Optical switch based on variable aperture

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We report on a pixel whose aperture can be varied electrically. The pixel is confined by a hole-patterned polymer wall and a dielectric liquid forms a ring shape around the wall surface. Without an electric field, the pixel has the largest aperture. The applied fringing field stretches the liquid surface, leading to a decrease in the aperture size. The switchable aperture ratio of the pixel is over 80% and the response time is ~10 ms. Such a device is useful for an optical attenuator, a light shutter, an adaptive iris, and an information display.

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The dielectrophoretic effect has found useful applications in particle manipulation [1], cell separation [2], microdroplet movement [3], liquid surface modulation [4], and liquid shape reconfiguration [5,6]. Among them, liquid shape reconfiguration is particularly attractive because various adaptive photonic devices can be obtained [5–9]. Similar to electrowetting [10,11], if the employed liquid is opaque, then the liquid device can also be used for optical switches and information displays [7,12,13].

A conventional way to realize an optical switch is to stretch the surface of a liquid droplet in one direction [13]. According to Kelvin's theory [14], when a liquid droplet is subject to a nonuniform electric field, the droplet can be stretched by the generated dielectric force if the dielectric constant of the liquid is larger than that of the surrounding liquid (or air). To obtain a large aperture change, the stretched droplet should travel a long distance so that a large area can be covered. Accordingly, when the droplet is relaxed, it will travel the same distance to return to its original shape. Largely stretching the surface of a droplet would cause two problems: high-operation voltage and slow response time [13].

In this Letter, we demonstrate a new optical switch based on variable aperture. In our proposed device, each pixel is a polymer hole whose inner wall is adhered by a liquid. At $V = 0$, the pixel has a maximum aperture ratio (~80%). As the applied voltage increases, the surface of the ring-shaped liquid is stretched toward the center of the hole, causing the aperture of the pixel to decrease. Upon removing the voltage, the stretched liquid returns to its initial state. Instead of being stretched along one direction, the ring-shaped liquid is stretched in a radial direction. As a result, it exhibits a relatively fast response time (~10 ms) and large aperture ratio. Moreover, our device has the following advantages: simple structure, easy fabrication, and good mechanical stability. For a large-area optical switch, we can simply build a pixel array.

To demonstrate the proposed optical switch, we prepared a liquid cell according to the fabrication procedures depicted in Fig. 1. First, a UV curable monomer, such as NOA65 (Norland Optical Adhesive 65, $\gamma \sim 40$ mN/m), was spread on a thin glass plate using a steel blade [Fig. 1(a)]. Second, the film was exposed to UV light through a photomask [Fig. 1(b)]. Third, the uncured monomer was completely rinsed off with ethanol and a solid hole-patterned polymer film was obtained [Fig. 1(c)]. Then the film was peeled off and tightly stacked to another glass plate, which was already coated with indium tin oxide (ITO) electrode and a thin Teflon layer [Fig. 1(d)]. To generate fringing fields, interdigitated ITO electrodes with 10 μm width and 10 μm gap were adopted.

Then the holes were filled with a suitable liquid, which was mixed with a solvent (such as dichloromethane) [Fig. 1(e)]. The solvent serves two purposes: it decreases the surface tension of the liquid and controls the amount of the liquid in the hole. After evaporation, a tiny amount of liquid was retained in each hole. Due to the uniform attraction of the polymer wall surface, it forms a bracelet-like shape [Fig. 1(f)]. The impact of the bottom Teflon layer on the ringed liquid is very weak because of its low surface tension ($\gamma \sim 18$ mN/m). To prevent any liquid leakage, the top surface of the polymer film was tightly sealed by another Teflon-coated glass substrate (not shown here).

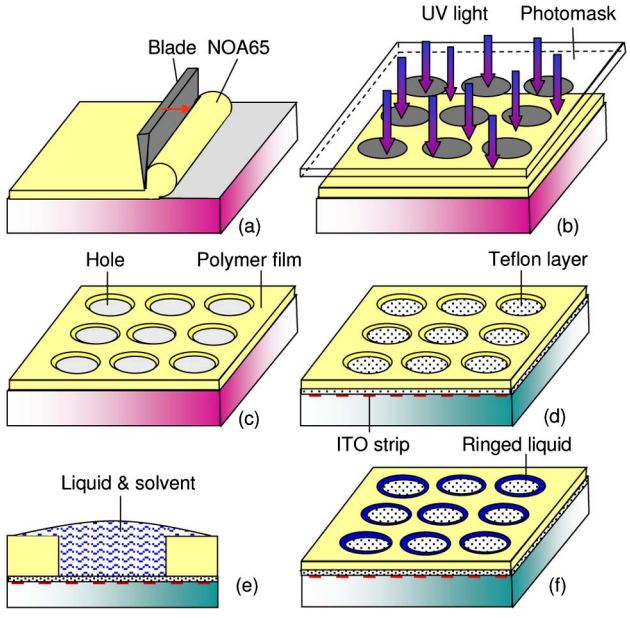

Fig. 1. (Color online) Fabrication procedure of an optical switch with bracelet-like liquid adhered to the polymer wall surface of each pixel hole.

Based on the above-mentioned procedures, a hole-array polymer film was prepared. Each hole exhibits an octagon shape and its aperture is about 0.23 mm. The thickness of the polymer film is ~0.18 mm. Nematic liquid crystal (LC) Merck ZLI-4389 was chosen as the liquid because of its large dielectric constant ($\varepsilon_{//} = 56$, $\Delta\varepsilon = 45.6$) and medium surface tension ($\gamma \sim 38$ mN/m). To easily prove the aperture change, the LC was mixed with 1.5 wt.% red dye (C10 Oklahoma dyes). Dichloromethane was used as the LC solvent, and the LC concentration was ~15 wt.% before evaporation. The thickness of the coated Teflon layer is ~1.5 μm.

It is convenient to use an optical microscope to observe the shape change of the red LC filled in a hole (or pixel). Figure 2 depicts the aperture change under various voltages. At $V = 0$, the central area of the pixel is clear and a dark ring is formed around the aperture edge [Fig. 2(a)]. It is mainly caused by the absorption of the dye and deviation of the curved liquid surface. When a voltage is applied to the bottom substrate, a fringing field is generated across the ITO stripes, and the ringed LC experiences a dielectric force. The force stretches the LC molecules along the ITO stripe direction.

At $V = 45$ V_{rms}, the LC ring expands as Fig. 2(b) shows. As the voltage keeps increasing to 54 V_{rms}, the LC spreads farther toward the center of the pixel [Fig. 2(c)]. The reduced aperture is not quite circular because the dielectric force exerted on the LC ring is asymmetrical. The force along the ITO stripe is larger than that along the perpendicular direction. At 60 V_{rms}, the opening area shrinks largely [Fig. 2(d)]. Finally at 70 V_{rms}, the whole aperture is covered by the LC [Fig. 2(f)]. Due to the large expansion of the LC ring, the dark area at the aperture border is significantly decreased in comparison to that observed in Fig. 2(a). After removing the voltage, the stretched LC surface returns to its original shape because the Teflon surface cannot hold the LC layer in the hole area. Such results can be simply explained in Fig. 2(f). The LC ring contacts with the bottom Teflon surface, the wall surface, and air at point P. The structure is stable if the force balance satisfies the following equation:

$$r_1 = r_2 \cos\theta + r_3 + F_d, \quad (1)$$

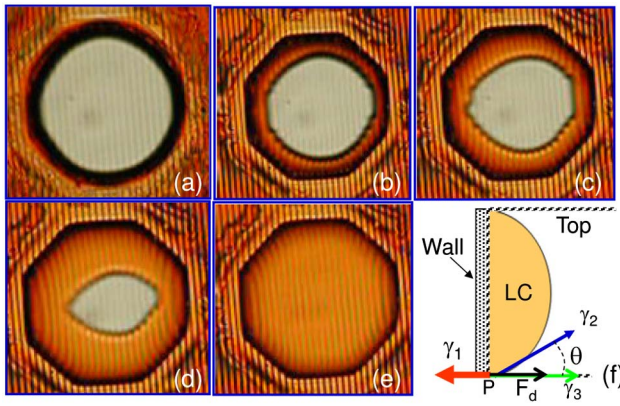

Fig. 2. (Color online) Aperture of a pixel changed with different voltages and (f) the force balance of the ringed LC on the wall.

where γ_1, γ_2, and γ_3 denote the interfacial tension of polymer wall/LC, LC/air, and LC/Teflon, respectively; F_d the horizontal component of dielectric force; and θ the contact angle of the LC ring on the bottom Teflon surface. At $V = 0$, $F_d = 0$. As V increases gradually, F_d increases, which drags the LC downward to the center of the hole. As a result, θ increases correspondingly.

For two-dimensional optical switches, a pixel array is desirable. The density of the pixel is dependent on the pattern of the photomask. The polymer film is mixed with ~1 wt.% black dye (S-428 Mitsui) in order to obtain a dark background. To demonstrate a color light switch, we filled the holes with a red-dye-doped LC. Figure 3(a) (upper left) shows a 3×3 pixel array at $V = 0$. For each pixel, the transmittance reaches the highest at $V = 0$. As the voltage increases to 80 V_{rms}, each aperture is closed and a reddish color is observed, as Fig. 3(a) (upper right) shows. Due to the defects of some ITO stripes, light leakage (short white bars) in some pixels is observed, which indicates the LC surface in those areas is disconnected. Once the voltage is removed, these stretched liquids with defect can quickly and safely recover to their original states. The pixel (in the top left corner) that was totally covered by the LC cannot return to its original state quickly. It has to wait for some time until the LC surface breaks up by itself. As a result, its response speed is slow. To show the difference visually, we include a dynamic response video of the upper pixel array [Fig. 3(a)].

To measure the response time of a defect pixel, 80 V_{rms} pulses from a LabVIEW data acquisition system were applied to the cell. A normally incident laser beam ($\lambda = 633$ nm) passing through one pixel was received by a photodiode. The received signal was analyzed by a digital oscilloscope. The measured stretching time and recovering time is ~9 and ~10 ms, respectively.

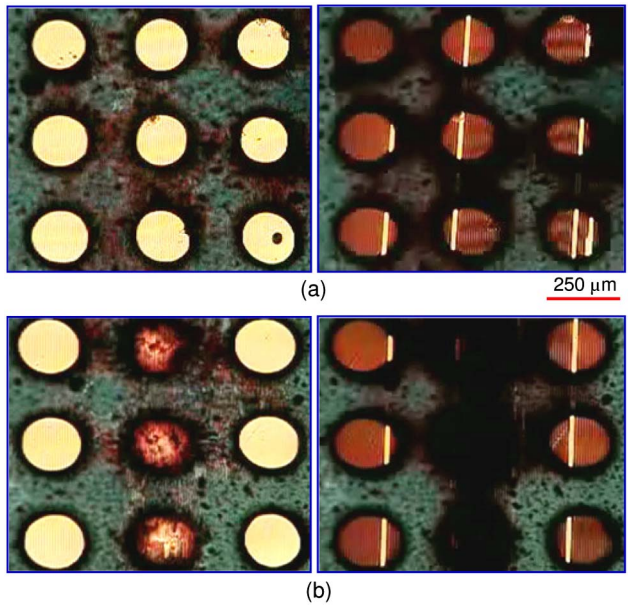

Fig. 3. (Color online) Hole array at (a) $V = 0$(upper left) and $V = 80$ V_{rms} (upper right) with or without surface defects (Media 1), and (b) $V = 0$ (lower left) and $V = 80$ V_{rms} (lower right) with normally filled (left and right columns) or excessively filled (middle column) LC.

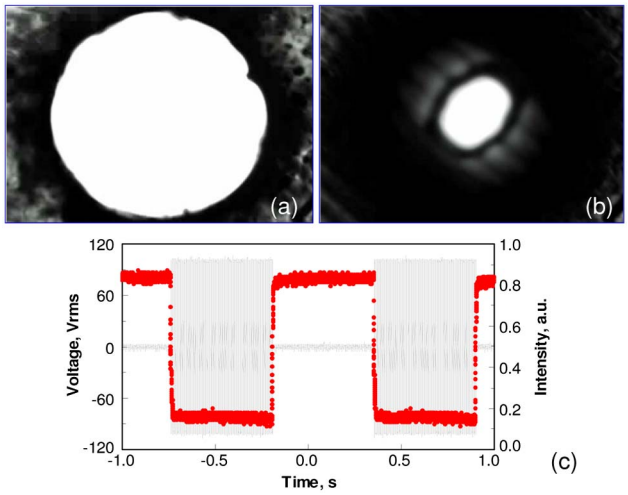

Fig. 4. (Color online) Aperture change of a pixel filled with black LC. (a) $V = 0$ (Media 2), (b) $V = 80$ V_{rms}, and (c) transmitted light intensity change with time.

To form a ringed LC, the amount of LC filled in each hole should be properly controlled. Figure 3(b) shows another 3×3 pixel array filled with different amounts of LC: the pixels in the left and right columns with normal filling and those in the middle column with excessive filling. At $V = 0$, the pixels in the left and right columns show the highest transmittance. For the pixels in the middle column, their apertures are totally covered by the LC, which indicates these holes are overfilled. At $V = 80$ V_{rms}, pixels in the left and right columns are covered by the expanded LC surface except some defect segments, while pixels in the middle column become even darker. Although the LC surface can still be reconfigured by the voltage, they do not switch light effectively. On the contrary, if the LC is insufficiently filled, then a higher voltage is required in order to cover the hole aperture. Moreover, the formed LC layer in the aperture will be too thin to effectively switch the light.

From Fig. 2(a), the amount of LC in the hole can be roughly estimated. Here the aperture is ~230 μm and the width of the LC ring is ~22 μm. If the thickness of the polymer wall is equal to that of the LC ring, then the LC occupies ~20% of the hole space. That means the maximal aperture ratio is ~80%. Increasing the LC volume in the hole will decrease the aperture ratio. Thus, the trade-off between aperture ratio and operation voltage needs to be taken into account when optimizing the device performance.

To switch white light, we filled some pixels with black-dye-doped LC (~1.5 wt.% black dye). Figures 4(a) and 4(b) show the aperture change of one pixel at $V = 0$ and $V = 80$ V_{rms}, respectively. At $V = 0$, the opening of the aperture is maximal and the transmittance is the highest. At $V = 80$ V_{rms}, the aperture is narrowed down dramatically and transmittance is reduced. The dynamic response of the pixel was measured, as shown in Fig. 4(c). Two cycles (red lines) show the time-dependent transmitted light intensity. The stretching and recovering times are measured to be ~10 and ~10 ms, respectively. To visually observe the dynamic response, we gradually applied a voltage (from 0 to 80 V_{rms}) to the pixel. Figure 4(a) shows the recorded dynamic response video.

Although only LC is employed in the pixels, their electro-optic properties are stable even when the cell is placed in a vertical position. One reason is that the employed liquid (LC) cannot wet the bottom and top Teflon surfaces due to the low surface tension. As a result, it only adheres tightly to the inner surface of the polymer wall. Furthermore, because of the small amount of LC in each hole, the impact of gravity force on the shape distortion of ring-shaped LC is not severe when the surface tensions play the major role.

Knowing the thickness of the polymer film, which is ~0.18 mm, the thickness of the stretched LC layer is estimated to be ~36 μm at $V = 80$ V_{rms}. The LC molecules and black dyes in such a thick layer are hardly reoriented by the fringing field, so they exhibit random orientation. As a result, such an optical switch is polarization insensitive.

In conclusion, we demonstrated a novel optical switch based on dielectrophoretic effect. Light transmittance is controlled by changing the aperture of the pixel. The filled LC occupies ~20% of its chamber space. To ensure the stretched liquid can safely return to its original state with fast response time, the stretched surface should not totally cover its aperture. In our demonstration, the response time of the pixel is ~10 ms and the aperture ratio is over 80%. For optical switch and display applications, a pixel array is required. The device based on our proposed cell structure has the key features of polarization insensitivity, fast response, simple fabrication, and good mechanical stability.

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