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Review

Characterizing aberration of a pressure-actuated tunable biconvex microlens with a simple spherically-corrected design

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ABSTRACT

A tunable biconvex microlens of 1000 μm diameter is micromachined and pressure-actuated for variable-focusing applications. The microlens consists of two thin membranes with reconfigurable shapes: a fluid chamber and the interconnected microchannel. The back focus length tuning range is demonstrated from 35 mm to 250 mm and zoom ratio of up to seven without any mechanical moving components. Aberration characterization is carried out systematically by the Shack–Hartmann measurements to clarify the potential adverse effect associated with focal length tunability, with particular attention placed on interpretation of the Zernike modes. Experimental results show that spherical mode (Z13) can be significantly degraded from −0.037 μm to −0.095 μm by injecting DI water of 1.11–4.43 μL. A facile and cost-efficient approach has been proposed to compensate spherical aberration based on differential thickness of elastic membranes. The thickness variation for the biconvex microlenses can be manipulated as the difference in deformation contour as well as the resultant surface profile when subjected to uniform applied pressure. Both ZEMAX simulation and experiment are used to validate the design concept and search for the optimal thickness ratio. By injecting the fixed fluid volume of 3.32 μL, the optimal thickness ratio of 1:4 can be experimentally obtained and the measured spherical aberration is −0.023 μm, or 56% improvement compared with 1:1 thickness ratio of −0.053 μm. The proposed microlens is robust and can be used potentially in medical imaging systems, for example, a dynamic environment and adaptive optics.

Contents

1. Introduction

A tunable liquid microlens is typically utilizing curvature change to achieve variable-focusing properties. For example, an elastomer-based tunable liquid-filled microlens array integrated on top of a microfluidic network is fabricated using soft lithographic techniques [1,2]. Both plano-convex and plano-concave configurations are achieved through changes of applied liquid pressure. Another novel microlens design with tunable double-focus is presented [3]. It is fabricated by adding only one SU-8 photolithography step to the well-developed liquid-filled microlens fabrication process. On the other hand, in order to fulfill the requirements of stringent image quality yet lighter and compact configuration, adjustable focal length without any mechanical moving parts were realized economically [4]. In addition, not only the lens properties can be tuned dynamically but also different lens types had been proposed [5]. Potential ophthalmic application with continuously varying optical

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powers to correct both myopic and hyperopic defocus is demonstrated [6]. In particular, adjustable fluidic lens with variable and controllable curvatures exhibited optical powers tunability between −20D and +20D [7] as well as phoroptors of adjustable astigmatic and defocus lenses [8]. A zoom ratio of 4.0 is achieved by incorporating both telephoto (concave–convex) and reverse-telephoto (convex–concave) into the one fluidic adaptive zoom lens system [9]. It is also demonstrated that liquid lenses can be integrated with stimuli-responsive hydrogels [10] and electromagnetic actuators [11] to produce functionally complex yet relatively simple optical systems, such as variable-focus liquid lenses for miniature cameras [12]. An adaptive liquid lens actuated by a photo-polymer under blue light irradiation, can change the focal length of the plano-convex lens [13]. Recently, the induced aberrations of fluidic lens were experimentally clarified due to injected fluid volumes as well as interfaces of Refractive Index Mismatch (RIM) between water/oil [14]. Adjustable fluidic lenses for aberration correction of defocus and astigmatism [15] and furthermore, for correcting piston aberrations induced by MEMS deformable mirrors [16] are experimentally characterized. Theoretically, a design procedure has been proposed for imaging properties of a pressure-actuated deformable mirror as adaptive compensation of rotationally symmetrical wavefronts [17]. However, the lack of a systematic research of liquid lenses on induced aberrations in terms of the Zernike modes and the potentials of adjustable fluidic lens are not fully explored. In this paper, we develop a pressure-actuated tunable biconvex microlens with a simple spherically-corrected design and investigate the associated aberrations in detail, experimentally and numerically.

2. Fabrication of microlens and optical setup of experiments

An indispensable component of the microlens is the elastic membrane that can be deformed to facilitate the variable-focusing capability. 10 μm thick polyvinyl chloride (PVC) stretch film (Nan Ya Co.) is selected as the membrane material due to its resilience, transparency and self-stickiness. The middle portion of the holder consists of a 1000 μm diameter circular aperture and 4 mm thick fluidic chamber and it is fabricated by polydimethylsiloxane (PDMS). The PDMS (Sylgard 184, Dow Corning) was mixed with a 10:1 ratio to curing agent and then poured into a mold cavity about 10 mm in diameter. The PDMS was then placed in a vacuum for about 30 min to remove excess air bubbles. Next, the chamber was baked in an oven at 65 °C for 4 h to completely cure the PDMS. The PDMS chamber was then removed from the mold and measured to be approximately 4 mm thick. Detail construction of microlens is shown in an explanatory view in Fig. 1(a) and (b) which show the schematic diagram of the fluidic system used to control the microlens properties. By controlling the fluidic pressure and selecting different membrane thickness, a bi-convex microlens with two curvatures under uniform pressure can be achieved with focal length tunability. Fabricated prototype shown in Fig. 1(c) reveals the black background and fluid channel connected in serial with syringe (diameter is 1.2 mm) by one tapped holes to provide volumetric changes. Two components of acrylic holder are designed to provide mechanical mounting of both membrane and PDMS chamber. The inset shows the enlarged view of the microlens aperture with 1000 μm in diameter. The edge of the aperture was beveled and sealed with two O-ring installations so that the membrane would maintain a minimum amount of tension to avoid unwanted ripples.

A Shack–Hartmann wavefront sensor (S–H) form Thorlabs was utilized to measure the wavefront aberrations. A schematic diagram explaining experimental setup is shown in Fig. 2. The laser beam (diode laser, λ=635 nm) is collimated by a pair of lenses (L1 and L2, 100- and 75-mm focal lengths) with a 0.75 magnification factor. The light passed another pair of relay lenses (L3 and L4, 75- and 75-mm focal lengths) and irradiated on the mirror. The laser beam reflected by the mirror then passed through one additional pair of lenses (L5 and L6, 75- and 75-mm focal lengths) and the BS (beam splitter) to conjugate the microlens array plane of the S–H. The microlens is located between L2 and L3. The quality of the laser diode beam before any sample is carefully calibrated and repeatedly measured by wavefront sensor to be less than root mean square (RMS) 0.15 μm.

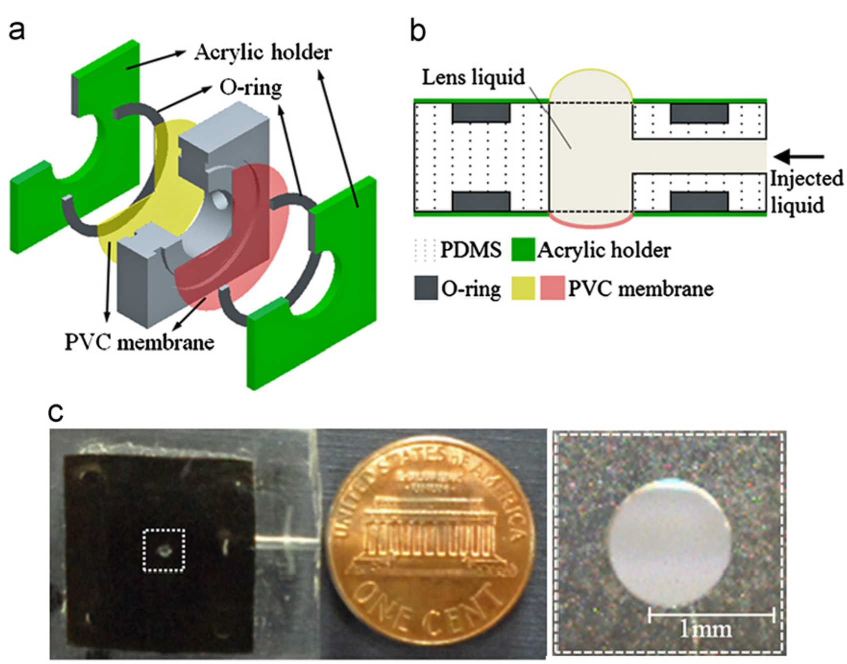

Fig. 1. Schematic for the construction of a microlens. Explosive view shown in (a). The thickness of PVC membrane can be adjusted from 10 to 50 μm thick. (b) Two membrane thicknesses under uniform liquid pressure can be easily tuned into two curvatures. (c) Optical photo of constructed microlens and close-view of aperture.