Evaluation and Analysis of Light Diffraction from One-dimensional Liquid Crystal Devices Using Pixel Pitches more than 1 μm

Junichi Shibasaki[†] (member), Kenichi Aoshima[†] (member), Shintaro Aso[†] (member),
Nobuhiko Funabashi[†] (member), Takahiro Ishinabe^{††} (member), Yosei Shibata^{††} (member),
Hideo Fujikake^{††} (member) and Kenji Machida[†] (member)

Abstract We compare the diffraction characteristics of ferroelectric (FLC) and nematic liquid crystal (NLC) devices with one-dimensional stripe patterns of 1–10 μm pixel pitches. The polarizing micrographs show pixel boundaries of black/white pixels blur as the pixel pitch becomes smaller. The blur of NLC is more remarkable than that of FLC. The first-order diffraction efficiency of NLC remains constant for the pixel pitch of 4–10 μm and sharply decreases for the pixel pitch of $< 2 \mu\text{m}$. By contrast, the FLC efficiency decreases with the pixel pitch decrease from 10 to 4 μm and remains constant for the pixel pitch of $< 3 \mu\text{m}$. The FLC efficiency (5.5%) is four times larger than that of NLC (1.4%) with a 1 μm pixel pitch. The Fourier transform calculation shows the efficiency degradation of FLC is caused by the blur at the pixel boundary, whereas that of NLC caused by the blur and contrast deterioration.

Keywords: Holographic Display, Spatial Light Modulator, Ferroelectric Liquid Crystal, Diffraction Efficiency, Narrow Pixel Pitch.

1. Introduction

Holography has attracted attention because of its potential for ultimate three-dimensional (3D) display capability. It can physically reconstruct the same light from an object and satisfies all visual cues for autostereoscopic vision, such as motion parallax, binocular disparity, vergence and accommodation. Moreover, it enables natural autostereoscopic displays [1–4].

3D holographic images are reconstructed from hologram patterns displayed on a spatial light modulator (SLM). However, the pixel pitch of conventional SLMs may not be sufficiently small for holography images with a wide viewing zone angle. The viewing zone angle is described by the equation, $\theta = 2 \sin^{-1} (\lambda/2p)$, where λ is the light wavelength and p is the pixel pitch of the display [5]. The latest commercial SLMs with a 3 μm pixel pitch generate 3D holographic images with a narrow viewing zone angle of 12° for displays [6]. An SLM with narrow pixel pitch of $< 1 \mu\text{m}$ is required to realize a viewing zone angle wider than 30° , which may open up a

new application (e.g., a personal terminal with 3D holographic images) [3].

Liquid crystal (LC) devices with a narrow pixel-pitch have recently been actively studied for holographic applications for smaller crosstalk with dielectric wall structures [7–10]. The pixel structure of LC SLMs is very simple having electrodes and LC layers compared to the pixel structure of DMD having electrodes, micromirrors and some mechanical systems to control micromirrors [21, 22]. This simple structure is very important for the high applicability for narrow pixel pitch. Isomae et al. showed that ferroelectric liquid crystal (FLC) could achieve a higher resolution compared to nematic liquid crystal (NLC) with narrow pixel pitches [8]. Chida et al. have showed that blurring the black/white pixel boundaries affects the decrease of the first-order diffraction efficiency on simulations with NLC devices [10].

The first-order diffraction efficiency is one of the most important factors for the quality of 3D holographic images. Thus, the quantitative evaluation of the first-order diffraction efficiency of the FLC device with almost 1 μm pixel pitch is very important for SLM devices in 3D holographic displays. The first-order diffraction efficiency is one of the most important factors for the quality of 3D holographic images. So the light diffraction

Received March 15, 2021; Revised May 21, 2021; Accepted June 7, 2021

[†] Japan Broadcasting Corporation
(Tokyo, Japan)

^{††} Tohoku University
(Miyagi, Japan)

efficiency should be as large as the theoretical value without crosstalk of the black and white pixels, although the efficiency decreased with an increase in crosstalk of the black and white pixels [8, 10]. We aimed to verify the effect of diffraction efficiencies of FLC and NLC devices with narrow pixel pitches.

Although it is desirable to have SLMs for 3D holographic images that can modulate both the phase and amplitude modulations at each pixel, it is very difficult to realize them using a single SLM device [3]. Phase modulation cannot display high-quality images without optimizations for several calculations [20]. Whereas, amplitude modulation can obtain high-quality images without optimizations. It is also easy for building experimental systems, where SLMs for the amplitude modulation are established in existing display devices, such as projectors.

In this study, we compare the first-order diffraction efficiency of amplitude-modulated one-dimensional (1D) patterns using FLC and NLC devices with 1–10 μm pixel pitches and quantitatively evaluate the pixel pitch dependence on modulation transfer function (MTF) or the first-order diffraction efficiency.

2. Experiments

2.1 Fabrication of 1D LC Devices

We fabricated 1D LC devices and illustrate them in Fig. 1. Transparent stripe electrodes made of indium-zinc-oxide (IZO) with 20 nm thickness were arranged on the glass substrate and fabricated with electron beam lithography and the ion beam milling process. The stripe electrodes were alternately connected to Ag (40 nm) pad electrodes 1 and 2. This structure enabled two independent driving

Fig.1 Schematic illustration of a fabricated 1D LC device: (a) perspective and (b) cross-sectional views.

Table 1 Pixel pitches of the fabricated 1D LC devices.

Pixel Pitch [μm]	1.0	1.5	2.0	3.0	4.0	5.0	6.0	10	Plane
-------------------------------	-----	-----	-----	-----	-----	-----	-----	----	-------

voltages to be applied to the adjacent electrodes. The stripe electrode was arranged in a $500 \times 600 \mu\text{m}$ area, which was larger than the laser spot size, for an accurate measurement of the diffraction efficiency.

Figure 1(b) shows the cross-sectional view of the fabricated device. Alignment films (AL-1254; JSR Co.) were spin-coated on the stripe and common electrodes. 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 (whose tilt angle is 22.5°) was sealed between the stripe and the counter common electrodes. The LC layer thickness was controlled to 1 μm using sealant containing 1- μm -sized spacer beads. The FLC layer structure was a surface-stabilized FLC (SSFLC), in which the FLC helical structure was unwound by thinning the LC layer [8]. Table 1 shows the pixel pitches of the fabricated 1D LC devices ranging from 1.0 to 10 μm . Then the width of 1D stripe electrodes are designed to be 80% width of pixel pitches.

2.2 Optical Setup for the Diffraction

Measurements

Figure 2 shows the optical system used to measure the diffracted light from the fabricated LC devices.

As shown Fig. 2, the He-Ne laser, with 632.8 nm wavelength entered the LC device through a polarizer and a lens with which the laser spot focused into the area where the stripe electrodes were fabricated. The 1D stripe patterns of LC devices were along the x-axis. The LC alignment direction in LC devices was along the y-axis as shown the arrow beside the LC device in Fig 2. We measured the intensity of the diffracted light from

Fig.2 Optical system for measuring the diffracted light.

Table 2 Polarization directions of the polarizer and analyzer.

LC Device	Polarizer	Analyzer
FLC	22.5°	112.5°
NLC	45.0°	135.0°

the LC device through an analyzer with a photodiode detector (PH100-Si-HA-OD1-D0; Gentec-EO). The polarization angles of the polarizer and analyzer were shown in Table 2. As for the NLC devices, the polarization direction was 45 degree from the LC alignment direction. As for the FLC devices, the polarization direction was same as one of the directions of the binary orientation in the SSFLC. The polarization directions of both analyzers were orthogonal to that of the polarizers, respectively. The first-order diffraction efficiency is defined in Eq. (1):

$$\eta = 100 \times \frac{I_{1st}}{I_{in}} \quad (1)$$

where, I_{1st} is the light intensity of the first-order diffracted light and I_{in} is that of the incident light. I_{in} is defined as the intensity of light that passes through the LC devices with plane electrodes (not with stripe electrodes) measured with the polarization direction of the analyzer oriented in the same direction as the polarization direction of the polarizer in Table 2.

3. Results

3.1 Polarizing Micrographs of the LC Devices

Figure 3 shows the polarizing micrographs of the FLC and NLC devices with plane electrodes. The applied driving voltage is described below. The common electrode was 0 V, and the counter plane electrode was DC + 5 V for the FLC device. Meanwhile, the common electrode was 0 V, and the counter plane electrode was 5 V 1 kHz alternating voltage for the NLC device.

As for the FLC devices, the direction of the polarizer is aligned to one of the tilted angles of the FLC molecules. The black image with DC +5V shows that the light cannot penetrate through the crossed analyzer (Fig. 3(a)). The white image with DC -5V shows that the light whose polarization direction is rotated by the FLC molecules can penetrate through the analyzer (Fig. 3(b)). In contrast, as for the NLC devices, the light cannot penetrate through the analyzer with applied voltage because the E7 molecules align perpendicular to electrodes and do not affect the polarization direction of the incident light (Fig. 3(d)). The light can penetrate

Fig.3 Polarizing micrographs of the LC devices with plane electrodes. The crossed arrows indicating the polarizer and analyzer angles of the microscope: (a) FLC with +5V, (b) FLC with -5V, (c) FLC with 0V, (d) NLC with Alternate 5V, (e) NLC with 0V

Fig.4 Polarizing micrographs: (a) FLC device applied DC ± 5 V, (b) NLC device applied 5 V 1 kHz alternating voltage. The crossed arrows indicating the polarizer and analyzer angles of the microscope. (c) LC molecular alignments and simulated electric potential and equipotential lines.

through the analyzer without applying voltage because the molecules align parallel to the electrodes and rotate the polarization plane (Fig. 3(e)).

Both the FLC and NLC devices applied a horizontally uniform driving voltage from the plane electrodes. Some horizontal wrinkles were observed at the arrows in Fig. 3, especially in the FLC device. These wrinkles may be caused by the LC orientational disorder arising from the uniformity in the alignment film caused by the rubbing process.

Figure 4 shows the polarizing micrographs of the fabricated LC devices. Figure 4(a) depicts the images of the FLC devices when the common electrode was 0 V, when pad electrode 1 was DC + 5 V, and when pad electrode 2 was DC -5 V. Figure 4(b) depicts the images of the NLC devices when the common electrode and pad electrode 1 were 0 V and when pad electrode 2 was 5 V 1 kHz alternating voltage. Figure 4(c) depicts the images of the LC molecular alignments and the simulated electric potential and equipotential lines with 1 and 5 µm pixel pitches.

Wrinkle noises were observed for most of the area in the FLC devices with 3–5 μm pixel pitches (not much seen for those with 6–10 and 1–2 μm) as shown in Fig. 4(a). Although the origin of the wrinkle is not clear, we think that the defect in the molecular alinement may be attributed because the wrinkle direction is parallel to the rubbing direction. And those defect-based noises may be originated to our limited fabrication facility or technique. The micrographs showed that the black/white boundaries gradually blur with the decreasing pixel pitches. The blur of NLC was more noticeable than that of FLC.

3.2 Evaluation of MTF

We calculated the MTF to investigate the high-resolution property of the fabricated LC devices. The values were calculated from the polarizing micrographs shown in Fig. 4, which are defined in Eq. (2):

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

Here, $I_{\max}$ and $I_{\min}$ are the maximum and minimum transmittance values after acquiring the cross-sectional profile from Fig. 4 by a commercial image processing software of ImageJ, respectively.

Figure 5 depicts that the MTF of the FLC remained constant for almost all pixel pitches, whereas that of the NLC sharply decreased where the pixel pitches are smaller than 2 μm .

3.3 Diffracted Light Distribution

We observed the diffracted light from the FLC and NLC devices with 1–10 μm pixel pitches.

Figure 6 shows photographs of the diffraction patterns. Panel (a) illustrates that of the FLC devices, while panel (b) depicts that of the NLC devices. The 2nd (or 4th) diffraction spots were not observed in the FLC devices but were observed in the NLC devices. See the diffraction patterns of the FLC and NLC devices with

Fig.5 Relationship between the MTF values and the pixel pitches of the LC devices.

Fig.6 Photographs of the diffraction patterns of the (a) FLC and (b) NLC devices.

Fig.7 First-order diffraction angles.

6.0 μm pixel pitch in Fig. 6. We did not comprehend this difference very well, but the difference in the LC modes (i.e., the difference between the electrically controlled birefringence mode for the NLC and the SSFLC mode may affect it.

Figure 7 shows first-order diffraction angles. The two types of dots denote the experimental values. The solid lines are the theoretical values. The experimental values were calculated by Eq. (3), whereas the theoretical values were calculated by Eq. (4).

$$\theta = \arctan(x/L) \quad (3)$$

$$\theta = \arcsin(\lambda/d) \quad (4)$$

Here, x is the distance between the first-order diffraction spot and the zeroth-order diffraction spot; L is the distance between the LC device and the screen fixed to 320 mm; λ is the light wavelength (632.8 nm); and d is the period of the black/white stripe patterns twice the pixel pitch in this experiment.

The first-order diffraction angles of the experimental values of the FLC and NLC devices were in good agreement with the theoretical values for all pixel pitches. This result shows that 1D LC devices using the NLC and FLC were fabricated as designed with a pixel

Fig.8 First-order diffraction efficiencies of the FLC and NLC devices with pixel pitch ranging from 1.0 to 10 μm.

pitch ranging from 1.0 to 10 μm.

3.4 Evaluation of the Diffraction Efficiencies

Figure 8 shows the first-order diffraction efficiencies. The blue and orange dots indicate the average values of multiple measurements for each pixel pitch. The error bars were from the maximum to minimum values in the observations. The solid lines are a guide of the eyes.

The diffraction efficiency of the FLC device gradually decreased with the pixel pitch narrowed in 10–4.0 μm pixel pitches and remained constant at ~5.5% for the pixel pitches < 4.0 μm. Meanwhile, that of the NLC remained constant at ~9% with 4–10 μm pixel pitches but decreased to 1.4% at 1.0 μm pixel pitch. The diffraction efficiency of the FLC device was approximately four times larger than that of the NLC device with a 1 μm pixel pitch.

The diffraction efficiency of the NLC device was larger than that of the FLC device with 3–6 μm pixel pitches. One of the main reasons for the low diffraction efficiencies of the FLC devices is the horizontal wrinkle noises in Fig. 4(a). Both the lower efficiencies and the wrinkle noises in the FLC devices noticeably appeared with 3–5 μm pixel pitches.

4. Discussion

Though we tried to compare our result to previous reports, there are no reports about the diffraction efficiency of FLC and NLC using amplitude modulation. Therefore, we tried to compare our result to ideal values calculated by Fourier transform [11–16].

Table 3 shows the relationship between the light modulation properties of the LC devices and the first-order diffraction efficiencies. The ideal stripe patterns and the ideal first-order diffraction efficiencies in Table 3 were calculated from the ideally assumed transmittance distributions shown in Table 3 (i.e., square wave, sinusoidal, and sinusoidal-2).

Table 3 Computed diffraction efficiency from the ideal intensity distributions.

	Ideal Pattern Images	Ideal Pattern Distributions	Ideal First-order Diffraction Efficiency
Square wave			10.13%
Sinusoidal			6.25%
Sinusoidal-2			2.72%

The "ideal first-order diffraction efficiency" in Table 3 was calculated from the transmittance distributions of the "ideal pattern images" shown in Table 3. by Fourier transform [11–16]. The square wave is expressed as

$$f(x) = \begin{cases} a & (t \leq x < t + 0.5) \\ b & (t + 0.5 \leq x < t + 1) \end{cases} \quad t = 0, 1, 2, \dots \quad (5)$$

and the first-order diffraction efficiency is given by

$$\eta_1 = \left| \frac{a - b}{\pi} \right|^2, \quad (6)$$

where a is the maximum value of the amplitude of distributions, b is its minimum value, and η_1 is the first-order diffraction efficiency. Note that the aperture ratio is 50% as in Eq. (5). The sinusoidal is expressed as follows in the same manner:

$$f(x) = \frac{a - b}{2} \cdot \sin \theta + \frac{a + b}{2}, \quad (7)$$

and the diffraction efficiency is given by

$$\eta_1 = \left| \frac{a - b}{4} \right|^2. \quad (8)$$

The sinusoidal-2 wave shown in Table 3 is defined as a sinusoidal wave with an amplitude of 0.66 corresponding to "a - b" in Eq. (7) because the MTF of the fabricated NLC device is 0.66 at the 1 μm pixel pitch in Fig. 5.

The steep transmittance distributions (square wave) had larger first-order diffraction efficiencies than the gradual distributions (like sinusoidal). The decrease in the waveform amplitude of the transmittance distributions also led to a decrease in the diffraction efficiencies.

Figure 9 shows a comparison of the ideal values shown in Table 3 and the experimental values shown in Fig. 8 of the first-order diffraction efficiencies. The experimental values of the FLC and NLC devices were close to the ideal square wave values with a 10 μm pixel pitch; however, they became closer to the ideal sinusoidal values with the decreasing pixel pitches. Finally, the FLC became closer to the "sinusoidal" green line shown

Fig.9 Comparison of the ideal and experimental values of the first-order diffraction efficiencies.

in Fig. 9, and the NLC became closer to the "sinusoidal-2" yellow line as the pixel pitch narrowed to a 1 μm pixel pitch. Thus, the black/white blur in the pixel boundaries led to a decrease in the first-order diffraction efficiency. The lower amplitude of the transmittance distributions also led to its decrease.

5. Conclusions

This study compared the diffraction characteristics of FLC and NLC devices with 1D stripe patterns of 1-10 μm pixel pitches.

The polarizing micrographs showed that the black/white boundaries with pixels gradually blurred with the decreasing pixel pitches. This was especially remarkable in the case of the NLC. The MTF of the NLC also showed a sharp decrease of < 2 μm pixel pitches, whereas that of the FLC remained constant for all pixel pitches. The first-order diffraction angles mostly agreed on the ideal values for all pixel pitches. The first-order diffraction efficiency showed that the FLC was four times larger than the NLC with 1 μm pixel pitch. The FLC remained constant, but the NLC sharply decreased for < 2 μm pixel pitches. The experimental values compared with the ideal values showed that the FLC and the NLC had steep distributions (square wave) with a 10 μm pixel pitch, and both showed gradual distributions (like sinusoidal) with almost 1 μm pixel pitches.

The FLC devices have much better potentials than the NLC devices in terms of solving the wider viewing zone angles for holographic applications with narrow pixel pitches. Increasing the first-order diffraction efficiency is very important for 3D holographic applications. The high first-order diffraction efficiency must suppress the blur and keep steep distributions with almost 1 μm pixel pitches.

Acknowledgements

The authors would like to thank Dr. Yoshitomo ISOMAE, a former student of Tohoku University, for the fabrication and evaluation of the FLC layer and the LC alignment process.

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) Byoungcho Lee, "Three-dimensional displays, past and present," *American Institute of Physics, Phys. Today* 66(4), 36 (2013)
- 5) J. Park, et. al, "Ultrathin wide-angle largearea digital 3D holographic display using a nonperiodic photon sieve," *Nature communications*, 10:1304 (2019)
- 6) A.K. Abeeluck, A. Iverson, et. al, "High-Performance Displays for Wearable and HUD Applications," *SID 2018 Digest*, 768-771 (2018)
- 7) Y. Isomae, Y. Shibata, T. Ishinabe, H. Fujikake, "Experimental study of 1- μm -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)
- 8) 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)
- 9) Y. Isomae, Y. Shibata, T. Ishinabe, H. Fujikake, "Optical Phase Modulation Properties of 1 μm -Pitch LCOS with Dielectric Walls for Wide-Viewing-Angle Holographic Displays," *SID 2016, ISSN 0097- 966X/16/4703-1670* (2016)
- 10) 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)
- 11) B. Kress, P. Meyrueis, *Digital diffractive optics*, K. Kodate et. al (translation), Maruzen & Wiley (2005)
- 12) T. Ohkoshi, *Holography*, IEICE (1977)
- 13) P.A. Blanche, *Field guide to holography*, SPIE (2014)
- 14) Eugene Hecht, *OPTICS*, person (2017)
- 15) Joseph W. Goodman, *Introduction to Fourier Optics*, Roberts & company (2005)
- 16) K. Kodate et. al, *The numerical analysis and application of DOE*, Maruzen (2011)
- 17) C. Provenzano, P. Pagliusi and G. Cipparrone, "Highly efficient liquid crystal based diffraction grating induced by polarization holograms at the aligning surfaces," *American Institute of Physics, Appl. Phys. Lett.* 89, 121105 (2006)
- 18) Gregory P. Crawford et. al, "Liquid-crystal diffraction gratings using polarization holography alignment techniques," *American Institute of Physics, J. Appl. Phys.* 98, 123102 (2005)
- 19) James E. Harvey and Richard N. Pfisterer, "Understanding diffraction grating behavior: including conical diffraction and Rayleigh anomalies from transmission gratings," *SPIE, Optical Engineering* 58(8), 087105 (2019)
- 20) Tomoyoshi Shimobaba et. al, *Computer Holography*, CRC Press (2019)
- 21) L.J. Hornbeck, "128 x128 Deformable Mirror Device," *IEEE*(1983)
- 22) L.J. Hornbeck, "Current Status of the Digital Micromirror Device (DMD) for Projection Television Applications," *IEEE*(1993)

Junichi Shibasaki received his M.S. degree from Waseda University, Tokyo, Japan in 2015. He joined Japan Broadcasting Corporation (NHK), Tokyo, in 2015. Since 2018, he has been a researcher at NHK Science and Technology Research Laboratories. Since 2018, he has been engaged in research on a liquid crystal spatial light modulator for electro holographic displays.

Kenichi Aoshima received B.S. in physics from Chiba University, Japan in 1990, and Ph. D in engineering at Nagaoka University of Technology. He worked for Fujitsu laboratory Ltd. from 1990-2003. He also worked at Stanford University as a visiting scholar from 2000 to 2002, where he has started a study of Spin electronics. He moved to Japan Broadcasting Corporation (NHK) in 2003. Since then he has been working for Magneto-optical spatial light modulator.

Shintaro Aso received his M.S. degree from Tokyo University, Tokyo, Japan, in 2010. He joined Japan Broadcasting Corporation (NHK), Tokyo, in 2010. Since 2014, he has been a researcher at NHK Science and Technology Research Laboratories. First, he was engaged in research on an ultra-high-density magneto-optical spatial light modulator (MO-SLM). Since 2017, he has been engaged in research on a liquid crystal SLM (LC-SLM) for electro-holographic displays.

Nobuhiko Funabashi received B. E., M.S., and Ph.D. degrees in Physical Electronics from Tokyo Institute of Technology, Tokyo, Japan in 1999, 2001, and 2011. In 2001, he joined Japan Broadcasting Corporation (NHK). Since then, he has been NHK Science and Technology Research Laboratories. He has been working for Magneto-optical spatial light modulator.

Takahiro Ishinabe received his B.S., M.S., and Ph. D. degrees in Electronic Engineering from Tohoku University, Sendai, Japan, in 1995, 1997 and 2000, respectively. From 2000 to 2002, he was a Research Fellow of the Japan Society for the Promotion of Science and from 2003 to 2012, he was an Assistant Professor, and since 2013, he has been an Associate Professor in the Department of Electronics, Graduate school of Engineering, Tohoku University. He has also been a Visiting Professor in the CREOL, The College of Optics and Photonics, University of Central Florida from 2010 to 2011. He has been performing a research on advanced liquid crystal displays such as wide viewing angle LCD, reflective full-color LCD, field sequential color LCD and flexible LCD. He is a Fellow of Society for Information Display since 2020.

Yosei Shibata received his PhD degree in engineering from Tokyo Institute of Technology, Japan, in March 2013. Then he joined the National Institute of Advanced Industrial Science and Technologies (AIST, Japan) as a postdoctoral position. In October 2015, he joined the Department of Electronics of Tohoku University as an Assistant Professor. His research interests are control of molecular ordering and its device applications. He received an M&BE7 student poster award in 2013, JSAP young scientist presentation award in 2015, ITE frontier award in 2019, JLCS Young Researcher's Award in 2020, and Tokin-foundation Industrial Achievement Award in 2021.

Hideo Fujikake received M.E and Ph.D. degrees from Tohoku University, Japan, in 1985 and 2003, respectively. In 1985, he joined Japan Broadcasting Corporation (NHK). In 1988-2012, he was with NHK Science and Technology Research Laboratories. Since 2012, he has been a professor at Department of Electronic Engineering, Tohoku University. He received Niwa-Takayanagi Best Paper Awards from ITE in 2003 and 2009, Best Paper Award from IEICE in 2001 and 2017. His current interests are concerned with flexible liquid crystal displays and functional optical devices including holography. He also served as a Program Chair in International Display Workshops in 2017, a Japan Chapter Chair in IEEE Consumer Electronics Society in 2012-2014, and a Vice President of Japanese Liquid Crystal Society in 2015-2016. ITE, IEICE and JSAP fellows.

Kenji Machida received the M.S. degree in materials science and engineering from Hiroshima University, Hiroshima, Japan in 1993, and the Ph.D. degree in electronics and information engineering from Tokyo University of Agriculture and Technology, Tokyo, Japan, in 2006. In 1993, he joined Japan Broadcasting Corporation (NHK). Since 1995, he has been engaged in research on magnetic recording, spintronics, and optical devices at NHK Science and Technology Research Laboratories.