

Tunable liquid microlens actuated by infrared light-responsive hydrogel

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We report on liquid-based tunable microlenses actuated by infrared (IR) light. Multiple micropost structures, made of IR light-responsive hydrogel with entrapped gold nanoparticles, are photopatterned around a lens aperture. The volumetric change in the hydrogel, controlled by IR light, regulates the curvature of a liquid-liquid interface forming the microlens at the aperture and its focal length. The focal length of the microlens can be tuned from -17.4 mm to $+8.0 \pm 0.4$ mm in seconds under IR irradiation. This microlens can be integrated into optical systems, for instance, for fiber endoscopy. © 2008 American Institute of Physics. [DOI: 10.1063/1.2996271]

Liquid-based tunable-focus microlenses are extensively used in a wide range of applications, such as cameras, projectors, microscope objectives, as well as machine vision.¹⁻³ The focus tunability can be achieved by mechanical pressure^{4,5} or displacement,³ electrochemistry,⁶ electrowetting,^{1,7} and environmentally adaptive hydrogel.^{8,9} However, because of the need for mechanical, electrical and environmental signals for tuning, there remains a challenge to integrate these microlenses with other optical components. In addition, in some biological and medical applications electrical controls or fluid circulation should be avoided,¹⁰ and other actuation mechanism for tuning microlenses is needed.

We recently reported liquid microlenses actuated by hydrogel responding to pH or temperature.^{8,9} In these devices, microstructures made of pH- or thermal-responsive hydrogel were used to regulate the curvature of a liquid-liquid interface to form tunable microlenses. Here, we present a liquid tunable microlens actuated by light-responsive hydrogel with entrapped gold nanoparticles. Benefitting from the heat converted from absorbed light by gold nanoparticles entrapped within the hydrogel network, the expansion and contraction of hydrogel, and the resultant tuning of microlenses, can be controlled by infrared (IR) light. Because both the patterning and the actuation of the hydrogel are done using light, this approach paves a way to intrinsically integrate such tunable microlenses with other optical components, such as optical fibers and switches.

Figure 1 shows the schematics and optical images of a tunable liquid microlens actuated by IR light-responsive hydrogel. The device is fabricated on a glass slide through liquid phase photopolymerization (LP³).¹¹ The sidewalls and bottom surfaces of the aperture plate are chemically treated hydrophilic, while the top surfaces are naturally hydrophobic, forming a hydrophobic-hydrophilic (H-H) boundary. Figure 1(a) shows different wettabilities of surfaces, hydrophilic for the bottom and sidewalls and hydrophobic for the top. A meniscus, serving as the microlens, is formed through a curved interface between water and oil, protruding upward at high pressure (*divergent*) and bulging downward at low

pressure (*convergent*). This water-oil meniscus is pinned at the H-H boundary at the top edge of the aperture. Oil prevents the evaporation of water and serves as lens material along with water since the refractive index of oil (1.48) is larger than that of water (1.33).

Multiple microposts made of IR light-responsive hydrogel are photopatterned in a water container through LP³ to actuate the microlens under IR light irradiation. IR light-responsive hydrogel consists of a thermoresponsive reversible *N*-isopropylacrylamide (NIPAAm) hydrogel and water-soluble gold nanoparticles with distinct and strong optical absorption of IR light, which has high heat efficiency.¹² With the IR light turned on, the gold nanoparticles absorb the IR light, generating heat to cause the hydrogel to contract and release water. With the IR light turned off, the heat dissipates

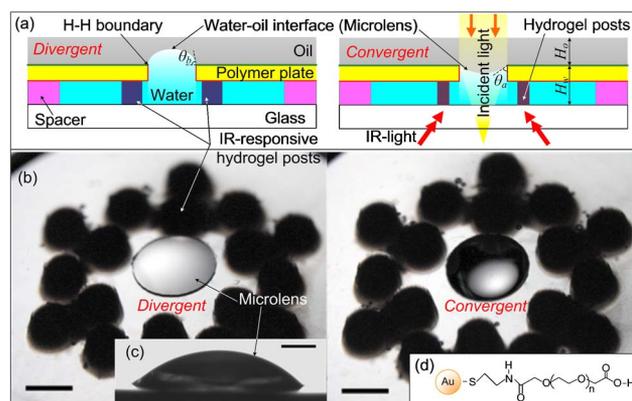


FIG. 1. (Color online) Schematic and optical images of an IR light-actuated tunable microlens. (a) Schematics of the microlens when it is divergent and convergent, respectively. A polymer plate with an aperture and a glass slide are used as the top and bottom plates of a water container, respectively. The sidewalls and bottom surfaces of the aperture are chemically treated hydrophilic, while the top surfaces are naturally hydrophobic. θ_a and θ_b are contact angles of DI water on respective surfaces. A meniscus, used as a microlens, is formed through a curved interface between water and oil and is pinned by the H-H boundary, protruding upward at high pressure (divergent) and bulging downward at low pressure (convergent). (b) Optical images of a microlens with 18 hydrogel microposts in divergent and convergent statuses, respectively, taken with a stereoscope from an oblique angle. The scale bar is 1 mm. (c) Side profile of water meniscus of the microlens in the divergent status at the starting point taken with a goniometer. The scale bar is 1 mm. (d) Chemical structure of the gold nanoparticles coated with thiolated PEG ligands.

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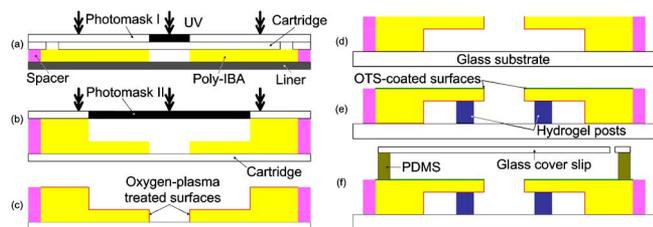


FIG. 2. (Color online) Fabrication process flow of a liquid tunable microlens actuated by IR light-responsive hydrogel.

to the surrounding fluid and the hydrogel expands back to its original volume and absorbs water. Since the volume change of the hydrogel itself is more than that of water into/out of the hydrogel,⁸ this resultant net volumetric change between hydrogel and water regulates the pressure difference across the water-oil interface. When IR light is on, the hydrogel contracts and releases water, and thus the pressure in the water container decreases. The curvature of the interface thus varies from divergent to convergent and the focal length of the microlens changes from negative to positive, as shown in Fig. 1.

The range of focal length is determined by two factors: the contact angles of de-ionized (DI) water on different solid surfaces θ_a and θ_b (Ref. 13) and the height of the water container H_w and oil container H_o , as shown in Fig. 1(a). To prevent the water from reaching the top cover of the oil container and the oil from touching the glass substrate at the bottom, two minimum heights, $H_w = [a/(\cos \theta_a)](1 - \sin \theta_a)$ and $H_o = [a/(\sin \theta_b)](1 - \cos \theta_b)$, respectively, are required to obtain the wide range of focal length, where a is the radius of aperture.

Two prepolymer solutions are used in the fabrication process: isobornyl acrylate¹¹ (IBA) and IR light-responsive hydrogel, namely thermal-responsive NIPAAm hydrogel^{8,11} with water-soluble gold nanoparticles.¹² The water-soluble gold nanoparticles coated with thiolated polyethylene glycol (PEG) ligands [Fig. 1(d)] are synthesized using Brust method^{14,15} and their concentration in the solution is measured to be 4.7 mg/ml. Benefitting from this coated polymer layer, the nanoparticles are water soluble and uniformly entrapped in the polymerized NIPAAm hydrogel network after polymerization. The absorption spectra of solutions show that gold nanoparticles in the solution and entrapped in hydrogel have high absorption of light in the near IR range.¹⁶

The device is fabricated through LP³ without the need for a clean room facility, as shown in Fig. 2. First, a polycarbonate cartridge cavity (HybriWells, Grace Bio-Labs, Bend, OR) is filled with IBA prepolymer solution. The thickness of the cavity is defined by a spacer and is 250 μm . The film photomask (Photomask I) is aligned on top of the cartridge to form a circular poly-IBA aperture in the cavity by using LP³ under UV radiance (intensity, $I_{UV} = 8.2 \text{ mW/cm}^2$; time, $t = 23 \text{ s}$), as shown in Fig. 2(a). The bottom liner plate is peeled off and the poly-IBA aperture plate is flipped over. Next, another film mask (Photomask II) is used as the top plate and a cavity 700 μm thick is formed. A microchannel is formed on top of the polymerized plate using the same exposure parameters ($t = 35 \text{ s}$), as shown in Fig. 2(b). Sidewalls and top surfaces of the poly-IBA plate are rendered with oxygen plasma¹³ from hydrophobic to hydrophilic. Then, the bottom cartridge plate is removed and the poly-IBA plate is

flipped over again and bonded onto a glass slide, forming the water container, as shown in Fig. 2(d). Multiple IR light-responsive hydrogel microposts are constructed in the water container by polymerizing IR light-responsive hydrogel prepolymer solution locally via a photomask (not shown here) under UV radiation ($I_{UV} = 12.5 \text{ mW/cm}^2$; $t = 19 \text{ s}$), as shown in Fig. 2(e). To achieve better hydrophobicity on the top surface of the aperture plate, an octadecyltrichlorosilane (OTS) solution diluted by hexadecane (0.2% v/v) is brushed onto it. Finally, a polydimethylsiloxane ring, whose surface is treated under corona discharge plasma (BD-20AC, Electro-Technic Products Inc., Chicago, IL) to improve adhesion,¹⁷ is bonded on top of the aperture plate and covered by a glass slide to form an oil container, as shown in Fig. 2(f).

The contact angles of DI water on the surfaces of natural, oxygen-plasma treated and OTS-coated poly-IBA are measured by a goniometer (OCA 15+, Dataphysics Instruments Inc., Germany) and are found to be 105° , 47° , and 116° , respectively. With oxygen-plasma treatment, the surface is rendered hydrophilic; with OTS coating, the surface is more hydrophobic than untreated. The required minimum heights of oil and water container can then be calculated to be $H_w = 0.40 \text{ mm}$ and $H_o = 1.16 \text{ mm}$, respectively, for $a = 0.9 \text{ mm}$, $\theta_a = 47^\circ$, and $\theta_b = 116^\circ$.

An initial meniscus is first formed by loading DI water into the water container through a pipet, its curvature depending on the amount of the loaded DI water. Then, silicone oil is filled into the oil container. More water would be required initially for a protruding water-oil interface and wider range of focal length; however, the transformation speed from divergent to convergent would also be decreased. A close-to-flat starting profile of the microlens has shorter transformation time.

Figure 3(a) shows the schematic of scanning image planes using the microlens. Two transparent films (Imagesetter, Inc., Madison, WI), printed with "W" and "UW" logos are 50 and 104 mm, respectively, below the glass substrate. A charge coupled device (CCD)-coupled stereoscope is placed above the microlens to monitor and record the images. An IR light lamp irradiates from the side at an oblique angle and the power intensity at the plate of IR responsive hydrogel posts is measured by a power meter (Field Max II, Coherent Inc., Santa Clara, CA) to be 1.42 W/cm^2 .

One scanning cycle includes a forward scanning with IR light on and a reverse scanning with IR light off. The focal length of the microlens when it is divergent is calculated from its profile taken by the goniometer, as shown in Fig. 1(c). It ranges from -17.4 mm to $-\infty$. As for the microlens when it is convergent, the positive focal length is measured by determining optically the minimum focused point of a collimated input light beam along the optical axis.¹⁸ To obtain the dynamic change in the positive focal length as a function of time, the focal length is first measured optically at different temperatures. Then the temperature change in the hydrogel caused by the same IR irradiation for actuation is recorded by a thermal couple (5SC-TT-K-40-36, Omega Engineering, Inc., Stamford, Connecticut). The dynamic change in the positive focal length of the microlens in one scanning cycle is then obtained, as plotted in Fig. 3(b).

Figure 3(c) shows the frame sequence of the focused images obtained by tuning the microlens within one scanning cycle shown in Fig. 1. Initially, the image is out of focus and

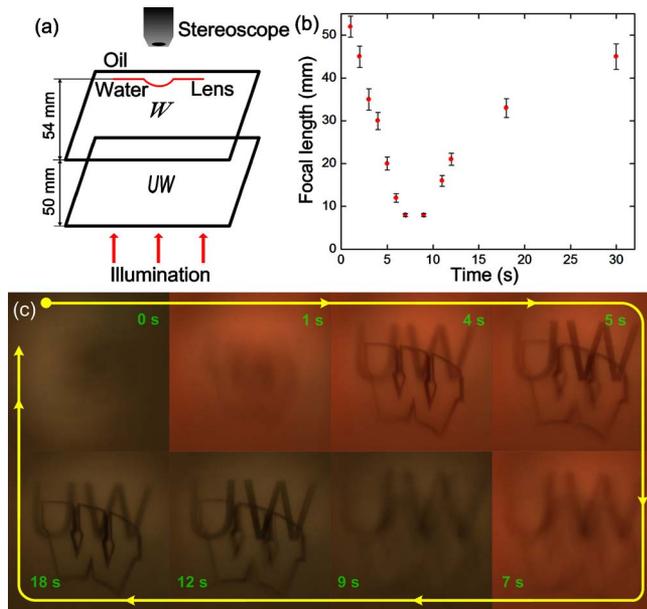


FIG. 3. (Color online) (a) Schematic of scanning image planes using a liquid tunable microlens. Two logos, W and UW, are printed on transparency films and are 54 and 104 mm, respectively, below the glass substrate with the microlens. A CCD-coupled stereoscope is placed above the microlens to monitor and record the images. (b) Dynamic change in the positive focal length of the microlens (convergent) in one scanning cycle as a function of time. (c) Frame sequence of the focused images in one scanning cycle obtained by tuning the microlens shown in Fig. 1.

blurry. From the time instant of 1 s, IR light is turned on and the microlens changes from divergent to convergent and begins to scan different planes. At 4 s, the image plate with the W logo is focused onto. The focal length of the microlens decreases and the resultant image is enlarged. At 5 s, the image plate with the UW logo is focused onto. Next, the positive focal length of the microlens reaches the minimum at 7 s and is 8.0 ± 0.4 mm. Then IR light is turned off and the microlens begins to scan reversely. At 12 and 18 s, it scans the two image plates again, respectively.

In summary, we have demonstrated a liquid-based microlens that can be tuned in focal length within seconds by IR light-responsive hydrogel microactuators. The microlenses can be extended to microlens arrays for larger field of view. Furthermore, the hydrogel microstructures can be pat-

terned and actuated directly by, thus self-aligned to, optical fibers; hence these microlenses can be inherently integrated with fiber optics based systems such as fiber endoscopes, which have significant biomedical and clinical applications. These microlenses may also be used in other optical imaging applications. To enhance the mechanical robustness of the microlenses, more robust H-H boundaries will be investigated. Packaging of the microlenses will also be studied.

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