A TUNABLE LIQUID MICROLENS DRIVEN BY TEMPERATURE-SENSITIVE HYDROGEL
Liang Dong¹, Abhishek K. Agarwal¹, Sudheer S. Sridharamurthy¹, David J. Beebe², and Hongrui Jiang¹,
¹Department of Electrical and Computer Engineering, University of Wisconsin-Madison
²Department of Biomedical Engineering, University of Wisconsin-Madison

ABSTRACT
In this paper, we present a tunable liquid microlens whose focal length can be tuned under the actuation of a temperature-sensitive hydrogel. The temperature-sensitive hydrogel ring undergoes a volumetric change as temperature changes. This causes the water-oil interface (liquid lens) to change its curvature, thereby tuning the focal length of the liquid microlens. The results show the focal length tuning of the microlens ranges from 7.8 to 13.1mm. This tunable microlens system actively responds to the local fluid temperature and does not require high voltage or external pressure, enabling the microlens to be of compact design facilitating use in new application areas.

Keywords: Tuning, microlens, focal length, hydrogel

1. INTRODUCTION
Lenses are key components of most optical systems. Tunable microlens holds promise for the miniaturization of optical systems by eliminating the need for mechanical moving parts to realize optical alignment and scanning [1]. Different approaches using liquid crystal [2], electrowetting [3], and pressure-driven mechanism [1] have been previously investigated. However, the performance of liquid crystal microlenses is influenced by non-uniformities in the electric field that results in aberrations. The operation of electrowetting-based microlenses requires high driving voltages. Additionally, pressure-driven microlens typically needs an additional pumping system to introduce liquid or air in and out of the chamber to change the curvature of the elastic membrane.

We demonstrate a tunable liquid microlens whose focal lengths can be tuned under the actuation of a temperature-responsive hydrogel. The microlens responds to its local fluid temperature and does not require high voltage or external pumping pressure. In addition, the microlens can be fully integrated in microfluidic systems, which enables miniaturization of on-chip optical elements for diverse applications.

2. CONCEPT
Fig. 1 describes the schematic diagram of the tunable liquid microlens. The microlens sits on a microscope glass slide substrate and is integrated with microfluidic channels. A temperature-sensitive hydrogel ring is constructed to actuate the deionized water drop inside it. A drop of mineral oil is placed on top of the water to prevent evaporation. A ring heater is adhered to the underside of the substrate to control the local temperature. Initially, the microlens provides an inverted image, which verifies the formation of a convex lens from the water-oil interface (Fig. 1(c)). When temperature increases (decreases), the hydrogel ring contracts (expands), causing the interface to become less (more) convex. A
change in the position of the interface also accompanies this. This tunes the microlens and induces a larger (smaller) focal length.

3. FABRICATION

The fabrication process of the device utilizes liquid-phase photopolymerization [4]. A 375µm thick polycarbonate cartridge (Grace Bio-Labs, Inc., Bend, OR, USA) is affixed to 1.0mm thick glass slide. A hole is previously punched through the cartridge at the center position of the microlens. The cartridge cavity is filled with an isobornyl acrylate-based pre-polymer (poly (IBA)). When exposed to UV light (intensity, I=7.8mW/cm²; time, t=32s) through a film photomask, the microfluidic channels are photopatterned. The device is developed in a bath of ethyl alcohol for 4 min. Next, an N-isopropylacrylamide-based temperature sensitive hydrogel (poly(NIPAAm)) pre-polymer is introduced to the cartridge and photopatterned to form an actuator ring (I=15mW/cm², t=10s), followed by a rinse with ethyl alcohol for 15min. The hydrogel is chemically designed to have a Lowest Critical Solution Temperature (LCST) (onset of operation) of 30°C.

4. RESULTS AND DISCUSSION

The fluid height is deliberately kept above cartridge surface to allow visual analysis with available instruments. Fig. 2 shows the shapes of the microlens at two temperature taken by a goniometer. At low temperatures, the expansion of the hydrogel ring squeezes the liquid. The water-oil interface rises, having a larger curvature, to push the fluid upward. Based on the topography of the microlens, the theoretical focal length is tuned from 7.8 to 13.1mm.

The repeatability of the change is studied by cycling the temperature between 24°C and 40°C, and measuring the height of the fluid above the cartridge surface (Fig. 3). The result shows the height change is nearly the same from the third cycle onwards.

A scanning test of the microlens is conducted with a stack of three arrows placed underneath the microlens with an alternate distance of 100µm. A CCD camera coupled to a microscope is used to videotape the experiment. As temperature changes, the focused image of one arrow gradually fades out, while another arrow becomes focused (Fig. 4).

The tuning mechanism of the microlens is not completely understood yet. In the case where the water-oil interface is kept beneath the underside surface of the cartridge, three factors affect the curvature change of the water-oil interface: 1) volumetric change of the hydrogel adjusts the inner diameter of the ring, 2) water transport through the hydrogel network interstitials affects the position of the water-oil interface, and 3) change of surface properties (hydrophobic/hydrophilic) of the hydrogel changes contact angles with water and oil [5]. However, in the other case where the water-oil interface makes contact with the underside surface of the cartridge (Fig. 5), the curvature change is determined by the surface tension along the bottom edge of the center hole. Since the cartridge is hydrophobic, as water is squeezed out or pulled downward, the contact line is pinned to the bottom edge. But the interface shape is free to change, resulting in contact angle variations and bringing about a focal length shift.

5. CONCLUSIONS

We have demonstrated a tunable liquid microlens driven by a temperature-sensitive hydrogel. The focal length is tuned from 7.8 to 13.1mm. The scanning function of the microlens is successfully realized which is promising for many applications. A more
compact microlens system can be realized by fabricating resistive wires directly on the glass substrate. Hydrogels can be chemically tuned to be responsive to different stimuli, such as pH, electric field, and light [6], allowing added flexibility in the design and operation of the tunable microlens for different applications.

REFERENCES


Figure 1. (a) Schematic structure of a tunable microlens. High local temperature causes the hydrogel ring to shrink (solid line), while low temperature causes it to expand (dashed line). (b) Optical image of a microlens. The scale bar represents 2mm. (c) An inverted real image ‘m’ indicating a convex lens.

Figure 2. The shape of the water-oil interface changes at different local temperatures due to the volumetric change exhibited by the temperature-sensitive hydrogel surrounding the liquid microlens.

Figure 3. The height of the liquid lens above cartridge in five temperature cycles (24-40 °C) to verify repeatability.

Figure 4. Series of images taken at different times as the local temperature is changing. The dashed blue circle shows the focused arrow at each time instance. The image taken at 83s is out of focus since the entire scanning distance goes beyond 200µm.

Figure 5. Surface tension plays a critical role on changing curvatures of water-oil interface by pinning the contact line to the bottom boundary of the punched hole.