# Evaluation and Analysis of Light Diffraction from One-Dimensional Liquid Crystal Devices with small Pixel-Pitch more than 1μm

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**ABSTRACT**

*We compared diffraction characteristics of ferroelectric liquid crystal (FLC) and nematic liquid crystal (NLC) devices with one-dimensional stripe pattern of 1-10μm pixel-pitch.*

*1st-order diffraction efficiency of the FLC with low-crosstalk was much larger than that of the NLC for less than 2μm pixel-pitch, indicating FLC's better potential for holographic application.*

## 1 INTRODUCTION

Holography has attracted attention due to its potential for the ultimate three-dimensional (3D) display capability. It can reconstruct physically the same light from an object and satisfies all visual cues for autostereoscopic vision, such as motion parallax, binocular disparity, vergence and accommodation, which enable natural autostereoscopic displays [1-3].

3D holographic images are reconstructed from hologram patterns displayed on a spatial-light modulator (SLM). The images reconstructed by conventional commercial SLMs have a narrow viewing-zone-angle issue because of an insufficiently small pixel-pitch of the SLMs. The viewing-zone-angle is described by the equation, $\theta=2\sin^{-1}(\lambda/2p)$, where $\lambda$ is the wavelength of light and p is the pixel-pitch of the display [4]. Which means that the latest commercial SLM with 3μm pixel-pitch generate holographic images with insufficient viewing zone angle of 12 degrees [5]. A SLM with narrow pixel-pitch less than 1μm is required to realize a viewing zone angle wider than 30 degrees, which makes possible to view 3D holographic images on personal terminals.

Recently, the liquid crystal (LC) devices with narrow pixel-pitches are actively studied for holographic application [6]. When the pixel-pitch is getting smaller, crosstalk issues between pixels are getting more remarkable [6]. Isomae et al. have shown that the FLC device with small pixel pitch has less crosstalk and higher black/white contrast compared to the NLC devices. It suggested that this device has the potential for a solution to the narrow viewing-zone-angle issue. [7]

The evaluation of diffraction characteristics is very important for holographic display since the holographic image is reconstructed by 1st-order diffracted light. There is a simulation study about how the crosstalk between adjacent pixels of NLC devices affect 1st-order diffraction efficiency, however, an experimental study with small pixel-pitch have not done in detail. [8] Therefore, it is very important to investigate how the diffraction properties of the FLC device with small pixel pitch comparing the NLC devices.

In this study, we evaluated Modulation Transfer Function (MTF) and diffraction efficiency of one-dimensional liquid crystal devices with FLC and NLC and analyzed transmittance distributions.

## 2 EXPERIMENT

### 2.1 Fabrication of One-Dimensional LC Devices

We fabricated one-dimensional LC devices illustrated in Figure 1. The stripe electrodes were made of transparent indium-zinc-oxide (IZO) with a thickness of 20nm on the glass substrate. They were fabricated using electron beam lithography and ion beam etching. The stripe electrodes were alternately connected to the pad electrode 1 and pad electrode 2, which are made of silver (Ag). This structure enables that different electric voltage can be applied to adjacent electrodes. The stripe electrode was covered throughout the 500μm × 600μm area, which is larger than the laser spot size for accurate measurement of the diffraction efficiency. Figure 1(b) shows the cross-sectional view of the device. Alignment films (AL-1254; JSR Co.) were spin-coated on the stripe and common electrodes, and a rubbing treatment was applied to achieve an anti-parallel LC alignment. The LC alignment direction was perpendicular to the stripe electrodes. NLC (E7) or FLC was sealed between the stripe and counter common electrodes. The thickness of the LC layer was controlled to be 1μm with micro beads.

Table 1 shows the pixel-pitches of the stripe pattern of the devices, ranging 1 to 10μm.

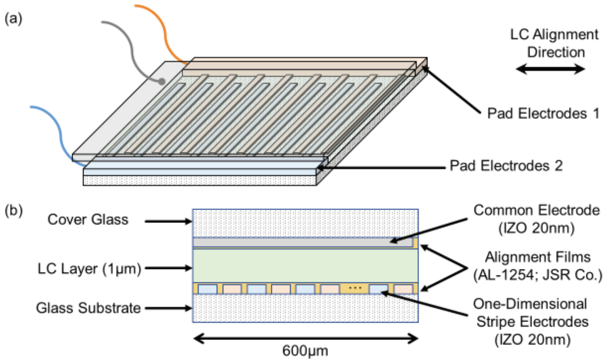



**Fig. 1. (a) Structures of a Fabricated One-Dimensional LC Device, a birds-eye view, (b) the cross-sectional view**

**Table 1. The Pixel-Pitch of Fabricated One-Dimensional Stripe Electrodes**

| Pixel-pitch [μm] | narrow | | | middle | | | Wide | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1.0 | 1.5 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 10 | Plane |

### 2.2 Optical Setup for Diffraction Measurement

Figure 2 shows an optical setup for measuring the diffraction from the intensity modulated SLMs.

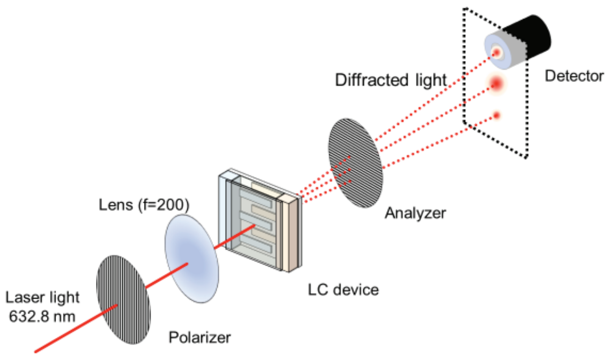



**Fig. 2. The Optical System for Intensity Modulation: (a) the optical system**

**Table 2. The Angles of Polarizer**

| | Polarizer | Analyzer |
|---|---|---|
| FLC | 22.5° | 112.5° |
| NLC | 45° | 135° |

The He-Ne laser with a wavelength of 632.8nm, was introduced to the LC device through polarizer and a lens to focus the laser spot in the stripe electrode area. We measured intensity of the diffracted light through the analyzer with the photodiode detector (PH100-Si-HA-OD1-D0; Gentec-EO). The relationship between angles of the polarizer and the analyzer is shown Table 2 because of making crossed Nichol.

The 1st-order diffraction efficiency is defined by equation (1).

$$\eta = 100 \times \frac{I_{1st}}{I_{in}} \tag{1}$$

Here, $I_{1st}$ and $I_{in}$ are light intensities of 1st-order diffracted light and incident light, respectively. The $I_{in}$ was defined as the light intensity measured through a LC device with open-Nicol position, which LC was sandwiched by IZO plane electrodes (not stripe electrode).

## 3 RESULTS

### 3.1 Optical Polarizing Microscopy Images

Figure 3 shows polarizing micrographs of the devices.

Figure 3(a) shows the FLC images when the common electrode was 0V, the pad electrode 1 was DC+5V (or DC-5V) and the pad electrode 2 was DC-5V (or DC+5V), respectively.

Figure 3(b) shows the NLC images when the common electrode and the pad electrode 1 were 0V and the pad electrode 2 was 5V 1kHz alternating voltage.

The boundary of black-and-white pixels was getting more unclear with decreasing the pixel-pitch for both FLC and NLC. This tendency is more remarkable for the NLC devices. The wrinkle type noise was observed in the FLC devices with 3-5μm in Figure 3(a), which may be attributed to a disorder of the LC alignment.

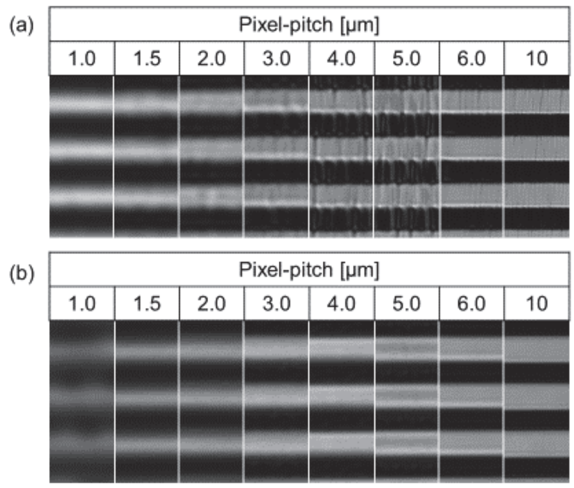



**Fig. 3 Polarizing Micrographs: (a) FLC patterns with an application of DC±5V, (b) NLC patterns with an application of 5V 1kHz alternating current**

### 3.2 Evaluation of MTF

MTF values were calculated from the micrographs in Figure 3 to evaluate optical polarizing microscopy image characteristics of display devices with black-and-white stripe patterns, which is defined by equation (2).

$$\mathbf{MTF} = \frac{I_{max}-I_{min}}{I_{max}+I_{min}} \quad (2)$$

Here, $I_{max}$ and $I_{min}$ are the maximum value and the minimum value of the intensity, which are the brightest point and the darkest point in each micrograph, respectively.

As shown in the Figure 4, the MTF of the FLC kept constant for almost all pixel pitch while that of the NLC decreased for pixel-pitch smaller than 2μm, which tendency was similar to the previous report [5].

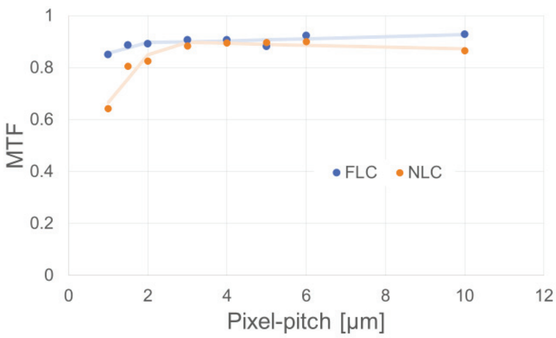



**Fig. 4. MTF Values of FLC and NLC Devices as a function of pixel pitch**

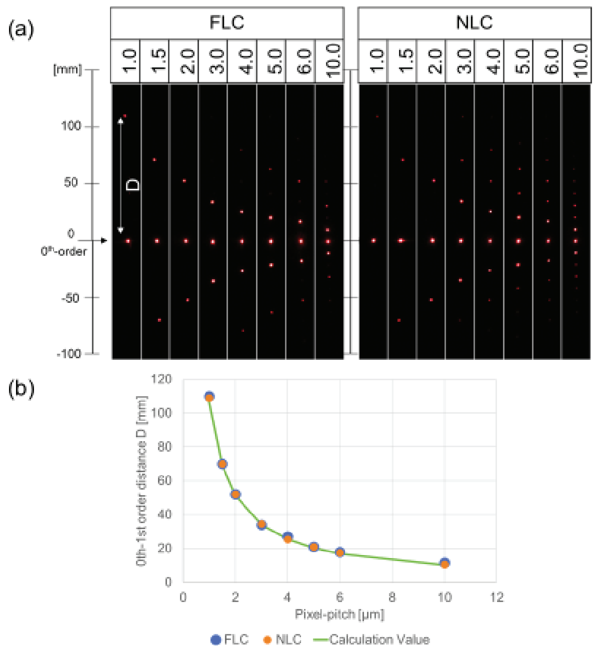



**Fig. 5. Diffraction Spots: (a) the photos of the FLC (left) and NLC (right), (b) position of the 1st-order diffraction spots of LC devices with 1-10μm**

### 3.3 Diffraction Spots Distribution

We have evaluated position of the diffraction spots for the samples with various pixel pitch. The distance from the LC device to the screen was 320mm.

Figure 5(a) is the diffraction spots of the FLC (left) and NLC (right) devices. We observed multiple higher order diffraction spots. It should be noticed that 2nd (or 4th) spots were not observed in the FLC while those were observed in the NLC (See the diffraction spots with 6μm pixel-pitch for FLC and NLC). We do not comprehend this difference very much but the LC condition may affect the difference.

Figure 5(b) shows the distance from 0th- to 1st-order diffraction spots, dot data indicated experimental results and solid line shows calculated results. Which was calculated by equation (3) and (4).

$$\boldsymbol{\lambda} = \mathbf{d} \cdot \mathbf{sin\theta} \quad (3)$$

$$\mathbf{x} = \mathbf{L} \cdot \mathbf{tan\theta} \quad (4)$$

Here, $\boldsymbol{\lambda}$ is the wavelength of the light, $\mathbf{d}$ is the period of the stripe pattern, $\mathbf{L}$ is the distance from the LC device to the screen (320mm) and $\mathbf{x}$ is the position of the 1st-order diffraction spots.

The 1st-order diffraction position of the FLC and NLC was almost identical and agreed with the calculated results. This shows the periodic structures of the stripe electrodes of LC devices were as designed.

### 3.4 Evaluation of Diffraction Efficiencies

Figure 6 shows the evaluation of 1st-order diffraction efficiencies, which values were average of multiple measurements and the error bars were the differences between maximum and minimum values in the observed values.

The efficiency of FLC was about 9% for the 10μm pixel-pitch, and it decreased as the pitch decreased for the 5μm pixel-pitch and kept constant about 6% for the pixel-pitch less than 5 μm pixel-pitch.

The efficiency of NLC was about 9% for the 5-10μm pixel-pitch, however, decreased drastically for the pixel pitch less than 2μm pixel-pitch.

One should notice that the 1st-diffraction efficiency of the FLC was three times higher than that of the NLC with 1μm pixel-pitch.

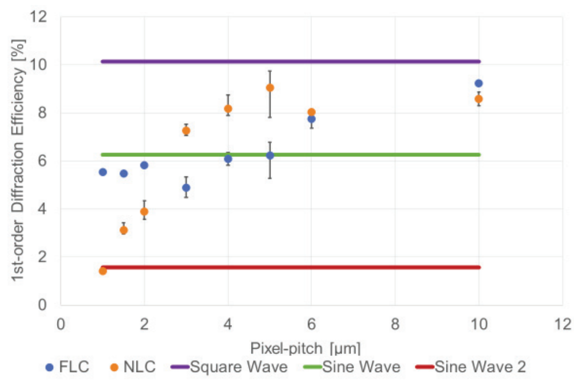



**Fig. 6. 1st-order Diffraction Efficiencies**

## 4 DISCUSSION

Table 3 shows the calculated 1st-order diffraction efficiency values with various one-dimensional transmittance distributions, such as sinusoidal and square wave distributions. Diffraction efficiency values were analytically calculated from the transmittance distributions with Fourier Transforms [10-12]. The calculation values of Table 3 are shown in Figure 6.

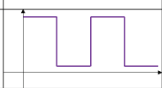
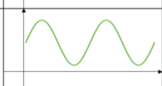
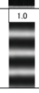
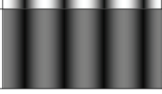
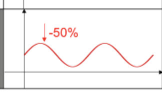
First, when the transmittance distribution is square waves, the 1st-order diffraction efficiency was 10.13% (square wave in Table 3). The distribution of FLC and NLC for 10μm pixel-pitch can be assumed to be square waves because the efficiencies were about 9%, which is close to 10.13%.

Second, when the transmittance distribution is sine waves, the 1st-order diffraction efficiency is 6.25%. The distribution of the FLC with 1μm pixel-pitch can be assumed to be the sine wave because the efficiency was about 6%, which is close to the efficiency of the sinusoidal transmittance distribution of 6.25%.

Third, When the transmittance distribution is sine waves whose amplitude is declined 50%, the 1st-order diffraction efficiency is 1.56%. The distribution of the NLC with 1μm pixel-pitch is assumed to be the sine wave 2 because the efficiency was about 1.5%, which is close to the efficiency of the declined sinusoidal transmittance distribution of 1.56%. The significant decease in the efficiency of the NLC can be attributed to the blur transmittance distribution as well as light amplitude decline due to the voltage crosstalk of adjacent pixel in the NLC.

Those results indicate that changing the shape of the transmittance distribution affects the 1st-order diffraction efficiency.

**Table. 3. 1st-order Diffraction Efficiency and Transmittance Distribution**

| | Pattern Image | Transmittance Distribution | 1st-order Diffraction Efficiency | Experiment Microscopy Image [μm pixel-pitch] | |
|---|---|---|---|---|---|
| | | | | FLC | NLC |
| Square Wave |  |  | 10.13% |  |  |
| Sine Wave |  |  | 6.25% |  | |
| Sine Wave 2 |  |  | 1.56% | |  |

## 5 CONCLUSIONS

In this study, we measured and evaluated MTF and 1st-order diffraction efficiency of one-dimensional LC devices with a pixel-pitch of 1 to 10μm.

1st-order diffraction efficiency of the FLC was much larger than that of the NLC for less than 2μm pixel-pitch, which was attributed to the sharp transmittance distribution of the black/white pixel boundary.

It should be noted that the FLC light modulator has potential for solving the narrow viewing zone issue with better diffraction efficiency for holographic application, which may contribute brighter holographic images.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## REFERENCES


[1] D. Gabor, “A new microscopic principle,” Nature, 161 (4098), 777-778 (1948).

[2] E. N. Leith and J. Upatnieks, “Reconstructed wavefronts and communication theory,” J. Opt. Soc. Am.,52(10):1123–8 (1962).

[3] L. Onural, F. Yaras, H. Kang, “Digital Holographic Three-Dimensional Video Displays,” Proc. IEEE, vol. 99, no. 4, pp. 576-589, (2011).

[4] J. Park, K. Lee, Y. Park, “Ultrathin wide-angle large-area digital 3D holographic display using a non-periodic photon sieve,” Nature communications, 10:1304 (2019)

[5] A. K. Abeeluck, A. Iverson, H. Goetz and E. Passon, “High-Performance Displays for Wearable and HUD Applications,” SID 2018 Digest, 768-771 (2018).

[6] Y. Isomae, Y. Shibata, T. Ishinabe, H. Fujikake, “Experimental study of 1-um-pitch light modulation of a liquid crystal separated by dielectric shield walls formed by nanoimprint technology for electronic holographic displays,” Opt. Eng. 57(6), 061624 (2018)

[7] Y. Isomae, S. Aso, J. Shibasaki, K. Aoshima, K. Machida, H. Kikuchi, T. Ishinabe, Y. Shibata, H. Fujikake, “Superior spatial resolution of surface-stabilized ferroelectric liquid crystals compared to nematic liquid crystals for wide-field-of-view holographic displays,” JJAP 59, 040901 (2020)

[8] K. Chida, Y. Isomae, T. Ishinabe, Y. Shibata, H. Fujikake, “Effect of Non-uniformity of Optical Phase Modulation in Liquid Crystal Devices on Holographic Image Quality,” IDW’19, ISSN-L 1883-2490/26/0212 (2019)

[9] Y. Isomae, Y. Shibata, T. Ishinabe, H. Fujikake, “Optical Phase Modulation Properties of 1μm-Pitch LCOS with Dielectric Walls for Wide-Viewing-Angle Holographic Displays,” SID 2016, ISSN 0097-966X/16/4703-1670 (2016)

[10] B. Kress, P. Meyrueis, *Digital diffractive optics*, K. Kodate et. al (translation), Maruzen & Wiley (2005)

[11] T. Ohkoshi, *Holography*, IEICE (1977)

[12] P.A. Blanche, *Field guide to holography*, SPIE (2014)