

Paper

Fabrication of LC-Polymer Films Separating Thick LC Layer for Reflect Arrays

Tomoya Haneda†, Takahiro Ishinabe† (member), Yosei Shibata†, Hiroyasu Sato†, Qiang Chen† and Hideo Fujikake† (fellow)

Abstract In this paper, we focused a multi-layer structure in which the LC layers are divided by LC-polymer films to stabilize the alignment of thick LC used in LC reflect arrays and to achieve a fast response time. We also fabricated LC-polymer films that divides the LC layers and evaluated its alignment state. As a result, it was revealed that the LC-polymer film has the ability to align the LC. This is expected to stabilize the alignment of the thick LC and speed up the response time.

Keywords: nematic LC, LC-polymer film, alignment stabilization, reflect arrays.

1. Introduction

In recent years, Beyond 5G have the advantage of enabling faster data transmission rates and simultaneous connection of a large number of terminals. Therefore, there is an urgent need to develop communication technology[1)2)]. The establishment of this communication technology is expected to lead to the development of autonomous driving and the realization of real-time remote medicine. In Beyond 5G, however, higher frequency bands such as microwave and millimeter wave bands are applied to increase radio communication speeds. As shown in Fig. 1, diffraction is less likely to occur in buildings such as skyscrapers. Therefore, the small coverage area has been a problem. Hence, reflect arrays (RA) are attracting attention as a method that can provide services over-the-horizon communication[3)4)]. Fig. 2 shows a conceptual diagram of reflect arrays.

Reflect arrays consist of periodically aligned reflectors as shown in Fig. 2. By changing the dimensions of each of the periodically aligned array elements, the phase of the scattered wave from each array element changes. High gain is achieved by controlling the phase so that the scattered waves are in-phase in the desired direction. Furthermore, the beam direction can be changed arbitrarily by freely controlling the phase of each

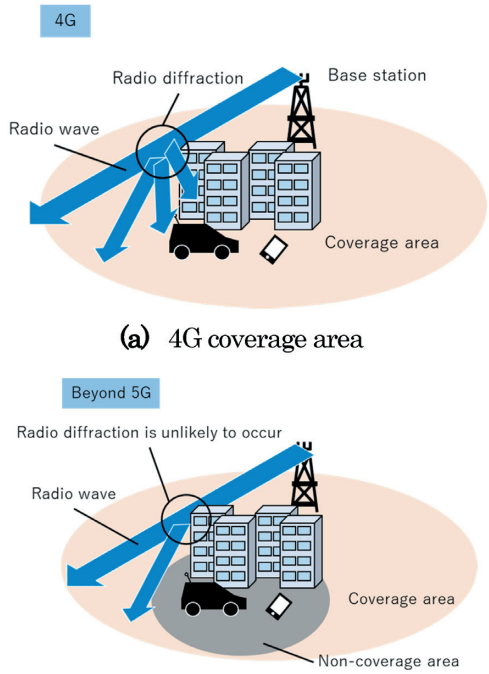

Fig.1 4G and Beyond 5G coverage area.

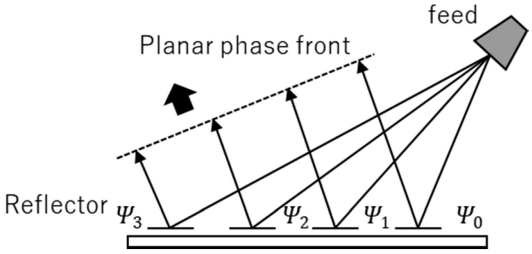

Fig.2 The reflection of radio wave.

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† Department of Electronics, Graduate School of Engineering, Tohoku University
(Sendai, Japan)

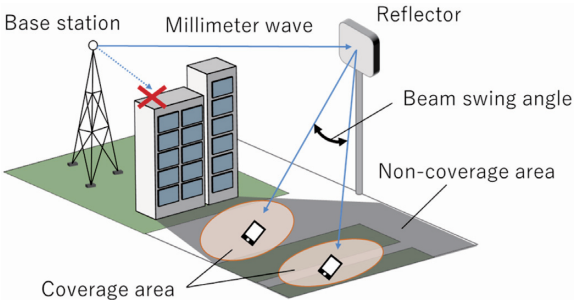


Fig.3 Application for IRS.

element. Therefore, it is expected to be applied to IRS (= Intelligent Reflecting Surface), which can direct the incoming radio waves to a specific direction[5] (Fig. 3).

As a typical example of phase control, a device that uses the change in electrical length caused by diode switching has been reported[6][7]. However, in the case of using a diode for the reflector, its rectification characteristics distort the current, which may cause harmonics. These harmonics may cause interference in other frequency bands. In the case of diodes using semiconductors with electrical resistance, the loss is expected to increase in the high-frequency band. In addition, the problems of complicated circuits and high cost have been reported[8]. On the other hand, when LC, which is a dielectric, is used, the loss due to the change in polarization of the LC molecules is considered to be generated. However, further improvement in loss in the high-frequency band is expected, as low-loss LC is also under development[9].

For these reasons, we focused on phase control using molecular alignment changes in nematic LC. Fig. 4 shows the basic structure and principle of operation of a reflect arrays unit cell using thick LC. Nematic LC has anisotropic dielectric constant, and its molecular alignment can be freely controlled by low-frequency AC voltage. Therefore, it is possible to control the beam by filling LC directly under the dielectric substrate and changing the effective length of each element by controlling the applied low-frequency AC voltage[10].

However, when applying a LC layer thickness of a few μm, which has been cultivated in ordinary LCDs, the short electrical length relative to the wavelength of the radio wave results in the small phase shift. Generally, longer electro length, that is, a thicker LC layer, is needed to increase the effect of the dielectric constant change due to the LC. In addition, when the LC layer is made thinner, the electric field tends to concentrate in the LC layer. Therefore, there is concern about increasing loss. For these reasons, thicker LC layers are needed. On the

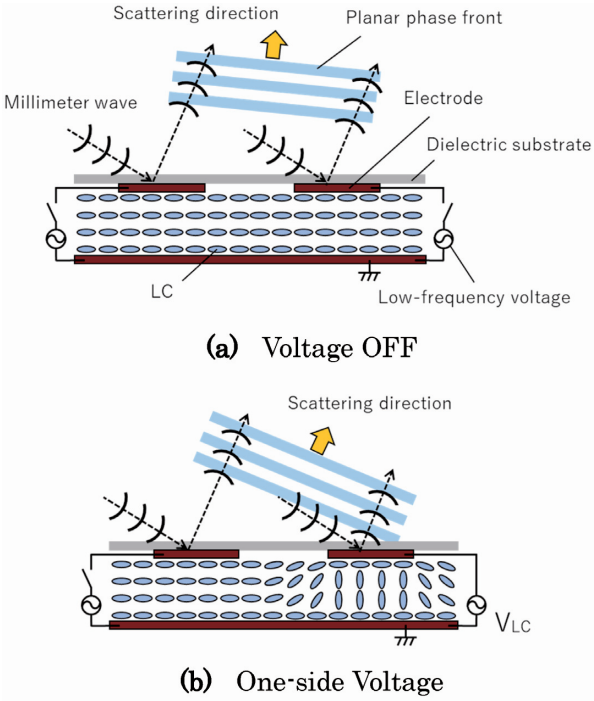


Fig.4 Reflect Arrays using LC (unit cell).

other hand, when the LC layer is thick, the time required for the LC molecules to return to their original alignment state due to their own elasticity when the applied voltage is removed is long. Suppressing losses in the microwave and millimeter wave bands requires LC layer thickness of approximately 100 μm or more, resulting in a slow fall response[11]. To improve the fall response, methods using PDLC[12] (polymer dispersed LC) and PSLC[13] (polymer-stabilized LC) have been reported. However, the high percentages of polymers in the LC layer of these devices make it difficult for LC molecules to move because they are constrained by the microscopic polymers. As a result, the dielectric anisotropy is reduced, and the amount of phase shift is reduced.

Therefore, we focused on the method of separating thick LC layers into multiple layers to both improve response speed and secure the amount of phase shift. As a previous study, the LC lens using an aligned polymer film has been reported to improve the response time of thick LC[14]. However, the polymer film used in this structure is a mixture of LC and polymeric material. Therefore, there is a possibility that LC may seep outward, and that the hardness (physical stability) may be limited due to the presence of LC, which is a liquid. To improve the physical stability of polymer films, we considered fabricating polymer films using only LC polymers (hereinafter referred to as "LC-polymer film"). In this report, we have fabricated it and evaluated its alignment state.

2. Principle of Fast Response with Multi-layer Structure

Fig. 5 shows a diagram of a multi-layer structure in a LC cell. As shown in Fig. 5, the LC layers are divided in the direction of thickness using mixed films of LC and polymer materials.

In general, it is known that the fall response time of LC molecules is given by equation (1), where is the viscosity coefficient[15]. From equation (1), the fall response time is proportional to the square of , the thickness of the LC layer (is the elasticity constant). Therefore, thinner each LC layers are expected to speed up the fall response. It is important to fabricate LC-polymer films to establish this structure.

$$\tau_d = \frac{\eta}{\pi^2 k} d^2 \tag{1}$$

Regarding the driving voltage, it is expected to be higher than that of a normal LC cell because of the inserted LC-polymer films. Fig. 6 shows the equivalent circuit of a multi-layer LC cell approximated as a series circuit of two capacitors in the LC-polymer films and the LC layers. Where, and are the composite capacitance of LC-polymer films and LC layers, and are the applied voltage to LC-polymer films and LC layers, and are the dielectric constant of LC-polymer films and LC layers, and are the total thickness of each layer, respectively. In addition, the voltage applied throughout (drive voltage) is , and the surface area of electrodes is . In this case, the voltage applied to the entire LC layer is given by Equation (2).

$$V_{LC} = \frac{C_p E_0}{C_p + C_{LC}} = \frac{E_0}{1 + \frac{\varepsilon_{LC} d_p}{\varepsilon_p d_{LC}}} \tag{2}$$

As shown in equation (2), the voltage applied to the LC layers of a multi-layer LC cell is lower than the voltage applied throughout. Therefore, the required driving voltage increases. However, if the dielectric constant of the LC-polymer film can be increased or its thickness can be reduced in the future, a lower driving voltage is expected.

In addition, the thinner each LC layer is, the stronger the electric field generated there, but this effect is offset by the anchoring from the interface[16]. Therefore, regarding the threshold voltage of the LC response, the value is considered to be the same as that of a LC cell without LC-polymer films.

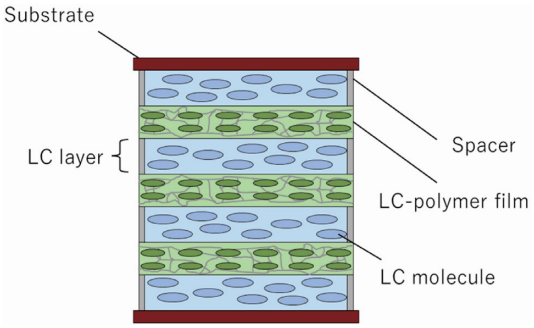


Fig.5 Structure of multi-layer LC cell.

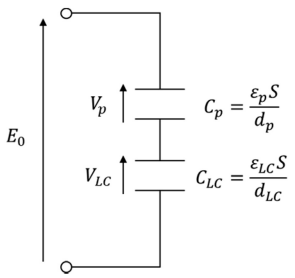


Fig.6 equivalent circuit of the multi-layer LC cell.

3. Fabrication and Evaluation of LC-polymer Film

3.1 Fabrication of LC-polymer Film

First, we fabricated the LC-polymer film for the multi-layer LC cell. UCL-011-AC1 (DIC), a polymer material (mixture of monofunctional and multifunctional monomers) that is liquid at room temperature and has excellent liquid crystalline properties, was used as the LC-polymer film. Table 1 shows details of the fabrication

Table 1 Fabrication conditions of LC-polymer films.

UV-light curable LC-monomer (Contains photoinitiator)	UCL-011-AC1 (DIC)
Alignment film	AL1254 (JSR)
Spin coating conditions	500 rpm 10 s 1500 rpm 10 s 3000 rpm 30 s
Substrate	Glass substrate (2.8 mm)
Rubbing conditions	Roller rotation speed: 500 rpm Substrate movement speed: 0.35 cm/s Roller push-in amount: 0.3 mm
UV irradiation	20 mW / cm^2 × 20 s Center wavelength: 365 nm
Spacer	25 μm

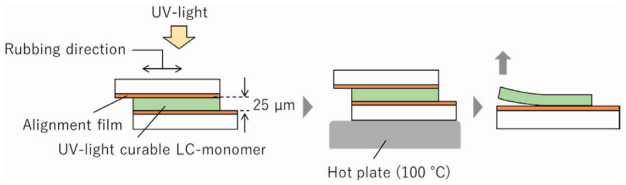


Fig.7 Procedure for fabrication LC-polymer films.

conditions of LC-polymer films and Fig. 7 shows the procedure for fabrication.

We applied the alignment film to the glass substrate by spin coating method. After that, the alignment film was formed by sintering process at 200 degrees Celsius for 1 hour. The alignment film was rubbed and an empty cell with a thickness of 25 μm was fabricated with two upper and lower substrates with the rubbing direction oriented in the anti-parallel direction. The empty cell was filled with UV-light curable LC monomer and subjected to UV polymerization. The film was then heated to 100 degrees Celsius on a hot plate, the upper substrate was removed, and the film was peeled off.

3.2 Evaluation of LC-polymer Film Alignment

The polymers used in this study are alignment materials, and are expected to align according to the rubbing direction of the alignment film. Therefore, we evaluated the alignment state of the LC-polymer film. Fig. 8 shows the alignment state of UV-curable LC-monomer under Crossed-Nicol polarizers before UV polymerization during the fabrication process.

The dark state was observed at an angle of 0 deg. in the rubbing direction relative to the transmission axis. This confirms that the LC monomers have a parallel alignment along the rubbing direction before UV polymerization. Next, the alignment state of the LC-polymer film after UV polymerization is shown in Fig. 9.

From Fig. 9 (a), The dark state was observed at an angle of 0 deg. in the rubbing direction relative to the transmission axis. The fabricated LC-polymer film was also confirmed to exhibit parallel alignment along the rubbing direction generally. However, a slight coloration was observed in the dark state. This result means that there are areas where the alignment of the polymer is not aligned with the transmission axis. This is thought to be due to polymer shrinkage during UV polymerization, resulting in the formation of polymers that do not follow the rubbing direction. Comparison of Fig. 8(b) and Fig. 9(b) shows that the polymerization changed the state from white to colored. In this experiment, it is unlikely that the thickness of the glass substrate changed because it is thick and not easily deformable. Therefore, a

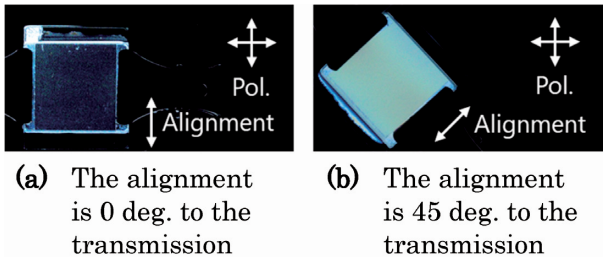


Fig.8 Alignment state of UV-light curable LC-monomer before UV polymerization.

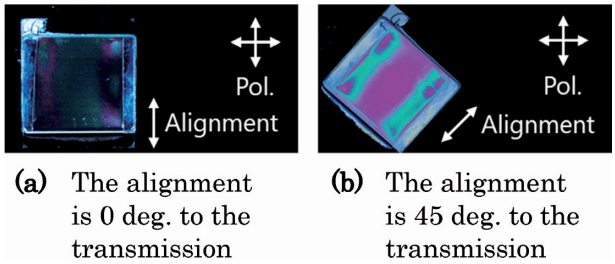


Fig.9 Alignment state of the LC-polymer film after UV polymerization.

Table 2 Fabrication conditions of LC-polymer film cell.

LC	E-7 (LCC)
Substrate	Glass substrate (2.8 mm)
Spacer	50 μm

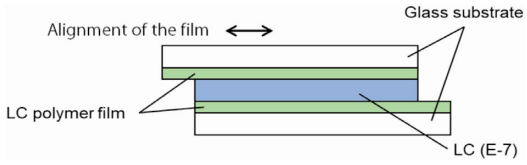


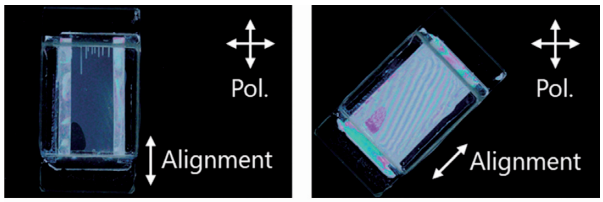
Fig.10 The cell structure of LC-polymer film cell.

decrease in birefringence is thought to be the cause. This would suggest that the orderliness of the polymer decreased during polymerization.

Next, we conducted experiments to confirm whether or not the LC-polymer film has the ability to regulate the alignment of the LC. The fabrication conditions are shown in Table 2. The empty cell with a thickness of 50 μm was fabricated by laminating the substrates after removal of the upper substrate. Then, LC was injected to fabricate the LC-polymer film cell as shown in Fig. 10.

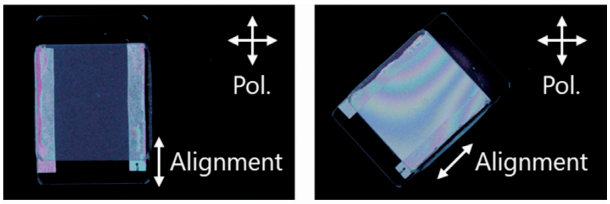
Fig. 11 shows the results of observation of the LC-polymer film cell under Crossed-Nicol polarizers. In addition, to show the comparison with a normal LC cell fabricated with an alignment film, Fig. 12 shows the observation results of the rubbed parallel-aligned LC cell (50 μm) under Crossed-Nicol polarizers.

Comparison of Fig. 11 and Fig. 12 shows that the LC-



(a) The alignment is 0 deg. to the transmission axis (b) The alignment is 45 deg. to the transmission axis

Fig.11 Alignment state of LC-polymer film cell.



(a) The alignment is 0 deg. to the transmission axis (b) The alignment is 45 deg. to the transmission axis

Fig.12 Alignment state of the parallel-aligned LC cell (50 μm).

polymer film cell exhibits the same degree of parallel alignment as the sample fabricated by rubbing. These results confirm that polymerization reduces the alignment order of the polymer compared to that before polymerization, but maintains sufficient orderliness to align the LC.

4. Conclusions

In this report, we focused a multi-layer structure using LC-polymer film to realize fast-response of the thick LC for reflect arrays. We fabricated and evaluated LC-polymer films for the realization of the multi-layer structure, and confirmed that LC-polymer films have the ability to regulate the alignment of LC. In the future, we plan to evaluate and control the anchoring strength of the LC-polymer film surface to achieve uniform alignment of LC. Furthermore, we plan to develop a method to fabricate the multi-layer LC cell using LC-polymer films.

5. Acknowledgements

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Tomoya Haneda received a B.E. degree from Tohoku University, Sendai, Japan, in 2021. He is a Master's student in the Department of Electronic Engineering at the Graduate School of Engineering, Tohoku University. His research interest is the Alignment Stabilization of Thick Nematic LC Layer using LC-Polymer Films for Millimeter Wave Reflect Arrays.

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 sequentialcolor LCD and flexible LCD.

Yosei Shibata received M. E. degree from Yamagata University, Yamagata, Japan, in 2010, and the Ph. D. 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 Research Center for Photovoltaic Technologies and Flexible Electronics Research Center. In October 2015, he joined the Department of Electronics of Tohoku University as an Assistant Professor. His research interests on molecular-ordering technique and organic crystalline devices such as organic transistors and photovoltaics. He received the Young Scientist Paper Award from Japan Society of Applied Pysics (JSAP) in 2015 and Japan Liquid Crystal Society (JLCS) in 2020.

Hiroyasu Sato received the B.E. and M.E. degrees from Chuo University, Tokyo, Japan, in 1993 and 1995, respectively and the D.E. degree from Tohoku University, Sendai, Japan, in 1998. He is presently an Assistant Professor with the Department of Electrical Communications, Tohoku University. His research area of interests is the experimental study of electromagnetic waves, computational electromagnetics, antennas in plasma, antennas for plasma production, broadband antennas, wireless power transfer and active/passive millimeter wave imaging. He received the 1th Place of the Best Paper Award from the International Symposium on Antennas and Propagation (ISAP) in 2017. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Qiang Chen received the B.E. degree from Xidian University, Xi'an, China, in 1986, the M.E. and D.E. degrees from Tohoku University, Sendai, Japan, in 1991 and 1994, respectively. He is currently Chair Professor of Electromagnetic Engineering Laboratory with the Department of Communications Engineering, Faculty of Engineering, Tohoku University. His primary research interests include antennas, microwave and millimeter wave, electromagnetic measurement and computational electromagnetics. Dr. Chen received the Best Paper Award and Zen-ichi Kiyasu Award in 2009 from the Institute of Electronics, Information and Communication Engineers (IEICE). He served as the Chair of IEICE Technical Committee on Photonics-applied Electromagnetic Measurement from 2012 to 2014, the Chair of IEICE Technical Committee on Wireless Power Transfer from 2016 to 2018, the Chair of IEEE Antennas and Propagation Society Tokyo Chapter from 2017 to 2018. He is now the Chair of IEICE Technical Committee on Antennas and Propagation. IEICE Fellow.

Hideo Fujikake received M.E and Ph.D. degrees from Tohoku University, Japan, in 1985 and 2003, respectively. In 1985, he joined the Japan Broadcasting Corporation (NHK). In 1988-2012, he worked for NHK Science and Technology Research Laboratories. From 2006, he was a visiting professor at Department of Physics, Graduate School of Science, Tokyo University of Science. Since 2012, he has been a professor at the Department of Electronic Engineering, Tohoku University. He received the Best Paper Award from the Institute of Electronics, Information and Communication Engineers (IEICE) in 2001 and 2017, the Best Paper Award from the Japanese Liquid Crystal Society (JLCS) in 2001, 2015 and 2020, the Niwa-Takayanagi Best Paper Award from the Institute of Image Information and Television Engineers of Japan (ITE) in 2003 and 2009, and the Electronics Society Award from IEICE in 2013. His current interests are concerned with flexible liquid crystal displays and functional optical devices including holography. He also served as a Japan Chapter Chair in IEEE Consumer Electronics Society in 2012-2014, a General Vice Chair of International Display Workshops from 2015-2016, and a Vice President of the Japanese Liquid Crystal Society from 2015-2016. He has been ITE, IEICE and JSAP (the Japan Society of Applied Physics) fellows.