# Rapid Liquid Variable-Focus Lens with 2-ms Response

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## 1 Introduction

Variable-focus lens technology has rapidly progressed recently. In particular, liquid variable-focus lenses based on electrowetting [1] gathered attention. This type of lens uses an interface between two immiscible liquids as a refractive surface. In particular, a variable focus lens studied by B. Berge et al. [2] or a variable-focus liquid lens by S. Kuper et al. [3] are famous for their practical image forming performance, low power consumption, and simple structure. All these characteristics were suited for miniaturization. Thus, these lenses are supposed to be a key component for very compact focusing or zooming lenses.

Another potential advantage of the variable-focus lens is high-speed response. Such lenses can change their focal length in very short time, since the slight change of the surface shape results in significant focal position shift. And high-speed response is important especially for optical instruments that need high-speed axial scanning such as laser scanning confocal microscopes. It's also important to realize high-speed focusing or zooming for visual inspections and security applications. The liquid variable-focus lenses based on electrowetting are, however, not enough fast for such applications. This is because this type of driving mechanism changes only the boundary condition of the interface. The interface shape change occurs only because of inherent surface tension. There are no additional forces to help the interface to change their shape.

The authors concentrated on speeding up focusing speed and proposed a variable-focus lens with 1-kHz bandwidth [4]. This lens transforms its lens surface rapidly using the liquid pressure generated by a piezo stack actuator. This mechanism also includes a built-in motion amplifier with high bandwidth to compensate for the short working range of the piezo stack actuator. The lens, however, included large aberrations because the refractive surface profile was not spheric.

To solve this problem, we propose a new structure of a variable-focus lens using the interface between liquids. The goal of this lens is to achieve both high-speed response less than 1 ms and an acceptable amount of aberrations for image forming optical systems. The initial prototype and its response time depending on kinematic viscosity of infused liquid will be reported in this paper.

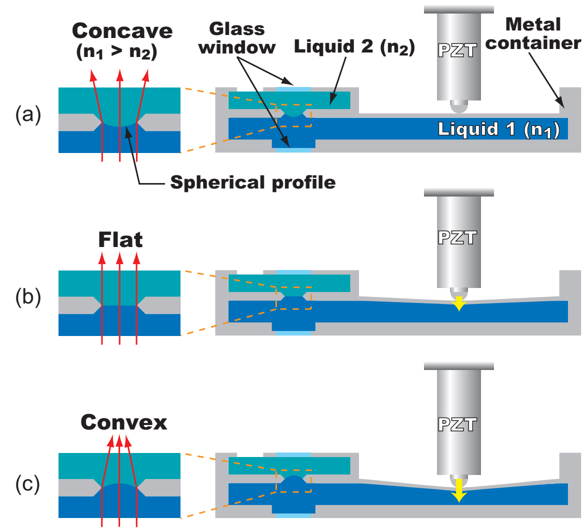


Fig. 1: Schematic cross-sectional figure of the ideal structure of the proposed lens : (a) convex, (b) flat, and (c) concave lens.

## 2 Proposed lens structure

The proposed lens focuses rapidly by changing the lens surface shape. Fig. 1 shows its structure and focusing mechanism. The interface between two different liquids works as a lens surface. The interface shape is controlled by a piezo stack actuator.

The liquid volume infused in the lower chamber was controlled to let the peripheral of the interface be at the edge of the circular hole. According to the law of Young-Dupré [5], the contact angle of the interface to a flat substrate is determined only by the surface tensions of liquid-liquid and liquid-solid interfaces. Here, we assume the contact angle is 90 degrees. The interface profile must be convex downward like Fig. 1 (a) when the peripheral of the interface is lower than the edge. If the piezo actuator presses the diaphragm and makes the interface move upward, the interface will change its curvature but keeping its peripheral on the edge as shown in Fig. 1 (b) and (c) until the contact angle to the upper surface reaches 90 degrees. Once the contact angle exceeds 90 degrees, the peripheral leaves the edge and moves into the upper surface.

Since the working range of the actuator is too

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short (∼10 $\mu$m) to modify the lens sufficiently, a built-in motion amplifier [4] was used. The area of the deformable plate pressed by the piezo stack actuator ($S$) is much larger than that of the lens surface ($s$) so that the change of the lens surface shape is approximately $S/s$ times that of the deformable plate. Practically, the ratio $S/s$ is designed to be 30∼100.

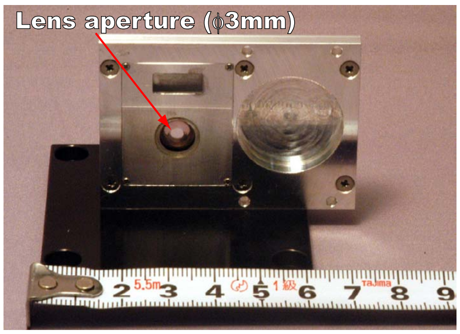


Fig. 2: A photograph of the prototype. The left hole is a lens aperture. A bottom plate of the right circular hollow is pressed by the piezo actuator.

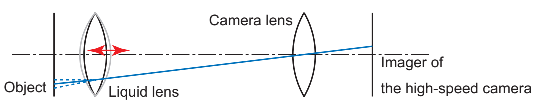


Fig. 3: Schematic figure of the setup to measure step response.

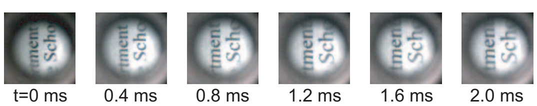


Fig. 4: Measured image sequence of the step response with kinematic viscousity 5000 cSt.

## 3 Experiments

A prototype shown in Fig. 2 was fabricated to measure the response time of the proposed lens structure. The lens body material was aluminum. Lens diameter of the prototype was 3.0 mm. The diameter of the diaphragm pressed by the piezo actuator was 24 mm. The prototype was actuated by a piezo stack actuator (P-841.10, Physik Instrumente) with a 15-$\mu$m working range and an 18-kHz natural frequency. We adopted poly-di-methyl-siloxane (PDMS) (refractive index $n_1 = 1.40$) as the liquid 1 shown in Fig. 1, and deionized water ($n_2 = 1.33$) as the liquid 2.

Step responses of the interface shape change were measured with three different kinematic viscosities ($\nu$) of infused PDMS. The response was observed by capturing an object image through the prototype using a high-speed camera of 5000 fps as shown in Fig.3. The object was letters printed on

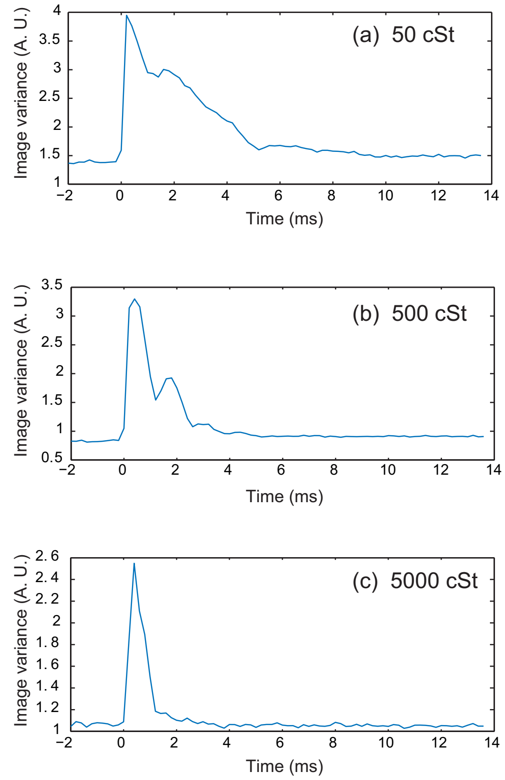


Fig. 5: Step responses of the prototype with three kinds of kinematic viscousity of PDMS ($\nu$): (a) 50 cSt, (b) 500 cSt, and (c) 5000 cSt. The vertical axis is the amount of variance between two successive images, which is summation of the absolute intensity difference of each pixel.

a paper. Fig.4 shows the captured image sequence when $\nu$ = 5000 cSt. Fig.5 shows the measured step responses. The fastest response time was 2 ms when $\nu$ = 5000 cSt.

In this paper, we proposed a new structure of variable-focus lens aimed sub-millisecond response. Two milliseconds response was confirmed for the initial prototype by the step response measurements.

## References

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