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Fast-response microlens array fabricated using polyvinyl chloride gel

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ABSTRACT

A droplet array which can function as a microlens array (MLA) is prepared by filling a small amount of polyvinyl chloride (PVC) gel into a polymeric cavity. The apex distance of each droplet decreases gradually as the applied DC voltage increases. The lens surface profile presents a spherical shape during actuation. By applying a voltage from 0 to 250 V, the focal length of the MLA changes from 2.75 mm to 3.15 mm and the measured total response time is 360 ms, which is lower operating voltage and much faster than that previously reported. The proposed MLA is free from gravitational effect, shaking, and vibration. It has potential applications in imaging, beam steering, biometrics, sensing, and electronic displays.

1. Introduction

Soft electroactive materials such as hydrogel gels [1,2], photo-polymers [3,4], conducting polymer actuators [5], ionic polymer-metal composite actuators [6], dielectric elastomer [7–11], and polyvinyl chloride (PVC) gels [12–15], have promising applications in artificial muscles, transducers, sensors, micro-electromechanical systems, and adaptive lenses. Among them, hydrogels, photo-polymers, conducting polymer actuators, ionic polymer-petal composite actuators can only be driven in water and/or their shape can be deformed only by bending. The dielectric elastomers have fast response time and low power consumption, but their driving voltage is over 3000 V. Moreover, the fill factor of a working area is not high due to waste of an area for stretching frames. By contrast, PVC gels can be driven with a modest electric field in air. Their advantages are thin and compact profile, and simple fabrication process. Besides, they are attractive for fabricating adaptive lenses because they are highly transparent, and their shapes can be deformed effectively in an electric field [16–22].

Based on creep deformation of PVC gels, various adaptive lenses have been demonstrated. For a large-aperture (circular diameter ≥1.5 mm) lens, its dynamic range is large. However, its operating voltage is high (>300 V) and response time is fairly slow [13,16,17]. If the PVC gels have creep deformation in transverse direction, memory effect may occur during actuation [12]. For a micron-sized lens driven with an interdigitated or zone-patterned electrode, the operating voltage can be reduced greatly [18–21], but the response time is too slow (over 100 s). Therefore, a proper compromise is to shorten response time while keeping operating voltage as low as possible. The reason for high operating voltage is that PVC gel has a poor conductivity, thus, a slightly increased voltage will not boost power consumption too much.

For LC lens, LC molecules need to be aligned in uniaxial direction with the help of surface treatments such as rubbing and photoalignment [23,24] and optical properties of LC lens depend on polarization state of an incident light, however, it can be driven relatively at low operating voltage since LCs has dielectric anisotropy, which will be disadvantages and advantage compared to the liquid lens.

In this paper, we prepare a microlens array (MLA) by filling a small amount of polyvinyl chloride (PVC) gel into a polymeric cavity array. These microlenses pinned on the polymeric wall are uniform, and their domes have spherical shapes. To study the MLA, we choose one microlens for evaluation. The apex distance of the microlens decreases as the applied DC voltage increases. From the measured surface profile, its focal length can be calculated precisely. The response time is measured to be ~160 ms, which is much faster than that reported previously [21]. The resolution of the microlens is ~20 lp/mm. In contrast to previous PVC-gel lenses, our microlens exhibits following advantages: 1) fast response time with a reasonable operating voltage, 2) good mechanical stability with negligible gravitational effect, and 3) no hysteresis effect. Therefore, either this type of microlens or MLA has promising applications in imaging, sensing, beam steering, biometrics, and electronic displays.

2. Device fabrication and mechanism

The fabrication procedure of the MLA is depicted in Fig. 1. First, a UV curable monomer, such as NOA65 (Norland Optical Adhesive), is coated on a glass substrate to form a film (top left). The thickness of the film is

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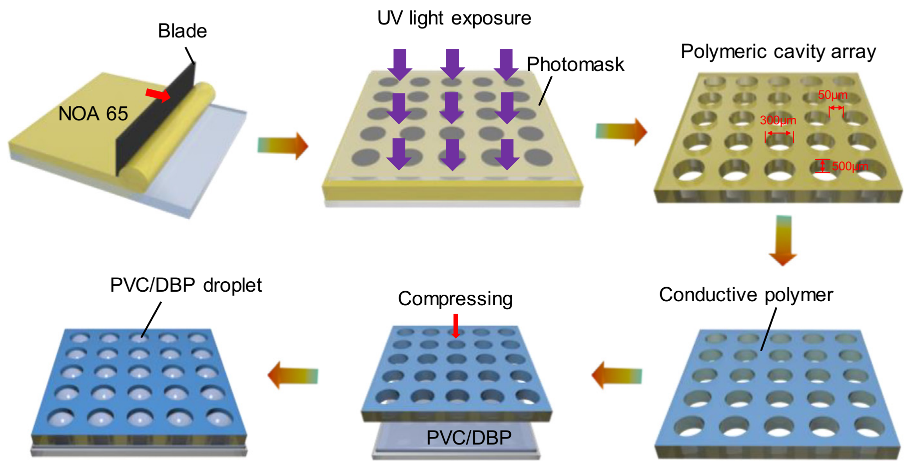

Fig. 1. Schematic of fabrication of a PVC/DPB microlens array prepared by filling a PVC/DBP gels in a polymeric cavity array.

~500 μm. After coating, the monomer is exposed using a UV light through a photomask (top middle). The photomask is prepared by forming chromium dots on a glass plate in which the diameter of each black dot is 300 μm. The cured intensity of UV light is ~20 mW/cm^2 and the curing time is 30 s. We then use a solvent, such as ethanol, to rinse the cured film. When the unexposed monomer NOA65 is removed thoroughly, a polymeric cavity array is obtained (top right). The cured NOA65 is then dried to evaporate the ethanol. A water-based conductive polymer in which the percentage of the conductive polymer ELP-3040 (Agfa-Gevaert, Belgium) in the solution is 5 wt. is used to coat the surface of the polymeric cavities (bottom right). After evaporating the water, the conductive polymer forms a thin film on the polymeric substrate. The conductivity of the conductive polymer layer is as good as that of the indium-tin-oxide (ITO) electrode. To fill the polymeric cavity array, a PVC gel is prepared by the following steps: 1) A small amount of PVC and dibutyl phthalate (DBP) are dissolved in tetrahydrofuran (THF, Sigma-Aldrich). The weight ratio of PVC: DBP is 1:9 where DBP is a plasticizer and THF is a solvent, 2) The PVC/DBP in the THF is thoroughly stirred, and then the mixture is coated on an ITO-glass substrate. The polymeric cavity substrate (coated with conductive polymer) is then used to compress the PVC/DBP gel (bottom middle). We placed the sample in a fuming cupboard for 24 h, and the THF could be completely volatilized at room temperature. After removing the THF, a droplet array is formed in the cavity array (bottom left).

It has been proven that the creep deformation of a PVC gel results from electron injection, ion transfer, and Maxwell force in an electric field [12–15]. Fig. 2 shows the operating mechanism of a droplet in its polymeric cavity. In the voltage-off state, the droplet is pinned by the polymeric cavity wall, having a spherical shape due to surficial tension, as shown in Fig. 2(a). When a voltage is applied across the conductive polymer (anode) and the bottom ITO electrode (cathode), electrons are injected to the PVC gel from the cathode, as Fig. 2(b) depicts. The charged DBP molecules shift toward the anode. Due to electrostatic force, the charged DBP molecules creep up on the polymeric wall with a shift, causing the shape of the droplet to change. Because the droplet has a lens character, the focal length of the droplet can be changed according to the applied voltage.

3. Results and discussion

To characterize the MLA, firstly we observed an optical imaging of the cell using an optical microscope (OM). The cell was placed on the stage of the OM and illuminated with a white light lamp. The light passing through the cell was recorded using a CCD camera. Fig. 3(a) shows a portion of the droplet array in the voltage-off state. The droplets are confined by the polymer walls. The diameter of each droplet is ~300 μm, and the gap between adjacent droplets is 50 μm. To observe the imaging behavior of the droplets, a transparent letter "V" etched on a black mask was used as an object. The object was placed under the cell. By adjusting the cell position, a clear image array in the voltage-off state was observed, as shown in Fig. 3(b). In contrast to the original object, the image "V" is inverted. This result indicates that the droplets are convex microlenses, and their shapes are quite uniform.

Since these droplets are adaptive, their image size can be changed by applied voltage. To observe the images of the droplets in focusing and defocusing states, here we demonstrated the image of one droplet as marked by "T" in Fig. 3(b). The image of the droplet magnified by the OM is shown in Fig. 4. At V = 0 V, a clear image is observed, as shown in Fig. 4(a). By applying a voltage (V = 200 V) to the cell, the image became blurry instantly due to the defocusing effect, as shown in Fig. 4(b).

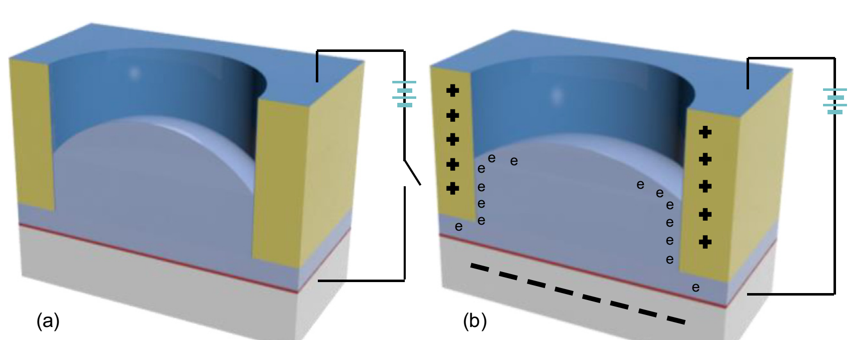

Fig. 2. Switching mechanism of a microlens in a polymeric cavity controlling a focal length with applied voltage: (a) voltage-off state and (b) voltage-on state.

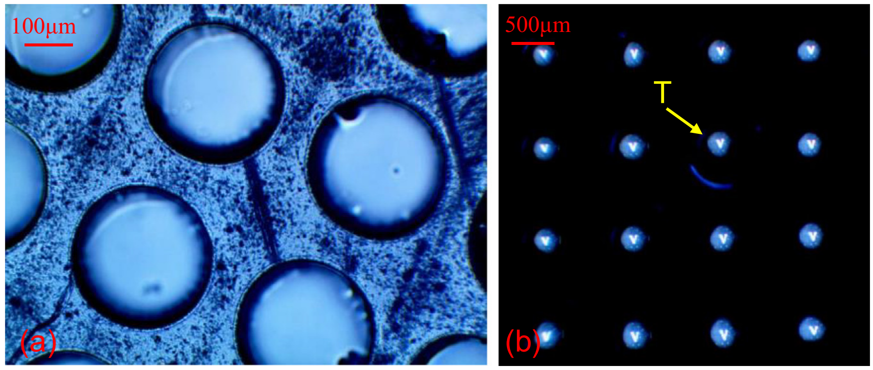

Fig. 3. (a) Surface of partial droplet array and (b) image array observed through the droplets.

To restore the clarity, the stage of the OM is shifted vertically while the applied voltage remained the same. The image after refocusing is clear again, as shown in Fig. 4(c). The size of the image is slightly enlarged. When the voltage is removed, the image became blurry again, as shown in Fig. 4(d). This result indicates that the focal length of the droplet is variable and reversible.

To evaluate the surface profile of the droplet, we used an optical surface profiler (NV-2400, NanoSystem) to characterize the dome of the droplet at different voltages and the results are given in Fig. 5. At V = 0 [Fig. 5(a)], the dome of the droplet presents a spherical shape, and the surface of the droplet is very smooth. The apex distance of the dome is ~9.17 μm. The root mean square (RMS) and maximal roughness (Rmax) of the surface is 50 nm and 90 nm, respectively. In contrast to the wavelength of visible light (λ ~ 550 μm), the roughness is negligible so that the surface will not scatter or deflect the incident light. When a DC voltage (V > 70 V) is applied to the cell (anode to the conductive polymer and cathode to the ITO electrode), the surface of the droplet can be deformed. At V = 100 V [Fig. 5(b)], the surface of the droplet remains smooth and spherical shape. The apex distance of the dome is reduced to 8.95 μm. At V = 150 V [Fig. 5(c)] and 200 V [Fig. 5(d)], the apex distances of the droplet is reduced to 8.75 μm and 8.53 μm, respectively. The dome of the droplet keeps its spherical shape. By increasing the

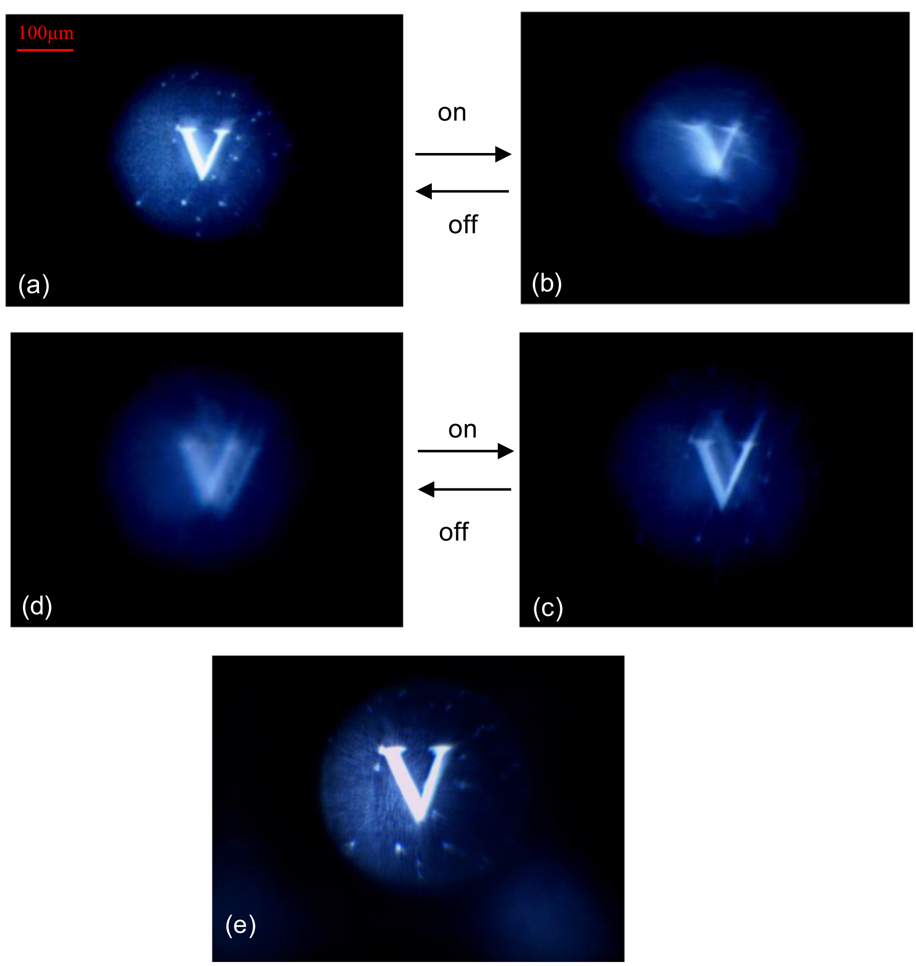

Fig. 4. Image of one droplet in focusing or defocusing state: (a) focusing state at V = 0 V, (b) defocusing state at 200 V, (c) refocused state at 200 V, and (d) defocused state at V = 0 V, (e) image of the "V" letter after 5000 operating cycles.

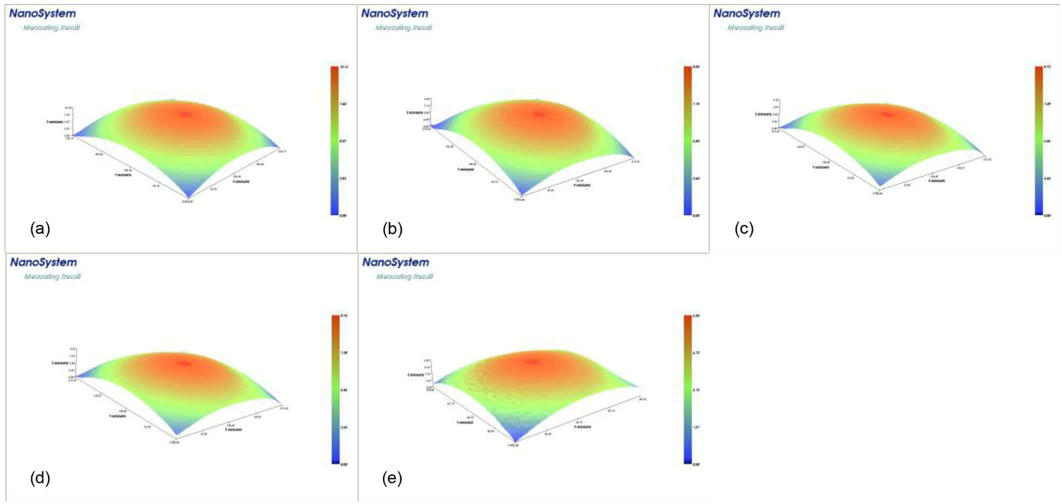

Fig. 5. Topography of the PVC dome at different voltages: (a) V = 0, (b) V = 100 V, (c) V = 150 V, (d) V = 200 V, and (e) V = 300 V.

voltage to 300 V, the dome of the droplet becomes much flatter without breakdown. This result indicates that the droplet can still work well even in a high voltage state.

From the surface profile of the dome, the focal length of the droplet can be expressed by

$$F = \frac{r^2 + h^2}{2h(n-1)} \tag{1}$$

where r is the radius of the cavity (~150 μm), h is the apex distance of the dome, and n is the refractive index of the PVC gel (~1.49). From the measured apex distance (h) at a voltage, the focal length of the droplet can be calculated. Fig. 6 shows the voltage-dependent focal length of the droplet. As the voltage increases, the focal length tends to increase. At V = 250 V, the focal length is measured to be ~2.7 mm.

The resolution of the droplet was also measured by observing a USAF resolution target. At V = 0 V, the image is clear. The corresponding resolution is ~20 lp/mm. At V = 200 V, the corresponding resolution is ~19 lp/mm. The resolution decreases slightly in the high voltage region. Response time is a key factor for an adaptive lens. The response time can be measured by using a pulse voltage to impact the droplet. When the droplet is deformed, the light passing through the droplet can be modulated. The light intensity change with time can be analyzed using a digital oscilloscope. Fig. 7(a) shows the light intensity change impacted by a pulse voltage of 100 V. The duration of the pulse voltage is 2 s. The rise time (τ_r) and fall time (τ_f) were measured to be ~160 ms and ~280 ms, respectively. Two driving cycles are given, and they repeat well. Using the same pulse voltage to sequentially drive the droplet for over 5000 cycles, and the results are repeatable. The response speed and imaging performance did not change significantly, indicating that the droplet has good mechanical stability.

The response time of the droplet is dependent on the amplitude of the pulse voltage. Fig. 7(b) shows the voltage-dependent response time. As the voltage increases, the rise time decreases quickly, while the fall time increases slightly. At V = 250 V, the measured rise time is ~60 ms and fall time ~300 ms. By measuring the leakage current of the sample at V = 250 V, the power consumption is estimated to be about 0.2 μW. Because the plasticizer DBP is not a good conductor, the power consumption is almost negligible. For the prepared MLA, the

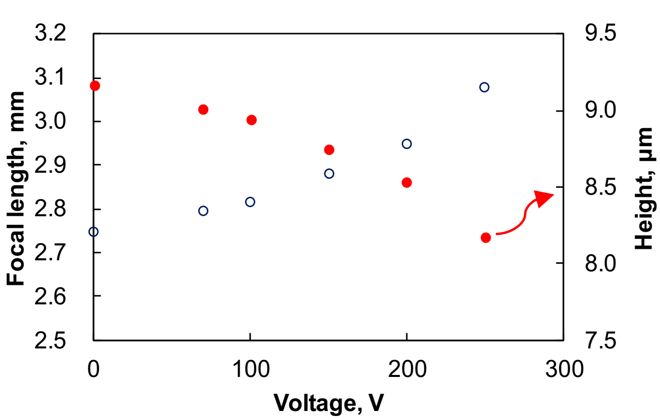

Fig. 6. Voltage dependent apex distance and focal length of the droplet.

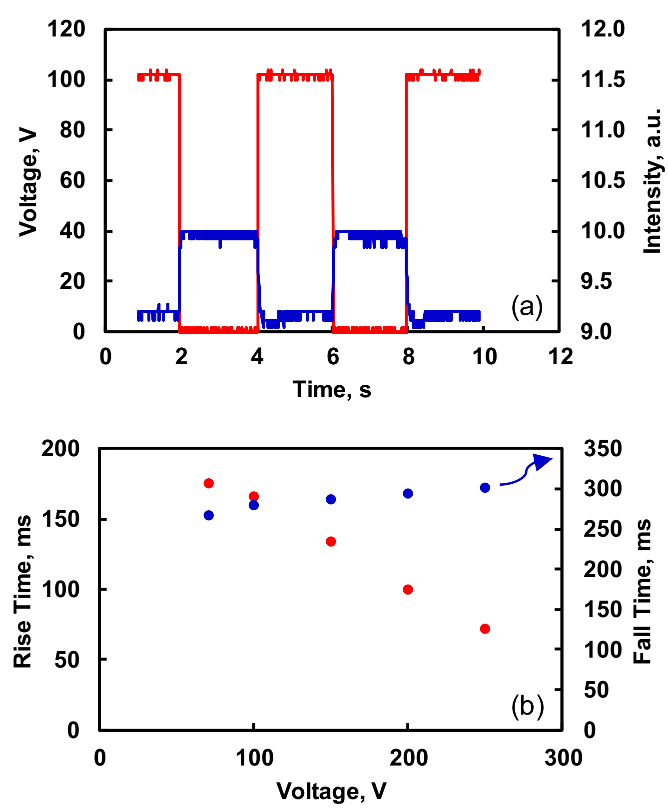

Fig. 7. (a) Light intensity change impacted by 100 V voltage pulse and (b) measured rise time and fall time at different pulse voltages.

topography of its surface profile is precisely described for the first time. Any droplet in the array presents similar spherical shape. This spherical shape helps us evaluate the focal length of the microlens with the smallest error. In contrast to previous PVC-gel lenses, the response time of our microlens is much faster for the following three reasons: 1) the PVC gel is stretched in longitudinal direction, 2) the surface tension of the PVC gel matches with that of the conductive polymer, and 3) high surface area between the PVC gel and the electrode area as well as the short distance (which causing high electric fields) between cathode and anode under applying DC voltage. The operating voltage of the droplet is much lower than that of previously reported single PVC-gel lens. Low resolution is due to slight surface wrinkles caused by extrusion. To enhance image resolution, one feasible method is to use a thin glass plate or metal plate to replace the soft polymer film. Because the PVC gel layer is firmly sandwiched between the two substrates. The droplet size in the hole is small, that is, the small volume of the gel is shaken so that it is unaffected by the effect of gravity without the fluidity of the liquid. Therefore, displacement and deformation of the droplets do not occur, giving rise to stable MLA even with vibration and shaking. After improving the optical performances, this type of microlens and MLA expects to be potential applications in imaging, biometrics, sensing, and electronic displays.

4. Conclusions

We prepare an MLA by filling a PVC gel in polymeric cavities. The PVC gel in the cavities forms a droplet array. Each droplet in the array presents a spherical shape. By applying a sufficiently high voltage, the apex distance of the droplets reduces, leading to an increased focal length. When the DC voltage increases from 0 to 250 V, the apex distance of the dome changes from 9.17 μm to 8.18 μm and the focal length changes from 2.75 mm to 3.15 mm. In contrast to previous PVC-gel lenses, the driving voltage is lower, while keeping a fast rise response time 160 ms at 100 V. The lower resolution of images is reasonable (~20 lp/mm) due to slight surface wrinkles caused by extrusion. The optical performance of the MLA can be improved by using a thin glass plate rather than a soft polymer substrate. Considering the compromises, our microlens has merits such as fast response, reasonable operating voltage, and no gravitational effect. Such a microlens or MLA has potential applications in imaging, optical communications, biometrics, and lab-on-a-chip devices.

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