TUNABLE MICRODOUBLET LENS ARRAY

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ABSTRACT

We report a tunable microdoublet lens capable of creating dual modes of biconvex or meniscus lens. The microdoublet lens consists of a tunable liquid-filled lens and a solid negative lens. It can be tuned either by changing the shape of the liquid-filled lens into bi-convex or meniscus or by changing a filling media with different refractive index. The microfabrication is based on photopolymer microdispensing and elastomer micromolding methods. The microdoublet lens can provide a solution for minimizing optical aberrations and maximizing the tunability of focal length or field of view by controlling variable and fixed lens curvatures.

1. INTRODUCTION

Tunable microlens array plays critical roles in medical stereoendoscopy, telecommunication, optical data storage, and photonic imaging, since microlens tunability can offer attractive figure of merits such as high light throughput and extinction for optical switching application, image magnification or field of view (FOV) change for multiple imaging. Tunable microlenses have been recently demonstrated using electrowetting, re-orientation of liquid crystal, or fluidic adaptive lens [1-5]. However, most previous works have been focused on a singlet microlens. Therefore the focal length tunability depends on the control of single lens curvature or the change of refractive index. A novel tunable microdoublet lens proposed here has two lens curvatures and it can create dual modes of biconvex or meniscus tunable lens. Unlike the previous tunable singlet microlenses, the focal length or FOV tunability of the microdoublet lens can be maximized by controlling the ratio of two lens curvatures as well as by selecting two different refractive indices. The suitable combination of two lens curvatures and refractive indices can also minimize optical aberrations through microdoublet lens. This paper presents the design, microfabrication and characterization of tunable microdoublet lens array based on photopolymer microdispensing, elastomer micromolding and bonding fabrication methods.

2. MICRODOUBLET LENS DESIGN

The microdoublet lens consists of a tunable liquid-filled microlens and a solid negative lens. Each liquid-filled microlens has a variable and fixed lens curvature, then all microlenses are connected by microfluidic networks as shown in Fig. 1. The variable lens curvature is dynamically modulated with the deflection of a thin elastomer membrane under the pneumatic control via microfluidic channels. The fixed lens curvature is predetermined by the geometry of lenslet mold. The microdoublet lens can be tuned either by changing the shape of the liquid-filled lens into bi-convex or meniscus, or by changing a filling media with different refractive index. In particular, the selection of two different refractive indices determines the tunable range of focal length as shown in Fig. 1. For higher refractive index of the tunable lens than that of the solid lens, under positive pressure is a high power converging lens and under negative pressure is a low power diverging lens, or vice versa.

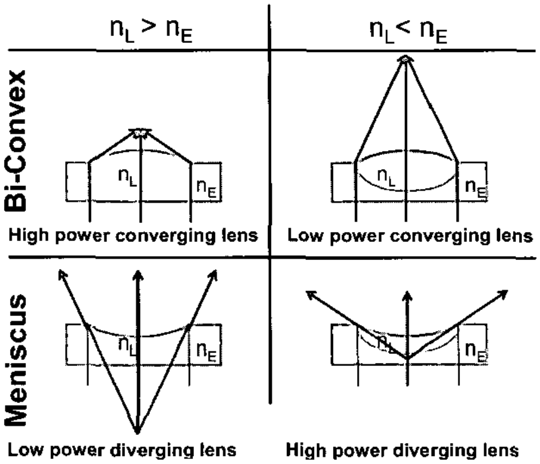

Figure 1: The basic configurations of a tunable microdoublet lens consisting of a tunable liquid-filled microlens and a solid negative lens of different refractive indices (n_E and n_L) acting in combination.

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The variable lens curvature of the microdoublet mainly depends on the deflection of the distensible circular membrane. The deflection can be approximated with the analytical formula for a uniformly loaded distensible circular plate with large deflections based on the theory of plates [6]. The maximum deflection, w_0 is derived by

$$w_o = 0.662a\left(\frac{\Delta Pa}{Et}\right)^{1/3} \tag{1}$$

, where ΔP is the pressure drop, a is the radius, t is the thickness and E is the elastic modulus of a membrane. The formula shows that the maximum deflection is proportional to the cube root of the pressure and inversely proportional to the cube root of the thickness. Assuming that the profile of a deflected membrane is modeled as a spherical cap, the radius of variable lens curvature, R_v is taken as

$$R_v = \frac{\left(w_o^2 + \varphi^2\right)}{2w_o} \tag{2}$$

, where φ is the aperture radius of microlens. The effective focal length of the microdoublet, f can be calculated by applying thin-lens equation for a microdoublet lens consisting of an elastomer solid lens and a liquid-filled tunable lens acting in combination as the below.

$$f = \frac{R_v}{(1-n_E)+(n_L-n_E)R_v/R_f} \tag{3}$$

, where R_v is the radius of variable curvature, R_f is the radius of a fixed curvature, n_E is the refractive index of elastomer, and n_L is the refractive index of a filling media.

3. MICROFABRICATION PROCEDURE

The microfabrication of tunable microdoublet lens array is based on soft lithography and photopolymer microdispensing technologies as shown in Fig. 2.

A 20 μm thick SU-8 photoresist as a mold of a solid negative elastomer lens array is initially defined on a glass substrate in order to define the patterns of microfluidic network and ring confinements of microdroplets. The surface of the patterns is hydrophobically modified with fluorine based plasma to maximize the surface energy of SU-8 ring confinements [7]. The photopolymer is dispensed onto the prepatterned hydrophobic ring confinements on a hydrophilic glass substrate to form a smooth lens surface under the precise control of a droplet volume using a micropipette (5 μm in inner diameter) and a pump regulator with timed control unit and then cross-linked under UV exposure (step I). The critical functions of the ring confinements are serving as providing microfluidic networks of all microlenses and spatial confinement of photopolymer droplets. In addition, the dispensed droplets are self-aligned in the center of the ring confinements. Fixed lens curvature is controlled with either a droplet volume of a dispensed photopolymer or a diameter of the ring confinement.

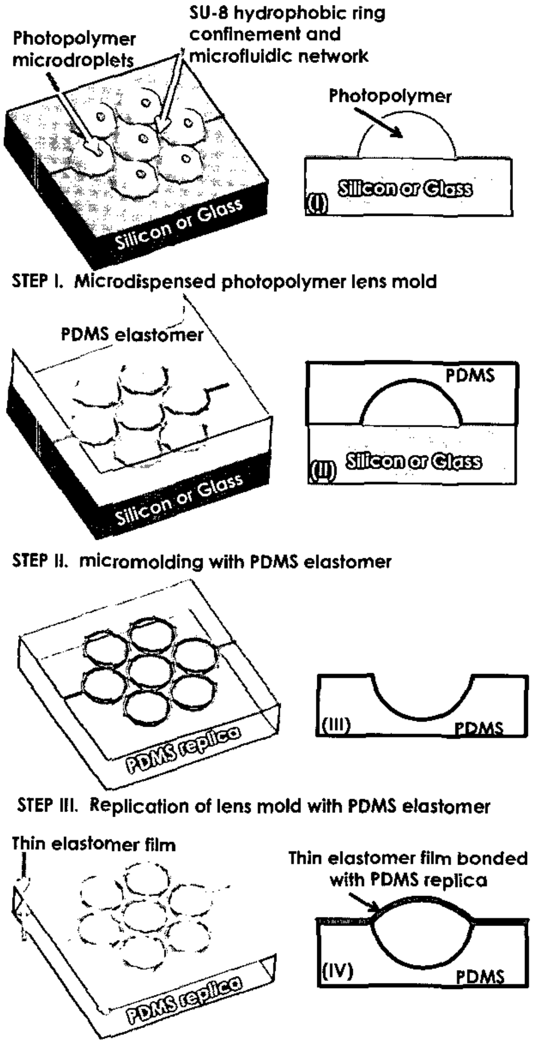

Figure 2: Microfabrication procedure of tunable microdoublet lens array based on soft lithography and microdispensing technologies

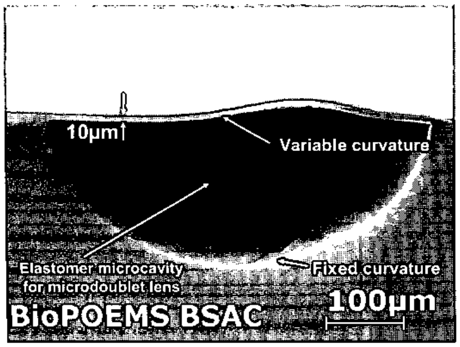

Figure 3: A cross sectional SEM image of an elastomer microcavity incorporating a fixed curvature and a variable curvature of microdoublet lens.

The lens mold is replicated with polydimethylsiloxane (PDMS) elastomer, which is spincoated on the mold, baked at 120 °C for 15 min., and peeled off from the mold (step II and III). If microdroplets on the lens mold are dense, anti-stiction coating such as Teflon®-like polymer or parylene is required prior to PDMS replication. The elastomer microcavities are formed by bonding the replica of fixed lens curvatures with a thin elastomer film (10µm) for variable lens curvatures. The thin elastomer film is separately prepared on another silicon substrate with an anti-stiction layer of photoresist. The replicated elastomer and thin elastomer film are permanently bonded together with an oxygen plasma surface treatment onto both sides and then directly detached from the substrate without dissolving the photoresist (step IV). Figure 3 is an SEM image of a microfabricated elastomer microcavity incorporating a fixed curvature and a variable curvature for a liquid-filled microdoublet lens, which can be tuned by an applied pressure through a microfluidic channel.

4. CHARACTERIZATIONS OF MICRDOUBLET

Two fixed and variable lens curvatures of microdoublet lens are characterized with an optical interferometric profiler (Wyko®). The fixed lens curvature of microdoublet is controlled by microdroplet volume of a photopolymer dispensed on hydrophobic ring confinements with various diameters on a hydrophilic substrate of a lens mold as shown in Fig. 4. The droplet volume was calculated with the measured height of a droplet volume under assumption that the profile is spherical cap.

Due to the hydrophobic confinement, the radius of fixed lens curvature decreases with dispensed volume without the expansion of droplet diameter. The change of radius of fixed curvatures slows down as dispensed volume increases. The volume variation of dispensed 20 droplets dispensed under the same pressure and timing conditions is less than 2.7 %.

The variable lens curvature of microdoublet is modulated with the applied pressure. The maximum deflection of the elastomer membrane under positive and negative pressure is measured. An elastomer membrane with the diameter of 520 µm and the thickness of 10 µm is elastically deflected from -73 µm to 65 µm as pressure varies from -10 kPa to +10 kPa. The measured results are in accordance with the deflection calculated by using (1) and also show the maximum deflections increase with the cube root of the applied pressure. The calculation is carried out with the elastic modulus of 4 MPa. The variable lens curvature with respect to the applied pressure was calculated by using (2) with the measured maximum deflection.

Figure 5 shows the characterizations of the microdoublet lens with DI water ($n_{water} = 1.33 < n_{PDMS} = 1.41$) and oil ($n_{oil} = 1.52 > n_{PDMS} = 1.41$) under the applied pressures between -10 kPa and 10 kPa. The focal length depending on the refractive index of the filling media is measured with a laser wavelength of 535 nm. Under the negative pressure is a positive meniscus lens which diverges a colliminated light. However, if the refractive index of a liquid-filled lens is higher than that of the elastomer lens (n_{PDMS}=1.41), the light can converge onto the focus under negative pressure.

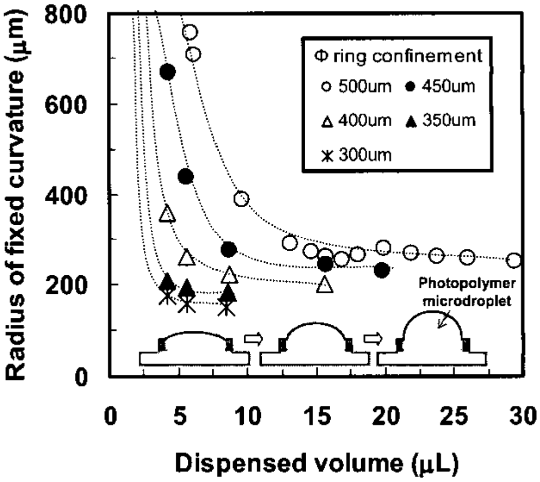

Figure 4: Fixed curvature controlled by the microdroplet volume of a photopolymer dispensed on a hydrophobic ring confinement on a hydrophilic substrate of a lenslet mold.

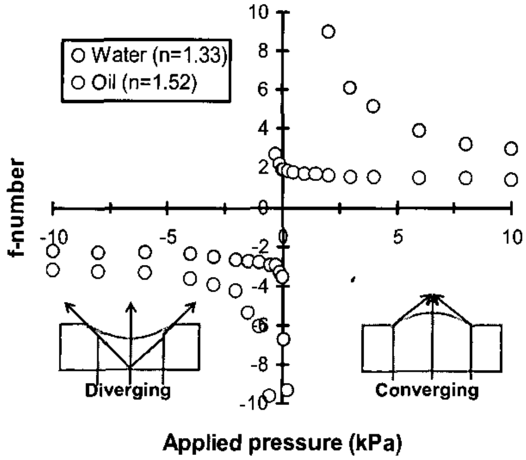

Figure 5: f-number measurements of the microdoublet lens filled with DI water ($n_{water}=1.33 < n_{PDMS}=1.41$) and oil ($n_{oil}=1.52 > n_{PDMS} = 1.41$) according to pressure changes.

Figure 6: Image magnification through the tunable micro-doublet lens filled with DI water.

For example, the focal length for the refractive index of 1.51 changes from negative into positive between -1.5 kPa and -2 kPa. Conversely, under positive pressure is a biconvex lens which converges onto focus. If the refractive index of the filling media is lower than that of elastomer, the light can also diverge even though the lens shape is biconvex. For water of $n_{water} = 1.33$, the focal length changes from negative into positive at the positive pressure between 1 kPa and 1.5 kPa. Especially, for higher refractive index than $n_{PDMS} = 1.41$, the microlens can be coarse tuned with negative pressure as well as fine tuned with positive pressure and vice versa for lower refractive index than that of the elastomer. The focal length ranges from several hundreds of microns to infinity in both positive and negative focal length. The results agree with the variation of tunable span according to the change of lens power as illustrated in Fig.1

The reflective image of micropatterned characters (BioPOEMS) via a tunable microdoublet lens is magnified with applied pressure as shown in Fig.6.

5. CONCLUSIONS

In this work the microdoublet lens array with wide range tunability has been designed, fabricated and characterized. The novel tunable microdoublet lens can create dual modes of biconvex or meniscus tunable lens. The microdoublet lens can provide a solution for minimizing optical aberrations as well as maximizing the tunability of focal length or field of view either by changing two different lens curvatures or by selecting lens materials of different refractive indices. The microdoublet lens array can be useful for numerous photonic applications including medical imagining in minimally invasive surgery as well as optical communication applications.

ACKNOWLEDGEMENT

This work was supported by the DARPA Bio-Optic Synthetic System (BOSS) program.

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