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Characterization of a tunable astigmatic fluidic lens with adaptive optics correction for compact phoropter application

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ABSTRACT

Fluidically controlled lenses which adaptively correct prescribed refractive error without mechanically moving parts are extensively applied in the ophthalmic applications. Capable of variable-focusing properties, however, the associated aberrations due to curvature change and refractive index mismatch can inherently degrade image quality severely. Here we present the experimental study of the aberrations in tunable astigmatic lens and use of adaptive optics to compensate for the wavefront errors. Characterization of the optical properties of the individual lenses is carried out by Shack–Hartmann measurements. An adaptive optics (AO) based scheme is demonstrated for three injected fluidic volumes, resulting in a substantial reduction of the wavefront errors from −0.12, −0.25, −0.32 to 0.01, −0.01, −0.20 μm, respectively, corresponding to the optical power tenability of 0.83 to 1.84 D. Furthermore, an integrated optical phoroptor consisting of adjustable astigmatic lenses and AO correction is demonstrated such that an induced refraction error of −1 D cylinder at 180° of a model eye vision is experimentally corrected.

1. Introduction

Fulfilling stringent image quality with lighter and compact configuration, adaptive lenses capable of adjusting focal length without any mechanical moving parts were favorably realized [1]. A typical tunable fluidic lens with variable-focusing properties functionally employs curvature change via adjustment of injected fluidic volume. Previously, different lens types and associated lens properties such as dynamical tunability had been proposed [2]. For example, a diffraction-limited resolution over a wide focal tuning range has been theoretically and numerically demonstrated by combining suitable optical liquids and appropriately reconfigured liquid's interfaces radii [3]. For the actuation mechanism, fluidic lenses can be integrated with stimuli-responsive hydrogels [4], photo-polymer [5] and electromagnetic actuators [6,7] to produce functionally complex yet relatively simple optical systems, such as miniature cameras with optical zoom [8–11]. In terms of other functionality, deformable liquid droplets can be used for optical beam control [12] and optical switch with a reconfigurable dielectric liquid droplet [13,14]. In ophthalmic application, myopic, hyperopic defocus and astigmatic aberrations were shown to be corrected by a fluidic lens with continuously varying optical powers [15–17].

Adaptive optics (AO) was initially used in astronomy to compensate for atmospheric turbulence and improves the performance of ground-based telescopes [18]. This technology is also capable of correcting ocular, standard low-order and higher-order aberrations, thus improving in vivo imaging of the retina in vision science and ophthalmic applications [19–21]. Recent investigations of AO integrated optical systems include aberrations induced by combinative effects of multiple layers with convex/concave interfaces and refractive-index-mismatch (RIM) [22], fluidic lenses with focal length tunability over curvature change and related aberrations [23,24]. In the opto-mechanical fields, an integrated roughness measurement system based on AO and binary analysis of speckle pattern images [25] and laser-scattering phenomena [26] was demonstrated. In addition, an oscillation-free implementation of an optical beam control device with reconfigurable fluidic lens was demonstrated [27], considering the AO enhancement [28]. In this paper, we will focus on aberrations expressed by Zernike polynomials, preferably the term of astigmatism aberration commonly encountered in ophthalmology, to correct wavefront aberrations induced by tunable astigmatic fluidic lens. An integrated optical phoroptor which includes fluidically adjustable astigmatic fluidic lenses and an AO correction scheme is constructed. Characterization of the optical properties of the individual lenses as well as AO correction capability is verified by Shack–Hartmann measurements. The AO based scheme is demonstrated to achieve a

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substantial reduction of the wavefront errors from 0.78 to 0.29 μm, corresponding to the optical power change of 1.2 D. In addition, an induced refraction error of −1 D cylinder at 180° of a model eye vision is experimentally corrected.

2. Fabrication of fluidic lenses and optical setup of experiments

The lens structure is intrinsically simple and functionally reconfigurable due to the deformation in membrane curvature and correspondingly changed lens shape. Tuning the optical power is easily achieved by varying the injected fluidic volume and induced pressure on the elastic membrane. Detail construction of an astigmatic fluidic lens and related section-view can be seen in Fig. 1(a) and (b). In order to facilitate the variable-focusing capability, a crucial elastically deformed membrane should be carefully designed and fabricated for the lens. We employed PDMS (Polydimethylsiloxane, Sylgard 184, Dow Corning) as the elastomeric material. PDMS was initially mixed with a 10:1 ratio to curing agent, poured into a mold cavity, and kept for 30 min under vacuum treatment for removing excess air bubbles. The completely cure PDMS membrane was measured to be approximately 550 μm thick after thermally baking at 65 °C for 4 h. The construction of lens is comprised of two PMMA holders to mechanically mount both PDMS membrane and glass (1 mm thick, Menzel-Glaser, Superfost, refractive index 1.523). The middle portion of the holder consists of a rectangular retaining ring that results in a restraining aperture of 30.0 mm × 15.0 mm, which is used to mechanically secure the elastic

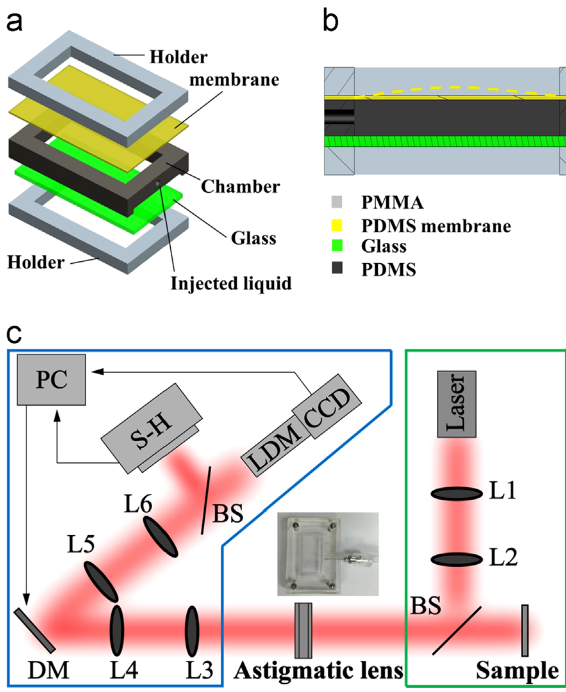

Fig. 1. Schematic for the construction of an astigmatic fluidic lens. (a) Diagram of an exploded view of the astigmatic fluidic lens and fluid pressure is applied to induce curvature change via PDMS membrane. (b) A section-view of rectangular aperture of constructed lens. The lens aperture is 30.0 mm × 15.0 mm and the dotted yellow line shows the corresponding profile for injected fluidic volume. (c) Schematic diagram of the experimental setup: L—lens; BS—beam splitter; LDM—long-distance microscope; and S-H—Shack–Hartmann wavefront sensor. The astigmatic fluidic lens is located between L2 and L3 and the inset shows an optical image of constructed lens. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

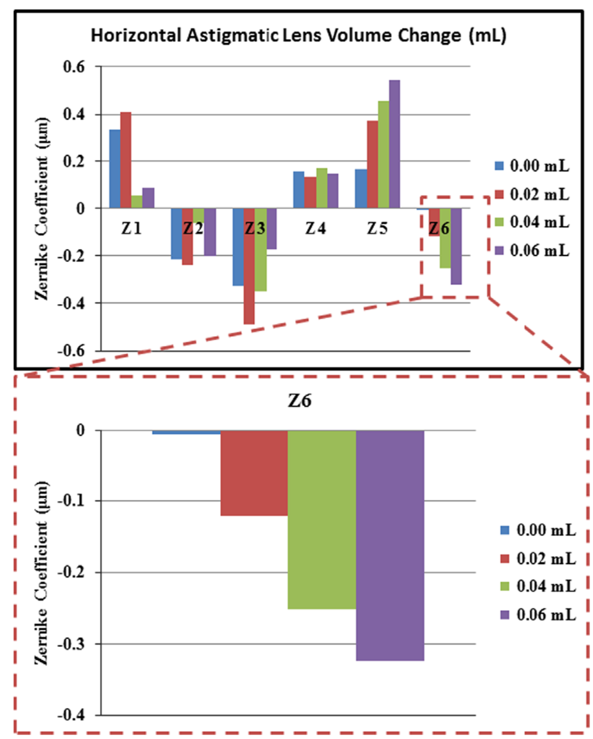

Fig. 3. 6th Zernike coefficients was extracted from the Shack–Hartmann measurements for three different aberrations conditions generated by astigmatic lens with injected volumes of 0.02, 0.04, and 0.06 mL DI water. The zoom-up dotted box shows the Z6 term of 0/90° astigmatism and clearly scales up as injected volume increases.

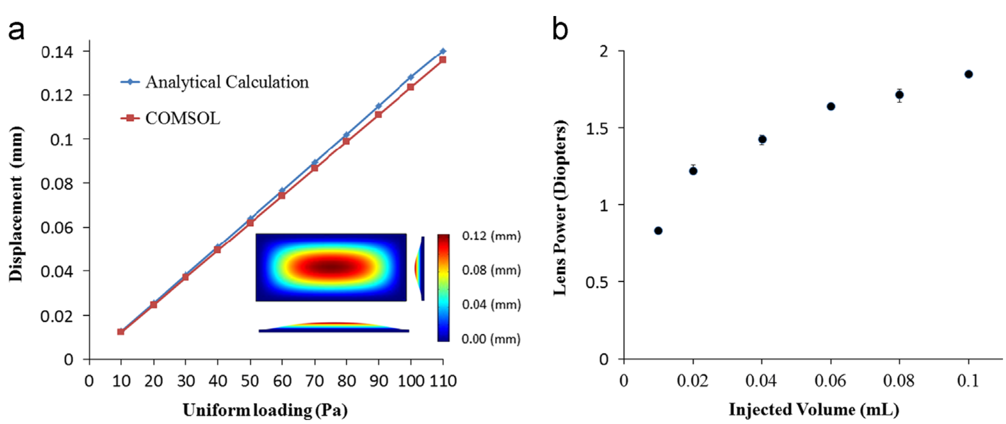

Fig. 2. (a) Analytical calculation of maximum deflection of rectangular aperture under applied uniform pressure. The inset shows the simulated displacement of rectangular membrane deformation as induced by the injected fluidic volume in both longitudinal and lateral directions. (b) Measured lens power of fabricated astigmatic fluidic lens as a function of the injected volume. The wavelength in this experiment is 635 nm laser diode.