

Relationship between Liquid Crystal Molecular Behaviors and Dielectric Loss for Microwave Frequency Phase Shifters

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ABSTRACT

For realization of phase shifter using liquid crystal (LC), we evaluated the relation between molecular structure of LC and dielectric loss in microwave frequency. We considered that dielectric loss can be reduced by thermal vibration suppression of LC molecules.

1 INTRODUCTION

In Massive growth of communication traffic urgently requires the development of next-generation communication technology, such as 5G system, in recent years due to the progress of the Internet of Things (IoT) society. The utilizing of microwave or millimeter-wave band is necessary for construction of 5G system. One of problems in 5G system is large propagation loss of radio wave. The phased-array antenna is promising as one of candidates.

Fig.1 shows schematic structure of phased array antenna. Many antenna elements are arranged at equal intervals on a plane. Radiated radio waves from each antenna elements are synthesized. The synthesized wave propagates toward straight direction when phase difference among antenna elements is zero. Phase shifters play a role of phase control between antenna elements. Geometrically, the relation between traveling direction of synthesized wave and phase difference is expressed by following equation (1):

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

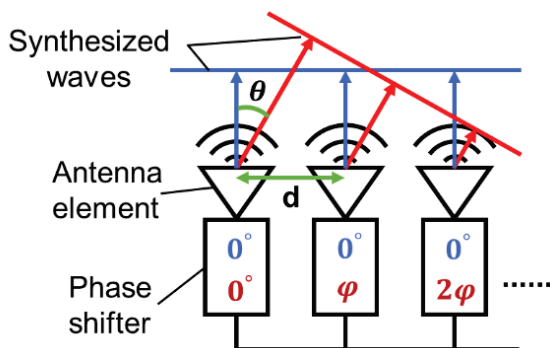


Fig. 1 Structure of phased array antenna

Phased array antenna has features of multi-beam radiation and beam scanning toward any directions by using phase shifters. These antennas suitable for next generation communication system like 5G.

Conventionally, the phase shift method by means of changes of electrical length in phase shifter has been reported[1]. However, directional control of synthesized wave is discrete. This drawback makes it difficult to follow mobile devices. In addition, diode switching induced high dielectric loss for microwave or millimeter-wave.

As the candidates of new phase shifter in order to overcome these problems, the phase shifter using nematic-phase liquid crystal (LC) as dielectric material have been studied[2]. There are two advantages as follows. One is continuous beam steering toward any direction. Molecular alignment of LC is freely controlled by low-frequency alternating current (AC) voltage. The amount of phase changes ($\Delta\phi$) is given by following equation (2):

$$\Delta\phi = 2\pi df\sqrt{\Delta\epsilon}/c \quad (2)$$

where f is frequency of radio wave, $\Delta\epsilon$ is difference of dielectric constant of LC, c is light speed in a vacuum. This equation means that alignment changes of LC enables continuous phase changes. The other is downsizing of phase shifter. There is a fact that part of LC materials exhibits low dielectric loss [3]. However, the optimal structural design of LC molecules was not clear for suppression of dielectric loss in radio wave. To overcome this issue, we focused on the basic skeleton of LC molecules. The nematic-phase LC material is generally composed of main chain, hydrocarbon group

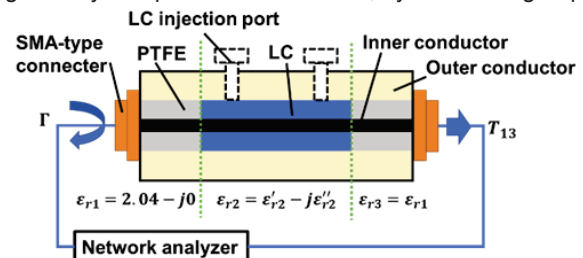


Fig. 2 Coaxial line to measure liquid complex permittivity

(alkyl chain) and polar group. They determine the optical characteristics of LC and molecular interaction among liquid crystal molecules. In this study, we discuss the relation between structural factors of LC and the dielectric loss evaluated with coaxial line method.

2 EVALUATION METHOD OF DIELECTRIC LOSS

Fig.2 shows the coaxial line composed of polytetrafluoroethylene (PTFE) and injected LC materials for evaluation of dielectric loss in radio frequency. The merits of coaxial line are that seal of liquid in center layer is easy by presence of PTFE and measurement of S-parameters in wide band frequency range with TEM-wave. In this study, $\tan \delta$ calculated from complex permittivity is used for evaluation of dielectric loss as shown in the equation (3).

$$\tan \delta = \varepsilon_r'' / \varepsilon_r' \quad (3)$$

The smaller $\tan \delta$ means the smaller dielectric loss. Complex permittivity is calculated from S-parameters as shown in the following equations (4-6) (transmission coefficient T_{13} and reflection coefficient Γ) of 3-layer coaxial line is measured with a vector network analyzer.

$$T_{13} = \frac{(1 - \Gamma_{12}^2) e^{-j2\pi l f \sqrt{\varepsilon_0 \mu_0 \sqrt{\varepsilon_2}}}}{1 - \Gamma_{12}^2 e^{-j4\pi l f \sqrt{\varepsilon_0 \mu_0 \sqrt{\varepsilon_2}}}} \quad (4)$$

$$\Gamma = \frac{\Gamma_{12} (1 - e^{-j4\pi l f \sqrt{\varepsilon_0 \mu_0 \sqrt{\varepsilon_2}}})}{1 - \Gamma_{12}^2 e^{-j4\pi l f \sqrt{\varepsilon_0 \mu_0 \sqrt{\varepsilon_2}}}} \quad (5)$$

$$\Gamma_{ij} = \frac{Z_j - Z_i}{Z_j + Z_i} = \frac{\sqrt{\mu_j / \varepsilon_j} - \sqrt{\mu_i / \varepsilon_i}}{\sqrt{\mu_j / \varepsilon_j} + \sqrt{\mu_i / \varepsilon_i}} \quad (6)$$

Because LC have anisotropy in a dielectric constant along long axis $\varepsilon_r(\parallel)$ and short axis $\varepsilon_r(\perp)$, dielectric constant of LC is measured with applying voltage of square-wave signal to the coaxial line. This applied voltage plays a role of alignment control of LC molecules. Without the voltage, LC molecules is randomly-aligned state because thickness of LC layer is thick enough (1.39 mm). Here, we defined the calculated dielectric constant in this condition as $\varepsilon_r(av)$. With the enough high voltage, LC molecules is aligned vertical to the inner and outer conductors and $\varepsilon_r(\parallel)$ is measured as shown in the figure 3. The dielectric loss was defined as $\tan \delta(av)$ and $\tan \delta(\parallel)$. The dielectric constant along short axis ($\varepsilon_r(\perp)$) of the LC molecule is expressed as following equation (7).

$$\varepsilon_r(\perp) = \frac{3\varepsilon_r(av) - \varepsilon_r(\parallel)}{2} \quad (7)$$

The $\tan \delta(\perp)$ value was calculated from equation (8).

$$\tan \delta(\perp) = \frac{3\varepsilon_r(av) \cdot \tan \delta(av) - \varepsilon_r(\parallel) \cdot \tan \delta(\parallel)}{2\varepsilon_r(\perp)} \quad (8)$$

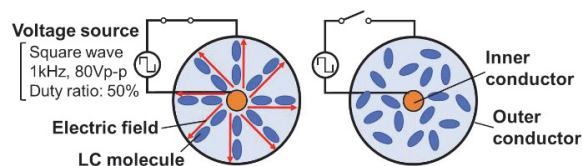


Fig. 3 Schematic images of cross-sectional coaxial line and LC alignment state

3 INVESTIGATION OF THE OPTIMAL MOLECULAR STRUCTURE OF LC

Prior to discussion, we investigated the effect of chain length in hydrocarbon on the dielectric loss using LC materials with cyano biphenyl. Table 1 summarizes relation between molecular structure of LCs and estimated values of. Here, we focused on the LC compound 1, 2, and 3 because these materials exhibited nematic phase in room temperature. From the results, we confirmed that the value of $\tan \delta$ was not affected by chain length. We considered that the reason is that structure of nematic LC is symmetrical with long axis. Then, we discussed the effect of main chain structure and polar groups on dielectric loss as follow.

Table. 1 Evaluated dielectric loss at 12GHz and chemical structure of LC molecules

Chemical structure	LC compound	ε_r		$\tan \delta$	
		$\parallel$	$\perp$	$\parallel$	$\perp$
<chem>C5H11-c1ccc(cc1)-c2ccc(cc2)C#N</chem>	1	3.32	3.00	0.024	0.052
<chem>C6H13-c1ccc(cc1)-c2ccc(cc2)C#N</chem>	2	3.07	2.71	0.030	0.053
<chem>C7H15-c1ccc(cc1)-c2ccc(cc2)C#N</chem>	3	3.14	2.72	0.020	0.053
<chem>R-c1ccc(cc1)-c2ccc(cc2)C#N</chem>	4	2.53	2.44	0.027	0.070
<chem>R-c1ccc(cc1)Cc2ccc(cc2)Cc3ccc(cc3)C(F)(F)F</chem>	5	2.62	2.41	0.016	0.041
<chem>R-c1ccc(cc1)Cc2ccc(cc2)Cc3ccc(cc3)C(F)(F)F</chem>	6	2.81	2.40	0.016	0.034
<chem>R-c1ccc(cc1)Cc2ccc(cc2)Cc3ccc(cc3)C(F)(F)F</chem>	7	2.67	2.35	0.016	0.028
<chem>R-c1ccc(cc1)C#Cc2ccc(cc2)F</chem>	8	3.33	2.86	0.030	0.062
<chem>R-c1ccc(cc1)C#Cc2ccc(cc2)C(F)(F)F</chem>	9	3.43	2.61	0.029	0.082
<chem>R-c1ccc(cc1)C#Cc2ccc(cc2)R</chem>	10	3.23	2.68	0.037	0.083

※compound 8 and 9 does not show LC phase at room temperature. Therefore, we added 20 wt% of them to compound 10.

We investigated two kinds of structural differences of main chain. One is the structural change from cyclohexane to benzene (see the combination of compound 4 and 1, and compound 5 and compound 6 in Table 1). The structural changes from cyclohexane ring to benzene ring reduced dielectric loss. The other is comparison between compound 6 with hydrocarbon spacer (C_2H_4) and compound 7 without C_2H_4 . The LC without hydrocarbon spacer show lower dielectric loss than that with hydrocarbon spacer. These results are attributed to more stable resonance structure of benzene due to the rigid ring structure and more rigid structure without hydrocarbon spacer than structure with hydrocarbon spacer. The dielectric loss might be suppressed by rigid molecular structure.

Next, we evaluated LC terminally-modified fluorine as a polar group (compound 5, compound 6 and compound 7). As a result of the value of $\tan \delta$ was improved. In addition, compound 8 having three fluorine atoms show lower dielectric loss than compound 9 having one fluorine atom. Since the fluorocarbon group has high electronegativity due to fluorine atom, C-F bonding energy is relatively high. In addition, molecular rotation was suppressed by steric interactions between adjacent fluorocarbon[3]. Therefore, we considered that the fluorocarbon group has role of suppression of molecular vibration loss by radio frequency.

4 TEMPERATURE DEPENDENCY OF DIELECTRIC LOSS OF LC

As mentioned above discussion, various factors of dielectric loss were indicated. In case of solid-state polymer, several dielectric loss factors are known which were rotation of molecular dipole, crystalline lattice vibration and vibration of molecular chains in amorphous region [4]. These factors are associated with molecular vibration. The strength of molecular vibration is closely related to temperature. To clarify the one of loss factors in nematic LC, we investigated the temperature dependency of $\tan \delta$. Here we used typical LC materials (E7, LCC corp.). Fig.4 shows that as temperature is high, the dielectric loss is high. Since dielectric loss is related to temperature, we consider the factor of dielectric loss is molecular vibration.

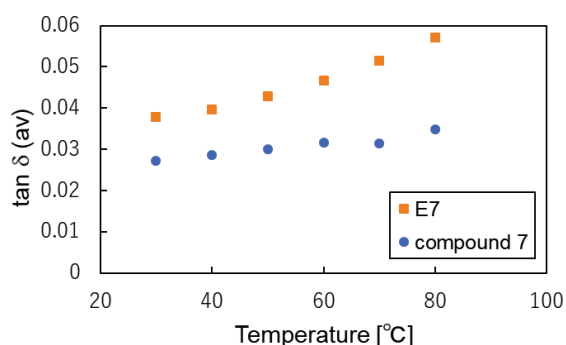


Fig. 4 temperature dependency of dielectric loss of LC

5 CONCLUSIONS

In this study, we investigated the structural factor of nematic-phase liquid crystal to the dielectric loss at radio frequency. As the results, we found that the dielectric loss was affected by rigidity of main chain and terminally-modified polar groups in the nematic LCs. Also, increasing of temperature in nematic LC materials contributed to increasing of dielectric loss in radio frequency. To reduce the dielectric loss, both of chemical modification of fluorine to LC molecule and suppression of thermal vibration will be important.

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REFERENCES

- [1] T. Kato, Y. Tanaka, H. Ueda, H. Noge, K. Nishikawa and K. Sato, "Phase Shifters for Phased Array Antennas," R&D review of Toyota CRDL, Vol. 27, pp. 37-45 (1992)
- [2] K. Kitatani and S. Yamamoto, "Beam Scanning of Series Fed Microstrip Antenna Using Liquid Crystal Phase Shifter," The transactions of the Institute of Electronics C, Vol. J85-C, No.7, pp.588-589 (2002).
- [3] A. Manabe, "Liquid Crystals for Microwave Applications," EuCAP, pp. 1793-1794 (2013)
- [4] M. Hird "Fluorinated liquid crystals - properties and applications," Chem. Soc. Rev., Vol. 36, pp. 2072-2074 (2007)
- [5] K. Nakagawa, The Society of Polymer Science, Vol. 27, No. 2, pp.97-101 (1978)