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Effects of the input voltage waveform on ultrasonic liquid crystal optical lenses

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1. Introduction

The advancement of optical imaging systems requires the development of sophisticated control circuits for image processing and stabilization, resulting in an increase in the size, cost, and power consumption of the entire system[1)]. Variable focus lenses with no mechanical actuators are attractive in the industrial field, and their control circuit systems must be designed with simplicity. Variable focus lenses using liquid crystal (LC) materials were invented by Sato, wherein transparent electrodes comprising rare metal indium are necessary to apply the electric field across the LC layer[2)]. Our group has proposed a variable focal lens that can change the molecular orientation of nematic LCs using ultrasonic vibrations[3)]. In this report, we investigated the effects of the input voltage waveform on the optical and electrical characteristics of the ultrasonic LC optical lens.

2. Configuration and methods

The ultrasonic LC optical lens was fabricated **(Fig. 1)**. Orientational polyimide films (vertical alignment type, SE-5611, Nissan Chemical, Japan) were formed on the inner surfaces of two glass discs without rubbing. The two glass discs (diameter: 15 and 30 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. 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: 20 mm; outer diameter: 30 mm; thickness: 1 mm) was attached to the 30-mm-diameter glass disc using epoxy.

In duty cycle driving, a square wave with a center frequency corresponding to the resonant frequency of the lens was applied to the PZT transducer. Note that the DC component of the voltage was set to zero. As the duty cycle was varied, the vibrational velocity at the center of the lens was measured using a laser Doppler vibrometer (LDV, VIO-130, Polytec, Germany), and the input current and voltage were measured to calculate power consumption of the lens. A birefringence profiler was used to visualize the two-dimensional effective birefringence distribution of the LC lens[4)]. The phase

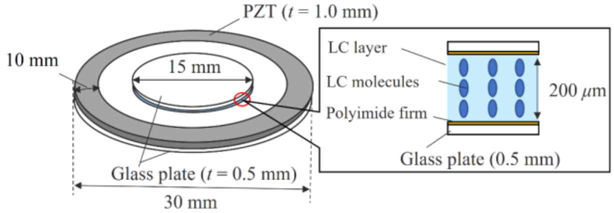

Fig. 1 Configuration and cross-sectional view of the ultrasonic LC optical lens.

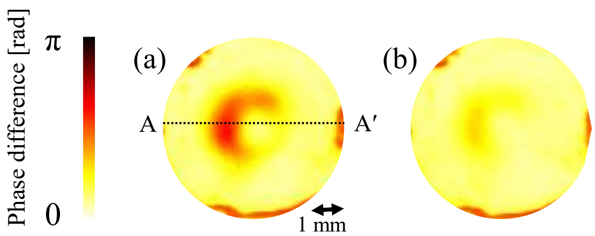

Fig. 2 Trans. light phase distributions for square-wave voltages with the duty cycles of (a) 50% and (b) 70%, 10 V_{pp} at 23 kHz.

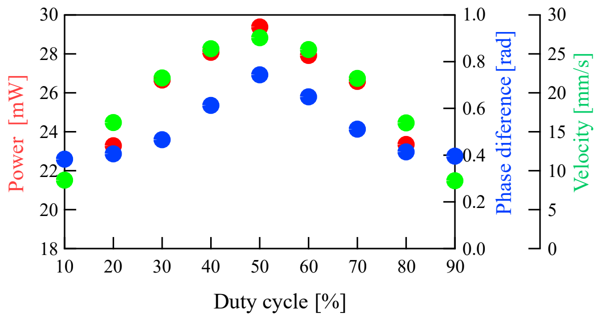

Fig. 3 Relationships between duty cycle, power consumption, optical phase difference, and vibrational velocity.

difference of the transmitted light $\Delta\phi$ can be converted to an optical path difference Δl (= $\Delta\phi\lambda/2\pi$) where λ is the wavelength of the light (λ = 633 nm). The focal length of the LC lens was estimated from the wavefront of the transmitted light, assuming that it could be fitted to a circular function using the Nelder-Mead simplex method on the experimental data points where the phase difference of the transmitted light exceeded 36.8% (1/e) of the maximum value[5)]. Since the effective diameter of the lens (approximately 5 mm) is much smaller than the focal length (> 5 m), the distance between each data point and the center of the lens was assumed to be zero, and the distance from the center of the lens to the center of the circle was defined as the focal length.

In burst sine driving, a burst sine wave with varying T_m and T_s was applied to the PZT transducer

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while maintaining the burst cycle (defined as the sum of T_m and T_s), where T_m is the number of cycles with the signal and T_s is the number of cycles with no signal. The electrical and optical characteristics of the LC lens, including power consumption and focal length, were evaluated under several driving conditions.

3. Results and discussion

Figs. 2(a) and (b) show the phase difference distributions of the transmitted light of the lens excited with duty cycles of 50% and 70%, respectively. The same patterns emerged with varying duty cycles, indicating that the LC molecular orientation is largely dependent on the central frequency component of the driving signal[6]. **Fig. 3** shows the relationships between the power consumption, the vibrational velocity, and the optical phase difference (averaged in the radial direction along line A-A' in Fig. 2(a)) when controlling the duty cycle from 10% to 90%. The power consumption, vibrational velocity, and optical phase difference reached their highest values at a duty cycle of 50%, indicating that these three factors can be controlled by the duty cycle. **Fig. 4** shows the relationship between the power consumption and the focal length estimated from the optical phase difference distribution when the duty cycle is varied from 30% to 50%. As the power consumption (duty cycle) increases, the focal length decreases. This result means that, the focal length can be adjusted by changing the duty cycle without employing a converter. Duty-cycle control has the potential to facilitate the miniaturization and cost reduction of optical devices.

Fig. 5 shows the optical phase difference distributions in the cases with burst sine driving with different cycles. The optical phase difference increased with the number of cycles with the signal T_m. **Fig. 6** shows the relationships between the power consumption and the focal length in the cases with the burst and continuous sine-wave drives. In both cases, the focal length decreased as the power consumption increased. Noted that the burst sine-wave drives under 1.9 W exhibited a shorter focal length than the continuous-wave drive, despite the same power consumption, suggesting that the burst sine-wave driving may potentially reduce the power consumption of ultrasonic LC optical lenses. These findings can be attributed to the fact that the response time of the LC lens is considerably longer than the total cycle of T_s.

4. Conclusion

In this report, the effects of the applied voltage waveform on ultrasonic LC optical lenses were examined. It was found that focus control was achievable by changing the duty cycle of the input

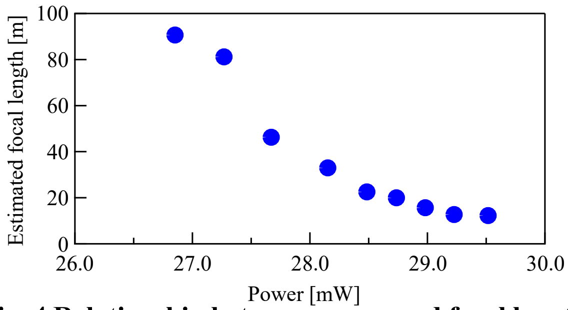

Fig. 4 Relationship between power and focal length.

signal, indicating focus control can be achieved without a converter and duty-cycle control has the potential for the miniaturization and cost reduction

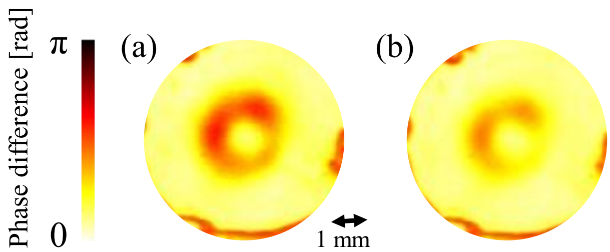

Fig. 5 Trans. light phase difference distributions for the burst sine-wave drives with (a) T_m of 480 and T_S of 20 and (b) T_m of 100 and T_S of 400 and 10 V_{pp} at 23 kHz.

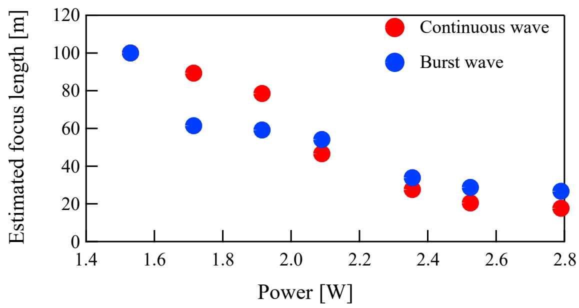

Fig. 6 Relationships power consumption and focus length for continuous-wave and burst-wave drives.

of optical devices.

Acknowledgment

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