Microjet Printing of Micro-Optical Interconnects

W. Royall Cox, Chi Guan, Donald J. Hayes and David B. Wallace
MicroFab Technologies, Inc.
1104 Summit Ave., Suite 110
Plano, TX  75074
Ph: (972) 578-8076 / Fax: (972) 423-2438 / email: rcox@microfab.com

Abstract

Fabrication of refractive, free-space optical interconnects by ink-jet printing offers advantages for numerous optoelectronic packaging applications for datacom and telecom because of the capability for reducing costs and providing higher levels of manufacturing process integration. We have demonstrated the printing of microlenses onto the tips of optical fibers for enhancing efficiency of light collection from edge-emitting diode lasers for potential use in telecom transmitters and for collimation of fiber output beams for potential wavelength division multiplexing applications. We have also printed arrays of microlenses for beam collimation and focusing in devices such as high power edge-emitting diode laser delivery systems and VCSEL-based, smart-pixel devices for massively parallel datacom switches. Finally, the potential power of this technology in providing enhanced levels of process integration in optoelectronic device packaging is exemplified by the printing of both solder bumps and microlenses onto the pads and emitters, respectively, of VCSEL arrays using a dual print head, high temperature printing platform.

Key words:
Micro-optics, Ink-Jet Printing, Optical Fibers

1. Introduction & Background

The continuing evolution of information transmission and processing systems of greater speed, parallelism and breadth of use will increasingly require lower-cost, high-performance optical-interconnect manufacturing technologies. This need has fueled the emergence of new micro-optical fabrication technologies, including direct-write of refractive microlenses and waveguides, by microjet printing\(^1\,^2\,^3\,^4\) or syringe dispensing\(^5\). These approaches are of particular interest because they are data driven, single-step processes with capabilities both for utilization of optical epoxies with higher thermal durability than the PMMA photo-resist used in photolithographic methods\(^6\) and for fabrication of micro-optical elements directly onto optical components of arbitrary geometry.\(^7\,^8\)

After a review of the processes and materials used for ink-jet printing of micro-optics we will discuss utilization of this “Optics-Jet” technology in printing refractive microlenses in arrays for use, firstly, in diode laser array, high power fiber delivery systems and, secondly, in massively parallel, VCSEL (vertical cavity surface emitting laser)-based, smart-pixel, datacom switches. Then we will address the printing of microlenses onto the tips of optical fibers, both to increase their angle of acceptance for light from edge-emitting diode lasers and to collimate their output beams.

![Figure 1. Concept of drop-on-demand ink-jet printer, where each pulse to driver produces one droplet directed to target substrate.](image-url)
In piezoelectric, drop-on-demand (DOD) ink-jet printing systems, illustrated schematically in Figure 1, a volumetric change in the fluid within a printing device is induced by the application of a voltage pulse to a piezoelectric transducer which is coupled to the fluid. This volumetric change causes pressure/velocity transients to occur in the fluid which are directed to produce a droplet from the orifice of the device. Here a voltage pulse is applied only when a droplet is desired, as opposed to continuous ink-jet printers where droplets are continuously produced but directed to the target substrate only when needed by a charge and deflect method. The process of droplet formation and ejection from the orifice of a DOD device is indicated in the time-sequenced photos of Figure 2, taken under stroboscopic illumination at the driving frequency of the dispensing device.

Optical epoxies and thermoplastic formulations may be used in printing micro-optics, as long as they may be reduced in viscosity to less than 40 cps, which is typically achieved by heating the print head to temperatures as high as 200°C, in a polymer/solder printing platform such as that shown in Figure 3. The volume of a printed lenslet is a digital function of the smallest droplet size which can be generated efficiently, and its aspect ratio (diameter/sag) is determined by the degree of spreading of the deposited fluid on the target substrate prior to solidification. For UV-cured optical epoxies, control of microlens aspect ratio is achieved by applying a low-wetting optical coating of the requisite free energy level to the substrate, in order to limit the flow of the liquid prior to curing, and/or by heating the substrate during printing. Hemi-spherical microlens printing accuracies and reproducibilities are currently both on the order of 1% & 2% of nominal values for diameter and focal length, respectively, with relative and absolute placement accuracies of about 2 μm & 5 μm, respectively.

Refractive microlens configurations which have been microjet printed range from plano-convex hemispherical, hemi-cylindrical, hemi-elliptical and square, to the convex-convex configuration exemplified by the photograph of Figure 4. This type of microlens, fabricated by printing two plano-convex lenslets coaxially on opposite sides of a 125 μm thick glass substrate, would be more challenging to make using conventional photolithographic methods and could potentially be utilized to reduce focal spot size in, e.g., optical recording applications.

2. High-Power Diode Laser Array Beam Shaping

A commonly utilized approach to couple the power from an array of edge-emitting diode lasers into an optical fiber is to circularize and collimate the beam from each emitter, using, for example, a prefabricated microlens array or crossed cylindrical lenses, and then, to focus all of the collimated beams into the fiber with a macrolens. The efficiency of performing the beam-shaping step could potentially be significantly improved by printing arrays of microlenses in-situ onto the emitter facets of the diode laser bars, since lenslets could be located at the actual (versus predicted) emitter facet positions and also could be slightly elliptical in shape to provide astigmatism correction as well.
as circularization.

One of the first questions that arises in using printed optical epoxy lenslets for this application is the degree to which they can withstand sustained operation at high power levels. To test this we printed 200 µm diameter hemispherical lenslets at the 24 emitter positions of a 20 W, 784 nm diode laser bar, as pictured in Figure 5, then cured them by UV-illumination and baking at 110°C. The microlenses were printed directly above the emitters onto a cover glass slide which had been epoxied onto the face of the device with the same material, in order to provide the offset needed to put the back focal points of the lenslets at the emitting facet plane. In this initial experiment alignment of the microlenses to the emitter positions was done passively by indexing in from the edge of the bar by the specified distance and assuming the design pitch, but active alignment to individual emitters could be employed in the future with an IR vision system.

The thermal durability of the printed microlenses was demonstrated by running the laser bar in the continuous mode at 20 W and observing a drop in total output power of only 0.3 W after 45 hrs. Effectiveness of collimation by the printed microlenses of the overall output beam of the bar, with nominal emitter divergences of 40°and 10° in the perpendicular and parallel planes, respectively, is shown by the data of Figure 6. It was found that near collimation (3° divergence) was achieved in the perpendicular plane, and that the existence of this residual divergence was due to the microlens focal points being about 30 µm behind the emitting facets. Lack of collimation in the parallel plane was anticipated due to beamlet overlap along the bar.

3. Printed Microlenses for VLSI Photonic Switches

One approach in using printed microlenses for collimating light from VCSEL arrays and/or focusing it into arrays of micro photodetectors is to print arrays of microlenses of the requisite characteristics onto glass wafers in array patterns with element pitches matching those of the device-array wafer, then locating the two wafers at the distance needed to place the focal lengths of the lenslets at the emitter/detector plane and translating one wafer relative

---

**Figure 5.** 200 µm diameter epoxy microlenses printed over 24 emitter facets of a 20 W diode laser bar, shown in emitter plane (top) and in profile (bottom).

**Figure 6.** Beam profiles perpendicular and parallel to diode laser bar of an emitter with printed hemispherical microlens, indicating near collimation (3°) in perpendicular plane.

**Figure 7.** Portion of printed interlaced arrays of 300 µm diameter lenslets for use in “smart-pixel”-based datacom switch, where box shows two lenses within a pixel area.
to the other to achieve element-to-element alignment.

We are currently using this approach in printing arrays of microlenses for use as free-space optical interconnects in massively-parallel, VCSEL-based, photonic switches under development in conjunction with the DARPA (Defense Advanced Research Project Agency) VIVACE (VCSEL-based Interconnects in VLSI Architectures for Computational Enhancement) program.11 These switches, the details of which are beyond the scope of this paper, will enable rapid switching from any one of 1028 fibers of an input array to any one of an identical number of output fibers and are reconfigurable. The microlens arrays are printed onto 3 inch diameter thin glass wafers in 12 group/chip patterns, where each group consists of two each 16 x 16 identical arrays of 300µm-diameter, 60µm-sag microlenses. The microlenses in each array are printed on 500 µm centers, and the two arrays are offset from each other by 250µm along a diagonal, as shown in the photograph of Figure 7. After printing, the microlens wafer is aligned to a GaAs wafer supporting identical patterns of VCSELs and photodetectors, with each smart-pixel unit cell consisting of a VCSEL/detector pair, where the corresponding two microlenses serve to collimate the beam from an emitter and focus a returning beam into the adjacent detector.

Selection of printed microlenses for this application was based on the greater coupling efficiency and wavelength independence of refractive lenslets compared to diffractive ones and the greater thermal durability of optical epoxy compared to the photoresist used in photolithographically fabricated refractive lenslets. For example, such microlens can operate at temperatures up to 80°C and withstand temperature cycling up to 220°C, e.g., for solder reflow.


Increasing the angle of acceptance of light into an optical fiber is of interest because it can relieve the sensitivity to alignment of an edge-emitting diode laser to an optical fiber in applications such as telecom transmitters, thereby potentially reducing alignment time while increasing overall device efficiency. We have previously shown that 125 µm diameter microlenses printed onto the tips of multimode optical fibers can increase their acceptance angles by at least a factor of three.7 Here the outer edge of the fiber cladding defines the diameter of the printed lens, so alignment of printing axis to fiber tip is not a critical issue, and the radius of curvature may be increased (within limits determined by surface tension) by increasing the number of droplets of deposited optical fluid.

To achieve similar acceptance angle increases in single-mode fibers is a more challenging proposition, because it requires placement of a much smaller

![Figure 8](image)

**Figure 8.** 70 µm diameter microlens printed onto the tip of a single-mode telecom fiber with cladding outside diameter of 125 µm.

![Figure 9](image)

**Figure 9.** Profile view of 65 µm diameter hemispherical microlenses printed onto the tips of single-mode fibers within a fiber array (fiber array courtesy of Radiant Research Inc).

![Figure 10](image)

**Figure 10.** Efficiency of coupling (%) of energy from an edge-emitting diode laser into a single-mode optical fiber as a function of microlens radius of curvature (in microns).
5. Microlenses Printed onto Optical Fibers for Collimating Fiber Output

Collimation of the output beam of a single-mode optical fiber may also be achieved by printing a micro lens onto its tip, but ray-trace modeling indicates that collimation requires a comparatively large micro lens which is offset axially from the fiber tip by the lenslet focal length, as indicated in the sketch of Figure 11. To achieve the requisite geometry, quartz collets with inside and outside diameters matching the fiber cladding and targeted micro lens diameters, respectively, were epoxied to the tips of fibers with their ends extending beyond the micro lens at the center of the fiber tip. An example of a hemispherical micro lens microjet-printed onto the end of a single mode telecom fiber is given in the photograph of Figure 8, where the lenslet diameter of 70 µm was achieved by depositing and UV-curing one 50 µm diameter droplet of optical epoxy after applying a low-wet coating to the tip of the fiber. Another example is shown in Figure 9, where 65 µm diameter micro lenses were printed onto the end of a linear array of single-mode fibers at the fiber positions.

In the coupling of an edge-emitting diode laser into a single-mode optical fiber the bottom-line figure of merit is the overall energy coupling efficiency, rather than fiber acceptance angle. The source-to-fiber coupling efficiency predicted for a single-mode fiber with a hemispherical micro lens printed on top of it may be calculated numerically to be an inverse function of microlens radius of curvature, as indicated in Figure 10. Parameter values used in generating this curve were: 1550 nm wavelength for fiber and diode laser; fiber step index of 1.4514/1.4469, with core and cladding diameters of 9.3 µm and 125 µm, respectively; diode laser emitter dimensions of 0.843 µm x 0.857 µm; and printed micro lens refractive index of 1.52. Here it can be seen that a 30 µm diameter (15 µm radius-of-curvature) printed hemispherical micro lens would be expected to enable about a 3X increase in overall laser-fiber coupling efficiency above the level (10-15%) typically achieved with a bare fiber. From this model another curve may be generated for a micro lens of a given diameter printed onto a fiber tip which predicts the variation of laser-fiber coupling efficiency with axial misalignment error, e.g., a fiber-core-to-lenslet-axis misalignment error greater than approximately 20% of the lenslet diameter would result in about a two-fold reduction in the coupling efficiency enhancement achieved by the printed micro lens.

Figure 11: Printed lens geometry for collimating output of a single-mode optical fiber

Figure 12. 70 µm diameter micro lenses printed onto the tip of a single-mode telecom fiber with cladding outside diameter of 125 µm (fiber courtesy of Nortel Networks).

Figure 13. Output beam width as a function of distance from fiber tip for a bare fiber and one having a printed micro lens as in Figs. 11 & 12.
fiber tips by the designed lenslet focal length. Then 50 µm droplets of optical epoxy were deposited in sufficient quantity to fill the cavity and form the microlens at the top of the collet, as exemplified by the photo of Figure 12. The two adjustable parameters utilized to achieve collimation, or a specific degree of fluence magnification short of collimation, are the distance from fiber tip to the top of the collet and the lenslet radius of curvature. For a bare fiber with an NA (numerical aperture) of 0.12 fitted with a 900 µm diameter collet, modeling results indicate that one combination of these parameters which will result in beam collimation with a printed microlens is a pedestal-height/lenslet-offset of 1,094 µm and a lenslet curvature radius of 476 µm. An example of the degree of beam collimation achieved with this approach is given by the data of Figure 13, which compares beam width as a function of propagation distance for a bare and lensed fiber. The data were obtained by coupling a HeNe laser into the fibers and measuring power distribution peaks at varying distances along the propagation axis. Although the lensed fiber does not indicate perfect collimation, due to the tolerances inherent in the current collet-fiber assembly process, it can be seen that the numerical aperture calculated from these data was reduced four-fold by this approach.

6. Process Integration: Microjet Printing of Microlenses and Solder Bumps

The potential for cost reduction and process integration in optoelectronics assembly and packaging provided by the microjet printing process may be illustrated for the case of VCSEL device manufacture, where both solder bumps and microlenses are applied in-situ by the microjet printing method. The microjet printing of solder bumps onto chip pads such as those in the photograph of Figure 14 offers advantages as a fluxless, one-step, additive process with throughput rates (400-600 pads/sec) comparable to currently utilized plating processes.15,16 The hardware required is essentially the same as that for printing micro-optics, with a modification of the high temperature print head to enable a co-flow of nitrogen gas around the droplet trajectory, in order to prevent oxide formation prior to solidification on the solder pads. Consequently one high-temperature microjet printing platform with two print heads multiplexed to the drive electronics may be used for both processes. Figure 15 indicates how microlenses may be printed directly onto the emitter facets of a VCSEL array for output beam divergence reduction and stabilization of laser operation by reduction of back reflections, while Figure 16 shows a VCSEL element of an array with microlens and solder bump printed onto the emitter and pad, respectively, using a solder-jetting print head at 220°C and a polymer-jetting print head at 110°C.

7. Conclusions & Future Work

It may be concluded from the advances achieved to date in development of this Optics-Jet technology that the microjet printing method of micro-optics fabrication provides the potential for reducing costs and enhancing assembly process integration in a number of optoelectronics manufacturing applications. It is currently being either explored for or used in the development of prototype photonic devices such as: VLSI smart-pixel switches; fiber and fiber-ribbon collimators; telecom transmitters; and high-power, diode-laser-array fiber delivery systems. Future evolution of the technology will focus on building and
testing such devices and, in the process, demonstrating the capabilities for precision and reproducibility required to incorporate micro-optics and solder-bump printing into optoelectronics component and systems manufacturing lines.

Acknowledgments

The underlying foundations and various components of this work have been supported in part by DARPA, the U.S. Army Research Office, the U.S. Air Force Phillips Lab, Honeywell, and Nortel Networks. Outside collaborators include Allen Cox, Yue Liu and Jim Tatum of Honeywell, along with Larry Marcanti and Michael Lovelady of Nortel Networks. Additional contributors within MicroFab include Hans-Jochen Trost and Rick Hoenigman. To all we express appreciation.

References