Adaptive liquid lens actuated by photo-polymer

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Abstract: An adaptive liquid lens actuated by a photo-polymer is demonstrated. The lens cell consists of a top glass substrate and a bottom plastic slab with two holes: reservoir hole and lens hole, which are sealed with elastic membranes. A photo-sensitive polymer is attached to the membrane of the reservoir hole. Under blue light irradiation, the polymer is bent which exerts a pressure to regulate the curvature of the membrane on the lens hole and then change the focal length of the plano-convex lens. The focal length is tunable from infinity to 21.2 mm in seconds. Non-mechanical driving, easy integration with other optical components and compact system are the key features of this lens.

OCIS codes: (010.1080) adaptive optics; (220.3620) lens design; (160.5470) polymers

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1. Introduction

Adaptive-focus liquid lenses are based on physical adjustment of the lens shape. The focal length can be tuned by fluidic pressure [1–3], electrochemistry [4], thermal effect [5], environmentally adaptive hydrogel [6], electro-wetting [7] and dielectrophoresis [8,9]. Compared to adaptive liquid crystal lenses, the adaptive liquid lenses exhibit some attractive features, such as polarization independence, large aperture size, broadband and strong focusing power. They show great potential in cell phone cameras, imaging processing, optical communication, sensors and other vision applications [1–11].

In an adaptive lens based on fluidic pressure, the focal length is controlled by pumping liquid in and out of the lens chamber, which changes the curvature of the liquid profile. The operation mechanism is simple but a fluid pumping system is necessary, which is not so convenient for portable devices [1,2]. In 2007, a revised lens structure for a liquid lens without a pumping system is proposed [3]. A liquid of a fixed volume is sandwiched between two slabs which are sealed with glue. Each slab has a hole and the two holes are sealed with elastic membranes. Without an external force, the elastic membrane of the lens cell is in a flat and non-focusing state. When an external pressure is applied to deform the outer elastic membrane, the liquid in the chamber is redistributed, causing the inner elastic membrane to swell outward and forming a plano-convex lens. Piezoelectric actuator, servo motor actuator or artificial muscle can be used to squeeze the outer elastic membrane. However, there remains a challenge to integrate the lens and the actuator into a compact system due to the bulky size of the actuator. Voice coil motor and shape memory alloys actuators have also been proposed for a compact lens system [12,13], however, in some biological and medical applications, electrical controls or fluid circulation should be avoided and innovative mechanism to actuate membrane liquid lens is needed [14]. A tunable liquid microlens actuated by infrared light is demonstrated in 2008, which makes it possible to integrate the microlens with fiber optics based systems such as fiber endoscopes [15]. This driving method is more favorable for micro-sized liquid lens.

In this paper, we demonstrated a tunable liquid lens actuated by a blue light. The lens structure consists of a top glass substrate and a bottom plastic slab with two apertures. One aperture is called as reservoir hole and the other as lens hole, and both are sealed with elastic membranes. A photo-sensitive polymer is attached to the membrane of the reservoir hole and it will push the membrane inward once it is actuated by a blue laser beam. The bending angle of the polymer, controlled by the power density of the blue light, regulates the curvature of the membrane on the lens hole which, in turn, changes the focal length of the plano-convex lens. The fabrication procedure is simple and the resultant liquid lens shows good stability. This actuation method can be adopted in a micro-sized, millimeter-sized or even larger size liquid lens. Compared with traditional methods, our lens offers a possibility to achieve a compact system, non-mechanical actuation, and easy integration with other optical components.

Polymer networks containing azobenzene liquid crystalline (azo LC) moieties are able to change their macroscopic shape when influenced by light. Several photo-polymers based on this mechanism have been reported [16–18]. The polymer film used in our experiment is made from 4, 4'-Di (6-acryloxyalkyloxy) azobenzene and LC monomer 4-(6-acryloxy) hexyloxy-4'-ethoxyazobenzene [19]. The azo LC moieties need to be aligned before thermal polymerization, and this alignment is considered as the film alignment. Fig. 1 shows the reorientation of azo LC molecules at different polarized incident light. The polymer film will bend away from the incident laser beam when the film alignment (**n**, red arrow in Fig. 1(a)) is *orthogonal* to the beam polarization (black cross in Fig. 1(a)), and bow towards when the alignment (red arrow in Fig. 1(b)) is *parallel* to the beam polarization (black arrow in Fig.

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1(b)). Because molecular reorientation shrinks (or expands) the polymer's volume locally along (or perpendicular) the polarization direction, the generated compression force is acting along the polarization direction. The film will maintain the optically-induced shape when the incident beam is turned off. The bending angle increases with the laser power density once it is above a threshold. This reversible bi-directional bending of the polymer film can be controlled by switching the polarization of the actuation beam in orthogonal directions. Large bending angle (–70°~70°) and fast bending speed (170°/s) could be obtained by a fairly low power density (~0.1 W/cm^2 at λ = 514 nm) [19]. These characteristics enable the photo-polymer to actuate the membrane liquid lens.

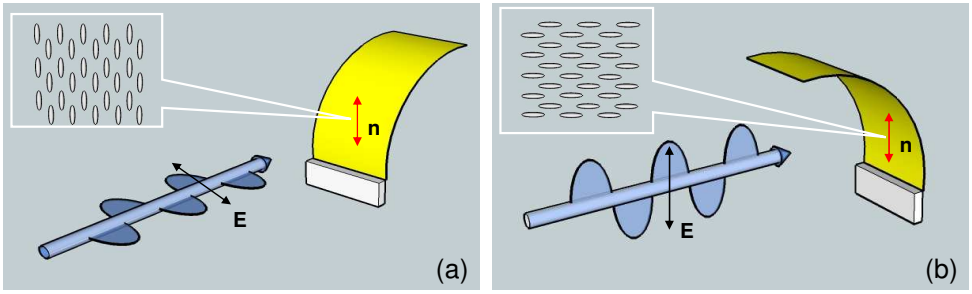

Fig. 1. Schematic of experimental geometry and the effect of laser-induced LC reorientation: (a) Bending away from the laser beam when E⊥n, and (b) Bending towards when E||n.

2. Device structure

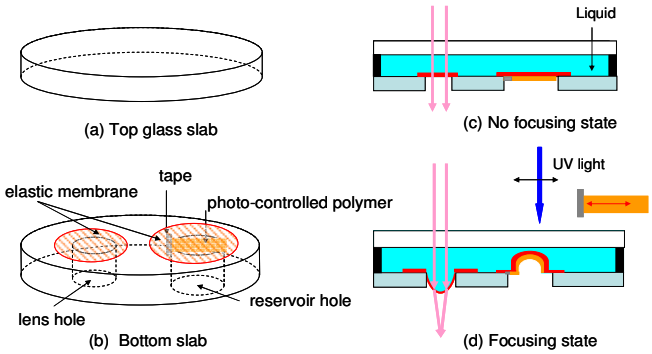

Fig. 2. Structure of a tunable lens actuated by photo-polymer: (a) Top glass slab, (b) Bottom glass slab, side view of the lens cell in (c) non-focusing and (d) focusing states.

Fig. 2 shows the fabrication process of the liquid lens actuated by a photo-polymer. A top glass substrate and a bottom plastic slab with two holes are used as lens frames, as shown in Figs. 2(a) and 2(b). The right aperture is called as reservoir hole and left one as lens hole. The two apertures are both sealed with elastic membranes. A piece of photo-polymer is fixed on the elastic membrane of the reservoir hole. The two slabs are sandwiched together and form a flat cell, and the periphery is sealed with epoxy glue except for a hole. A liquid is injected into the lens chamber through the hole, and after that, the hole is sealed with glue. Fig. 2(c) shows the cross-sectional view of the lens cell in the non-focusing state. When the beam is polarized parallel to the film alignment direction with the power density above the threshold, the polymer film will bend towards the incident light and push the adhering elastic membrane on the reservoir hole inward. Because the volume of the liquid is not constringent, the liquid in the lens chamber is redistributed, causing the elastic membrane on the lens hole to swell outward, as shown in Fig. 2(d). A plano-convex lens is obtained and the incident light is focused. The focal length can be tuned by the power density of the actuation beam because the bending angle increases with power density. This tuning process is reversible, only if the

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beam polarization direction is rotated by 90°, which can be achieved by switching a twisted nematic (TN) liquid crystal (LC) cell [20].

3. Experiment

To fabricate a liquid lens cell according to Fig. 2(c), we drilled two holes on the bottom plastic slab. The two holes were both sealed with polydimethylsiloxane (PDMS) membranes from inside. PDMS is a well-studied hydrophobic membrane and is transparent in ultraviolet-visible regions. Its super elastic and soft nature makes it easy for reversible deformations in fluid manipulations [21]. The diameters of the reservoir hole and the lens hole are 6 mm and 4 mm, respectively, and the thickness of the PDMS membrane is 60 μm. A piece of photo-polymer (2 mm x 4 mm x 20 μm) was one-end fixed on the outer surface of the PDMS membrane on the reservoir hole by tape, and the position of the polymer film is adjusted to make its alignment direction (red arrow in Fig. 2 (d)) parallel to the beam polarization direction (black arrow in Fig. 2 (d)). The two slabs were sandwiched together to form a flat cell, and pure water (n = 1.33) was injected into the cell. The thickness of the top slab and bottom slab is 3 cm and 1 cm, respectively.

To activate the liquid lens, a CW He-Cd laser (λ = 442 nm) was employed as the actuation beam. A movie was taken for visually observing the deformation of the photo-polymer under blue irradiation, shown in Fig. 3(a). The film bends towards the incident laser beam because its alignment direction is parallel to the laser's polarization direction. The experimental setup for the lens actuation is shown in Fig. 3(b). Two solid lenses placed on the optical bench were used to focus the laser beam on the polymer film. The focal point of the two-lens system can be adjusted by changing the distance between the lenses. The liquid lens cell was placed out of the initial focus of the two lenses system and was adjusted to let the laser beam go through the polymer. Shortening the distance between the two solid lenses by moving lens 2, the focus of the two lenses system moved towards the polymer, accordingly the irradiance exposed on the polymer increased. Once the power density exceeded the threshold, the polymer began to bow towards the incident laser beam and the liquid lens began to focus.

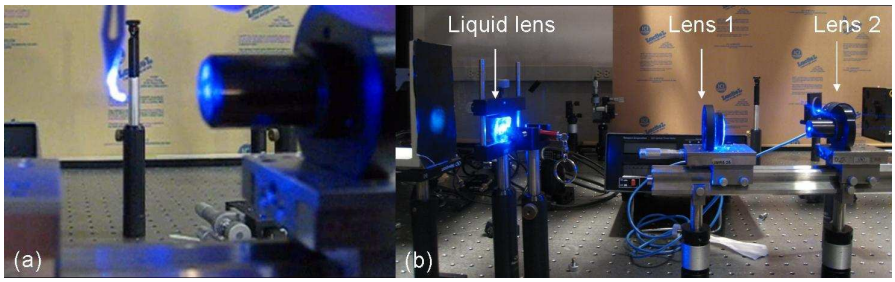

Fig. 3. (a) Deformation of the photo-polymer under blue laser irradiation (Media 1), and (b) Experimental setup for the actuation of the membrane liquid lens.

4. Results and discussions

To evaluate the lens performance during focus change, we recorded the image of an object through the liquid lens under white light irradiation. A picture, printed with two letters "do" was set at ~0.2 cm behind the lens, and a CCD camera was used to record the image change. The distance between the liquid lens and lens 1 is fixed at 19 cm. Fig. 4 shows the photos taken at 2 different focusing states of the liquid lens. Firstly, the laser was off and the liquid lens was in the non-focusing state so that the observed image had the same size as the object, as Fig. 4(a) shows. An enlarged image is shown in the lower-left corner. Then we turned on the laser and focused it on the polymer film gradually. The initial separation between lens 1 and lens 2 was 14.5 cm. The power density was increased to 0.47 W/cm^2 when the separation between lens 2 and lens 1 was shortened to 12 cm. The focal length of the resultant plano-convex lens was decreased to 21.2 mm in ~10 seconds and the observed picture is shown in

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Fig. 4(b). Because the distance between the object and the lens cell is shorter than the focal length, the observed image is upright, virtual, and magnified.

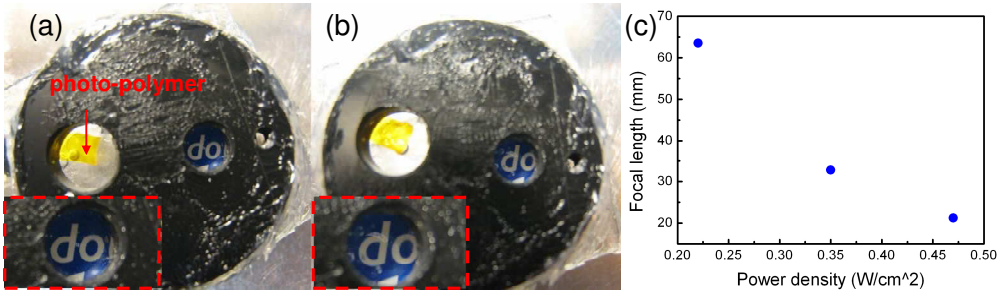

Fig. 4. (a) Liquid lens at non-focusing state, (b) Liquid lens at a focusing state, and (c) Measured focal length of the lens at different power densities.

Fig. 4(c) is a plot of the irradiance dependent focal length of the liquid lens shown in Fig. 4(a). The focal length is determined by the smallest focused point of a collimated input light beam along the optical axis. In our experiment, a collimated white light was used as the probing light source. At the rest state, the lens cell is in flat state and its focus is at infinity. The focal length decreases with increasing power density for the polarization parallel to the alignment of the polymer film. As the power density increases, the polymer film deforms further so that the PDMS membrane swells outward further and the radius of the curvature is reduced. The focal length is decreased to 21.2 mm when the power density reaches ~0.47 W/cm^2.

From Fig. 4, we can see that the photo-polymer can be used to actuate a membrane liquid lens. However, the detected focus change is not very large. Qualitatively speaking, to enhance the mechanical robustness of the liquid lens, we could take the following steps: 1) Using a larger and thicker polymer film, thus the bending force induced by the polymer deformation can be enhanced. 2) Applying an actuation beam with a high power density, hence a large bending angle can be obtained because the bending angle increases with the power density of the laser beam. 3) Selecting the wavelength of the actuation beam which can induce the largest deformation under the same irradiation. 4) Optimizing the lens structure and finding the best position for the polymer so that it can work more efficiently. The typical thickness of the photo-polymer is 10~50 μm [19], the sample used in our experiment is 20 μm thick. If the polymer thickness is increased to 50 μm and its size is large enough to cover the whole reservoir aperture, and meanwhile if the actuation beam with a sufficient power density can also cover the whole reservoir, then the mechanical robustness, the dynamic range, and the response time of the lens could be improved substantially.

To make a compact optical system for practical applications, the employed He-Cd laser can be replaced by a laser diode (LD), as shown in Fig. 5(a). Because the bending direction of the photo-polymer is polarization sensitive, we use a 90° TN cell to switch the polarization of the laser beam. Let us assume the alignment direction of the polymer film (red arrow in Fig. 5(a)) is along z axis, the polarization direction of the laser beam and the rubbing direction of the bottom glass substrate of the TN cell (Fig. 5(b)) are parallel to each other, both along y axis. A movie of the bi-directional bending of the polymer film controlled by a 5-μm E7 TN cell is shown in Fig. 5(c). In the voltage-off state, the TN cell rotates the polarization of the incident laser beam by 90°, thus the polarization direction of the laser beam after passing through the TN cell becomes parallel to the film alignment. The polymer bows towards the laser beam and a plano-convex lens is obtained. The focal length decreases with increasing power density of the laser beam. In the voltage-on state, the polarization rotation effect of the TN cell vanishes, and the polarization of the laser beam stays along z axis. Therefore, the polymer bends away from the incident laser beam and the focusing power of the lens decreases. The focal length increases with increasing power density of the laser beam. The switching time of the TN cell depends on the LC cell gap and the material employed. For a

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typical 5-μm E7 TN cell, the response time is ~25 ms [22]. This switching time is much faster than that of photo-polymer (~170°/s) [19]. As a result, it has almost no influence on the response time of the liquid lens system. The deformation direction can be selected by the TN cell, and the deformation magnitude can be controlled by the laser power density, thus, both forward and backward actuations of the membrane liquid lens can be achieved.

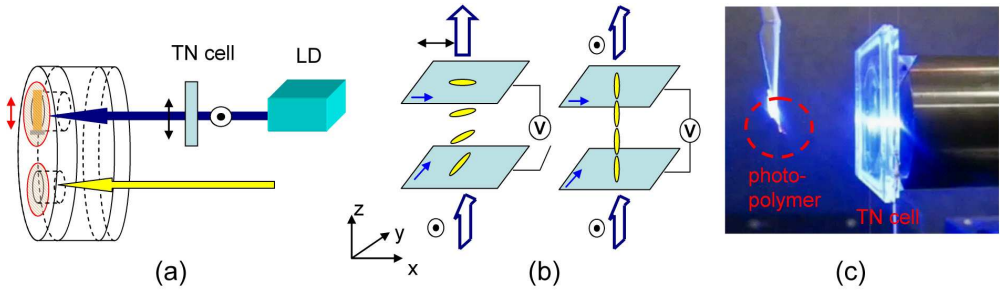

Fig. 5. (a) Tunable liquid lens system, (b) On state and off state of a TN LC cell, and (c) Bi-directional bending of the polymer film using a TN cell (Media 2).

5. Conclusion

An adaptive liquid lens actuated by a photo-polymer is demonstrated. Benefiting from the photo-induced deformation, the bending direction and bending angle of the polymer, and the resultant liquid lens can be tuned by a laser beam. The focal length can be tuned from infinity to 21.2 mm in seconds under blue light irradiation. This approach paves a way to achieve non-mechanical driving, easy integration with other optical components and compactness. The mechanical robustness, dynamic range, and response time of the liquid lens can be enhanced using a larger and thicker polymer film and an actuation beam with a higher power density.

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