ENVIRONMENT-ADAPTIVE VARIABLE-FOCUS LIQUID MICROLENCES

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ABSTRACT

Variable-focus microlenses have the potential for miniaturizing optical systems since they do not rely on manual positioning of the microlens. Previous variable-focus microlenses generally have small tuning range of focal lengths and/or require additional control systems. Here, inspired by human eye's lens, we realize environment-adaptive variable-focus liquid microlenses by combining the advantages of stimuli-responsive hydrogels and pinned liquid-liquid interfaces at the microscale. These microlenses have a large focal length tuning range ($-\infty$ to $+\infty$; divergent – convergent) and do not require additional control.

INTRODUCTION

Traditional man-made optical systems are comprised of multiple lenses where one or more of these lenses are physically displaced to realize variable focus. Nature, however, accomplishes this same function much more elegantly with an individual lens. Although advancements in miniaturization technologies have led to single microlens embodiments that are widely used in photonics, displays, and biomedical systems, these microlens technologies rely on either fixed or externally-controlled variable-focal length [1-4].

Instead, we look to nature for inspiration to realize smart microlenses using pinned liquid-liquid interfaces. In the human eye, ciliary muscles are controlled by the body's nervous system, thereby relaxing and contracting the shape of the lens to enable the eye to focus on different distances. Our microlenses autonomously adapt to local environmental parameters via stimuli-responsive hydrogels (e.g., pH, temperature, light, electric field, and antigen) [5]. Stimuli-responsive hydrogels modulate the shape and focal length of the liquid microlens (analogous to ciliary muscles) formed through a liquid-liquid interface [6] without the need for additional external control systems. The hydrogels simultaneously exhibit both sensing and actuating functions. The favorable scaling of ionic diffusion and fluidic surface tension can be elegantly leveraged to realize relatively short hydrogel response times [7] and pinned liquid-liquid interfaces, respectively. The creation of our smart liquid microlens takes advantage of these scaling properties, which allow a single microlens to have a focal length ranging from $-\infty$ to $+\infty$ (divergent – convergent).

In this paper, we report two types of liquid microlenses by taking advantage of the volume change of the hydrogels differently. The hydrogels used here as models to demonstrate the environment-adaptive functionality are acrylic acid (AA)-based pH-responsive and *N*-isopropylacrylamide (NIPAAm)-based temperature-responsive hydrogels [8].

STRUCTURE AND FABRICATION OF DEVICES

In the 'TYPE-1' liquid microlens (Fig. 1a), a set of stimuli-responsive hydrogel posts are fabricated in a microfluidic chamber. When exposed to a specific stimulus, the hydrogel posts expand and contract to bend a flexible aperture slip up and down. Consequently, the water-oil interface pinned at a hydrophilic-hydrophobic boundary bows downward and bulges upward, varying the focal length of the microlens. The 'TYPE-2' liquid

microlens (Fig. 1b) has a hydrogel ring located underneath a rigid aperture. The water is enclosed by the hydrogel ring. A rigid slip is used to restrain the change in the height of the hydrogel. A changing stimulus outside the ring can cause a volume change in the inside periphery of the ring. The hydrogel ring expands and shrinks in width by absorbing and releasing water via the hydrogel network interstitials. The net volume change of water enclosed by the ring regulates the pressure difference across the water-oil interface; this induces a change in the shape of the liquid microlens, and hence the focal length.

Figure 1. Structures and mechanisms of two types of environment-adaptive variable-focus liquid microlenses. (a) 'TYPE-1'. (b) 'TYPE-2'. In both types, microlenses are formed through curved interfaces between oil and water-based solutions which are stably pinned at a hydrophobic-hydrophilic contact line.

Figure 2. Fabrication process for both types of liquid microlenses.

Fig. 2 shows the fabrication process of the devices. The isobornyl acrylate-based polymer (poly(IBA)) apertures of the microlenses are photopatterned (45 μm -thick for 'TYPE-1' and 125 μm for 'TYPE-2') within cartridges using liquid-phase photopolymerization (LP³) based on UV photolithography [7] (Fig.

2a). After removing the liner, an oxygen plasma treatment is carried out to make the backside and sidewall of the aperture hydrophilic (Fig. 2b). The cartridge is removed and a cavity is formed by adhering the poly(IBA) aperture slip to a glass substrate. The microfluidic channels (also poly(IBA)) and hydrogel posts and rings are fabricated inside the cavity using LP³ (Figs. 2c-d). To achieve the hydrophobic property on the top surface of the aperture slip, an octadecyltrichlorosilane (OTS) solution diluted by hexadecane (0.2 v/v %) is coated on to it (Fig. 2d). To store the oil, a poly(dimethylsiloxane) (PDMS) fence, bonded with a glass cover slip, is glued to the aperture slip (Fig. 2e).

RESULTS AND DISCUSSION

Figs. 3a-b shows the shape and focal length of a pH-sensitive liquid microlens (TYPE-1) with different pH buffers. The AA hydrogels expand in basic solutions and contract in acidic solutions with a volume transition point of pH 5.5. The transition of the microlens from divergent to convergent occurs between pH 6.0 to 8.0. The focal length can be varied from -7.6 mm to $-\infty$ (divergent) and from 8.5 mm to $+\infty$ (convergent). The response time of the microlens is 10-15 s. The change in environmental temperatures can vary the focal length of a liquid microlens using the temperature-sensitive hydrogel ('TYPE-1' in Figs. 3c-d). The NIPAAm hydrogels expand at low temperatures and contract at high temperatures with a lowest critical solution temperature of 32 °C. The focal length transition from positive to negative infinity occurs between 31 °C and 33 °C. The response time of this microlens is 13-20 s.

Figure 3. (a) The focal length of the microlens (TYPE-1) using AA hydrogel as a function of pH. Syringe pumps are used to transfer buffer solutions with different pH through the input channels. (b) The shape of the liquid meniscus when varying pH. Scale bars, 1.0 mm. (c) The focal length of the microlens (TYPE-1) using NIPAAm hydrogel as a function of temperature. An external heater is used to simulate a change in environmental temperature. (d) The shape of the liquid meniscus at varying temperatures.

The 'TYPE-2' liquid microlens (Fig. 1b) also functions to adapt to a changing temperature by using NIPAAm hydrogel. The microlens adjusts its focal length from -7.8 mm to $-\infty$ and from 11.8 mm to $+\infty$ as the temperature varies (Fig. 4a). The 2×4 microlens array (Fig. 4b) has a ~10% variation in focal length. Each lens pixel can be tuned individually.

Figure 4. (a) The focal length of a microlens (TYPE-2) as a function of temperature. (b) A liquid microlens array.

CONCLUSION

A variety of stimuli-responsive hydrogels are used to implement multi-parameter, environment-adaptive smart liquid microlenses. These microlenses can potentially be integrated with other microfluidic components fabricated through a similar process [8] to realize functionally complex systems such as biological and chemical sensors and bio-optical microfluidic systems, and to advance lab-on-chip technologies.

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