Printing of polymer microlenses by a pyro-electrohydrodynamic dispensing approach

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The investigation of a method for fabricating microlenses by a nozzle-free inkjet printing approach is reported. The new method, based on a pyroelectrohydrodynamic mechanism, is also able to dispense viscous liquids and to draw liquid phase drops directly from the reservoir. Specifically, by dispensing optical grade polymer dissolved in different solvent mixtures, microlenses were printed with a pattern defined directly through this deposition method. The reliability of the microlenses and the tunability of their focal properties were demonstrated through profilometric and interferometric analyses. © 2012 Optical Society of America

Micro lenses are key components for optical devices and are widely applied in several application fields, such as communications, three-dimensional (3D) displays, optical data storage, and photodetectors, playing a fundamental role in many optical systems. Numerous classes of micro lenses exist, depending on the embedding technology and the specific applications. And now, micro lenses with variable focusing have been obtained by actuation of liquid crystals or other liquids through electro-wetting, electrophoresis, or hydrodynamic pressure \(^{1-4}\). On the other hand, a large variety of fabrication processes have been developed for plastic/polymer-based micro lenses \(^{5,6}\), such as embossing \(^{7}\), soft lithography \(^{8}\), micromolding \(^{9}\), photolithography \(^{10}\), electron beam lithography \(^{11}\), reactive ion etching \(^{12}\), the laser assisted technique \(^{6}\), and printing techniques \(^{13-16}\). In particular, these last techniques were advised as direct methods for high-quality and high-precision processes, making the fabrication less time consuming and more cost effective. The emerging application of these techniques in the micro-optical field was mainly promoted by the development of optical grade polymers with proper thermal and mechanical properties \(^{17}\). Among the different printing technologies, inkjet printing is attracting an increasing interest as a single-step process with wide versatility in the definition of patterns, employable substrates, and its capability for the rapid prototyping of optical structures \(^{18}\). The restrictions of this technology related to the ejection of high viscosity materials and the clogging troubles can be overcome by nozzle free processes.

Recently, a novel technique based on the pyroelectrohydrodynamic (pyro-EHD) approach was proposed for dispensing liquids with high spatial resolution \(^{19}\). The main advantage of this approach consists in avoiding the nozzle because the liquid is drawn directly from the liquid reservoir (drops or layers). Being nozzle free, it can be applied also for high viscosity liquids, greatly extending the fabrication capabilities of the conventional inkjet printing processes. A lithium niobate (LN) crystal wafer (\(z\)-cut, optically polished and 500 \(\mu\)m thick from Crystal Technology, Inc.) was thermally stimulated using the hot tip of a conventional soldering iron. According to the intrinsic properties of such crystals, a temperature gradient \(\Delta T\) induces locally a pyroelectric effect. This temperature variation causes a modification in the polarization (\(\Delta P\)), which builds up an electric potential across the \(z\) surfaces. The subsequent electric field is able to exert a hydrodynamic pressure onto the reservoir liquid, leading to the formation of a bridge or a conical tip. It is possible to define a critical distance \(D\) between the two plates of the setup so that for distances \(d < D\) a stable liquid bridge can be formed, while for \(d > D\), the dispensing process is activated \(^{19}\). In this study, we investigated the direct formation of microlenses by the spontaneous breakdown of an unstable polymer liquid bridge created through the pyro-EHD effect, as illustrated in Fig. 1. The setup used for the experiment consists of a microscope glass slide, above which is placed the polymer drop reservoir, while a plate of LN crystal faces the base slide and drives the process. A computer controlled the translation of the target substrate, which is inserted between the facing plates and used to collect the microlenses produced in this nozzle free process.

Fig. 1. (Color online) (a) Scheme of the printing system consisting of a lithium niobate (LN) plate, a heat source, and a drop reservoir; and formation of the (b) pyro-polymer bridge and of the (c) polymer microlens on the translating target substrate.

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The dynamic evolution of the polymer layer was observed online by a high-speed CMOS camera.

In this work, polymer microlenses of poly(methyl methacrylate) (PMMA) were realized directly onto the target substrate. PMMA was chosen as the polymeric material for its good optical and mechanical properties. The substrates were coated with a hydrophobic tetra-ethyl orthosilicate/1H, 1H, 2H, 2H-perfluorodecyl-triethoxysilane (TEOS/PFTEOS) film, which was spin-coated from a solution. This layer induces a strong pinning of the printed droplets, thus minimizing their spreading on the substrates and reducing the solvent evaporation rate. The inks were prepared by dissolving 200 mg/mL of PMMA in pure N-Methyl-2-pyrrolidone (NMP) and different mixtures of toluene (TOL) and NMP (volume mixing ratios 7:3 and 6:4). Both the solvents are suitable to dissolve PMMA and have the right volatility and surface tension (ST) properties for pyroelectrohydrodynamic processing (TOL: Tb = 110.6°C, γ = 28.53 mN/m; NMP: Tb = 202°C, γ = 40 mN/m).

In Fig. 2, 3D plots of the optical microstructures obtained by microprofilometer analysis (Tencor P10, vertical resolution 10 Å) with PMMA inks at different NMP:TOL mixing ratios (10:0, 7:3, 6:4) are reported. The focal length of this structure was estimated by using the following equation:

\[ f = \frac{R}{n - 1} \]

with

\[ R = \frac{h_L}{2} + \frac{r^2}{2h_L}, \]

where \( n \) is the refractive index of PMMA, \( h_L \) is the height of the microlens, and \( r \) is the base radius. The results of this analysis are summarized in Table 1. The structures showed that the ink chemico-physical parameters, such as boiling point and surface tension, have a key role in the definition of the microstructure’s shape. In particular, as the toluene content increases from 0% to 40%, the base diameter of the microstructure also increases from 500 to 700 μm, while the height decreases from 88 to 45 μm. As a consequence, the focal properties are affected by those parameters. This effect can be explained in terms of the wetting properties of the ink substrate system. In detail, the measured surface energy (SE) of the TEOS/PFTEOS substrate is about 17.08 ± 17 mN/m, while the ST of the inks are 37.99 ± 0.24, 33.53 ± 0.14, and 32.45 ± 0.13 mN/m for solvent mixing ratios 10:0, 7:3, and 6:4, respectively. Since the wetting increases when \( \text{SE} > \text{ST} \), by increasing the content of toluene, the ST decreases, thus increasing the splashing of the ink on the target substrate. This last effect is observable in the printed droplet shape whose diameter increases as the TOL content increases. Measured lens profiles were fitted with a conical surface in order to define how the shape of the lenses deviates from a spherical one, thus obtaining the low values of the conic constants (i.e., for the lens with \( F = 880 \) μm, the fitted radius was \( R = 460 \) μm with a conic constant \( K \) very close to null value, about 1.5e-5).

The microlenses were also analyzed by means of the digital holography (DH) setup in transmission mode. This interferometer is schematically shown in Fig. 3. Through the numerical managing of complex wavefronts, it is possible to compute the amplitude and phase of the light transmitted by the sample.

As an example, the digital hologram of the microlens obtained by employing PMMA dissolved in NMP:TOL 7:3 is shown in Fig. 4(a). Intensity and phase maps of the object wavefront can be numerically reconstructed by the hologram. Fig. 4(b) shows the wrapped phase map modulus \( 2\pi \), while Fig. 4(c) reports the corresponding unwrapped phase map that allows calculation of the wavefront curvature of the microlens. Moreover, the focal length can be estimated by fitting the unwrapped

![Fig. 2. (Color online) 3D image of the microlens obtained printing PMMA dissolved in (a) pure NMP; (b) NMP:TOL 7:3; and (c) NMP:TOL 6:4.](image)

![Fig. 3. (Color online) Schema of the digital holographic microscope (DHM).](image)
phase map $\Delta \phi(x, y)$ with a second-order polynomial function according to:

$$
\Delta \phi(x, y) = \frac{\pi (x^2 + y^2)}{\lambda f}.
$$

The measurement gave a focal length value of about 1.6 mm, which is in accordance with the typical value obtained for the polymer structures by profilometric analysis. For all the other realized microlenses, the interferometric analysis gave geometrical parameters that diverge about 6% from the corresponding ones by profilometric analysis.

In summary, the feasibility to employ the innovative printing technique based on pyro-EHD effect for the direct fabrication of polymeric microlenses was investigated. The technology limits strongly depend on the viscosity of the polymeric material. The higher the viscosity, the higher is the diameter of the lenses. For the used polymer concentration in our measurements, the minimum diameter of the printed lenses was about 20 $\mu$m, even if smaller lenses can be obtained \[19\]. The distance between two contiguous lenses can be easily varied, controlling the high precision scanning/translation stage of the target substrate. The microstructure shape was controlled by employing a pure solvent and solvent mixtures at different mixing ratios. It was investigated how the chemico-physical parameters of the ink (boiling point and surface tension) properly combined with the SE of the substrate allow to modify the wetting of the printed droplet and, hence, the structure profile. Specifically, by varying the content of the solvents in the mixture, it was possible to vary easily the geometrical parameters and the focal properties of the microstructures. Preliminary results, supported by profilometric and interferometric analyses, demonstrated the feasibility of obtaining optical microlenses through this innovative nozzle-free technique. This approach could be employed for manufacturing high optical quality microlenses provided that a systematic study will be performed.

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References