Evaluation of Dielectric Loss in Randomly-Aligned Liquid Crystal Molecules for Millimeter-Wave Reflect Array Antenna

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ABSTRACT

In this paper, we investigated dielectric characteristics within millimeter-wave band of structurally-modified liquid crystal molecules based on free space method for next-generation wireless communication system. As the results, we clarified that liquid crystal molecule having rigid groups and strong interaction among molecules has reduction of dielectric loss value.

1 Introduction

Currently, fifth-generation (5G) wireless communication or beyond 5G has attracted much attentions because realization of their technologies enables fast-speed and low-latency communications. Based on these features, utilization of millimeter wave is progressing gradually. To construct technical transfer from current 4G communication system to 5G standard near the future, there are some issues. One of the issues is over-the horizon communication between base station and terminal devices because intensity of diffracted light is weaker than electromagnetic wave with 4G standard, such as shadow effect by high buildings (see Fig. 1). Therefore, efficient communication technology between base station (sender) and terminal mobile (receiver) has been required for next-generation communication system.

As the candidates, reflect array antenna using liquid crystal (LC) materials has been proposed [1]. The advantages of this reflect array is to do directional control of reflected millimeter wave in any direction. The free electrons in electrodes having equal interval are vibrated by electrical field of incident millimeter wave. The vibrated electric field feels dielectric anisotropy ($\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\perp}$) of LC layer. Then, direction of emitted wave is determined by phase difference. The applied voltage to LC layer leads to directional control of reflected wave because molecular alignment of LC is easily changed by low-frequency electrical field. On the basis of the operational principle, development of LC material having large tunability ($\Delta\varepsilon/\varepsilon_{//}$) and low dielectric loss well known as ratio between real and imaginary dielectric constant (defined as tan δ) is one of important challenges for 5G communication.

In previous study, many LC materials for radio-frequency application have been investigated intensively. Of these, GT3-group LC materials which were synthesized from Merck KGA showed excellent dielectric characteristics: tunability and tan δ were 0.25 and 10^{-3}, respectively [2]. However, the molecular design of LC material for improvement of dielectric characteristics has been not cleared. This problem restricts smooth LC-material development for next-generation communication system.

To clarify the optimal structural design of LC molecules for reduction of dielectric loss, we investigated dielectric loss of some nematic LC materials within millimeter wave band. Here, we focused on fundamental molecular structure of nematic-phase LC, alkyl chain, polar group and main chain. In this paper, we discuss the relation between evaluated dielectric loss of LC materials and its material characterization.

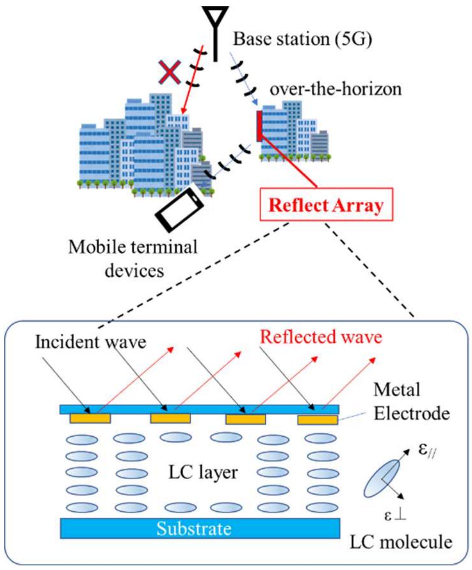


Fig. 1 Schematic illustration of 5G wireless communication and reflect array devices using liquid crystal materials.

2 Experimental

To estimate dielectric loss of LC materials, we adopted free space method due to the advantages of wide-frequency analysis. Fig. 2(a, b) shows images for evaluation of dielectric characteristics. First, two-port

VNA equipment is connected to antenna. The emitted radio-frequency wave from an antenna was focused to liquid crystal sample via dielectric lens. After that, transmitted wave is entered to VNA via same dielectric lens and antenna. For this setup, frequency-dependent transmission coefficient value (S_{21}) was monitored by VNA. The complex dielectric constant is calculated by the S_{21} and numerical calculation (supplied from Keysight solutions). We calculated values of tanδ from complex dielectric constant. The temperature in the room for measurement kept 20 ºC.

The LC materials for the measurement were injected into aclyric container, as shown in Fig. 2(c). Here, thickness of LC layer corresponds to 5 mm. Also, there is light scattering behavior (see Fig. 2(d)). For the reasons, the dielectric characteristics shows averaged information of dielectric anisotropy in LC materials in the following discussion. Prior to measurements, we examined LC mixture (E7, LCC corp.) and calculated complex dielectric loss using this system in order to confirm the validity. Conventionally, dielectric constant of E7 has been reported as 2.7-3.2 [3,4]. The obtained dielectic constant was 2.74, and we confirmed validity of this system.

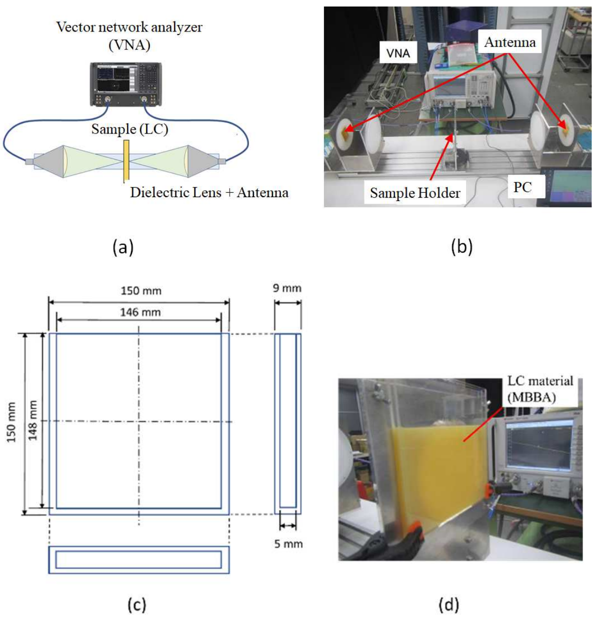


Fig. 2 Measurement system of dielectric loss of LC materials in millimeter wave band (40-60GHz). (a) top view of the system (b) photograph of the system (c) size of acrylic container for injection of LC material (d) photograph of LC injected into the container

3 Results and Discussion

3.1 Effect of Alkyl Chain Length on Dielectric Loss

To investigate the effect of alkyl chains, we prepared three kinds of cyano-biphenyl LC materials, as shown in Fig. 3(a). The *n* value means number of carbon atoms. Their LC materials are defined as 5CB (*n*=5), 6CB (*n*=6) and 7CB (*n*=7). These materials exhibit nematic phase at room temperature. Fig. 3(b) shows frequency dependence of complex dielectric constant. According to Debye theory, dielectric constant of imaginary part (Im(ε)) means thermal loss when alternating electrical field is applied to dielectric material. The only 6CB shows high Im(ε) at 57GHz. This behavior is similar to data of frequency-dependence dielectric loss, as shown in Fig.3(c). The dielectric loss of LC in millimeter wave region might be thermal energy loss. As the results, 7CB is low dielectric loss. This is attributed to high rigidity of LC molecule.

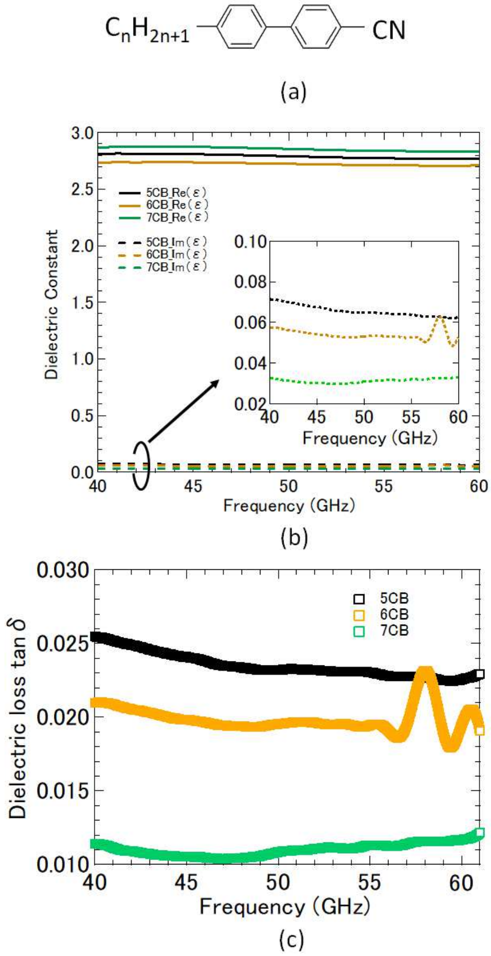


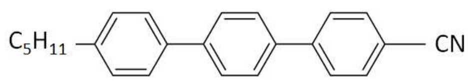
Fig. 3 Investigation of the effect of alkyl chain length (a) Schematic of molecular structure of cyano biphenyl liquid crystal (b) complex dielectric constant (c) Dielectric constant

3.2 Doping Effect of LC with Terphenyl Group

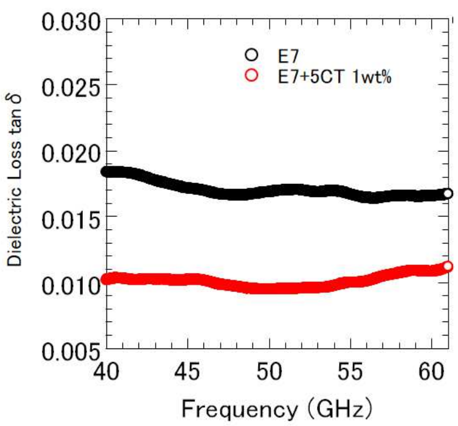
In previous section 3.1., rigidity of a LC molecule by long alkyl chain indicated reduction of dielectric loss. To confirm this effect, we investigated dielectric loss by structural changes of main chain. Here, we focused LC material with cyano terphenyl groups having three benzene rings (5CT), as shown in Fig. 4(a). According to molecular orbital theory, the molecule with benzene rings induces excellent rigidity due to their resonant effect of electronic structure. Unfortunately, this material didn't show nematic phase at room temperature: N-I transition temperature is 239°C. For this reason, we attempted doping of 5CT to nematic-phase LC mixture (E7) because E7 includes molecules with terphenyl group slightly. The 5CT can be treated as nematic liquid crystal by doping. Prior to measurement, we confirmed E7 with 1wt% 5CT has fluidity and birefringence behavior.

Fig. 4(b) shows frequency-dependent dielectric loss characteristics of LC mixture E7 and 5CT-doped E7. Compared with E7, dielectric loss was decreased drastically. The minimum dielectric loss was 9.3×10^{-3} at 52GHz. This dielectric loss is comparable to that of world-recorded class of low-loss LC materials. Furthermore, this decreasing trend of dielectric loss might support the conclusion of dependence of alkyl chain length.

In this study, we found that molecular rigidity of LC molecules contributed to reduction of the dielectric loss within millimeter wave. We will discuss the trade-off parameters to molecular rigidity



(a)



(b)

Fig. 3 Investigation of the doping effect of LC molecule with terphenyl group (a) Schematic of molecular structure of 5CT (b) Frequency-dependent dielectric loss

4 Conclusions

In this paper, we investigated dielectric loss in millimeter wave band of nematic LC materials for low-loss reflect array devices. Their systematic investigations focused on basic molecular structure implied that molecular vibration was responsible for dielectric loss. We found that the rigidity of a LC molecule leads to reduction of dielectric loss.

Acknowledgements

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