Advanced Liquid Crystals with Low Loss Tangent and Fast Response for Intelligent Reflecting Surface Antennas

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ABSTRACT

We investigate liquid crystals to be suitable for a reflective antenna. The method for evaluation of liquid crystals in gigahertz is presented. Low loss tangent reaching closely to 0.01 and short decay time in switching response were achieved simultaneously by introducing compounds having para-terphenyl group without polar groups.

1. Introduction

Liquid crystals have been paid attention to an attractive material to be a tunable propagation of gigahertz wave or terahertz wave. Components using liquid crystals such as an antenna in telecommunication are extensively investigating from basic research to their applications. We have been investigating of a reflective antenna using liquid crystals (LCs) called the intelligent reflecting surfaces (IRS) possessing a capable of a beam steering, which is controlled by tuning phase change on each element of antenna arrayed on the glass substrate [1]. The antenna is designed with which controllable dielectric layer using LCs are sandwiched between the arrayed antenna plate on the top and ground plate on the bottom. The LC layer are utilized as a part of dielectric layer, which act as tuning the resonant frequency by phase change depending on the voltage applied to the antenna.

Requirements of physical properties in LCs to adapt the IRS antenna operating in region of gigahertz frequency are as follows.

(1) High tunability depending on quantities in phase change by the LC dielectric layer.
(2) Operating voltage <30 Vrms for LC layer.
(3) Low loss tangent (tan δ) of LCs.
(4) Fast switching time to achieve a necessary speed of beam steering.

Obtaining a large phase change more than 360 degrees by the LC dielectric layer is an essential to controlling the beam steering. It has proven that the IRS antenna requires a thick dielectric layer more than 50μm to attain sufficient tunability of phase change from our results of evaluation on the antenna. Such an increasing the thickness of layer causes an insufficient steering speed due to an increase of switching time derived from an inherent property of LCs and is leading to a decrease of intensity on the beam with an increase of dielectric loss in LC layer. These issues influence to the performances of antenna to relate closely to the physical properties of LCs described the requirement above. Therefore, improvement of LCs play an important role to progress the performance of the antenna in the gigahertz region.

2. Experiment

We use a coaxial transmission line method for measurement of dielectric permittivity and loss tangent in LCs due to a capable of wide frequency range [2]. The setup using semi rigid coaxial cable consists of a cylindrical outer conductor and an inner conducting wire (0.5mm in diameter) placed at center of coaxial line as shown in Figure 1 (a). Polytetrafluoroethylen (PTFE) as a dielectric layer is placed between the outer and the centered inner conductor with 1mm in distance. A middle section for PTFE is removed from the cable in order that a part of PTFE is replaced with LCs as shown in Figure 1 (b, c). The structure of outer conductor is forming a cavity of semicylindrical channel on the one side of surface in the outer conductor that is divided into two pieces as shown in Figure 1 (c). The LCs are held between the outer and the inner conductor by overlapping two pieces of the cavity face in outer conductors as shown in Figure 1 (d).

For the measurement for gigahertz, LCs are carefully injected to the filling channels to avoid an insertion of air. Keysight two-port Vector Network Analyzer (VNA) P5008A as shown in Figure 2 is connected to both terminals on the setup of semi rigid cable to analyze propagation of wave through scattering parameter (S-parameter).

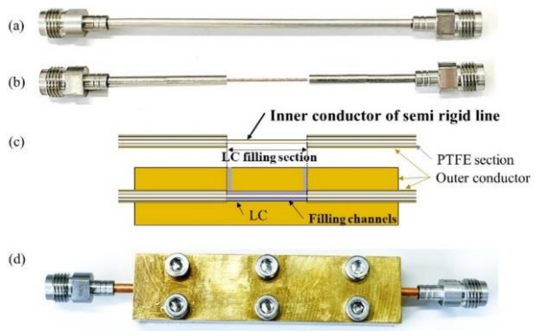

Fig.1 Experimental setup of coaxial line
(a) Coaxial semi rigid line using PTFE, (b) Coaxial semi rigid line with LC filling section, (c) Cross sectional view of the opened setup, (d) Overview of complete setup of coaxial line.

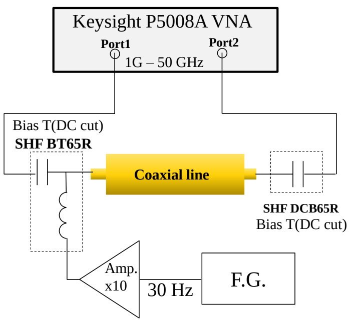

Fig 2. Equipment to measure S-parameter and connection to apply a low frequency voltage.

For the rise time in switching response in the real IRS antenna, occurring a continuous change of capacitance at the transition of alignment from a parallel to a vertical by the applied voltage of bursting square wave at 1 kHz was measured with the elapsed time. he apparatus for measurement used Keysight LCR meter E4980AL, and the change for capacitance was acquired with a 70 msec of sampling rate. For the decay time, the change of capacitance occurred at the transition of alignment from a vertical to a parallel was measured.

2.1 Characterization of Liquid Crystals in Gigahertz

Complex permittivity, which give an influence on the propagation of wave, is calculated by extracting the propagation constant γ to be based on the wave equation in low loss media from S21 in s-parameter.
γ is expressed by equation (1) as the sum of the attenuation constant α for the real component and the phase constant β for the imaginary component.
(j: imaginary unit)

$$\gamma=\alpha+j\beta \tag{1}$$

The complex dielectric permittivity in real part is obtained from equation 1, where ω is the angular frequency, and c_0 is the speed of light in vacuum.

$$\varepsilon_r' = -\frac{(\alpha^2-\beta^2)c_0^2}{\omega^2} \tag{2}$$

The complex dielectric permittivity in imaginary part is calculated with equation 2.

$$\varepsilon_r'' = \frac{j(2\alpha\beta)c_0^2}{\omega^2} \tag{3}$$

Equations (1) and (2) above represent the case of a plane propagation wave in a dielectric media. However, since PTFE and LCs section exist along with one coaxial transmission line used in the experiment, it is necessary to separate the information concerning LCs from the s-parameter including both information of PTFE and LCs.
β related to LCs is calculated from the phase difference between two transmission lines based on the condition that the length of line is a same length each other. One is the semi fix cable as show in Figure 1(a). The other is a coaxial transmission line consisted of PTFE and LCs section as shown in Figure 1(b, c).
α related to LCs is extracted from the difference of magnitude in S21 between two coaxial transmission lines with a same line length each other.
The complex dielectric constant of LCs is obtained by the substituting α and β above into equation (2) and (3). And then, the loss tangent of tan δ is obtained from the ratio of ε" to ε'.

3. Results and Discussion

To adapt LCs for the IRS antenna, the improvement of physical properties in LCs in a low frequency region and a gigahertz region are important issues. The dielectric constant and the loss tangent in a radio frequency as well as switching response driven by voltage of a low frequency are described.

3.1 Properties in Liquid Crystal at Gigahertz

The frequency dispersion of dielectric constant ε' as a real part of complex permittivity determined from S21 of S-parameter is shown in Figure 2. The ε' of PTFE is almost independent on the frequency in the range from 1 GHz to 50 GHz, whereas the ε' of TD1020 (JNC Corp.) and E7 exhibit tendency that the ε' decreases as frequency slightly increases. Moreover, anisotropy of dielectric constant is observed by change of applied voltage at 0 volts and 50 volts.

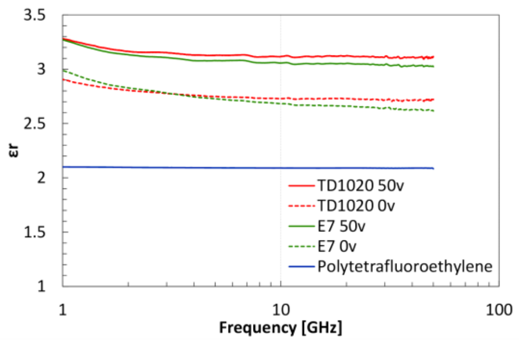

Fig. 3 Frequency dispersion of dielectric constant ε_r' for different applied voltage

The ε' of PTFE is almost independent on the frequency in the range from 1 GHz to 50 GHz, whereas the ε' of TD1020 and E7 exhibits the tendency that the ε' decreases monotniously as frequency increases. Moreover, change of dielectric constant based on anisotropy is observed by change of applied voltage at 0 volts and 50 volts as shown in Figure 3.

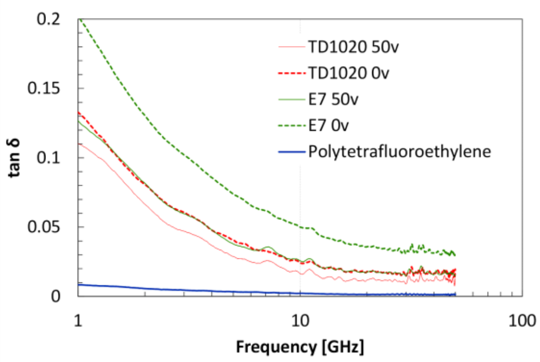

Fig. 4 Frequency dispersion of loss tangent for different applied voltage

The frequency dispersion of loss tangent to be ratio of ε" to ε' in complex permittivity is shown in Figure 4.

A similar tendency of frequency dispersion that loss tangent decreases gradually toward higher frequency is observed in comparison with the case of dielectric constant. In addition, the loss tangent becomes a minimum in a 40 GHz region.

It is suggested that these frequency dispersion in both these are derived from a dipole relaxation occurred in the lower frequency region less than 1 GHz. This is because it is presumed that the influence of dipole relaxation decreases gradually as frequency increases.

The anisotropy of LCs in loss tangent is observed in the difference between loss tangent at absence of voltage and that at 50 volts. The anisotropy of loss tangent exhibits opposite behavior against the case of dielectric constant that is increased as applied voltage to the line increases. In other words, the loss tangent is reduced by the change of alignment from parallel to vertical alignment. In previous investigation, we found that a 0.01 of loss tangent was achieved by adding simply a 1 wt% of 4'-cyano-4-n-pentyl-p-terphenyl (5CT) into E7 through the measurement of free space method. From this point of view, it is considered that the part of p-terphenyl in molecular structures is exhibiting properties of a low loss tangent to be similar to 5CT. Moreover, p-terphenyl compound without cyano groups is lower viscosity than 5CT. When such a compound introduces to the mixture, it is presumed that reduction of viscosity and that of loss tangent are achieved simultaneously. Consequently, the loss tangent for TD1020 closely reaches to a 0.01 in 40 gigahertz region, when the voltage is applied to the line at 50 volts as shown in Figure 4. While the loss tangent of E7 at 50 volts is higher than that of TD1020. In addition, the achievement of lowering viscosity is realized. The concerning effects of viscosity will be described next section in detail. We have presumed that the one of factors to associate with loss tangent is the molecular vibration, because the loss tangent increase as a temperature increases [3].

It is assumed that lowering loss tangent is derived from the p-terphenyl structure involved to suppress the molecular vibration.

3.2 Properties of Liquid Crystal at Low Frequency

Reducing both viscosity and loss tangent is important for adapting LCs for the IRS antenna that require a thick cell gap. The decay time in switching response is strongly governed by viscosity in LCs and thickness of cell gap, whereas rise time is strongly affected by dielectric anisotropy and applied intensity of electric filed. As the viscosity depends on molecular structure of liquid crystal, it is possible to reduce the viscosity by selection of components indicating a low viscosity. On the other hand, increase of dielectric anisotropy result in a fast rise time and an increasing viscosity of mixture due to containing a high polarity of compound.

In the point of view to reduce viscosity, p-terphenyl compound without a cyano group is introduced instead of 5CT to be contained in E7 of well-known mixtures. Because it is presumed that non-polar compound of p-terphenyl is a lower viscosity than that of 5CT having a polar group, and an advantage against loss tangent. The dielectric anisotropy for E7 is 14.4 at 1 kHz, while a 0.4 of a slight dielectric anisotropy for TD1020 is obtained when the amount of the p-terphenyl compound without cyano group is exceeded to 70 wt%.

Reduction of rotational viscosity γ_1 from a 252 [mPa s] for E7 to a 107 [mPa s] for TD1020 is realized by reduction of content in the polar compounds. This reduction of the viscosity leads to advance the decay time from 22 seconds at 100μm of cell gap for E7 to 10 seconds for TD1020. In addition, 2.5 seconds are achieved at a 50μm of cell gap in the IRS antenna, which is confirmed to operate with a sufficient change of phase. Although a further improvement is required, this decay time reaches to the level to be possible to a beam steering.

By increasing amount of non-polar p-terphenyl compound without cyano groups, it is possible to attain simultaneously a lowering both viscosity and loss tangent. As a result, the loss tangent for TD1020 reaches to a 0.01 in gigahertz region in comparison with a 0.02 for that of E7. We have presumed that the one of factors to associate with loss tangent is the molecular vibration, because the loss tangent increase as a temperature increases [3].

It is assumed that lowering loss tangent is derived from the three-ring molecular structure involved to suppress the molecular vibration.

4. Conclusions

It is important to develop the method for evaluation of LCs in gigahertz region. The proposed method is characterized with that frequency dispersion of dielectric constant and loss tangent are determined directly from the difference between the coaxial line having liquid crystal section and the PTFE coaxial line as the reference without any model for curve fitting. It has been proven that the ε' of TD1020 and E7 exhibits the tendency that the ε' decreases monotonously with increase of frequency, and the loss tangent in TD1020 reaches closely to 0.01 in 40 gigahertz regions.

To satisfy specification of IRS antenna, a lowering loss tangent in gigahertz region and a switching time at transition of liquid crystalline alignment between parallel and vertical have been investigated. By introducing liquid crystal compound having p-terphenyl group without polar groups, it is revealed that switching time and loss tangent are improved simultaneously. The reason for the improvement is considered with two reasons. One reason is that liquid crystal compounds without polar groups show lower viscosity than that with polar groups. The other reason suggests that the suppression of molecular vibrations by p-terphenyl group in liquid crystal compounds lead to the reduction of loss tangent.

Acknowledgements

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