

# Microlens array fabrication via microjet printing technologies

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We review recent advances in optical microlens array fabrication using piezoelectric microchannel mounted nozzles to deposit polymer droplets to various substrates via drop-on-demand (DOD) fashion. The technique produces microlenses in a similar fashion to photoresist and can be employed to produce spherical and nonspherical lenses on the order of  $20\mu\text{m}$  to  $3\text{mm}$  at rates of up to  $25\text{ kHz}$  on demand. Advantages include high reproducibility, flexibility and process automation while offering a simple and cost-effective fabrication solution to produce microlens arrays in multiple application domains.

**Keywords:** MEMS, optical fabrication technology, drop-on-demand, microjet, microlens arrays

## Introduction

Microlens arrays offer a unique enabling technology in critical domains such as sensors, communications, metrology, and medical imaging, often providing solutions where other technologies prove unsuitable, unwieldy or cost-prohibitive. Beam collimation and focusing, astronomy, telecommunications and optical switching, industrial manufacturing, hybrid sensors and defense and security applications are heavily reliant on optical lenses and microlens array integrated components.

Multiple fabrication techniques have been developed to provide solutions given design and specification constraints, which sometimes require one-off, customized lens and optical components. Traditional optical fabrication technologies often require cleanroom or multistep fabrication setups, using fused silica or silicon photo-

lithography processes. Other common fabrication processes employ resist processing, epitaxial growth, reactive ion etching, hot pressing or mechanical fabrication, which are often costly or labor-intensive [1].

## Microjet printing technology

Microjet fabrication offers an affordable alternative to conventional manufacturing techniques, employing a single-step process with superior flexibility to produce microlens arrays ranging from  $20\mu\text{m}$  to  $5\text{mm}$  [2], offering high repeatability, accuracy and lens-to-lens uniformity [3]. The process offers competitive precision while remaining a low-cost, highly-automated and integrated manufacturing technology.

Inkjet printing is a familiar and relatively mature industry, and the well-supported industrial infrastructure and ubiquity of off-the-shelf printing solutions offers microjet lens array fabrication as a low barrier-to-entry, cost-effective and low complexity fabrication process.

The fabrication process allows for single-step molding and mounting, which further reduces complexity and costs. Robust thermal durability and high coupling efficiency offer further incentives to utilize microjet-produced microlens arrays as an alternative to traditional photolithographic production.

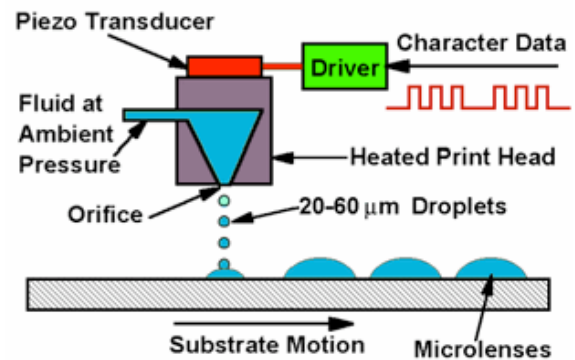
Two distinct classes of microjet fabrication are in widespread use [4] – continuous stream microjet and drop-on-demand (DOD). Continuous microjet printing is often employed in industrial applications such as product labeling, proofing and textile printing. However, the fluid jet in a continuous microjet stream printing breaks apart into uniform droplets, typically  $50\mu\text{m}$  to  $80\mu\text{m}$  in diameter en route to the substrate, due to Rayleigh instability induced by amplification of capillary waves in the stream [5]. While continuous stream microjet systems have higher throughput for industrial applications, they are more complex to operate and offer less precision than piezoelectric channel, drop-on-demand microdispensing commonly employed for the fabrication of microlens components.

## Drop-on-demand production

Drop-on-demand microlens fabrication consists of a basic setup utilizing a heated fluid reservoir coupled to a piezoelectric ceramic, through which a machined nozzle dispenses uniform polymer droplets to the substrate mounted to an  $xyz$  microcontroller

as illustrated in fig. 1. As the drops are rotationally symmetrical, minimization of surface tension leads to spherical lens formation. Automated microcontrollers allow for lens spacing of  $\sim 1\mu\text{m}$ , focal lengths up to 1%, and sphericity to a quarter wavelength at  $1550\text{nm}$  [5].

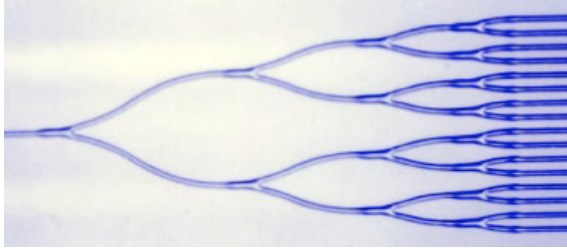
Commonly employed optical polymers incorporate UV sensitive hybrid organic-inorganic sols in combination with photo-initiator [6]. Once deposited to substrate, the polymer is cured through exposure to UV illumination. Variation in UV curing time can be employed to modify lens shape, depth of field, and lens height, and tailoring sol-gel composition can further modify refractive index [6].



**Figure 1:** Schematic of a microlens array produced via drop-on-demand method [2].

Automated control over lens parameters can be induced by variance of print head temperature, substrate temperature, or drive input waveform to optimize performance for a given application. Volume of dispensed polymer can be varied to modify curvature or height of the microlens for a given diameter of microlens. Recent work utilizing solvent mixtures has led to the production of aspherical microlenses [7]. Hemi-elliptical and doublet lenses can be

formed by depositing lenses closer together and allowing them to merge [2]. Multimode waveguides may further be produced by line depositing droplets, which coalesce to form a single unit as in fig. 2.



**Figure 2:** 100µm waveguide splitter [2].

## Novel applications

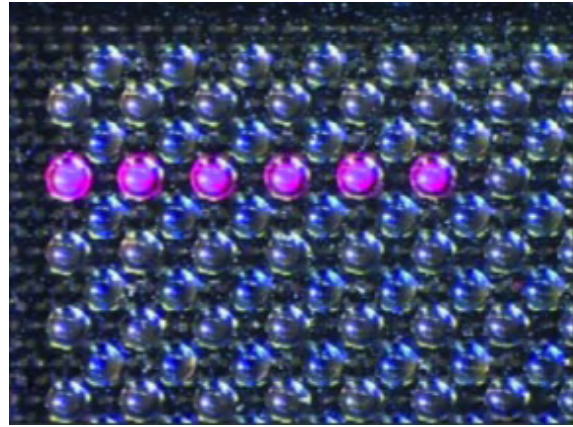
The flexibility and affordability of drop-on-demand printing allows for microlens production in sectors previously limited to more costly or labor-intensive fabrication methods. Interdisciplinary collaboration has led to several innovative uses of microoptics and microelectronics composite systems:

Optical neural networks offer high-speed processing and enormous throughput potential. Microlens array-based neural networks have been developed at IBM Zürich using stacked planar diffractive microlens arrays for illumination, imaging and recurrent fan-in [8].

*MicroFab Technologies Inc.* has produced high-dimensional microlens arrays for use as free-space optical interconnects in massively parallel VCSEL<sup>†</sup> datacom photonic switches under DARPA VIVACE research grant “VCSEL based

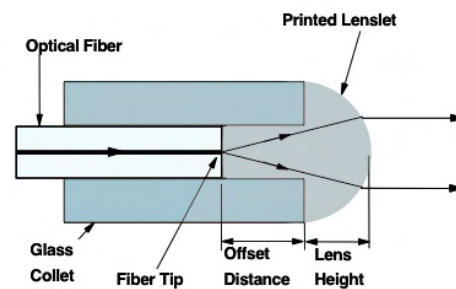
<sup>†</sup> Vertical-cavity surface-emitting laser

interconnects in VLSI Architectures for Computational Enhancement” [9], fig. 3.



**Figure 3:** Smart pixel microlens array in a vertical-cavity surface-emitting laser module with six lenses active [2].

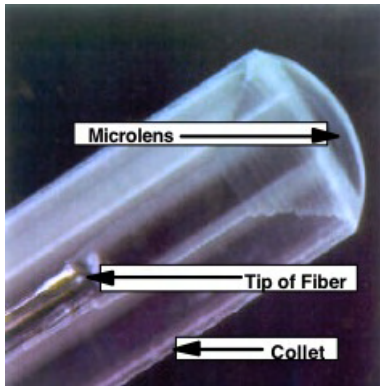
Microlenses can be tip-mounted to gradient index of refraction (GRIN) rods and cylindrical optical fiber arrays as beam collimators and waveguides, as well as directly mounted to optical fiber tips to reduce signal loss and increase transmission efficiency [5], as illustrated in figs. 4 and 5.



**Figure 4:** Microlens beam collimator printed onto a single-mode optical fiber [8].

In medical, environmental monitoring and defense applications, optical sol-gels with enhanced porosity have been doped with

biochemical sensors to produce micro-optical fiber composites for potential use in both clinical diagnosis and environmental biochemical sensing [2].



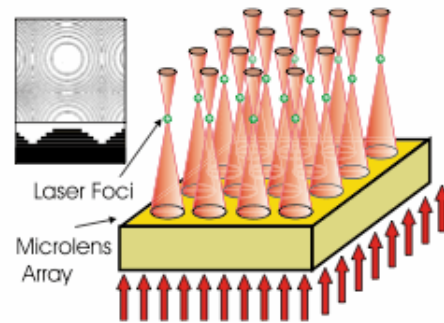
**Figure 5:** Microlens beam collimator printed onto a single-mode optical fiber [10].

## Conclusion and Future Directions

As costs decline and microjet deposition precision advances, fabricated microlens arrays will continue to offer a cost-effective production alternative to conventional lithographic fabrication processes. More broadly, innovations in optical fabrication will continue to grow in both scope and scale as new technologies emerge which call for novel design solutions and lens specifications.

Microlens arrays have already shown potential in scalable quantum information processing, an emerging field which promises to undergo rapid growth as practical implementations reach maturity. Arrays have been employed to generate noiseless subsystems in neutral atom traps [10, 11] – typically, a two-dimensional array of spherical, diffractive microlenses with focal length of  $625\mu\text{m}$  and lens

diameter of  $125\mu\text{m}$  is used in combination with a diode laser to localize neutral  $^{85}\text{Rb}$  atoms in a magneto-optical trap for selective addressing and coherent information processing [11], as shown in schematic 6. Linear optical quantum information processing elements have endowed rapid progress in sub-shotnoise quantum metrology and quantum imaging applications. Recent work has shown that scalable quantum computation is possible using only linear optical elements and single-photon sources and detectors [12].



**Figure 6:** A single laser is focused on a two-dimensional microlens array. Multiple foci allow for selective positioning, trapping and addressing of neutral  $^{85}\text{Rb}$  atoms [13].

In quantum cryptography, coherent optical networks have been deployed to offer guaranteed secure communication links using entangled photon sources to provide encryption of critical data. This year, the government of Geneva will conduct its elections using coherent optical networks developed by *id Quantique*, as the first step of the Swiss Quantum initiative under the EU SECOQC Sixth Framework Programme [14].

Continuing advances in optics and photonics will serve as enabling technologies for these rapidly-progressing technological innovations – which in turn will trigger second-order impacts as society and culture adapt to these disruptive technologies. As the drive for miniaturization continues, microlens arrays will play a prominent role in many of these applications.

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