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Board-mounted ultrasonic variable-focus liquid crystal lens

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1. Introduction

Camera modules are commonly installed in electric devices such as cellular phones, enabling to control the focal position through a compound lens system that uses several lenses. Consequently, the module tends to be bulky and the robustness is decreased since the system requires mechanical actuators to move the lenses along the optical axis. Variable-focus lenses without mechanical actuators are attractive in the industrial fields. Variable-focus lenses using liquid crystal (LC) materials were reported, in which transparent electrodes using rare metal indium are required to apply the electric field across the LC layer[1]. Our group proposed a variable-focus lens where the molecular orientation of nematic LCs was changed by ultrasound vibration[2, 3]. In this report, board-mounted type ultrasonic LC lens was examined for future application of the lens in the industrial market.

2. Configuration and methods

An ultrasound LC variable-focus lens was fabricated (**Fig. 1**). Orientational polyimide films (vertical alignment type, SE-5811, Nissan Chemical, Japan) were formed on the inner surfaces of two glass discs without rubbing. The two glass discs (diameter: 19 and 22 mm; thickness: 500 µm) were fixed coaxially using a polyethylene terephthalate film spacer so that a 200-µm-thick LC layer with vertical alignment could be formed between the two glass discs because the LC-layer thickness of 200 µm was suitable for the variable focusing function in our previous work[3]. Nematic LC, 4-Cyano-4'-pentylbiphenyl (C1550, Tokyo Chemical Industry-TCI, Japan), was injected into the small gap, and the surrounding parts were sealed completely using epoxy. An annular piezoelectric lead zirconate titanate (PZT) transducer (inner diameter: 10 mm; outer diameter: 16 mm; thickness: 1 mm) was attached to the 19-mm-diameter glass disc using epoxy. The LC lens was attached to an aluminum plate (A5052; thickness: 10 mm) with a 10-mm-diameter hole (same as the PZT transducer's inner diameter) with epoxy.

By applying a continuous sinusoidal electric signal to the PZT transducer at its resonant frequency, the vibration mode in the radial direction is generated via the inverse piezoelectric effect, generating concentric flexural standing-wave vibrations on the two glass discs in the thickness direction. The vibrational velocity distribution of the lens was measured using a laser Doppler vibrometer (LDV, VIO-130, Polytec, Germany). A 16×16 mm^2 measurement area around the center of the lens was scanned using the LDV. **Fig. 2(a)** shows the observational system. The LC lens' focal position was measured under the single-Nicol condition with a polarizer using an optical microscope (VW-9000 and VW-300C, Keyence, Japan) with 200× magnification. A test target (1951 USAF) was observed through the LC lens and moved along the optical axis to determine the focal position. The focusing characteristics were investigated by varying the input current to the LC lens. The distance between the LC lens and the microscope objective lens was 1 mm, and the spatial gradient in the brightness of the microscopic images was calculated using ImageJ software[4] to determine the focal positions; we defined the position where the spatial gradient of the image brightness was maximized as the focal position.

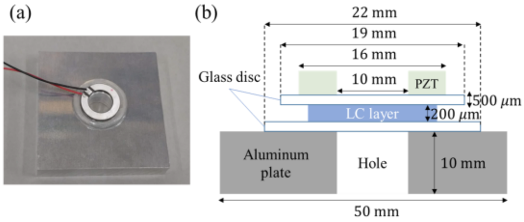

Fig. 1 (a) Photograph and (b)cross-sectional view of the ultrasound liquid crystal lens.

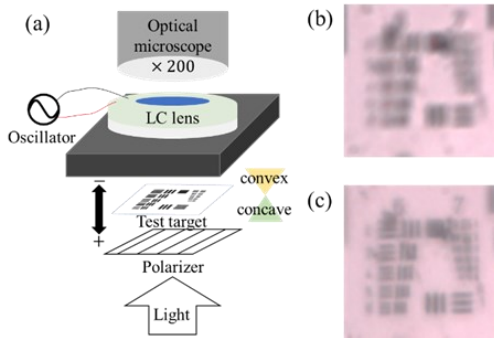

Fig. 2 (a) Observational system and photographs captured through the LC lens (b) without and (c) with ultrasound excitation.

3. Results and discussion

There were several resonance frequencies on the LC lens from 20 to 200 kHz, and the resonance flexural vibration modes with concentric vibrational nodal circles appeared at several resonance frequencies. **Figs. 2(b)** and **(c)** are the typical microscopic photographs captured through the LC lens without and with ultrasound excitation at 44 kHz, respectively, indicating that the focal position was changed by ultrasound excitation. **Fig. 3** shows the vibrational distribution on the lens normalized by the maximum value when the lens was excited with 5 V_{pp} at 44 kHz. The diameter of the smallest nodal circle was 9.6 mm, which mostly corresponds to the radius of the hole on the aluminum substrate (10 mm). This result means that the attached part of the LC lens to the substrates, the fringe of the lens, acted as a fixed condition when the radius of a hole on the substrate (10 mm) was much larger than the lens thickness (1.2 mm), resulting in the flexural vibration mode efficiently. The maximum vibrational displacement amplitude at 5 V_{pp} was 19 nm.

Fig. 4 shows the relationship between the input current and the change in the focal position at 44 kHz. The vertical axis indicates the moving distance from the default focal point without ultrasound excitation, and the negative values means that the focal position approached the lens surface and the lens then acted as a convex lens. The focal position approached the lens as the input current was increased from 25 to 31 mA_{pp}, indicating that the focal position could be controlled by the input current and the lens acted as a variable-focus convex lens in this range. In the case from 31 to 35 mA_{pp}, the focal position changed slightly between −400 and −430 μm and the transparency of the LC layer decreased due to dynamic scattering of LC molecules, which was observed in our conventional LC lenses when applying a larger current than the threshold[5]. On one hand, regarding this board-mounted lens, the aluminum plate made it easier to radiate the heat from the PZT transducer and prevent LC's phase transformation. As a result, it seems this lens did not show the steep scattering and expanded the variable-focus range.

4. Conclusion

In this report, we developed the board-mounted ultrasound LC lens. By fixing the lens to a substrate with a hole, the concentric resonance flexural vibration mode was excited efficiently on the lens. In addition, the mounting of the lens on the aluminum substrate was helpful to heat dissipation, preventing the phase transition of LC molecules and improving the variable-focus range.

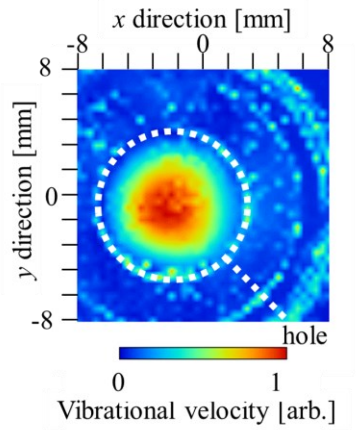

Fig. 3 Vibrational distribution of the LC lens at 44 kHz.

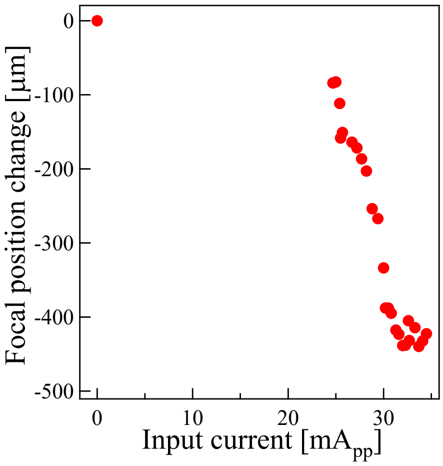

Fig. 4 Relationship between the input current and the focal length.

Acknowledgment

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