Improvement of Response Time and Dielectric Loss in Thick Dendrimer/Liquid-Crystal Composites for Microwave-band Phase Control Applications

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ABSTRACT

For realization of phase shifters using liquid crystal (LC), we evaluated fall response time and dielectric loss of dendrimer/LC components in microwave frequency. The fall response was improved and dielectric loss was reduced by adding self-assembled dendrimer.

1 INTRODUCTION

In recent years, the massive growth of communication traffic has prompted the development of next-generation communication technology, such as fifth-generation (5G) systems. The system enables greater file capacity, higher data rates and much lower latency than that of conventional communication system. These features are useful for future progress of Internet of Things society [1] and self-driving support of automotive. To construct a communication system according to 5G standards, microwave and millimeter wave bands have been used in an attempt to improve the speed of wireless communications; however, this process has been limited by transmission loss of radio waves in the atmosphere [2]. Advances in antenna technology are necessary to achieve effective transmission, i.e., the sending and receiving of radio waves without disturbances in communications.

As the candidates of antenna for 5G communication system, the phased array antenna is promising due to its beamforming functionality. Fig. 1 shows a schematic diagram of the phased array antenna [3,4]. This antenna is composed of many antenna elements, arranged at equally spaced intervals on a plane. Radiated radio waves from each antenna element are synthesized on the basis of the Huygens–Fresnel principle, and a plane wave with directivity along a direction is formed. The phase shifters, which are connected to each antenna element, play important role of directional control of emitted radio wave. The relation between direction of radio-frequency beam (θ) and phase difference (ϕ) is given by following equation (1):

$$\varphi = d \sin\theta \qquad (1)$$

where d represents the distance between each antenna element. Therefore, continuously-modulated phase leads to control of beam toward any direction.

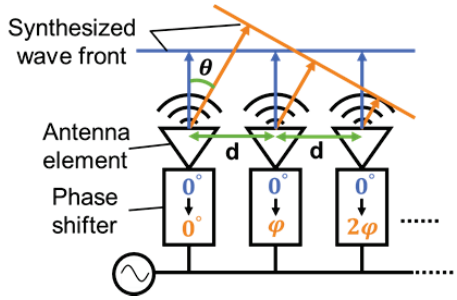

Fig. 1 Schematic view of phased array antenna

For realization of the phase shifter, we focused on application of nematic liquid crystal (LC) materials because the use of liquid crystal induces easily continuous phase modulation by applied voltage to LC. To date, the phase shifters exploiting the alignment changes of a nematic-phase liquid crystal (LC) have been examined in several studies [5-7]. However, three kinds of problems in thick LC layer for radio-frequency application should be cleared for phase shifters using liquid crystal: large dielectric loss, slow response time to voltage and high driving voltage. There are necessary reasons of thicker LC layer than LC display application. One is that the insertion loss increases remarkably in thin LC layer. Another reason is impedance matching to radio-frequency electrical field is difficult. Considering these balances, the thickness of the LC layer is required to be about 100 μm in the microwave band. Although we have been cleared that the dielectric loss was dominated by structural factor and thermal vibration in previous study [8,9], the issues for improvement of voltage response and driving voltage in thick LC was remained. The intensive studies for their improvement have been attempted so far, such as using membrane impregnated with LC [10] and polymer-dispersed LC [11]. However, the comprehensive manner to three issues in thick LC layer was not found.

In this paper, we proposed the self-assembled dendrimer/LC composites for microwave-band phase shifters. The dendrimer with lysine groups (POSS-Lys) enables stabilization of LC alignment with extremely few concentration [12], compared with photo-polymerized monomer additive. For this reason, simultaneous improvement of their three issues is expected. Here, we discuss low-frequency voltage response and radio-frequency characteristics in thick dendrimer/LC composites.

2 EVALUATION METHOD OF FALL RESPONSE TIME

In thick LC layer, fall response time (defined as time from turn-off voltage to stabilize LC alignment) become long owing to elasticity of LC molecules. Then, we describe how to evaluate the fall response time in this section. In the field of liquid crystal display, the fall response time is generally defined as the time when the amount of change rate in Δn (difference of refractive index) reaches from 0% to 90%. In this study, the fall response time of $\Delta\varepsilon$ (difference of dielectric constant) should be defined uniquely because the amount of change rate in $\Delta\varepsilon$ determines phase modulation in microwave application. According to the literature [13], Utsumi et.al reported the time changes of Δn from 0 to 90% coincides with the time that of $\Delta\varepsilon$. Therefore, Δn - time characteristics which is evaluated by optical measurements is also important for estimation of fall response time in this study. Fig.2. shows the optical evaluation system of fall response time to thick LC. Here, we fabricated rubbing-treated cells (parallel alignment) having 100um-thickness LC layer.

The transmitted light intensity I_t through birefringent material like LC can be described by equation (5) using incident light intensity I_i.

$$I_t = I_i\left\{\cos^2\chi - \sin 2\phi \cdot \sin 2(\phi+\chi)\sin^2\left(\frac{\pi\delta}{\lambda}\right)\right\} \quad (5)$$

From Fig. 2, $\chi = \pi/2$ (angle between the polarizers), $\phi = \pi/4$ (angle between the polarizer and the orientation direction of LC). Based on these values, equation (5) is deformed to equation (6).

$$I_t = I_i\sin^2(\pi\delta/\lambda) \quad (6)$$

If I_t is maximum, retardation δ is represented by equation (7). In contrast, δ of equation (8) minimize I_t value.

$$\delta = m\lambda \qquad m = 0,1,2\cdots \quad (7)$$

$$\delta = m\lambda \qquad m = \frac{1}{2},\frac{3}{2},\frac{5}{2}\cdots \quad (8)$$

We can obtain the sine-wave like I_t-time (t) characteristics. From the apexes of the measured $I_t - t$ characteristic, the $\delta - t$ characteristic was obtained. This $\delta - t$ characteristic can be converted to $\Delta n - t$ characteristics. Thickness of LC layer in the glass cell used for the measurement is made with 100 μm thick Mylar film as spacers. We used polyimide films (AL-1254, JSR Corp.) for formation of parallel alignment. Since the POSS-Lys has transition temperature from gel to sol state at 120°C in LC, the dendrimer/LC composites are injected into the glass cell at 150℃.

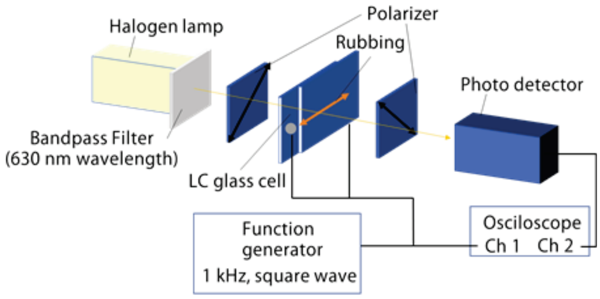

Fig. 2 Evaluation system of fall response time in thick LC cells.

3 EVALUATION OF LC RESPONSE TIME

3.1 Single-component NEMATIC LC

First, the fall time was evaluated with the cyanobiphenyl-based LC material 5CB alone without POSS-Lys. Fig. 3 shows the the δ-t characteristics in that cells.

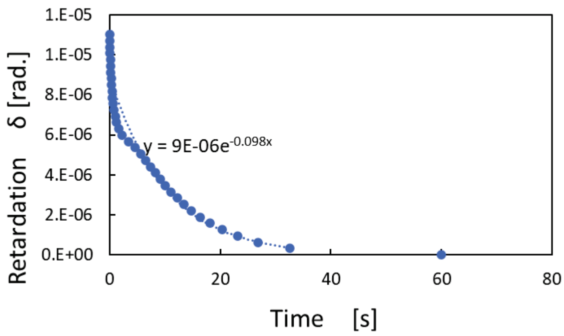

Fig. 3 $\delta - t$ characteristic of 5CB (without dendrimer)

From Fig. 3, The retardation δ decreased exponentially over time. In the case of LC layer is 100 μm, it is considered that the nematic LC only cannot be used for phase shifter because the fall response time is as slow as 21 seconds.

3.2 DENDRIMER/LC COMPOSITES

The fall response time of 5CB to which the dendrimer was added at a ratio of 0.01 wt% was evaluated. Fig. 4 shows the transmitted light intensity-time characteristics of three glass cells (No.1-3) injected POSS-Lys/5CB composites. These characteristics of three cells are well-matched. Therefore, fall response behavior in POSS-Lys/5CB composites is stabilized by additive of dendrimer. After voltage was off-state, transmitted light intensity is rapidly increased. Then, light intensity is decreased immediately. This behavior In Fig.4, while the

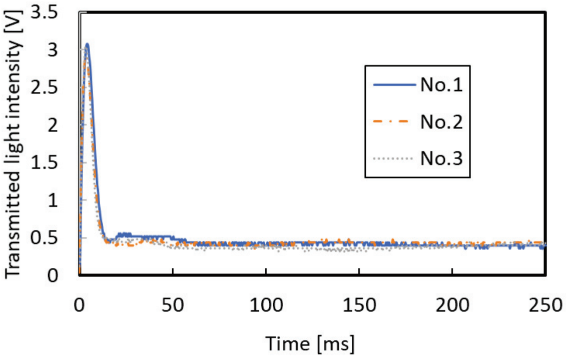

Fig. 4 $I_t - t$ characteristic of POSS-Lys/5CB components (birefringence)

transparent POSS-Lys/5CB components become scattered, the POSS-Lys/5CB components become multi-domain and a slight birefringence response induced by the alignment film is observed.

Unlike the case where the measurement was performed with 5CB alone, the sine curve according to Eq. (6) could not be observed. We considered the fact that the parallel orientation of 5CB could not be maintained by the strong anchoring force from aggregated dendrimer molecules, and LC molecules have randomly-aligned state without applying voltage. At this time, the incident light is scattered in their cells. With applying voltage, the incident light is transmitted due to alignment changes of LC. As the evidence, transmitted light intensity-time characteristics without bandpass filter and two polarizers show decay with temporal time as shown in Fig. 5. The transmitted light intensity decreased exponentially over time. Here, if the fall response time is regarded as the time required to achieve 10% of maximum light intensity, in Fig. 4, the average of fall response times is 11 ms. In Fig. 5, the average of fall response times is 35 ms. It is considered that since birefringence is observed only in the transparent state and not appeared in the scattered state, the response time in Fig. 4 is faster than that in Fig. 5.

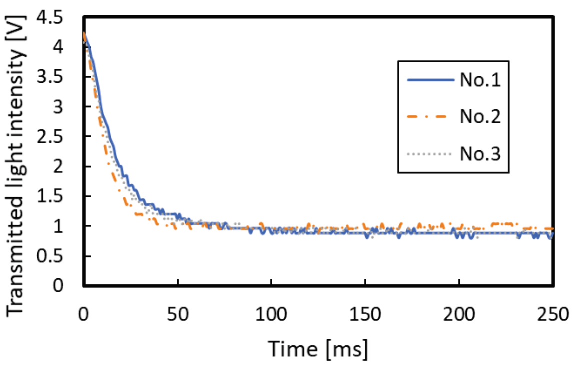

Fig. 5 $I_t - t$ characteristic of POSS-Lys/5CB components (scattering)

These fall response times are drastically improved by additive of dendrimer. However, the amount of change rate in the dielectric constant and phase modulation will be lower than that of parallel-aligned LC because the LC alignment is random without applying voltage.

4 EVALUATION OF DIELECTRIC LOSS IN DENDRIMER/LC COMPOSITES

In the previous section, we confirmed the fast response of POSS-Lys/5CB composites. To clear the influence of POSS-Lys additive on dielectric loss, we evaluated the dielectric loss of POSS-Lys/5CB composites at added concentration of 0, 0.01, 0.03 wt%. To evaluate dielectric loss of LC materials, we used coaxial line method in previous study. [12]. In this method, dielectric loss can be obtained by numerical calculation to measured frequency-dependent S parameters using network analyzer. Unfortunately, driving voltage of POSS-Lys/5CB composites was extremely high. For the reason, we evaluated dielectric loss of randomly-aligned POSS-Lys/5CB composites without external voltage. The evaluated data were shown in Fig. 7.

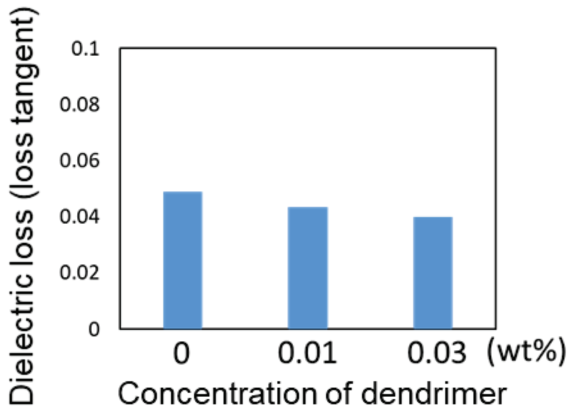

Fig. 5 Dielectric loss of POSS-Lys/5CB composites

The increasing of the amount of dendrimer reduces the dielectric loss. It is considered that gel network suppressed thermal vibration of LC molecules and reduced dielectric loss. We found that the dielectric loss of POSS-Lys aggregates was very low.

Finally, we discuss the future prospect of LC phase shifter briefly based on the results in sections 3 and 4. The sections 3 and 4 show that the fall response time and the dielectric loss can be simultaneously improved by adding the dendrimer into nematic LC.

Polymer/LC composites materials such as polymer dispersed liquid crystal are added in large amounts of photo-polymerized monomer, and the amount of change rate in permittivity is significantly reduced [14]. The used dendrimer in this study reduce the amount of change rate in permittivity, but this is due to the disturbance of the initial alignment state. If developing the novel material which enables LC alignment control and formation of network structure with a small amount of addition is realized, excellent voltage response and low dielectric loss can be realized simultaneously without decline of dielectric constant. Therefore, requirements for the novel materials for radio-frequency phase shifter using LC will be as following factor: liquid crystalline, easier formation of network structure under extremely low concentration.

5 CONCLUSIONS

In this study, we investigated the fall response time and dielectric loss of thick dendrimer/LC composites for application of radio-frequency phase shifter. As a result, the fall response time was estimated as less than 50 ms by adding the self-assembled dendrimer to the LC. Increasing the concentration of the dendrimer reduces the dielectric loss of LC. We have succeeded in simultaneous improvement of dielectric loss and fall response time using the proposed dendrimer/LC composites.

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