

Suppression Effect of Randomly-Disturbed LC Alignment Fluctuation on Speckle Noise for Electronic Holography Imaging

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SUMMARY In this paper, we proposed the phase disturbing device using randomly-fluctuated liquid crystal (LC) alignment to reduce the speckle noise generated in holographic displays. Some parameters corresponding to the alignment fluctuation of thick LC layer were quantitatively evaluated, and we clarified the effect of the LC alignment fluctuation with the parameters on speckle noise reduction.

key words: *speckle noise, speckle contrast, LC alignment fluctuation, random phase disturbing*

1. Introduction

Electronic holography has attracted attention as one of the 3D displays. The reasons are based on the following features. One of the reasons is to provide a natural stereoscopic display that fulfills all the physiological factors of stereopsis for human beings. In addition, playing movies is possible by switching the reconstruction image electronically in electronic holography [1]. Coherent laser light is commonly used for projecting electronic holography. The laser light causes speckle noise on the reconstruction image due to the phenomenon of light interference [2]. The phase difference is caused when there is a difference in optical path length between laser beams. This phase difference causes the unintended phenomenon of light interference. As a result, speckle noise is generated. This phenomenon degrades the quality of the reconstructed image and causes visual fatigue for human beings [3]. Therefore, the ideal method to cancel speckle noise has been required for high-quality electronic holography.

A lot of studies for speckle noise reduction have been reported to overcome these issues. The most common method is to change the speckle pattern within the response time of the human eye for averaging the actual speckle [4]. As well known, this method achieves effective noise reduction by preparing many speckle patterns in a short time [5]. There are related studies on speckle noise reduction as follows: randomizing the propagation angle and distance of laser light using a movable diffuser [6], [7] and dividing the phase to time into binary using ferroelectric LC [8], [9]. The former method has the disadvantage of low light utilization

efficiency. The latter method is less effective in reducing speckle noise. Existing methods cannot solve these problems simultaneously. Therefore, a method that achieves both high light utilization efficiency and high speckle noise reduction is needed.

Then, we proposed the speckle noise reduction method using the optical phase disturbing device based on nematic LC alignment fluctuation. Unlike diffusers, this device is designed to randomly change the phase of light without diffusing it. Both light utilization efficiency and noise reduction effects can be expected because random phase modulation of laser light is suppressed by controlling the LC alignment. In this method, the LC device is not driven by voltage as in conventional methods. It is unique because it uses only phase disturbance obtained by LC alignment fluctuations.

In this paper, we investigated the changes of phase distribution that reduce speckle noise by optical simulation. Besides, we evaluated the quantitative evaluation of spontaneous and random LC alignment fluctuations based on the results of the simulation.

2. Proposal of Suppression Method for Speckle Noise

2.1 LC Optical Phase Disturbing Device

In this study, we proposed the speckle noise reduction method using the LC optical phase disturbing device. Here, we focused on two characteristics of the LC materials. One is the anisotropic refractive index of LC molecules. The refractive index received by the incident light is changed with the angle between the polarization direction of the incident light to LC director. Another is alignment fluctuation among LC molecules which is induced by thermal vibration. Therefore, when light is incident on the LC device with large alignment fluctuation, the phase distribution of the transmitted light changes with time variation of the long axis direction. Figure 1 shows how the speckle noise is reduced by observing the Spatial Light Modulator (SLM) through the phase disturbing device. As shown in the lower part of Fig. 1, random LC alignment fluctuation occurs inside the phase disturbing device due to thermal motion. This method changes the phase distribution of transmitted light through the LC layer by inducing temporal and spatial random alignment changes of the LC. This effect allows a large number of speckle patterns generated by the light interference phenomenon to change randomly, thereby canceling

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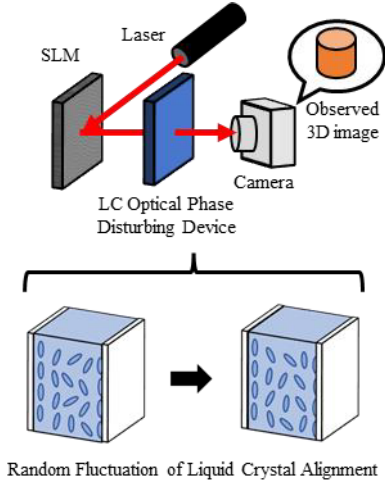


Fig. 1 Proposal of electronic holography system using LC optical phase disturbing device.

speckle noise. This method does not require driving the LC by applying voltage because it uses LC alignment fluctuation for speckle noise reduction.

In the proposed method, a large number of speckle patterns are produced within the response time of the human eye without strong light scattering. High noise reduction is expected due to the large number of speckle patterns available for noise reduction. Also, light loss can be minimized because strong light scattering does not occur. For these reasons, the phase disturbing devices have the potential to provide both light utilization efficiency and noise reduction effects. However, the effect of phase disturbance caused by LC and the optimal LC alignment fluctuation for noise reduction is not clear.

2.2 Investigation of Operation Principle for the Proposed Method

We simulated light propagation to investigate the effectiveness of the proposed method. Light propagation is calculated using the angular spectral method [10]. In the angle spectrum method, diffracted light is decomposed into plane waves with Fourier transform. Light propagation is calculated for each plane wave. The Wave Field Library, an open source library for wave optics calculations, was used to calculate light propagation with the angular spectral method. Exact calculations for anisotropic media and polarized beams need to consider changes in polarization. In this study, however, the angular spectral method is used to investigate the effect of optical phase perturbations on speckle noise reduction.

To evaluate the speckle noise, we used the speckle contrast C . The speckle contrast C is expressed as the ratio of the standard deviation of the light intensity σ to the mean value of the light intensity $\langle I \rangle$. The $\langle I \rangle$ is the spatial average of light intensity in the plane. The σ is the standard deviation of the light intensity in the plane, calculated from the spatial variance of the light intensity in the plane.

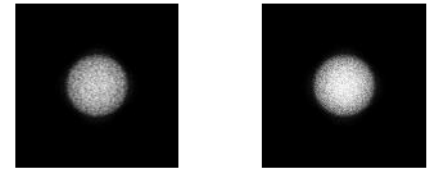
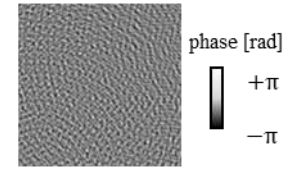
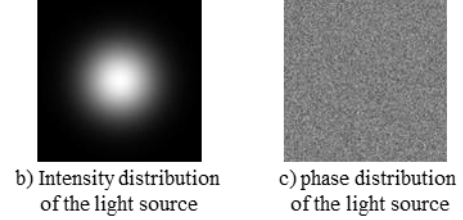
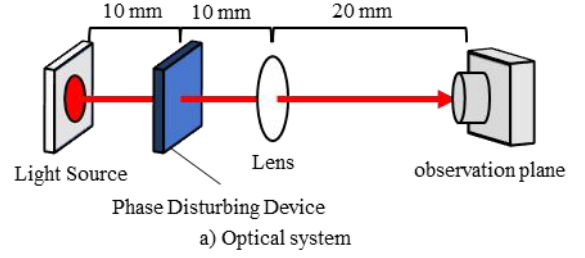


Fig. 2 Optical simulation for verification of the principle.

$$C = \frac{\sigma}{\langle I \rangle} \quad (1)$$

When the reconstructed image is smooth without noise, C is small. Equation (2) represents the noise reduction rate of C . C_0 is the speckle contrast before the reduction.

$$\alpha = \frac{C_0 - C}{C_0} \quad (2)$$

Figure 2(a) shows the model of the optical system which is set up in the simulation. This optical system consists of a light source, a phase disturbing device, a lens, and an observation plane. The light source, the phase disturbing device, and the lens are placed 10 mm apart. The light source is a Gaussian beam with a diameter of 4 mm and a wavelength of 632 nm, which is similar to a laser beam. The distance between the lens and the observation plane is 20 mm. The lens is used to image the light spot generated by the light source onto the observation plane. The lens is a convex lens with a diameter of 4 mm and a focal length of 10 mm. Since the light source was given a random phase distribution, speckle noise was generated. The phase of the light emitted from the light source was modulated 20 times by the phase disturbing device, and the 20 speckle patterns were generated. Next, the light intensities of each pixel in

the 20 obtained speckle patterns were added and averaged. This operation allows us to simulate the averaging of the speckle noise within the exposure time of the camera. Figure 2 (b) shows the light intensity distribution of the light source. Figure 2 (c) shows the random phase distribution of the light source. Figure 2 (d) shows the time-varying phase distribution given to the phase disturbing device. When light propagating from the light source passed through the phase disturbing device, the phase delay was calculated for each pixel of the phase distribution of the phase disturbing device. Here, the thickness of the phase disturbing device is set to zero. This allowed us to calculate the total amount of phase modulation that is obtained by light passing through the device. In the time-varying phase distribution, sin waves radiated from 20 points in the plane shown in Fig. 2 (d). The spatial frequency of each sin wave was chosen randomly from the range of $0.02 \sim 0.05 \mu\text{m}^{-1}$ and the temporal frequency was chosen from the range of $10 \sim 50$ frames per cycle. The sum of the sin waves at each pixel is the amount of phase modulation in the transmitted light at the pixel. This phase distribution of each sin wave was set to consider the randomness in the elastic vibration of the LC. However, it does not fully reproduce the phase modulation due to elastic vibration of the LC. In this simulation, we verified whether high speckle noise reduction can be expected with only random phase modulation of light. By changing the phase distribution with time, the phase of the transmitted light also modulated with time. The speckle noise was evaluated by calculating the speckle contrast before and after time averaging and calculating the reduction ratio. The speckle noise before averaging, shown in Fig. 2 (e), was $C = 0.56$. In contrast, the noise after averaging, shown in Fig. 2 (f), was $C = 0.24$. As a result, the noise reduction ratio was $\alpha = 0.57$. This value is higher than the noise reduction ratio $\alpha = 0.29$ obtained using ferroelectric LC [8]. Figure 3 shows the dependence of speckle contrast on the number of speckle patterns. Each speckle pattern was formed using the same settings of the optical system. In this simulation, only the phase distribution of the phase disturbing device is time-varying. As a result, the more speckle patterns there were, the more speckle contrast decreased. It also shows that the more speckle patterns there are, the smaller the decrease in speckle contrast.

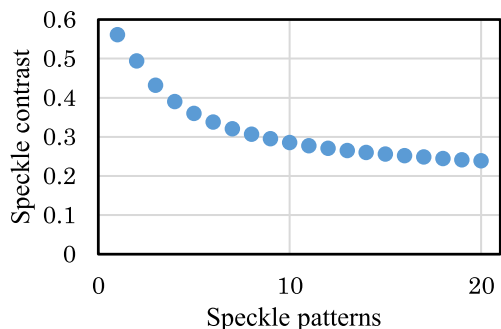


Fig. 3 Dependence of speckle contrast on the number of speckle patterns.

These simulation results indicate that changes in the phase of transmitted light are effective in reducing speckle noise.

3. Fabrication of LC Cells for Observation of LC Alignment Fluctuation

In this paper, we use the random LC alignment fluctuation to randomly change the phase distribution. The principle of LC alignment fluctuation is explained by continuum elastic theory and thermal fluctuations. Thermal vibrations among LC molecules are transmitted to the surroundings and overlap complexly. As a result, the elastic vibration of the director becomes more complex, resulting in random alignment fluctuation.

The behavior of the LC domain is discussed in terms of the continuum elastic theory and thermal fluctuations [11]. Therefore, the LC alignment fluctuation can be considered as vibration with three parameters: spatial frequency, temporal frequency, and amplitude of alignment vibration, similar to elastic vibration. Obtaining these parameters leads to quantitative clarification of LC alignment fluctuation. To evaluate these parameters, we fabricated four kinds of LC cells.

To clarify the suitable nematic LC alignment mode exhibiting fluctuation, we investigated the fabrication conditions of the LC cells. We investigated the effect of the alignment mode in the LC cells on the alignment fluctuation. Here, we fabricated four kinds of typical LC cells: parallel alignment, vertical alignment, twisted nematic alignment, and hybrid alignment. The LC alignment mode was controlled by coated parallel alignment films (JSR, AL-1254) and the vertical alignment films (Nissan Chemical, SE-4811) on the ultrasonically-cleaned glass substrate. The LC material (JNC, TD-1021XX) with large refractive index anisotropy Δn was used; $\Delta n = 0.27$ at wavelength $\lambda = 589 \text{ nm}$. The thickness of the LC layer was standardized at $50 \mu\text{m}$.

Figure 4 shows Crossed-Nicol polarizers microscope images of the LC cells. Non-uniformity brightness on the images means that the angle of the director is partially shifted due to LC alignment fluctuation. Comparing with four images, the largest alignment fluctuation was observed in the hybrid alignment LC cell (see Fig. 4(c)). Figure 5 shows the transmittance distributions in parallel alignment, hybrid alignment, and twisted nematic alignment in Fig. 4. The green line shows the background noise of the camera. Intensity is normalized to the maximum value of hybrid alignment. By comparing the graphs, we can understand that the intensity changes more significantly in the hybrid alignment than in the other alignments. In addition, the intensity changed at a lower frequency in the hybrid alignment than in the background noise. The vertical alignment was omitted because it produced only the same level of change as the background noise. This graph also shows that the hybrid alignment LC cell has a large alignment variation. This can be explained that the hybrid alignment has a larger intermolecular distance and weaker intermolecular force in

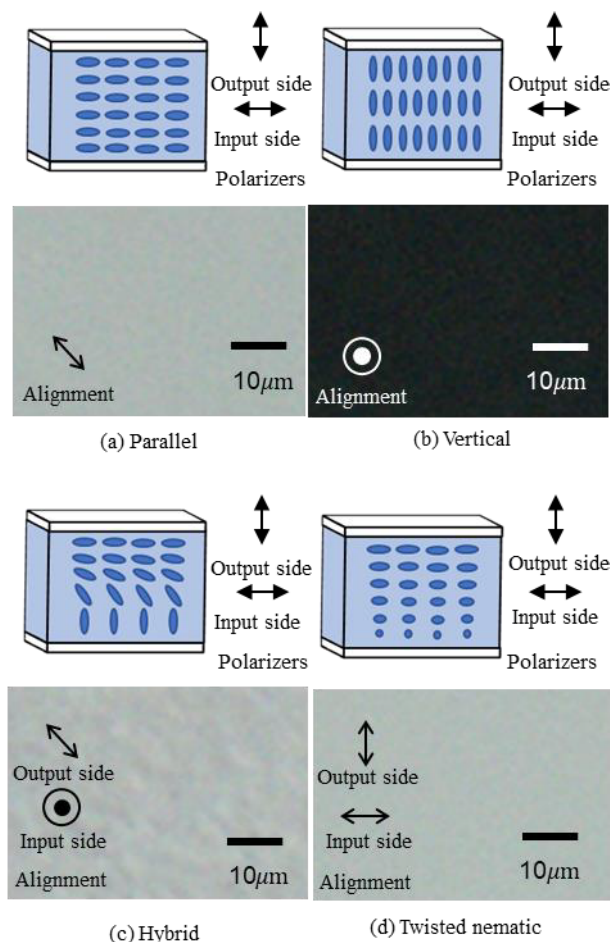


Fig. 4 Crossed-Nicol polarizing microscope images of fabricated LC cells and schematic illustration of LC alignment.

LC than the other alignment modes.

The alignment fluctuation effect seems to be higher when the LC layer is thicker. This is due to the fact that LC alignment is stabilized by elastic forces from the substrate interfaces. As the distance between the LC molecules and the substrate interfaces increases, the alignment becomes unstable and the LC alignment fluctuation increases. We fabricated hybrid alignment cells with thicknesses of 5, 10, 25, 50, 75, and 100 μm , and observed them with a microscope to evaluate the relationship between the alignment fluctuation and the LC layer. Figure 6 shows representative images of the 5, 50, and 100 μm cells. Figure 7 shows the transmittance distribution of the cell in Fig. 6. From these results, it is visually and numerically confirmed that the alignment fluctuation is larger when the LC layer is thicker.

However, too thick LC layer is unsuitable for electronic holography projection because of light scattering. In LC devices, the degree of light scattering is quantitatively expressed by haze. Haze is a parameter that indicates the percentage of diffuse light out of the total transmitted light. Haze H is expressed by Eq. (3) using diffuse light transmittance T_d and total light transmittance T_{all} .

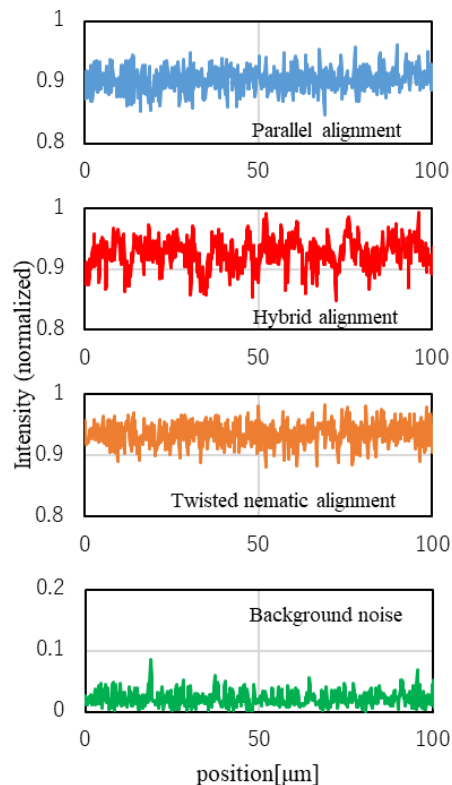


Fig. 5 Light intensity distribution in each alignment LC cell.

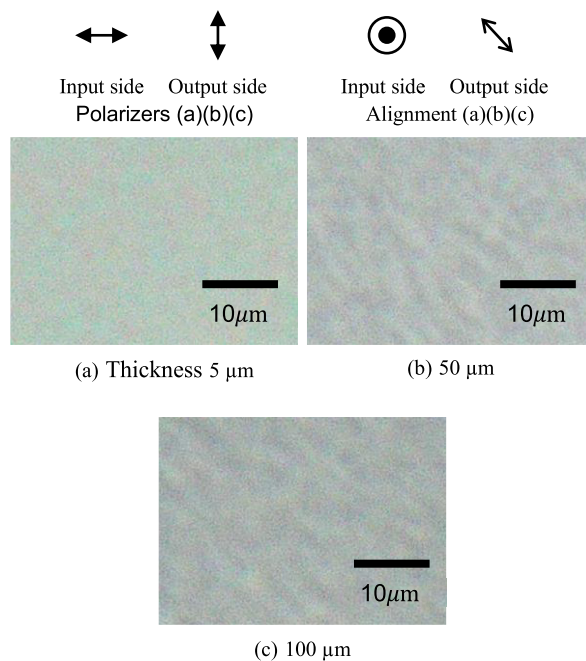


Fig. 6 Crossed-Nicol polarization microscope images of hybrid alignment LC cells with various thicknesses.

$$H [\%] = \frac{T_d}{T_{all}} \times 100 \quad (3)$$

Here, light refracted more than 2.5 degree from the straight light was defined as diffuse light. Figure 8 shows the haze

measurement method. A haze meter HM-150 (Murakami Color Technology Laboratory) was used to measure haze. Dependence of light scattering on thickness of the LC cells was quantitatively evaluated by measuring the haze of each 5 ~ 100 μm hybrid alignment cell. As a result, a relationship between thickness and scattering was obtained as shown in Table 1. Table 1 shows that the thicker the LC layer, the more light is scattered.

Considering these characteristics, we decided on a thickness of 50 μm for the LC layer with film spacers.

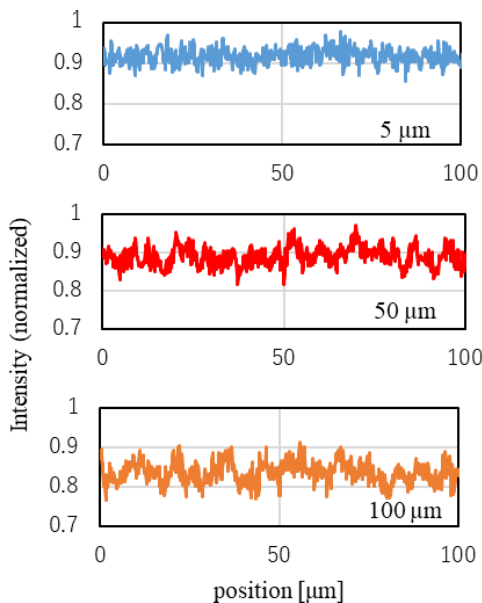


Fig. 7 Light intensity distributions in the hybrid alignment LC cells of various thicknesses.

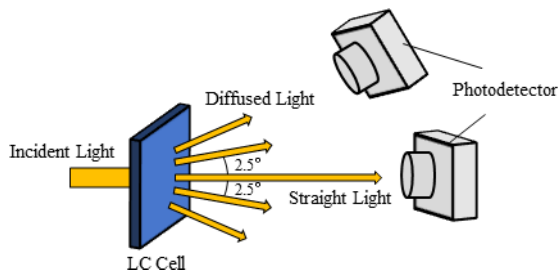


Fig. 8 Haze measurement method.

Table 1 Haze of the hybrid alignment LC cells with various thickness.

Thickness	Haze
5 μm	0.7 %
10 μm	1.2 %
25 μm	1.6 %
50 μm	6.7 %
75 μm	7.4 %
100 μm	9.8 %

4. Evaluation of LC Alignment Fluctuation Parameters in the Hybrid Alignment LC Cell

4.1 Spatial Frequency of Alignment Fluctuation in Hybrid Alignment LC Cells

In chapter 3, we clarified that the LC alignment fluctuation is violent in hybrid alignment mode. Here, we focused on of the spatial frequency of hybrid alignment LC cells. The spatial frequency of LC alignment fluctuations was determined by polarizing microscope images analysis. In this case, the alignment axis of the hybrid alignment LC cell was placed at a parallel position to the polarization axis in a Crossed-Nicol polarizer. In the region where the director angle is partially changed by LC alignment fluctuation, the light intensity increases due to the birefringence effect of LC molecules.

Figure 9 shows the hybrid alignment cell under Crossed-Nicol polarizers. This alignment direction is parallel to the polarization axis. Figure 10 shows the spatial frequencies obtained by analyzing the light intensity extracted from the part of the orange line on Fig.9. The red line in Fig.10 shows the intensity of light transmitted through the LC cell. The green line shows the background noise of the camera. The alignment fluctuation has the frequency

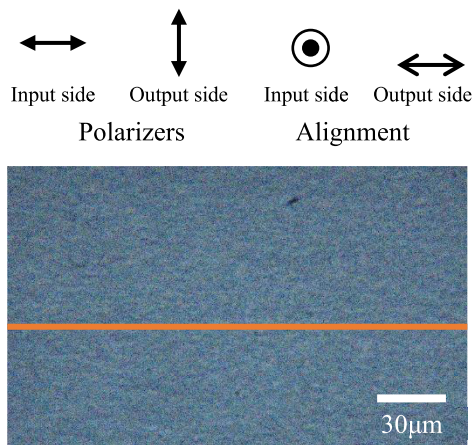


Fig. 9 Crossed-Nicol polarizing microscope image of the hybrid alignment LC cell.

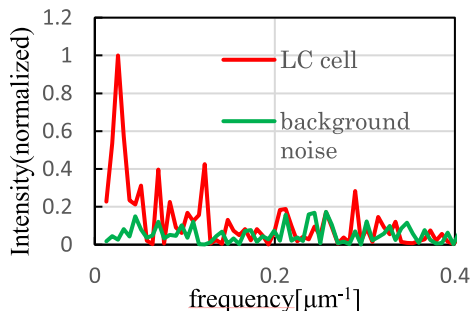
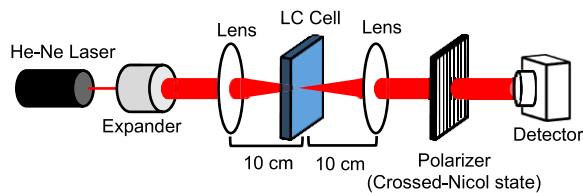
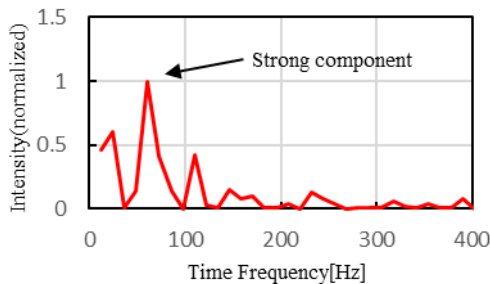


Fig. 10 Spatial frequency distribution of transmitted light intensity in the hybrid alignment cell.



(a) Optical system for time-frequency measurement



(b) Time-frequency distribution of light intensity

Fig. 11 Time-frequency distribution of transmitted light intensity in hybrid alignment LC cell.

with higher intensity than the background noise. The results show that the LC alignment fluctuation has a strong frequency component of less than $0.15 \mu\text{m}^{-1}$.

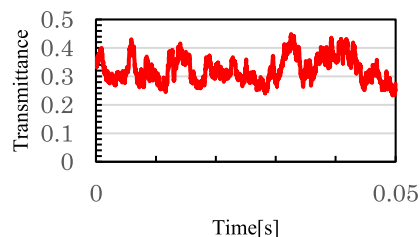
4.2 Temporal Frequency of Alignment Fluctuation in Hybrid Alignment LC Cells

Next, the time-frequency of alignment fluctuation in the LC cell was evaluated with the optical system shown in Fig. 11 (a). To measure the time variation of the transmitted light intensity in a small area, two lenses are used to focus the laser beam to a point in the LC cell. The laser entered the lens with the beam diameter magnified to 1.5 cm. The focal length of both lenses was 10 cm. The polarizer was oriented so that the polarization axis was perpendicular to the polarization direction of the laser beam. The LC cell was oriented so that the alignment direction of the LC cell was parallel to the polarization axis of the polarizer. In this optical system, laser light is transmitted through the polarizer due to the effects of birefringence and LC alignment fluctuation. The time-frequency of the LC alignment fluctuation was evaluated by measuring the time variation of the transmitted light intensity. The response time of the detector is $50 \mu\text{s}$.

Figure 11 (b) shows the time-frequency distribution obtained by analyzing the measured light intensity. The measurement result shows that the LC alignment fluctuation in this LC cell has a strong time-frequency component of less than 150 Hz.

4.3 Amplitude of Alignment Fluctuation in Hybrid Alignment LC Cells

As mentioned in chapter 3, LC alignment fluctuation is caused by overlapping vibrations of LC molecules. In

**Fig. 12** Time-transmittance characteristics of hybrid alignment LC cells.

speckle noise reduction using the phase disturbing device, total phase modulation of the light is important. The LC director vibrates equally in all directions, and all vibrations are considered to contribute to phase modulation. In the optical system as shown in Fig. 11 (a), phase shift changes caused by the alignment fluctuation along the direction parallel to the polarizer are observed. In this section, the amount of phase modulation in this direction was estimated by observing phase difference.

Figure 12 shows the time variation of transmittance measured with the optical system shown in Fig. 11 (a). Here, the transmittance is the value normalized to 1 for the light intensity measured with the polarization axis of the polarizer parallel to the polarization direction of the laser in the optical system shown in Fig. 11 (a), without the LC cell. In the waveform shown in Fig. 12, the maximum transmittance was 0.45. By converting this transmittance variation into the phase difference between orthogonal polarizations, we can estimate that the phase difference between orthogonal polarizations obtained by using LC alignment fluctuation is 1.5 rad. The LC director can be considered to vibrate similarly in all directions. Therefore, the same level of phase difference can be expected between the same polarization at different positions in the plane. LC alignment fluctuation causes due to the superposition of vibrations from various regions. Therefore, the phase was modulated complexly and the polarization was changed. At the moment of maximum transmittance, we assumed that multiple vibrations were intensifying each other.

4.4 Noise Reduction Effect of Hybrid Alignment LC Cells

Finally, we evaluated the speckle noise reduction effect of the hybrid alignment LC cells which were fabricated in this study. Figure 13 (a) shows the optical system used in the experiment to measure the speckle noise reduction effect. The spot on the screen where the laser beam was emitted was taken using a Charge Coupled Device (CCD) camera. The camera was focused on the screen. The distance between the screen and the LC cell was 10 cm, and the distance between the LC cell and the camera was 5 cm. The camera was focused on the screen. Figure 13 (b) and (c) show images with/without the fabricated hybrid alignment LC cell. The exposure time was set to 15 ms, close to the response time of the human eye. The purpose of this exposure time is to simulate the same noise reduction effect as when speckle noise is observed by the human eye. Speckle contrast was reduced

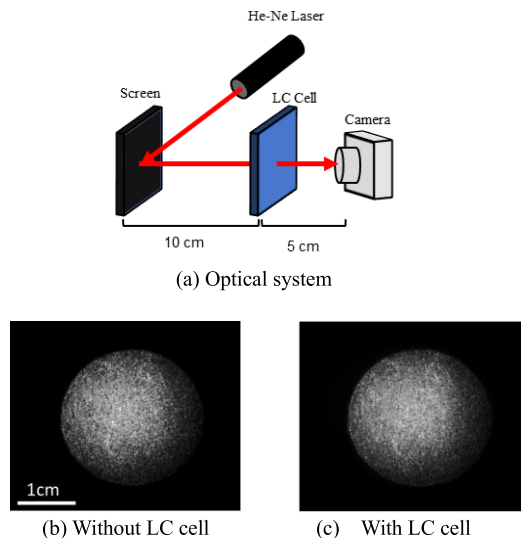


Fig. 13 Speckle noise reduction with the hybrid alignment LC cell.

from $C = 0.40$ (Fig. 13 (b)) to $C = 0.36$ (Fig. 13 (c)). The result shows the effect of LC alignment fluctuation frequencies obtained in Sects. 4.1 and 4.2 on speckle noise reduction. The target of speckle noise reduction is to reduce the speckle contrast to at least less than 0.1 [12], [13]. This is the value at which speckle is no longer perceived by humans. In this experiment, the target value was not reached. The hybrid cells showed a little effect of speckle noise reduction. As shown in Fig. 13, the noise reduction effect of the current LC cells alone is visually insufficient. To increase the speckle noise reduction effect, an even larger phase disturbance will be needed. In order to improve the noise reduction effect, we will investigate the optimal LC material and temperature control or applied voltage for obtaining the large phase disturbing effect. The search for the best LC material, temperature control, or applied voltage conditions for optical phase disturbing is necessary.

5. Conclusions

We proposed the LC optical phase disturbing device as a speckle noise reduction method that combines high light utilization efficiency and speckle noise reduction. The method utilizes the random LC alignment fluctuation of the nematic LC. We confirmed the feasibility of the noise reduction due to the optical phase disturbance by the simulation to verify the principle of the proposed method. Furthermore, the experiment using the hybrid alignment LC cell revealed the spatial frequency, temporal frequency, and the phase change magnitude of the LC alignment fluctuation. Although the hybrid alignment LC cell showed somewhat effective noise reduction in the experiments, improvements are required. It is necessary to explore the fabrication conditions and driving method of LC cells to achieve the optimum LC alignment fluctuation for noise reduction. In particular, we plan to investigate driving methods, including voltage driving, that promote LC alignment fluctuation.

Acknowledgments

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