

Activation and control of Microlens Liquid Arrays on functionalized polar electric crystal substrates by electro-wetting effect and temperature

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Abstract. In recent years a variety of liquid bases optical elements have been conceived, designed and fabricated even for commercial products like digital cameras or cellular phone cameras. The impressive development of microfluidic systems in conjunction with optics has led to the creation of a completely new science field of investigation named optofluidics. Optofluidics, among others topics, deals with investigation and methods for realizing liquid micro-lenses. A variety of liquid micro-lenses have been designed and realized by using different configurations. We demonstrate that a lensing effect can be obtained in an open microfluidic system by using a thin layer of liquid on a polar electric crystal such as Lithium Niobate (LiNbO_3). Electrowetting patterning on LiNbO_3 surface is obtained by pyroelectric effect consisting in a simple but reliable electrodes-less and circuit-less configuration. The electrodes are intrinsically embedded into the substrate. The material is functionalised by means of a micro-engineering electric filed poling process. Lens array with variable focus has been demonstrated with a large number of lens elements (10x10) on micrometric scale (aperture of single lens 100microns).

1. Introduction

The possibility to realize tunable and adaptive optical elements has attract scientist attention in last years. These devices are well suitable in several field such as optical communication, multiplex focusing components or biological applications. One way to accomplish lens with tunable focal length is to employ liquids using their capability to modify own shape changing the surface tension, this feature is useful in particular for sub-millimeter devices. Lensing effect by liquids is very common and several examples in nature can be found [1]. Two classes of microfluidic liquid lenses exists: one based on the elettrowetting effect and another based on the hydrostatic pressure. The first class comprises many configurations: sometimes two immiscible liquids are used inside special cases made of hydrophobic coating and electrodes. The applied voltage changes the equilibrium among the forces acting on the liquid-liquid and solid-liquid interfaces causing a changing in the curvature of the meniscus at the liquid-liquid interface. In this way, the applied voltage variation allows to switch between converging and diverging lens with flexible focal lengths [2-7]. In some cases a free standing sessile liquid drop is placed on a plane surface acting as first electrode while the second one is a

needle just immersed on the top of the drop [8]. The second class of liquid lenses makes use of small liquid reservoir having flexible and transparent membranes. By changing the pressure in the liquid volume it is possible to change the shape of the lens [9, 10]. The hydrostatic pressure is responsible for changing the focal power of the microfluidic lens.

Electro-wetting or more in general studies on wettability and de-wettability [11-22] of surfaces have been studied and investigated since long time with the aim to pattern liquids on surfaces. An interesting overview about scope, methods and results is given in ref. [15].

In this paper we demonstrate the liquid lens formation based on electro-wetting effect without electrode patterning. The substrate is made of a lithium niobate (LN) crystal, the liquid employed is an oily substances (pentanoic acid) that change its topography by means of the pyroelectric properties of the substrate. Conventional electro-wetting microfluidic devices needs complex electrode geometries to actuate a liquid lens, thus requiring some technological steps and materials for the fabrication. We functionalize the LN substrate to get a microfluidic lens array without electrodes and on a single chip.

2. Materials and method

The substrate used to create the lens array is a LN crystal that is a ferroelectric material widely used for fibre optic telecommunications and for non-linear optic devices. The crystal property we employ is the pyroelectricity. This is the manifestation of the spontaneous polarization change ΔP_s following to a temperature variation ΔT , according to $\Delta P_i = p_i \Delta T$, where ΔP_i is the coefficient of the polarization vector and p_i is the pyroelectric coefficient. At equilibrium, all P_s in the crystal are fully screened by the external screening charge and no electric field exists.

The spontaneous polarization of LN crystals has been reversed by the electric field poling process, thus enabling the fabrication of periodically poled LN (PPLN) crystals. An external voltage exceeding the coercive field of the material (around 21 kV/mm) is necessary to reverse the ferroelectric domains and the inversion selectivity is usually ensured by an appropriate resist pattern generated by photolithography. Fig.1 shows the optical microscope image of two PPLN samples fabricated by the electric field poling and used for the lens effect experiments investigated here. The samples consist of a square array of bulk reversed domains with a period around 200 μm along both x and y direction. The two samples in Fig. 1 differ only for the geometry of the resist openings and both of them were used for the same lens effect experiments, in order to test the reliability of the technique.

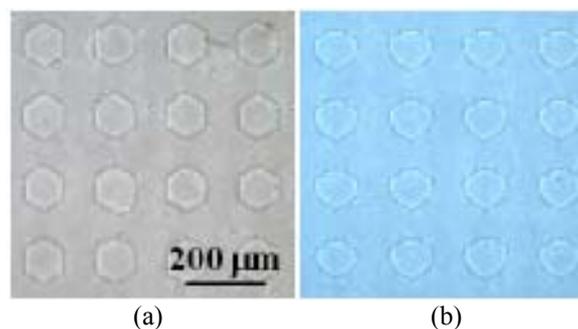


Figure 1. Pictures at optical microscope of two samples of PPLN; hexagons (a) and circles (b) used as substrates for the producing array micro-lensing effect via pyroelectric effect.

The PPLN substrate is covered by a thin film of an oily substance (pentanoic acid - $\text{C}_5\text{H}_{10}\text{O}_2$) and then positioned on a hot plate. The thickness of the oily film was about 200 μm , the temperature of the sample is digitally controlled and so it's subject first to an heating process up to 100 $^\circ\text{C}$ at a rate of around 20 $^\circ\text{C}$ per minute, and then let cooling down to room temperature. The effect produced on the oil is showed in Fig.2 where four frames of the heating (a, b) and cooling (c, d) processes are displayed. The change of the oil film topography is clearly visible across the four images, we observed

that the lens effect is more pronounced in case of the cooling process. The liquid microlenses were formed in correspondence of the hexagonal domains and thus with a lateral dimension of about 100 μm .

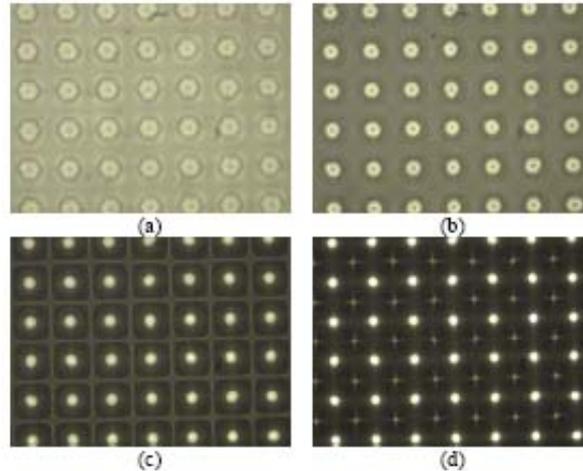


Figure 2. Optical microscope images of the oil film topography. (a-d) images recorded at different time of the micro-lens array formation during the cooling process.

As said before LN crystal exhibits pyroelectric properties so the change of the polarization, occurring with temperature variation, perturbs the equilibrium reached at room temperature, causing a lack or excess of surface screening charge. Consequently, an electrostatic state appears and generates a high electric field at the crystal surface [24,25]. The lens-like array topography can be considered as the result of the equilibrium condition between the surface tensions and the electric forces related to the charge redistribution on the substrate. In the general case of a sessile droplet, the surface tensions at the solid-liquid γ_{sl} , solid-gas γ_{sg} and liquid-gas γ_{lg} interfaces are described by the one-dimensional Young equation:

$$\gamma_{sl} + \gamma_{lg} \cos \mathcal{G} = \gamma_{sg} \quad (1)$$

where \mathcal{G} corresponds to the contact angle of the droplet. The charges at the solid-liquid interface reduce the surface tension according to the Lippman equation [26]:

$$\gamma_{sl}(V) = \gamma_{sl0} - \frac{1}{2} c V^2 \quad (2)$$

where γ_{sl0} corresponds to zero charge condition and c is the capacitance per unit area assuming that the charge layer can be modelled as a symmetric Helmholtz capacitor [12].

To best characterize the microlens array we positioned the hotplate with the sample in a Digital Holographic Microscope as it's drawn in Fig.3. The holographic setup, indeed, allows to recover the complex wavefield after passing through the lens array and so it's possible to recover the intensity and the phase of the optical field after the lensing effect of the device.

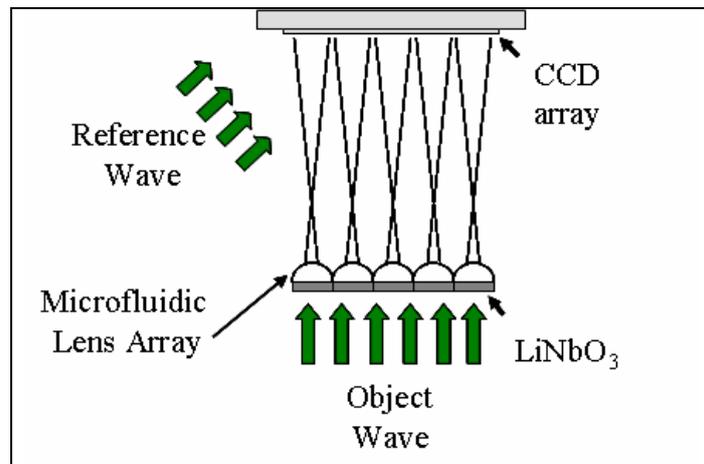


Figure 3. Schematic view of the recording holographic process.

3. Experimental Results

In Fig.4 we show the effect that the lens array produces on a test object. The target shown in Fig.4a is positioned under the microfluidic device and as can be seen from Fig.4b,4c in correspondence on the microlenses the magnification of the target changes and this magnification depends on the size of the test object parts. Fig.4b,4c correspond to different image plane

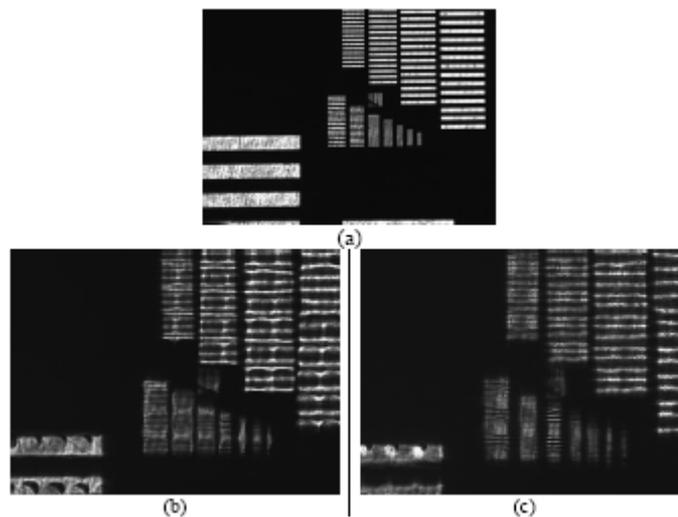


Figure 4. Imaging properties of the lens array by means of a test target. (a) In focus target image without lens array. The target is then positioned before the micro-lens array. (b, c) show different magnification for distinct part of the targets, the two images are recorded at different plane.

3.1. Interferometric Analysis

By means of the interferometric setup, the wavefront modifications induced by the micro-lens array onto a collimated laser beam (plane wavefront) were analysed. The phase-map of the transmitted wavefront at the exit pupil of the microlens array can be obtained by the numerical reconstruction of digital holograms, which consists in recovering the complex wavefront transmitted by the microlens array by back-propagating the diffraction field. Intensity and phase maps of the object wavefront can be retrieved from the complex wavefront. Several holograms were recorded at a rate of 1 image per

second. Fig. 5 shows the wrapped phase maps modulus 2π corresponding to 3×4 lens elements during the cooling process. The phase curvature indicates the existence of the lens effect. This curvature change corresponding to the temperature variation. Finally the number of fringes decreases during the cooling, indicating that the liquid layer is returning back to its initial condition corresponding to a completely erased waviness and thus to an infinite focal length.

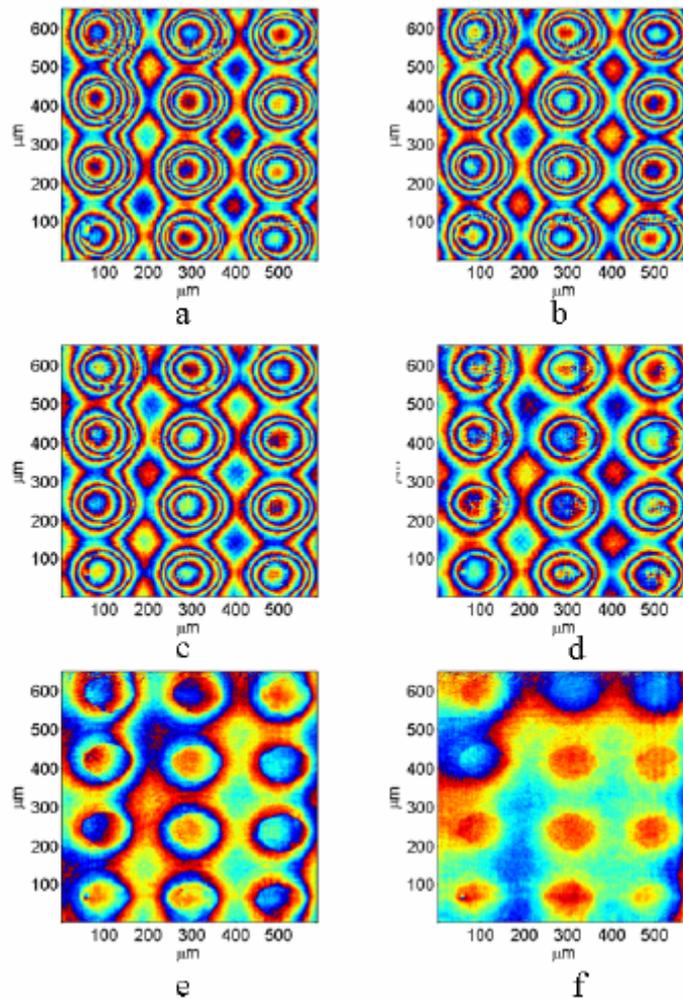


Figure 5. Time evolution of the wrapped phase map at $t=1\text{s}$ (a), $t=5\text{s}$ (b), $t=10\text{s}$ (c), $t=15\text{s}$ (d), $t=25\text{s}$ (e), $t=30\text{s}$ (f) while the temperature of the sample is cooling. The starting temperature was $120\text{ }^\circ\text{C}$. The curvature of the wavefront decreases with time increasing the focal length of the microfluidic lens array system.

Fig. 6a shows a portion of the mod 2π unwrapped phase map that allows to estimate the wavefront curvature in correspondence of 2×2 micro-lenses of the array. The focal length f of the liquid lenses can be retrieved by fitting the unwrapped phase map $\Phi(x, y)$ to a 2nd order polynomial according to

$$\Phi(x, y) = \frac{2\pi}{\lambda} \frac{(x^2 + y^2)}{2f} \quad (3)$$

Fig. 6b shows the variation of the focal length (from 1.75 mm up to 2.1 mm) during the cooling process. This effect could be used to have an array of microlenses with variable focus.

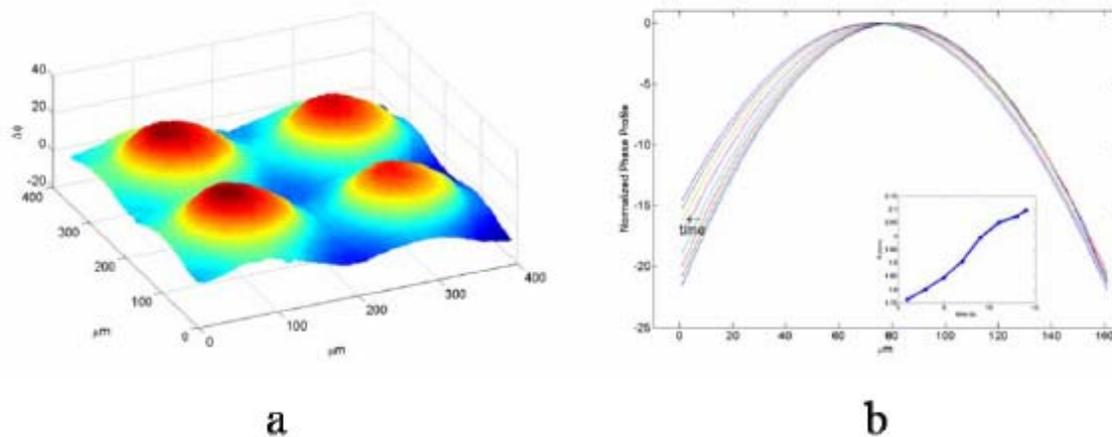


Figure 6. Wavefront curvature of the light transmitted by the lensing array. (a) shows the 3D shape of the phase curvature for 2x2 liquid lenses of the array; (b) illustrates the time evolution of the wavefront for a single lens of the array; the inset shows the wavefront curvature as measured vs time (while the system is cooling).

4. Conclusion

In this paper we demonstrate the possibility to build microfluidic devices based on a new concept of electrowetting. In particular, we show the electrical activation of PPLN substrates by the pyroelectric effect. The configuration is electrodes-less and circuit-less, meaning that the electrodes are “intrinsically embedded” into the material thanks to the micro-engineered LN substrate, thus avoiding the use of heterogeneous materials and processes to change selectively the wettability of the solid surface. Moreover, the material itself is functionalized and can be controlled and activated by temperature variations without any external electric source and physical circuit.

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