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Quantitative Evaluation of LC Alignment Fluctuation in Random Phase Disturbing Devices for Speckle Noise Reduction in Electronic Holography

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ABSTRACT

To reduce the speckle noise generated in holographic 3D displays, we proposed the phase disturbing device using randomly-fluctuated liquid crystal (LC) alignment. Optical simulations showed that the phase disturbance can reduce the speckle noise. In addition, the parameters corresponding to the alignment fluctuation of thick LC were quantitatively evaluated.

1. Introduction

As one of 3D displays that can present depth information, electronic holography has been attracted attention. The reasons are based on the following features. One is providing a natural stereoscopic display that fulfills all the physiological factors of stereopsis. Another is that electronic holography enables playing movies by switching the reconstruction image electronically [1]. The coherent laser light is commonly used in the projection of electronic holography. For this reason, speckle noise is generated due to the interference phenomenon of light [2]. The speckle noise is induced by the difference in optical path length between laser beams. This speckle noise causes poor image quality of reconstruction images and visual fatigue for human beings [3]. Therefore, the ideal method for canceling speckle noise has been required for electronic holography.

To reduce the speckle noise, many studies have been reported so far. Of these, most of the method is to average the actual speckles by changing the speckle pattern within the response time of the human eye[4]. As well known, a good effect of reduction in this method was obtained by the preparation of many speckle patterns during the averaging procedure [5]. The related studies on reduction of speckle noise include as follows: randomly-changed propagation distance of a laser beam using a movable diffuser[6, 7], and varying the phase to time in a binary manner using a ferroelectric LC[8, 9]. The former method has the drawback of low light utilization efficiency. The reduction effect of the later method on speckle noise was low.

In this study, we propose the speckle noise reduction method using the optical phase disturbing device using LC alignment fluctuation. This proposed method as mentioned below is expected to the achievement of balance between light utilization efficiency and noise reduction effect. It is because randomly-modulated phase of laser light is controlled by the alignment control of LC molecules.

Here, we explored the necessary changes of phase distribution in order to reduce the speckle noise by optical simulation. Based on their simulated results, the quantitative evaluation of spontaneous and random LC alignment fluctuation was discussed.

2. Proposal of Method

2.1 LC Optical Phase Disturbing Device

In this study, we propose the speckle noise reduction method using the LC optical phase disturbing device, which changes the phase distribution of transmitted light by inducing a temporal and spatial random alignment change of LC, as shown in Fig. 1. The aim of the proposed method is to change randomly the speckle pattern generated by light interference phenomena.

In the proposed method, a large number of speckle patterns can be generated within the response time of the human eye without strong light scattering. Therefore, the proposed method has the potential to achieve both light utilization efficiency and noise reduction effect. However, the basic nature of the LC alignment fluctuation has not been cleared yet. In addition, the effect of phase disturbance by the LC is unknown. For this reason, the optimal conditions for noise reduction have not been obtained.

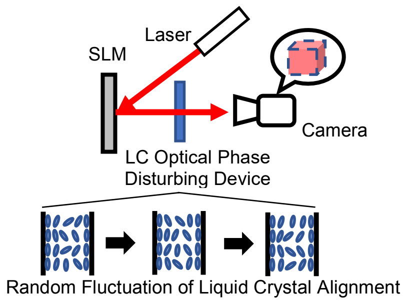

Fig. 1 Proposal of LC optical phase disturbing device

2.2 Verification of Operation Principle for the Proposed Method

Simulations of light propagation were performed to verify the effectiveness of the principle of the proposed method, which is to reduce the speckle noise by using random time variation of the optical phase distribution.

Speckle noise is evaluated by the speckle contrast C, which is expressed as the ratio of the standard deviation of the light intensity σ to the mean value of the light intensity $< I >$.

$$C = \frac{\sigma}{< I >} \quad (1)$$

The smoother the reconstruction image is, the smaller C is. Using the speckle contrast C_0 before the reduction, the reduction rate of C is expressed as following equation (2).

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

Fig. 2 (a) shows the model of the optical system which is set up in the simulation. The light source was given a random phase distribution which causes speckle noise. Fig. 2 (b) shows the time-varying phase distribution given to the phase disturbing device. Speckle noise was evaluated by comparing the speckle contrast before and after time averaging. Fig. 2 (c) and (d) show the speckle noise before and after time averaging obtained by optical simulation. Before averaging, the noise was $C = 0.51$, while the noise was $C = 0.26$ after averaging. Based on these values, calculated reduction ratio was $\alpha = 0.49$. These simulated results indicate that speckle noise reduction is possible due to phase disturbance of transmitted light.

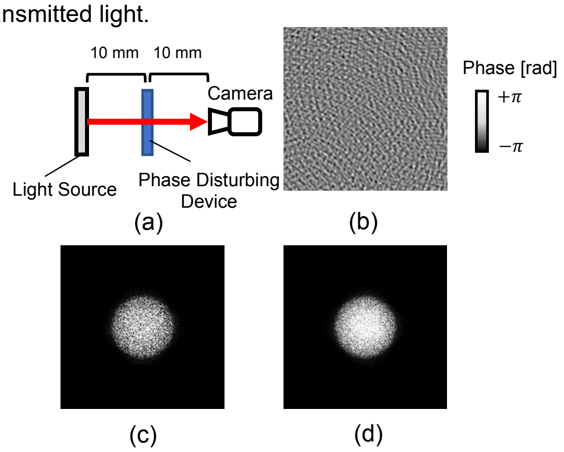

Fig. 2 Optical simulation for verification of the principle: (a)Simulation model(b) Phase distribution (c) Speckle before reduction(d)Speckle after reduction

3. Experiment

In this paper, we focus on the random alignment fluctuation of LC to realize random phase disturbance. As well known, molecular groups of LC have elastic properties. The continuum elastic theory is used to consider its behavior in response to alignment state and voltage. As for the LC alignment fluctuation, it can be considered that the elastic vibration of the director is caused by the thermal vibration of the LC molecules being transmitted to the surrounding molecules.

The group composed of many LC molecules is moving based on the continuum elastic theory. Therefore, the LC alignment fluctuation can be thought of as vibration with three parameters: spatial frequency, temporal frequency, and amplitude of alignment vibration, similar to elastic vibration. To evaluate these parameters, we fabricated some kinds of LC cells.

We investigated the fabrication conditions of the LC cells which is suitable for observation of the LC alignment fluctuation. To increase the alignment fluctuation in the LC cell, it was effective to increase the thickness of the LC layer in order to weaken the effect of anchoring strength from the substrate surface. The effect of the alignment mode in the LC cells on the alignment fluctuation was also investigated. We fabricated four kinds of LC cells: parallel alignment, vertical alignment, twisted nematic alignment, and hybrid alignment. The parallel alignment film (JSR, AL-1254) and the vertical alignment film (Nissan Chemical, SE-4811) were used to fabricate the LC cells, and the LC material (JNC, TD-1021XX) with a large refractive index anisotropy of $\Delta n \approx 0.67$ was used. The thickness of the LC layer in these cells was 50 μm with film spacer. To confirm the alignment state, Fig. 3 shows Crossed-Nicol polarizers microscope images. The hybrid alignment cells exhibited the largest alignment fluctuation frequently. In the hybrid alignment, the distribution of LC director curved and distorted from top to bottom substrate in LC cells. These results are attributed to the relatively large intermolecular distance of the LC and the weak intermolecular force. In the following discussion, we focused on the hybrid alignment LC cells having large alignment fluctuation.

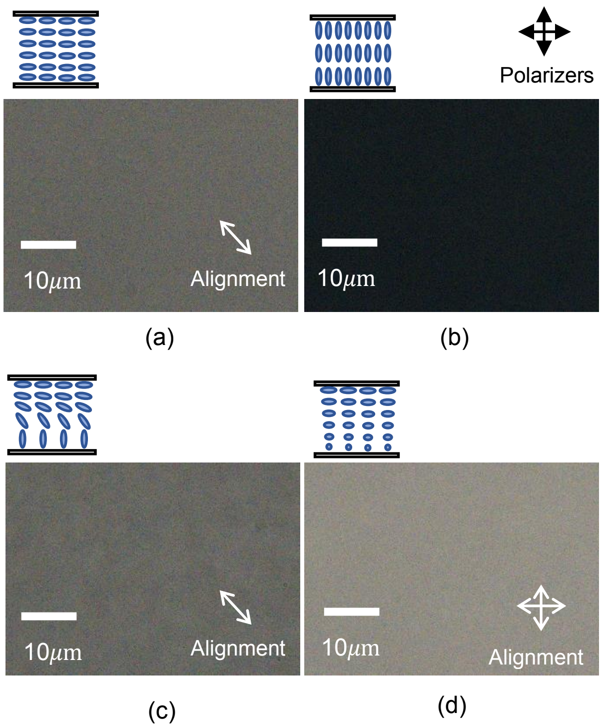

Fig. 3 Crossed-Nicol polarizing microscope images of fabricated LC cells: (a)Parallel (b)Vertical (c)Hybrid (d)Twisted nematic

4 Results and Discussion

4.1 Spatial Frequency of Alignment Fluctuation in Hybrid Alignment LC Cells

Under Crossed-Nicol polarizers, the alignment axis of the hybrid alignment LC cell was placed parallel to the polarization axis. The spatial frequency of the alignment fluctuation was obtained by analyzing images taken with a polarizing microscope. In the region where the light was transmitted through, the angle of the director was partially changed due to the effect of alignment fluctuation. Therefore, we considered that the polarization direction changed due to birefringence. Fig. 4 shows the Crossed-Nicol polarizing microscope image of hybrid LC cells when the alignment direction of the hybrid alignment cell is parallel to the polarization axis. Fig. 5 shows the extracted spatial frequency distribution of the light intensity from the part of the red line on the image, as shown in Fig. 4. This measurement means that the LC alignment fluctuation has a strong spatial frequency component of less than 0.15 μm^{-1}.

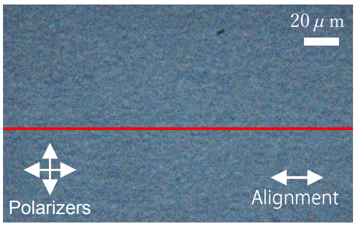

Fig. 4 Crossed-Nicol polarizing microscope image of the hybrid alignment LC cell

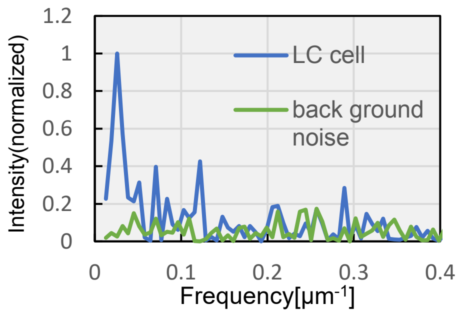

Fig. 5 Spatial frequency distribution of transmitted light intensity in the hybrid alignment cell

4.2 Temporal Frequency of Alignment Fluctuation in Hybrid Alignment LC Cells

Fig. 6 (a) shows the optical system used to measure the time-frequency of alignment fluctuation in the LC cell. Using lenses, the laser beam was focused on a point in the LC cell, and the time variation of the transmitted light intensity was measured. The polarizer was placed so that the polarization axis was perpendicular to the polarization direction of the laser beam. The alignment direction of the LC cell was parallel to the polarization axis of the polarizer. The polarization direction of the transmitted light changes due to the alignment fluctuation. The time-frequency of the LC alignment fluctuation was determined by monitoring the time variation of the detected light intensity.

Fig. 6 (b) shows the time-frequency distribution of the measured light intensity. From this measurement, it can be seen that the time-frequency of the alignment fluctuation in the fabricated hybrid alignment LC cell is particularly strong in the frequency region below 150 Hz.

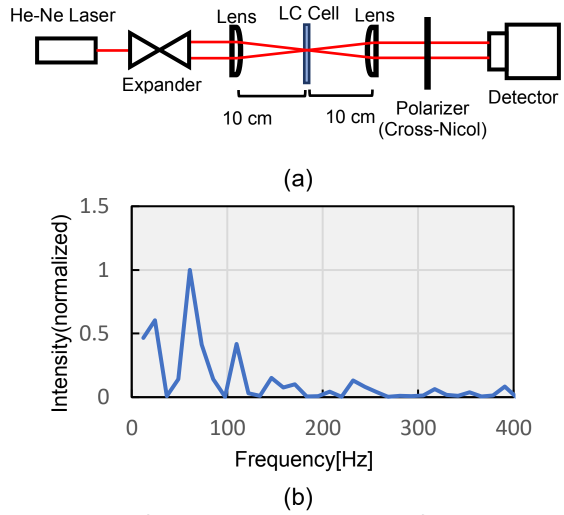

Fig. 6 Time-frequency distribution of transmitted light intensity in hybrid alignment LC cell
(a)Optical system for time-frequency measurement
(b) Time-frequency distribution of light intensity

4.3 Amplitude of Alignment Fluctuation in Hybrid Alignment LC Cells

In analyzing the amplitude of the LC alignment fluctuation, it is not possible to measure the magnitude of the vibration of each LC molecule. When the alignment fluctuation is used in the LC optical phase disturbing device, it is important to know the extent to which the phase of the transmitted light through the LC cell is modulated. In the optical system shown in Fig. 6 (a), only alignment fluctuation along the direction which is parallel to the polarizer can be observed. The LC molecules are considered to vibrate in the thickness direction as well, which contributes to the phase modulation. The amount of phase change by alignment fluctuation can be estimated from the phase difference change between orthogonally polarized light measured with the optical system, as shown in Fig. 6 (a).

Fig. 7 shows the time variation of the transmittance measured with the optical system shown in Fig. 6 (a). In the LC layer, alignment fluctuation transmitted from various regions overlap. As a result, transmitted light with a change in polarization was detected. At the moment of maximum transmittance in the measured time waveforms, multiple waves of alignment fluctuation are considered to be strengthening each other. In the time waveform shown in Fig. 7, the maximum transmittance was 0.45, and the phase difference (retardation) between the orthogonally polarized lights at this time was calculated to be 1.5 rad.

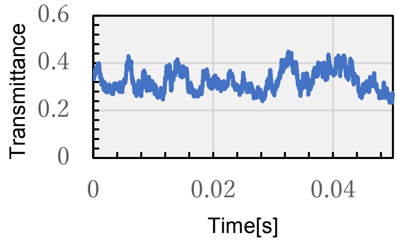

Fig. 7 Time-transmittance characteristics of hybrid alignment LC cells

4.4 Noise reduction effect of hybrid alignment LC cells

In this paper, we estimated the vibration parameters of the alignment fluctuation in the hybrid alignment LC cell. When the speckle noise reduction was performed using the LC cell fabricated in this study with the same optical system, as shown in Fig. 6 (a). The speckle contrast was reduced from $C = 0.40$ to $C = 0.36$. 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 disturbance effect.

5. Conclusions

In this paper, we proposed the random phase disturbance devices using alignment fluctuation of nematic-phase LC molecules. The principle of the proposed method is verified and the vibration parameters of the LC alignment fluctuation are measured and optically quantified to realize the LC optical phase disturbing device with both high light utilization efficiency and reduction rate of speckle noise. Based on the clarified parameters in this study, we will research the optimal phase distribution change for speckle noise reduction and investigate LC cell structure and driving method.

6. Acknowledgements

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