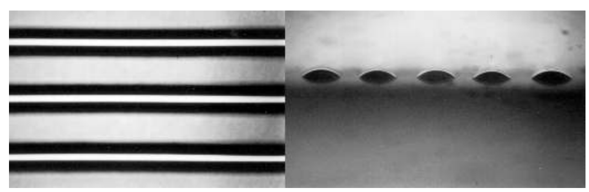

Figure 9. **165µm wide, 37µm high printed cylindrical microlenses shown in focal (f/1.3) plane (left) and in profile (right)**.

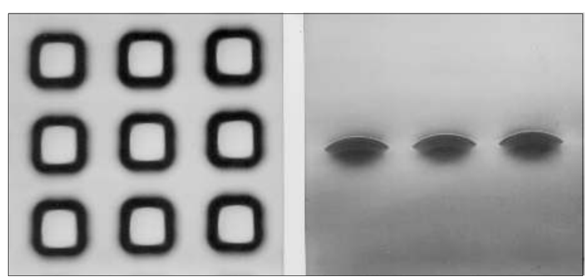

Figure 10. **Array of high speed 300µm square, 50µm high printed microlenses shown in focal (f/0.76) plane (left) and in profile (right).**

Guided-Wave Optical Interconnects

The basic process for the microjet printing of micro-optical waveguides is similar to that utilized for hemi-cylindrical microlenses, except that the deposited optical material must be higher in refractive index than the target substrate, and the control system must have the capabilities (e.g., circular interpolation) for printing the requisite patterns of such structures.

In Figures 11 & 12 are photographs of an array and a segment, respectively, of straight waveguides printed by depositing 50µm droplets of optical thermoplastic of refractive index of 1.70 at 145°C on 65µm center spacings onto a glass (1.52 index) substrate at 40°C. In such a structure the roughest portion, namely, the edges of the guide-substrate interface, may be kept on the order of the wavelength of the transmitted light.

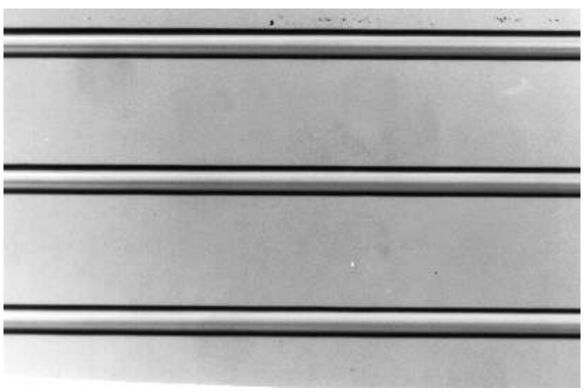

Figure 11. **Hemi-cylindrical ridge waveguides, 116µm wide X 35µm high on 625µm centers, fabricated by microjet printing of a high-index (n_D = 1.704) optical thermoplastic at 145°C onto 40°C glass.**

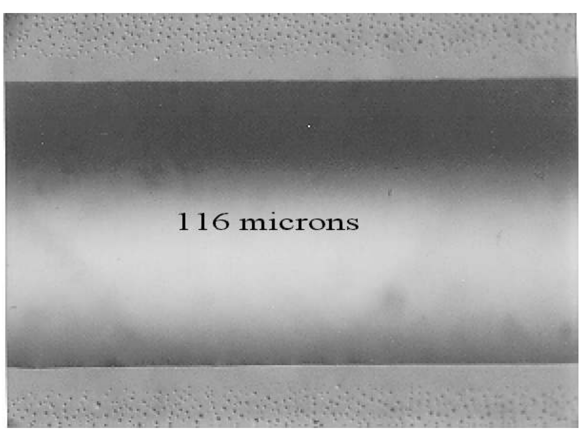

Figure 12. **Magnified section of a straight, hemi-cylindrical waveguide from Fig. 11, showing edge roughness at guide/substrate interface on order of 0.5µm.**

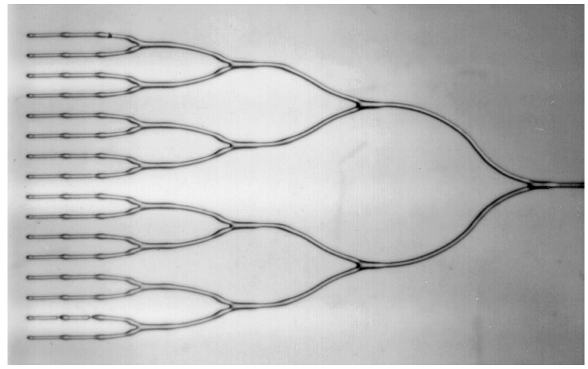

Figure 13. **25mm long, 1-to-16 branching waveguide printed as in Fig. 11, but using software to specify the pattern layout.**

Arbitrary patterns of waveguides may, similarly be printed by utilizing software which enables precise adjustment of features such as number & location of branching points, turning radii and segment lengths, as illustrated in the photograph of Figure 13 of a 1-to-16 branching multimode waveguide for potential application in optical power distribution.

Printed Micro-Optical Element Characterization

Microscopic measurements of microlens dimensional and focal properties indicate lens-to-lens reproducibility of a given configuration to within standard deviations of 1% and 2%, respectively. By comparing focal plane power distribution peaks, such as those shown in Figure 14 for the two planes of a hemi-elliptical lenslet, with idealized Airy [8] peaks, it can be deduced that printed microlens optical performance quality varies inversely with speed in the 1-2X diffraction-limited range.

The waveguides printed to date have also exhibited "good" guiding performance, based on coupling of a HeNe laser light in and out through the thin glass substrate, utilizing 45° micro-mirrors cut into the ends of the guides. We hope soon to be able to measure total insertion loss for such structures.

Summary and Conclusions

We have demonstrated that microjet printing methods may be successfully employed, given the appropriate print head and optical materials performance capabilities, to fabricate microlenses (i.e., free-space optical interconnects) of many useful configurations, either directly onto optical components or into customized arrays on optical substrates. Some of these configurations, such as spherical lenslets with substrate surface angles much greater than 90° or speeds greater than f/1 (e.g.,f/0.76), cannot readily be fabricated by more established methods such as photo-lithographically patterned photoresist island laser micro-machining and melting [9].

The microjet printing of multimode ridge waveguides for optical power transfer has also been demonstrated. Here the edge-smoothness obtainable by the micro-jetting process suggests that such structures could be developed which would be at least comparable in optical performance to multimode guides fabricated by current methods such as selective uv-exposure of photoresist films [3]. In addition, the flexibility of the waveguide printing process would make it especially useful in the fabrication of guided, board-to-board optical interconnects in optoelectronic packages.

In summary, we have indicated how the microjet printing of microlenses and multimode optical waveguides may be used to advantage *in reducing the cost* of optoelectronic component and package manufacture in a variety of important applications, through automation, reduced materials usage and increased flexibility of manufacture. In addition, we might suggest that significant value-added, cost-reduction benefits in optoelectronic package and interconnect manufacturing could potentially be realized by integrating compatible microjet printing process capabilities, such as the printing of micro-optics and 63/37 Sn/Pb solder balls [10], into a single production platform.

Acknowledgments

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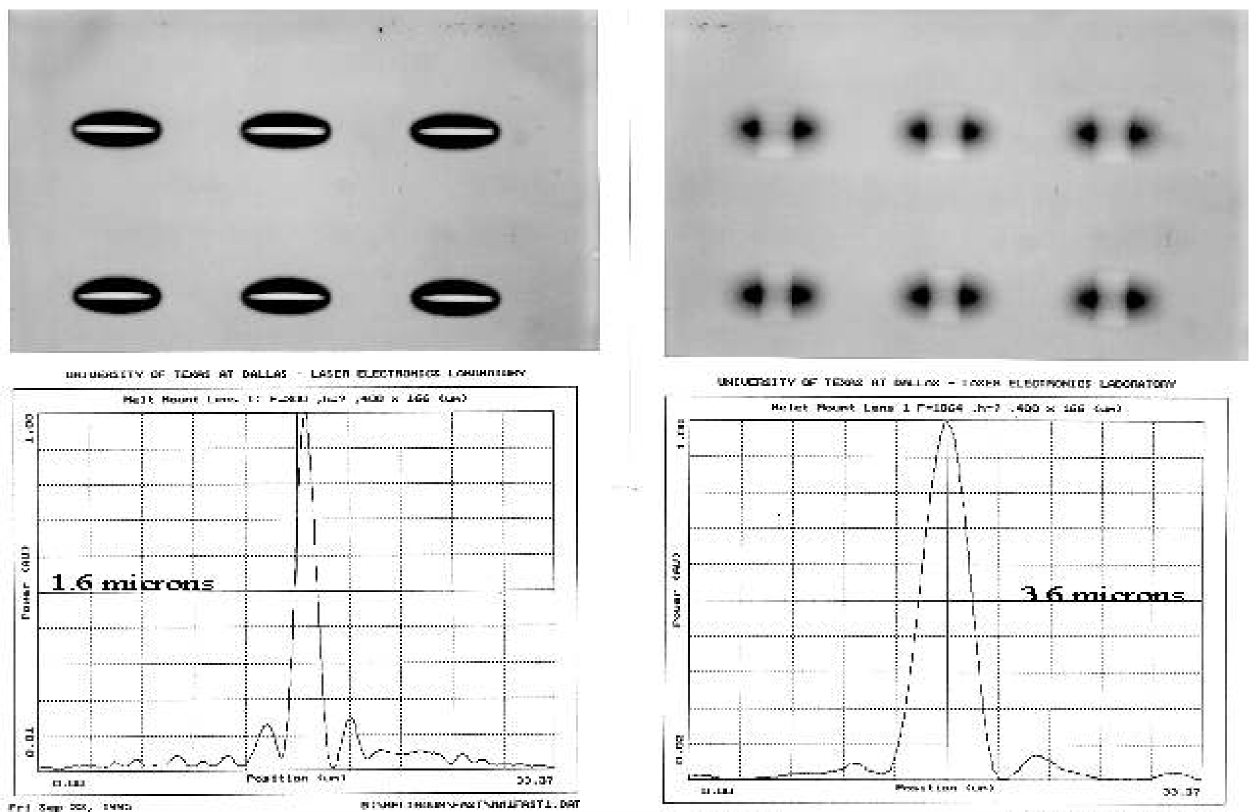

Figure 14. Power scans across "fast" (left) and "slow" (right) focus lines of a printed hemi-elliptical microlens from above array.

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