Variable-focus liquid lens

Hongwen Ren and Shin-Tson Wu

College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816
swu@mail.ucf.edu

Abstract: A variable-focus liquid lens using a transparent flat cell is demonstrated. The top substrate has an aperture which is sealed with a thin elastic membrane on the outer surface and the bottom aperture is sealed on the inner surface of the bottom substrate. By applying a pressure to the outer membrane inward causes the liquid to redistribute and swell the inner membrane outward which, in turn, forms a plano-convex lens. To prove principles, a water lens with 5 mm aperture was fabricated. The resolution is better than 25 lp/mm and the response time is ~40 ms. Potential applications of such a lens for real-time active imaging are emphasized.

OCIS codes: (010.1080) adaptive optics; (220.3620) lens design; (220.2560) focus

References and links

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1. Introduction

Variable focus liquid lenses are attractive for cellular phone, camera, eyeglasses, and other machine vision applications. Similar to a glass lens, a liquid lens focuses light based on the surface-relief profile and its focal length can be tuned by changing the surface profile. According to the operation mechanism, liquid lenses can be classified into two types. The first type is the electro-wetting lens whose focal length can be tuned continuously by applying an external voltage [1-3]. The pros of the electro-wetting lens are large focusing power and no mechanical moving part. However, the required driving voltage is relatively high and the shock wave stability and liquid evaporation are serious concerns. The second type is the

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mechanical lens whose focal length is controlled by pumping liquid in and out of the lens chamber which, in turn, changes the curvature of the liquid profile [4-11]. The operation mechanism of this lens is simple however it requires a fluid pumping system. As a result, the lens is sensitive to vibration and inconvenient for portable devices.

In our previous paper [12], we demonstrated a liquid lens whose focal length is variable based on pressure-induced liquid redistribution. In such a lens structure, the reservoir chamber is around the periphery which is wrapped using an elastic membrane. This approach is attractive for making a single large aperture lens. However the elastic membrane wrapped on the lens border occupies a large area. As a result, the lens is bulky and has a relatively small effective aperture. Thus, it is difficult to extend this design to microlens arrays where a large aperture ratio is crucial.

In this paper, we demonstrate a liquid lens based on pressure-induced liquid redistribution. The lens cell has two apertures and is flat in the initial non-focusing state. One aperture is sealed with an elastic membrane on the outer side of the top substrate surface and another aperture is sealed with an elastic membrane on the inner surface of the bottom substrate. These two apertures do not overlap. Let us call the top aperture as reservoir hole and bottom one as lens hole. Because there is no periphery reservoir, the thickness of this new lens is reduced by ~50% as compared to that reported in [12] if the same substrates are used. The thin lens will greatly suppress the lens aberration, reduce the gravity effect, and improve the response time. Such a lens design can be easily extended to microlens arrays.

2. Device structure

Figure 1 depicts the fabrication process of the lens. Two clear glass or plastic slabs are used as lens frames. Each slab is drilled with a hole and each hole is sealed with an elastic membrane, as Figs. 1(a) and 1(b) show. The two slabs are sandwiched together to form a flat cell. The periphery of the cell is sealed with epoxy glue except for a hole which connects to the chamber. A liquid was injected into the chamber through the hole and afterwards the hole was sealed with glue. Figure 1(c) shows the cross-sectional view of the lens cell in a flat state. Because the volume of the liquid is not constringent, when an external pressure is applied to deform the outer elastic rubber inward the liquid in the lens chamber is redistributed causing the inner elastic membrane to swell outward. As shown in Fig. 1(d), the resultant lens is a plano-convex lens and the incident light is focused. Unlike most of liquid crystal lenses [13,14], such a liquid lens exhibits a large dynamic range and its focusing behavior is polarization independent.

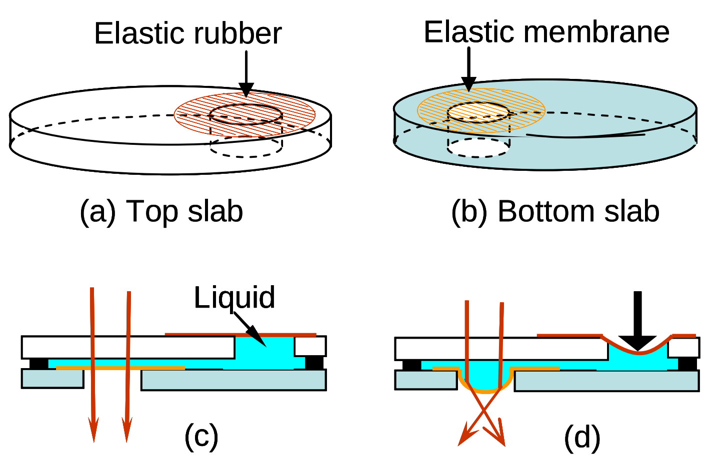

Fig. 1. Structure of a liquid lens cell: (a) top slab, (b) bottom slab, and side view of the lens cell in (c) non-focusing and (d) focusing states.

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To activate the liquid lens, an electrically controlled actuator or a mechanical lever can be employed [12]. To prove concept, here we just use a mechanical lever which has a spherical head for pressing the elastic membrane. The moving distance of the mechanical lever was controlled by a precision low-profile ball bearing linear stage (from Newport). By pressing the outer elastic membrane using the mechanical lever, the liquid inside the cell chamber is redistributed which causes the inner elastic membrane to swell outward and form a convex profile.

3. Experiment

To fabricate a liquid lens according to Fig. 1(c), we drilled a 5-mm hole on each of the disc-like slabs. One hole was sealed using a polydimethylsiloxane (PDMS) membrane from inside and the other was sealed using an elastic rubber from outside. The thickness of the PDMS membrane is ~50 μm and its Young's modulus is ~3 MPa. The outer rubber that we chose has a similar Young's modulus as that of the PDMS but with a thickness of ~100 μm. The gap between the two slabs is controlled at ~1 mm. The thickness of each slab is ~4.5 mm. The cell periphery was sealed with epoxy glue. After a pure water (refractive index n=1.333) was injected into the chamber through a hole and the hole was then sealed with the same glue.

To characterize the light focusing properties of the lens, we measured the two dimensional focused spot pattern of the outgoing beam. The lens cell was intentionally set in vertical direction so that the gravity effect of the liquid on the membrane curvature is taken into consideration. An expanded He–Ne laser beam was used as the probing light source. A CCD camera was set at ~16 cm behind the lens cell to record the images.

4. Results

Figures 2(a) and 2(b) show the three dimensional intensity profiles of the liquid lens at null and activated state, respectively. In the non-focusing state, as Fig. 2(a) shows, the recorded beam spot is larger than 5 mm. The output intensity profile is not symmetric because the incident He-Ne laser beam is not very uniform. The beam size is somewhat larger than the diameter of the PDMS membrane. In the activated state, as Fig. 2(b) shows, the laser beam is tightly focused. To avoid saturating the CCD camera, we used a neutral density filter to reduce the light intensity. The focused beam diameter is about 200 μm.

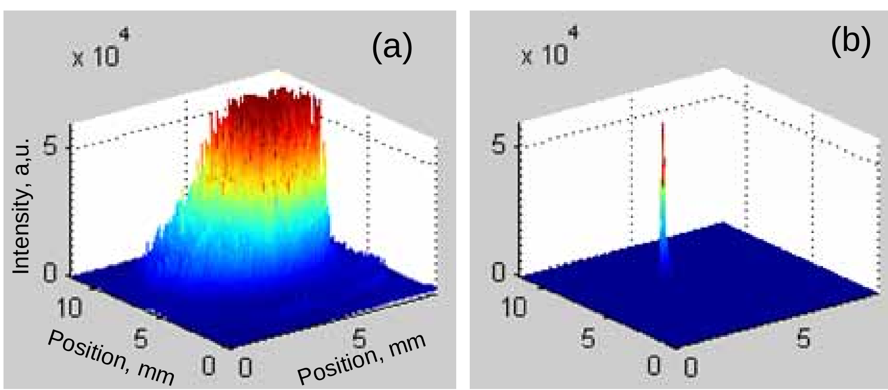

Fig. 2. Three-dimensional intensity profiles of the liquid lens at (a) non-focusing and (b) focusing states. The probing beam is a collimated He-Ne laser.

To check whether the focused beam is diffraction limited, we compare our measured results with the following Fraunhofer diffraction equation [15]

$$\rho = 2.44\lambda f / D, \tag{1}$$

where λ is the incident light wavelength, *D* is the diameter of the lens hole, and *f* is the focal length of the lens. In our experiment, D=5 mm, λ=0.633 μm, and *f*=160 mm. Using these

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parameters, we find ρ~50 μm from Eq. (1). Our measured result is ~4X larger than that of diffraction limited. This difference is believed to originate from the spherical lens aberration. For a long focal length, the PDMS film is only slightly deformed so that the spherical aberration is small. As the focal length gets shorter, the PDMS membrane is deformed more tightly and the curvature may no longer be spherical. Our theoretical calculation shows that a severely deformed PDMS membrane is basically a paraboloid. Under such a circumstance, the lens aberration is worsened and the image quality degraded. In our plano-convex liquid lens, the observed lens aberration is attributed to the nonuniformity of the PDMS film, a relatively thick top slab, and rough edge of the drilled hole.

To evaluate the lens performance during focus change, we recorded the image of an object through the liquid lens under white light environment. A resolution target was set at ~7 cm in front of the lens and a digital CCD camera (C-3040 zoom with 3.3M pixels) was behind the lens cell. Figure 3 shows the photos taken at 5 different focusing stages of the liquid lens. Initially, the lens is in the non-focusing state so that the observed image has the same size as the object. When we apply a pressure to the reservoir hole, the lens starts to focus. Since the distance between the object and the lens cell is shorter than the focal length, the observed image is upright but virtual. When the focal length becomes shorter, the observed imaged is magnified further. In stages 2 and 3, the observed images at the border of the field-of-view are as clear as that observed in the center, although the lens is in vertical direction. In stages 4 and 5, there is a little blur at the aperture border due to lens aberration. Before the aberration becomes severe, our liquid lens can resolve better than 25 lp/mm clearly.

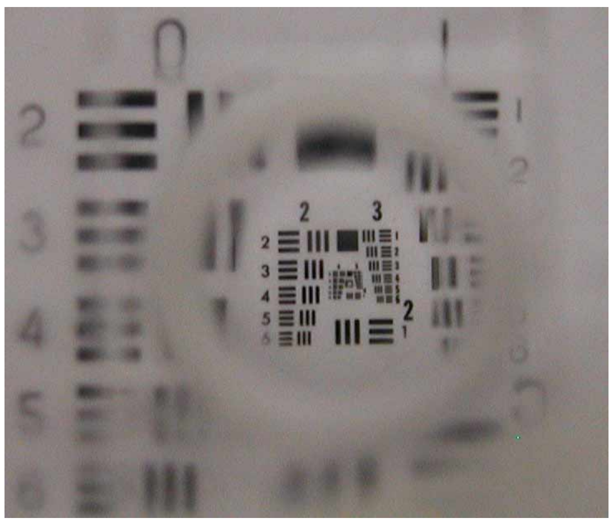

Fig. 3. Five-stage image magnification of the liquid lens. (1.6 MB)

To correlate how the volume change affects the focal length of the liquid lens, we assume the swelled state of the PDMS membrane has an ideal spherical profile if the volume change is not too large. Under this approximation, the standard spherical lens equation is still valid. Similar to a thin glass lens, the effective focal length of the liquid lens can be calculated from following equation

$$f = \frac{R_v}{n_{liquid} - 1}, \tag{2}$$

where R_v is the radius of the variable curvature of the PDMS membrane and n_{liquid} is the refractive index of the employed liquid. We calculate how the volume change in reservoir hole affects the radius of the PDMS curvature and the effective focal length of the lens hole.

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The liquid we used for calculation is pure water. For simplicity, the influences of the PDMS thickness variation during deformation and its refractive index on the lens are neglected.

Figure 4 shows the calculated results. As the displaced volume is increased, the PDMS film is deformed further so that its radius of curvature is reduced. As a result, the focal length of the lens decreases, according to Eq. (2). Three experimental data (open triangles) are included in Fig. 4 for comparison. The simulated and experimental results agree well. Because the lens performance is affected by the f-number and aberration, the resolution could vary during focus change. At resolution of 25 lp/mm, as shown in Fig. 3, the f-number is estimated to be ~f/20. Further decreasing the f-number will decrease the lens resolution correspondingly.

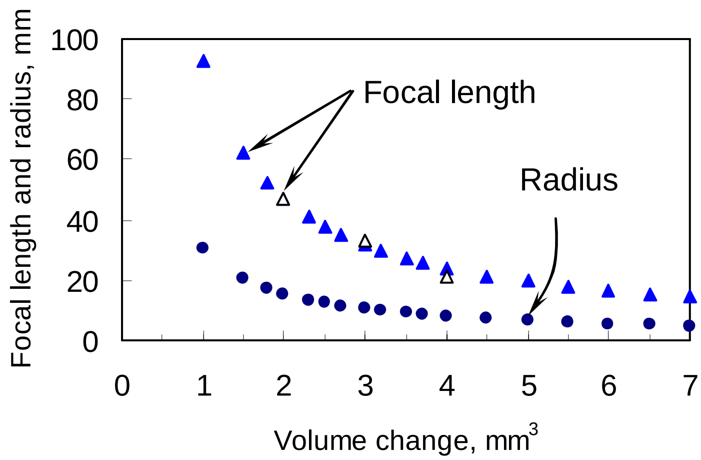

Fig. 4. Calculated PDMS radius of curvature and focal length of the liquid lens as a function of volume change. The open triangles are experimental data.

Response time is another important parameter for active imaging devices as it determines the data acquisition rate. We tried to estimate the response time of the liquid lens by probing the lens activation using an expanded He-Ne laser beam. A diaphragm with ~2.5 mm diameter was placed behind the liquid lens to control the transmitted laser beam. When the lens is in the non-focusing state, the beam is large and some light is blocked by the diaphragm. Thus, the received beam intensity is weak. When the PDMS membrane is pressured to form a convex lens, the beam is converged so that more light can pass through the diaphragm. In experiment, we deformed the PDMS membrane by gently pressing the outer elastic membrane of the lens by a pen. The transient laser transmission was recorded by a digital oscilloscope.

Figure 5 shows the measured results. The rise time is ~35 ms and the recovery time is ~40 ms. The rise time is inversely proportional to the pressure acting on the rubber membrane. For a fixed volume change, as the applied force increases the rise time decreases. To achieve fast rise time, we could use a piezoelectric actuator. As soon as the external force is removed, the lens recovers quickly to its original state. The measured relaxation time is not sensitive to the force we applied.

It would be desirable to quantitatively correlate the recovery time with volume change and material parameters. However, this is not an easy task as it involves the dynamics of liquid redistribution which is governed by the elastic and viscous torques. Qualitatively speaking, to shorten the lens recovery time we could take the following steps: 1) to choose the outer elastic rubber with a high elastic modulus, 2) to decrease the cell gap of the liquid lens and the distance between the reservoir hole and the lens aperture so that less liquid is involved in the flow, and 3) to select a liquid with low density. Some liquids, such as silicon oil and liquid monomer, are suitable for the lens because they have a high refractive index and low

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density. By optimizing the lens parameters, it is possible to improve the response time of the liquid lens and achieve video rate for real time active imaging applications.

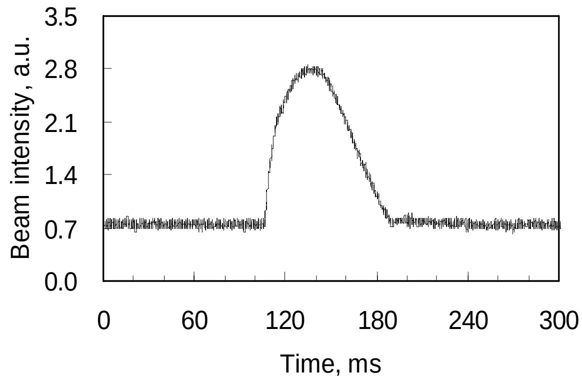

Fig. 5. Measured response time of the liquid lens. Volume change is induced by an impulse pressure on the outside elastic membrane of the lens.

In our experiment, water was chosen for feasibility demonstration. Water has two major shortcomings: low refractive index (n=1.33) and high frozen temperature (4^{o}C). For practical applications, some high refractive index and low frozen temperature liquids, such as microscope immersion oil (n=1.51), dimethyl silicon oil (n=1.60) or liquid polymer (Norland optical adhesive, n=1.56) can be considered. For a higher index liquid, a smaller volume displacement will achieve the same focal length without deforming the PDMS membrane too severely. Thus, the lens aberration will be decreased.

In addition to a single large aperture lens, we can also fabricate lens array. To do so, we simply drill arrays of holes on the glass or plastic substrate and seal the holes with an elastic membrane. The device structure is similar to that sketched in Fig. 1, except the single lens aperture is now replaced by an array of holes.

5. Conclusion

We have demonstrated a variable-focus liquid lens based on pressure-induced liquid redistribution. The aperture size of the liquid lens is determined by the uniformity and sturdiness of the PDMS film which could range from millimeters to centimeters. The focal length of the lens can be controlled by a mechanical or piezoelectric actuator. The resolution of the lens is better than 25 lp/mm and response time is ~40 ms. This compact liquid lens can be used for cellular phone zoom lens, machine vision, and real time satellite imaging.

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