Micro-Optics Fabrication by Ink-Jet Printing

W. ROYALL COX, TING CHEN, and DONALD J. HAYES
With hand assembly currently constituting a major portion of the costs of manufacturing many optoelectronic components, devices and systems, process automation and integration will become increasingly important factors in the competition for worldwide market share. The ink-jet printing method of micro-optics fabrication addresses these factors because it is a fully automated, data-driven process with which micro-optics may be written directly onto optical substrates and components such as diode lasers, optical fibers and waveguides.  As a low-cost, additive process capable of dispensing volumes as low as 20 picoliters, the ink-jet printing method is also being employed in other optical applications such as fabrication of organic LED displays and optical fiber biochemical sensors.

In the direct-writing of micro-optics we have used the piezoelectric-actuator-based, “drop-on-demand” (DOD) mode of ink-jet printing, in which a volumetric change in the fluid within a printing device is induced by the application of a voltage pulse to a transducer 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. Plano-convex microlenses of spherical profile may be printed onto a substrate by dispensing droplets of optical material at target sites at frequencies up to 8 kHz, as indicated schematically in Fig. 1. The printing may be accomplished using either a step-and-print or print-on-fly process. In the print-on-fly process, droplets are dispensed continuously as the substrate rasters back and forth under the print head.

The materials best suited for micro-optics fabrication are typically UV-curing, 100%-solids solutions of optical monomers and prepolymer, which are heated in the print head to the temperature required to reduce their viscosity below the 40 centipoise level required for droplet formation by this method. Droplet diameter is controlled by the diameter of the orifice of the dispensing device and is volumetrically stable over time to better than 2%. One of the characteristics of ink-jet printing technology that makes it generally attractive as a precision fluid micro-dispensing method is the repeatability of the process. The temporal, spatial and volumetric stability of the DOD printing process is illustrated in the 1-s photo-graphic exposure in Fig. 2 by the clarity of the superimposed images of 2000 droplets, using stroboscopic illumination at the droplet generation frequency.

Printed micro-optical elements

Arrays of refractive microlenses with circular substrate footprint are fabricated by printing the number of droplets required for the lenslet volume at predetermined locations on a target substrate. Microlenses ranging in diameter from 20 µm to 5 mm have been fabricated by this method. Substrate surface treatment processes enable control of microlens spacing and diameter within an array to the 1-µm level, of focal lengths to 1%, and of sphericity to a quarter wavelength at 1550 nm. Microlens speeds may be varied at a given diameter over a wide range (f/1.5 – f/10), even within the same array.

Microjet-printed arrays of plano-convex microlenses are now being used for free-space optical interconnects in massively-parallel, smart-pixel-based photonic switches, which are under development in conjunction with the DARPA (Defense Advanced Research Project Agency) VIVACE (VCSEL-based Interconnects in VLSI Architectures for Computational Enhancement) program. These switches are based on hybrid integration of VCSEL/photodetector arrays, Si ASICs, and microlens arrays. A smart pixel consists of a VCSEL and an adjacent detector with two microlenses above for collimating the laser output beam and focusing a return beam into the detector element. Photographs of this switch module and of the printed microlens array incorporated in it are shown in Fig. 3. These arrays are printed in 32 chip patterns onto 3-inch diameter, thin quartz wafers, in which each chip consists of two each 16 x 16 identical arrays of 250-µm-diameter, 60-µm-sag microlenses, giving a total of 16,384 microlenses. The microlenses in each array are printed on 500-µm centers, and the two arrays are offset from each other by 250 µm along a diagonal. Printed microlenses were selected for this application based on the greater coupling efficiency and the wavelength independence of refractive lenslets compared to diffractive ones. Another factor was the greater thermal durability of optical epoxy compared to the photoresist used in photo-lithographically fabricated refractive lenslets, which enables a solder re-flow step at 200°C after assembly of the modules.
Multimode ridge waveguides of spherical cross-section may be printed in arbitrary patterns from data files by depositing, along a line, droplets of optical material having higher index of refraction than the underlying substrate. To print a line of constant width, the spacing between droplets must be small enough to provide coalescence of adjacent deposits but not so large as to create discontinuities in the printed lines. An example of a waveguide structure printed from data onto a glass substrate with optical thermoplastic having a higher index than the glass is given in the photo in Fig. 4. By extending to two dimensions the process of printing adjacent droplets of material, anamorphic microlenses having non-circular substrate footprints may be fabricated by direct writing. Examples include square, rectangular/cylindrical and elliptical footprints.7 Hemi-elliptical microlenses are of special interest, because they can be printed to have a specified degree of difference in focal length in two orthogonal directions. For example, the four hemi-elliptical microlenses in Fig. 5, formed by printing six each 35-µm diameter droplets of optical thermoplastic on 30-µm centers, bring collimated light from below the glass substrate initially to a line focus at 218 µm above the surface by the curvature along the minor axis, then to an orthogonal line focus at 921 µm by the curvature along the major axis. The difference between these “fast” and “slow” focal lengths may be fine-tuned by adjusting droplet spacing and the difference in temperature between the printing device and the substrate. One application for such printed hemi-elliptical microlenses would be in circularization, collimation and astigmatism correction of anisotropically diverging light from sources such as edge-emitting diode lasers.

Printing onto optical components
A commonly used approach for coupling 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 macro lens.8 The cost of performing the beam-shaping step could potentially be significantly improved by ink-jet printing arrays of microlenses in situ above the emitter facets of the diode laser bars; the lenses could be made hemi-elliptical to assist with collimation or astigmatism correction.

A question 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 find out, we printed 200-µm-diameter hemispherical lenslets with an optical epoxy formulation at the 24 emitter positions of a 20 W, 784-nm diode laser bar, as pictured in Fig. 6, 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 from the edge of the bar by the specified design pitch, but in the future, active alignment to individual emitters could be used 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 h. 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 mi-
molecules focal points being about 30 μm behind the emitting facet.

It has been shown that forming a spherical microlens on the tip of an optical fiber can significantly increase the efficiency of coupling of light from an edge-emitting laser diode, thereby potentially reducing laser-fiber alignment time while increasing overall transmission efficiency. Here the coupling efficiency varies inversely with both the radius of curvature of the microlens and the magnitude of its misalignment to the core of the fiber.

An example of a hemispherical microlens microjet printed onto the end of a single-mode telecom fiber is shown in Fig. 7; here, the lenslet diameter of 70 μm was achieved by depositing and UV-curing one 50-μm-diameter droplet of optical epoxy, after applying a de-wetting coating to the tip of the fiber.

Another optical application of microjet technology is the fabrication of multifunctional fiber optic biochemical sensors, with potential use in clinical diagnosis, manufacturing process control, and environmental monitoring, for example. If the UV-curing optical epoxies are adjusted to provide enhanced porosity and are doped with biochemical indicators, they may be printed into patterns of sensor elements onto the tips of imaging fiber bundles, providing a sensor configuration as shown in the photographs in Fig. 8. Biochemical fiber optic sensors in use today typically consist of one indicator chemistry attached to a single fiber, where the indicator chemistry is designed to change its optical properties (e.g., fluorescence or absorption) quantitatively in response to a target ligand under illumination of a suitable wavelength. The unique opportunity provided by microjet printing technology in this arena is the low-cost, reproducible fabrication of large numbers of uniformly sized sensor elements consisting of different indicator chemistries on the same optical fiber bundle, in order to provide multifunctionality in a single sensor. Signals from different indicator elements are distinguished by spatial and spectral filtering in the detector system. Initial characterization of fluorescent intensities from the seven elements printed with the same material on fibers in the configuration of Fig. 8 have shown an element-to-element variation of less than 5%. Using multiple print heads with differing indicator chemistries, such multifunctional fiber-optical array sensors could be manufactured with microjet printing technology at very high throughput rates and low materials costs.

Future development of optics-jet technology

It may be concluded from the advances achieved to date in the development of optics-jet technology that the microjet printing method of micro-optics fabrication provides the potential for reducing costs and enhancing assembly process integrity in a number of optoelectronics manufacturing applications. Such applications include: microlens arrays for VLSI smart-pixel and micro-opto-electrical-mechanical switches; fiber and fiber-ribbon collimators; telecom transceivers; and high-power, diode-laser-array fiber-delivery and amplifier-pumping systems. Future development of the technology will focus on building prototype microjet-printed components and assemblies for testing in these applications and, in the process, on demonstrating the capabilities for precision and reproducibility required to incorporate micro-optics printing, alongside solder-bump printing, into optoelectronics component and system manufacturing lines.

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References


W. Royall Cox, Ting Chen, and Donald J. Hayes are with MicroFab Technologies, Inc. W. Royall Cox can be contacted via e-mail at rcox@microfab.com.

Figure 8. Array of 80-μm-diameter hemispherical indicator elements printed onto 480-μm-diameter fiber-optic bundle, shown from above (top) and in profile (bottom). (Fiber bundle courtesy of B. Coleston and S. Brown of Lawrence Livermore National Laboratories.)