Effect of Non-uniformity of Optical Phase Modulation in Liquid Crystal Devices on Holographic Image Quality

Kazuma Chida[1], Yoshitomo Isomae[1,2], Takahiro Ishinabe[1], Yosei Shibata[1], Hideo Fujikake[1]

[1]Tohoku University, 6-6-05, Aoba, Aramaki, Aoba-ku, Sendai, 980-8579, Japan
[2]Research Fellow of Japan Society for the Promotion of Science

Keywords: Electronic Holographic Display, Liquid Crystal on Silicon, Phase Modulation, Image Quality

ABSTRACT

We investigated the effect of non-uniformity of phase distribution in liquid crystal phase modulator on holographic image quality by using simulation. As a result, non-uniform phase distribution in a pixel degrades diffraction efficiency, and non-uniform phase distribution on the entire liquid crystal on silicon panel decreases resolution of holographic images.

1 INTRODUCTION

As a next-generation three-dimensional (3D) display, electronic holographic display has attracted attention because it enables natural stereoscopic display that satisfies all physiological cues of stereoscopic vision [1].

In electronic holography, a liquid crystal (LC) device called liquid crystal on silicon (LCOS) is generally used as optical phase modulator [2]. Typically, for electronic holographic display, LCOS with a pixel pitch of several micrometers is used in order to obtain a wide field of view. However, when pixel pitch of LCOS is smaller, LC alignment in a pixel becomes non-uniform due to fringe electric field and elastic force of LC from adjacent pixels, thereby causing non-uniform phase distribution in a pixel (local non-uniform phase distribution) [3]. In addition, non-uniform thickness distribution of LC layer causes non-uniform phase distribution on the entire LCOS panel (global non-uniform phase distribution) [4]. The non-uniform thickness distribution of LC layer is caused by surface curvature and roughness of a cover glass, a silicon substrate, and deflection of LCOS panel, which occur when assembling LCOS.

It has been known that the above-mentioned non-uniform phase distributions qualitatively degrades image quality of holographic reconstructed images [4], [5]. However, it has not been quantitatively clarified which image quality factor is affected by these non-uniform phase distributions. Knowing this is important in design and production of LCOS for electronic holographic display.

In this paper, we investigated the effects of the local and the global non-uniform phase distribution on image quality factors by using simulation. We evaluated two image quality factors: diffraction efficiency and resolution characteristics. The diffraction efficiency is an important factor in holographic displays because they are based on diffraction and interference of light. The resolution characteristic is also an important factor in holographic displays. This is because the resolution of a display image is determined by the resolution of pixels in LC displays and organic LED displays, whereas the resolution of a holographic image is determined by the condensing point size of light.

2 SIMULATION

2.1 Non-uniform phase distribution model

Figures 1 and 2 show the local and the global non-uniform phase distribution model in LCOS used in the simulation, respectively. Here, the pixel pitch of LCOS is 8 μm, and the size of LCOS is 1024 × 1024 pixels. The physical parameters of LC are those of E7 (Merck), and wavelength of light is 633 nm.

The local non-uniform phase distribution (Fig. 1) is set by a simulation method proposed in the reference [5]. In this method, the phase shift distribution in a pixel was calculated by LC orientation simulation based on the elastic continuum theory. In the ideal case (Fig. 1(a)), the phase distribution in the OFF-state pixel is uniform. However, in the actual case (Fig. 1(b)), the phase distribution in the OFF-state pixel is not uniform because of non-uniform LC alignment due to the influence of fringe electric field and elastic force of adjacent ON-state pixels. By applying the calculated non-uniform phase distribution to all pixels on LCOS plane in the optical simulation, we created the phase distribution on LCOS plane considering the local non-uniform phase distribution.

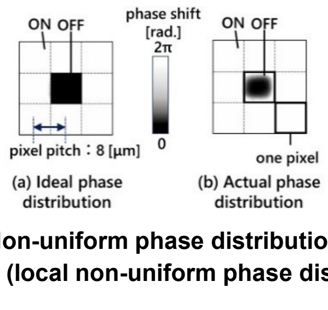

Fig. 1 Non-uniform phase distribution model in a pixel (local non-uniform phase distribution)

Figure 2(a) shows the non-uniform thickness distribution of LC layer that occurs on the entire LCOS panel. The center area in the LCOS is a thick area with a thickness of 2.0 μm. The edge area in the LCOS is a thin area with a thickness of 1.9 μm. Since this LCOS is designed to modulate phase of light with 1.9-μm-thickness LC layer, the desired phase shift is obtained in the edge area of LCOS. Figure 2(b) shows the global non-uniform phase distribution calculated based on the non-uniform thickness distribution. This is the phase distribution when a phase shift of 2π radians is output on the entire LCOS panel.

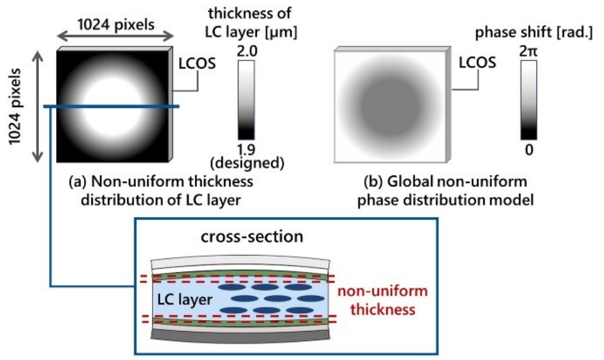

Fig. 2 Non-uniform phase distribution model on the entire LCOS panel (global non-uniform phase distribution)

2.2 Definition of diffraction efficiency and optical system in calculation of diffraction efficiency

The diffraction efficiency of nth-order diffracted light is defined by equation (1).

$$\text{Diffraction Efficiency (nth-order)} = \frac{I_{nth}}{I_{in}} \qquad (1)$$

Here, I_{in} and I_{nth} are light intensities of incident light and nth-order diffracted light, respectively. Figure 3 shows the optical system assumed in the calculation of diffraction efficiency. On the LCOS plane, the non-uniform phase distribution is applied to the binary phase grating of 0 and π. Then, on the Fourier plane of the 2f-system using a lens (f = 5 cm), diffraction efficiencies of 0th-order, +1st-order, and +2nd-order diffracted light were calculated in a region of approximately 1 mm × 1 mm.

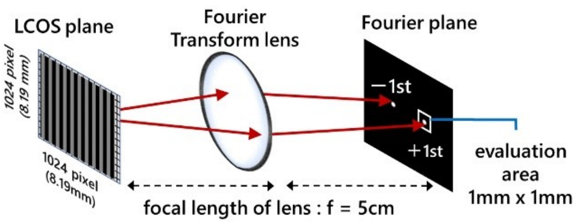

Fig. 3 Optical System in calculation of diffraction efficiency

2.3 Definition of Modulation Transfer Function (MTF) and optical system in calculation of MTF

We investigated resolution characteristics by reconstructing sine wave stripe images varying spatial frequencies. Figure 4 shows the optical system assumed in the simulation of resolution characteristics. We created a phase hologram that can obtain sine wave grating with different spatial frequencies by using the angular spectrum method [6] and Gerchberg-Saxton algorithm [7]. Then, the non-uniform phase distribution was applied to the phase pattern, and MTF of the reconstructed image was calculated. MTF used to evaluate resolution characteristics is defined by equation (2).

$$\text{MTF} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \qquad (2)$$

Here, I_{max} and I_{min} are the maximum value and the minimum value of the intensity, respectively, in the case that a sine wave stripe image is output. The propagation distance between LCOS plane and reconstructed image plane is 50 cm. A 4f-system is assumed to eliminate 0th-order diffracted light.

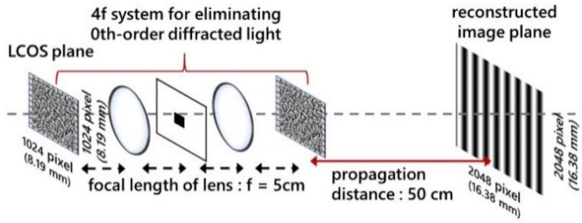

Fig. 4 Optical system in calculation of resolution characteristics

3 RESULTS AND DISCUSSION

Figure 5 shows the results of diffraction efficiencies of 0th-order, +1st-order, and +2nd-order diffracted light when each non-uniform phase distribution is applied. The influence of the global non-uniform phase distribution on diffraction efficiency is small. Whereas, the local non-uniform phase distribution degrades diffraction efficiency. If there is the local non-uniform phase distribution, efficiency of +1st-order diffracted light, which forms reconstructed image in holographic display, is decreased, and efficiency of 0th-order and +2nd-order diffracted light is increased. The reason for this result is that the wavefronts of 0th-order and 2nd-order diffracted light are formed by the phase near the boundary with the adjacent pixel when there is the local non-uniform phase distribution. Specifically, when a reconstructed image is displayed, 0th-order diffracted light is a light traveling straight from LCOS, and 2nd-order diffracted light is a light that travels at an angle twice that of 1st-order light. Therefore, these lights overlap with a reconstructed image.

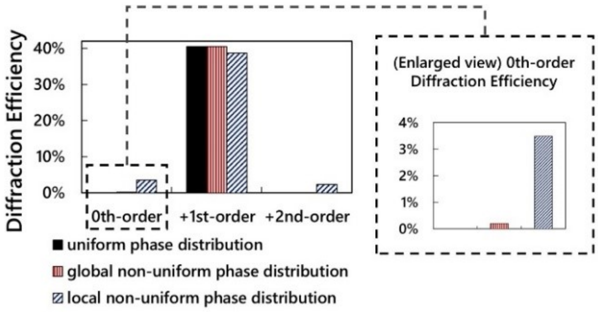

Fig. 5 Effect of non-uniform phase distribution on diffraction efficiency

Figure 6 shows the results of resolution characteristics when the non-uniform phase distribution is applied. The influence of the local non-uniform phase distribution on resolution characteristics is small. On the other hand, when there is the global non-uniform phase distribution, the resolution of reconstructed image decreases as the spatial frequency of the sine wave stripe increases.

When there is the global non-uniform phase distribution, the angle of the 1st-order diffracted light is deviated, and the condensing point of the diffracted light that forms a reconstructed image is expanded. This causes the drop of the resolution characteristics of reconstructed images with global non-uniform phase distribution.

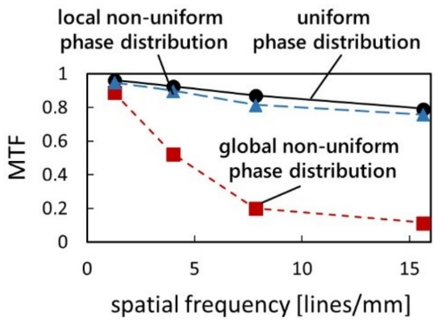

Fig. 6 Effect of non-uniform phase distribution on resolution characteristics

4 CONCLUSIONS

In this study, we investigated the effects of the non-uniform phase distribution in LC layer of LCOS on diffraction efficiency and resolution characteristics. As a result, if there is the non-uniform phase distribution in a pixel, efficiency of 1st-order diffracted light that contributes to reconstructed image decreases, and efficiency of 0th-order and 2nd-order diffracted light, which is obstructive to observe reconstructed images, increases due to the phase near the boundary with the adjacent pixel. On the other hand, if there is the non-uniform phase distribution on the entire LCOS panel caused by the non-uniform thickness distribution of LC layer, the angle of the 1st-order diffracted light is deviated, and the resolution of the hologram reconstructed images is lowered.

REFERENCES

[1] L. Onural, F. Yaraş, and Hoonjong Kang, "Digital Holographic Three-Dimensional Video Displays," *Proc. IEEE*, vol. 99, no. 4, pp. 576–589, Apr. 2011.

[2] Z. Zhang, Z. You, and D. Chu, "Fundamentals of phase-only liquid crystal on silicon (LCOS) devices," *Light Sci. Appl.*, vol. 3, no. 10, pp. e213, Oct. 2014.

[3] Y. Isomae, Y. Shibata, T. Ishinabe, and H. Fujikake, "Optical Phase Modulation Properties of 1 μm-Pitch LCOS with Dielectric Walls for Wide-Viewing-Angle Holographic Displays Yoshitomo Isomae , Yosei Shibata , Takahiro Ishinabe , and Hideo Fujikake," *SID Symposium Digest of Technical Papers*. pp. 1670–1673, 2016.

[4] X. Xun and R. W. Cohn, "Phase calibration of spatially nonuniform spatial light modulators," *Appl. Opt.*, vol. 43, no. 35, pp. 6400–6406, 2004.

[5] Y. Isomae, Y. Shibata, T. Ishinabe, and H. Fujikake, "Simulation of Reconstructed Holographic Images Considering Optical Phase Distribution in Small Liquid Crystal Pixels," *IEICE Trans. Electron.*, vol. E100.C, no. 11, pp. 1043–1046, 2017.

[6] J. W. Goodman, *Introduction to Fourier optics*. Roberts & Co, 2005.

[7] R. W. Gerchberg and W. O. Saxton, "A Practical Algorithm for the Determination of Phase from Image and Diffraction Plane Pictures," *Optik (Stuttg).*, vol. 35, no. 2, pp. 1–6, 1972.