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Electrohydrodynamic jet printing of micro-optical devices

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Abstract

The Electrohydrodynamic-jet (E-jet) printing process combines high resolution printing with a large variety of printing materials, making E-jet suitable for applications ranging from flexible electronics to high resolution biosensors. In this article, we explore a novel E-jet printing application fabricating high-resolution micro-optical devices. Examples given are a microlens array, an optical waveguide multiplexer, and a multi-refractive index diffraction grating. Additionally, this work presents the potential use of a multi nozzle printhead to perform low cost and flexible heterogeneous integration of multiple materials with different optical properties.

Keywords: Electrohydrodynamic-Jet printing; Additive manufacturing; Optics; Microfabrication

High resolution printing has become a viable technique for nano/micro-scale device fabrication. In 2007, Park et al. introduced the E-jet printing process and reported various applications primarily in the area of printed electronics [1]. Further work [2] made process improvements including the resolution, reliability, and throughput. Since E-jet is very flexible with respect to printing materials, including heterogeneous integration [3], there is a wide array of promising opportunities for printed electronics and biological sensing applications [4–7]. This article explores a new application domain; the use of E-Jet printing for fabricating micro-optical devices.

Micro-optical devices are used to emit, collect, distribute or modify optical radiation. They have become a ubiquitous part of modern technology and provide solutions to many technological challenges including: visual displays, spectroscopy, medicine, and biophotonics [8]. Micro-optical devices are usually fabricated by either laser ablation or lithographic processes. Some optical devices require a considerable amount of blank material removal and, consequently, inkjet printing has been considered as an additive fabrication process [9,10]. Despite the potential benefits of ink-jet printing, many photonics applications require a much higher integration density which exceeds the available feature resolution for inkjet printing. This motivates the consideration of E-Jet printing for fabricating high resolution micro-optical devices.

The physics of the E-Jet printing process is detailed in [2,11]. A potential difference between the nozzle and the substrate is applied. An electric field is then generated at the tip of the nozzle causing a concentration of charge on the pendant drop emanating from the tip. This concentrated charge generates shear stress, deforming the meniscus to a conical shape termed a Taylor cone [16]. The shear stress generated by the charge overcomes the ink surface tension; thereby releasing a droplet.

Fig. 1 illustrates a multi-nozzle E-jet system whereby a multiple simultaneous depositions can be achieved to greatly increase throughput. This toolbit consists of three nozzles in a planar arrangement. The middle nozzle is held stationary and acts as a positioning reference for the two outer nozzles. The outer nozzles are mounted on three degree of freedom miniature linear stages to compensate for any translational misalignment. The inset displays the

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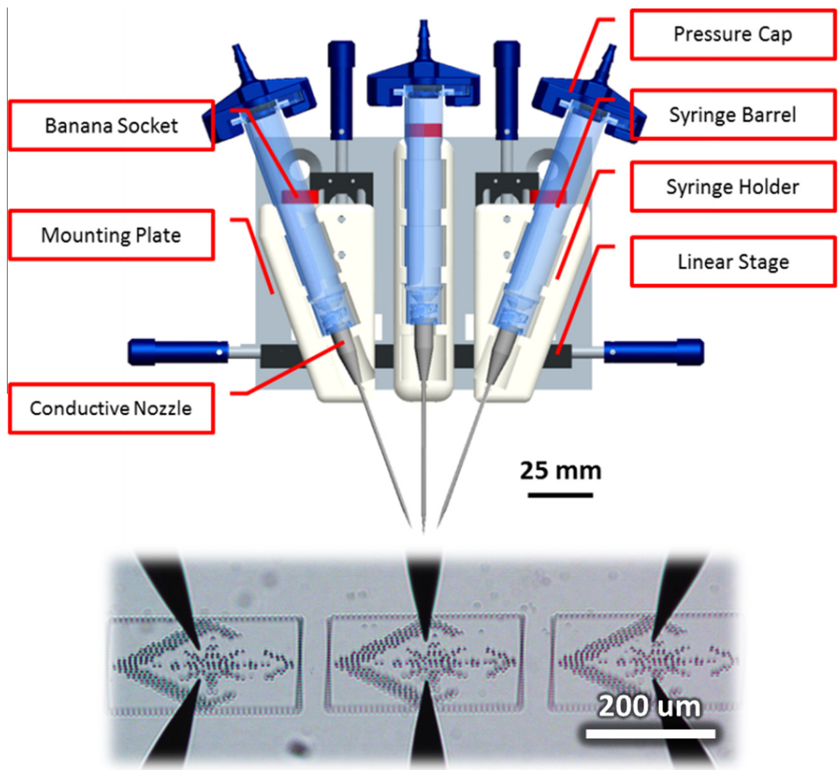

Figure 1. The design of a multinozzle toolbit. The inset shows the experimental setup after the three collocated nozzles successfully printed identical patterns.

experimental setup after the three nozzles successfully printed identical patterns. Each nozzle can be individually controlled and may hold identical or different materials depending on the printing applications. Further system details can be found in [12].

The following section, 'E-Jet printing of micro-optical devices,' details individual types of micro-optical devices that can be fabricated using the system of Fig. 1. Subsequently, a section on 'Conclusions and future work' provides a brief conclusion and outlines future opportunities.

1. E-Jet printing of micro-optical devices

This section presents 3 distinct examples of micro-optical components that can be fabricated through E-Jet printing. These are: a microlens array, an optical waveguide splitter, and a refractive diffraction pattern.

1.1. Micro-lens array

Microlens arrays are commonly used for concentrating photons on a photosensitive target. They improve the optical fill factor of CCD sensors and increase the conversion efficiency of PV cells. These passive micro-optical components are also used as free-space optical interconnects for a highly parallelized intra-chip communication [9,13]. High density sensor arrays for imaging, which can be found on the latest SLR cameras, require a very high spatial resolution to deliver a good image quality. Additionally, to prevent local aberrations, it is critical for all of the microlenses to be uniform in size.

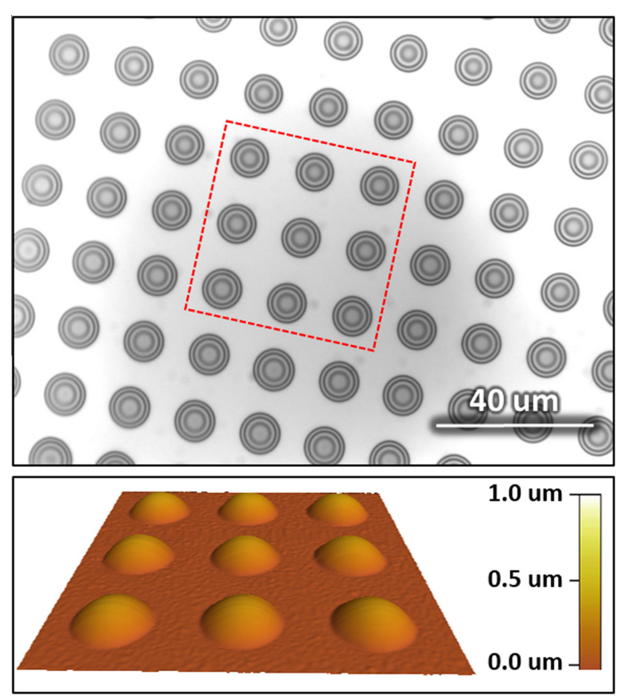

Figure 2. Optical microscope image of the E-Jet printed microlens array. The AFM image demonstrates the uniformity of the lens morphology.

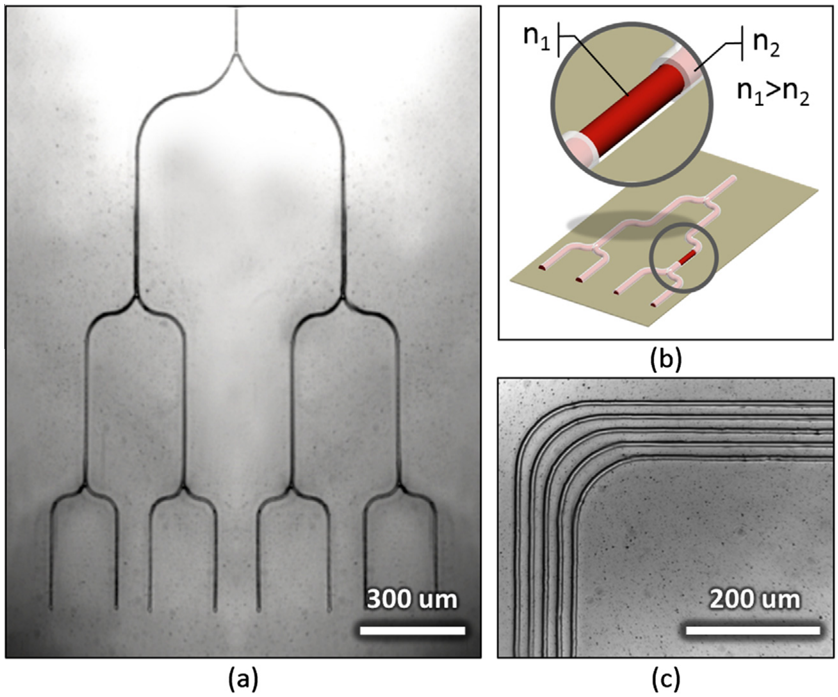

Figure 3. (a) E-Jet printed optical waveguide multiplexers (b) illustration of the overall printed waveguide structure (c) a set of waveguides in parallel arrangement with 20 μm offset.

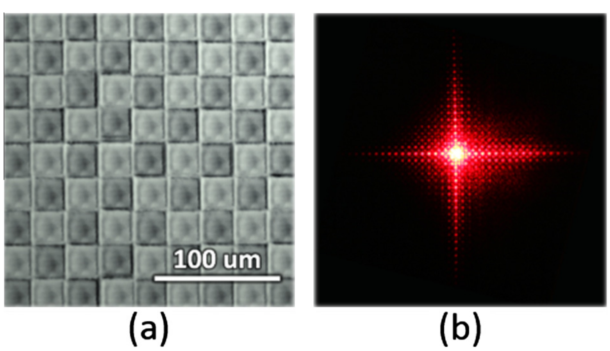

Figure 4. (a) Multi-material E-Jet printed diffraction grating. (b) Projection of collimated laser beam passing through the diffraction grating shown in Fig. 4a.

The E-Jet printing system in Fig. 1 was used to deposit droplets of a UV curable polymer (NOA 74, $n = 1.52$) to fabricate the microlens array presented in Fig. 2. A drop-on-demand printing approach [2] was used to precisely meter the amount of polymer, and hence lens size, present in each location. The substrate on which the microlenses were deposited was fluorinated to improve the contact angle of the lenses. After printing, the liquid microlenses were subsequently cured using a high intensity UV light to obtain a solid form. For optical microscope visualization purpose, the diameter of the printed microlenses in Fig. 2 was chosen to be 10 μm. The lens diameter can be tailored from several hundred nanometers to tens of microns depending on the application by carefully controlling the drop on demand printing parameters.

The uniformity of droplets is also quite high. According to an image analysis of the diameter performed on 100 lenses, the standard deviation is approximately 112 nm. The AFM image in Fig. 2 suggests an average height of 460 nm, again with very high uniformity.

1.2. Optical waveguide

In digital communication technology, optical interconnections are often favored over electrical interconnects for ultrahigh bandwidth data transmissions. Routing optical transmissions involves the use of waveguides where photons are trapped inside a material with a high index of refraction relative to its surroundings. Fig. 3a presents a high resolution E-Jet printed optical waveguide multiplexer. It is used to not only route but also distribute photons in an integrated optical circuit. The advantage to E-Jet printed manufacturing is the inherent flexibility that permits optical waveguides of arbitrary shape.

The waveguide presented in Fig. 3 is fabricated using two UV curable polymers with dissimilar refractive indexes. In this work, NOA164 ($n = 1.64$) and NOA1375 ($n = 1.375$) are the materials used for the core and the cladding of the waveguide, respectively. Printing of the waveguide structure is performed on a gold-coated silicon wafer that is treated with oxygen plasma for enhanced wettability of the substrate with the ink. The waveguide core is directly printed on the substrate and cured with a high power UV light source. The cladding layer is then deposited on top of the already solidified waveguide core and cured immediately after. Fig. 3b illustrates the final overall structure of the E-Jet printed waveguide. The final width of the waveguide demonstrated here is approximately 7 μm. Fig. 3c presents a set of equally spaced optical waveguides with a 20 μm offset. This demonstrates the ability to create complex routing patterns suitable for opto-electronics.

1.3. Multi-material diffraction grating

The diffraction grating is one of the most versatile optical components and a mainstay in many scientific research activities. It is used in electromagnetic spectroscopy, spatial filtering, metrology, and numerous other electromagnetic wave related applications [14]. Fig. 4a presents a heterogeneously integrated transmissive diffraction pattern consisting of a checkerboard arrangement. Two materials of different refractive indexes are directly printed on a 0.16 mm thick transparent Corning cover glass.

The lighter color in the checkerboard pattern is NOA1375 ($n = 1.375$) and the darker squares are printed using NOA74 ($n = 1.52$). Fig. 4b shows the projection of a collimated laser beam passing through the diffraction pattern displaying a unique signature.

The multi-material grating pattern can be used as part of a sensor. It is possible to seed the polymer with material which is sensitive to environmental changes, such as temperature and pH level [15,16]. Alternately, environmentally sensitive polymers can be directly printed without seeding. Changes in the projected pattern can be calibrated to environmental changes. Heterogeneous integration of these environmentally sensitive materials can be easily performed with E-Jet printing thereby creating a rich opportunity to fabricate multipurpose optical sensing devices.

2. Conclusions and future work

This work has demonstrated the potential use of E-jet printing as a low cost and flexible additive manufacturing process for fabricating high-resolution micro-optical devices. The key enabler to this process is the multi-nozzle print head, which allows for the integration of multiple materials with different optical properties. With the effectiveness of the overall printing process demonstrated, future work will include the performance analysis and integration of these passive micro-optical components on a highly integrated optical circuitry.

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