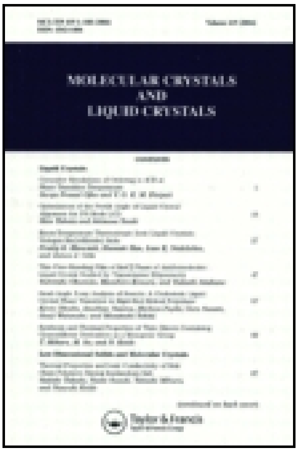

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Basic Performance of Refractive Index Measurement Method for LC Materials in Super High Frequency Region by Using Coplanar Wave Guide

R. Ito [a] , S. Yanagihara [b] , K. Ito [b] , T. Watanabe [b] , T. Nose [a] & M. Honma [a]

[a] Faculty of Systems Science and Tech., Akita Pref. University, Yurihonjyo, Japan

[b] Yurikogyo Co. Ltd., Nishime Yurihonjyo, Japan

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Basic Performance of Refractive Index Measurement Method for LC Materials in Super High Frequency Region by Using Coplanar Wave Guide

R. ITO,[1] S. YANAGIHARA,[2] K. ITO,[2] T. WATANABE,[2] T. NOSE,[1] AND M. HONMA[1]

[1]Faculty of Systems Science and Tech., Akita Pref. University, Yurihonjyo, Japan
[2]Yurikogyo Co. Ltd., Nishime Yurihonjyo, Japan

Novel measurement method of complex refractive indices of liquid crystal (LC) materials in the ultrahigh frequency region such as microwave and millimeter-wave (MMW) is investigated to reduce the quantity of test sample by using a coplanar waveguide (CPW) substrate, which is known as an excellent planar type waveguide. Although it needs some calibration method for precise measurement, the amplitude and phase properties of the propagating electromagnetic waves are sufficiently sensitive to the extremely small amount of test sample and the basic performance for the loss and refractive index measurements is investigated by using the well known K15 LC material.

Keywords Coplanar waveguide; microwave; millimeter-wave; refractive indices

1. Introduction

Liquid crystal (LC) materials are very attractive electro-optic materials for various application fields from the point of view of their compact and light weight with low power consumption nature. Advantages of the LC materials should not be limited within the visible light region in the extremely wider electromagnetic wave frequency spectra. Standing on such ideas, several researchers have been investigated fundamental properties of LC materials in the super high frequency regions around microwave and/or millimeter wave (MMW) regions extending to the THz region [1–6], and some electrically control devices using the LC materials have been proposed so far [7–14]. Although these regions have been long undeveloped by various technological difficulties, they are recently gathering much attention for novel sensing method, high speed wireless communication and collision avoidance radar of automobile. LC material is one of the leading candidates for various control devices

Address correspondence to T. Nose, Faculty of Systems Science and Tech., Akita Pref. University, Yurihonjyo, 015-0055 Japan. Tel.: +81-184-27-2106; Fax: +81-184-27-2106; E-mail: t_nose@akita-pu.ac.jp

in the new application fields. However, there are not so sufficient information about LC materials except visible light and very low frequency region, and then various evaluation methods for refractive index and loss parameter of LC materials in the super-high frequency region have been proposed so far by using coaxial transmission line [3,4], rectangular waveguide [2,6] and so on. Unfortunately, there is a serious drawback for applying them to the LC materials because they usually need large quantities of test sample for measurements by their balky structure.

In this study, we focus on coplanar waveguide (CPW), which is well known as an excellent planar type of transmission line in the super-high frequency region, to develop a novel measurement method of LC materials expecting an extreme reduction of test sample quantity and a very wide measurement frequency range. Since the CPW has both signal and ground electrodes on the same surface, the simple structure is advantageous for integration with various electronic devices such as transistor, diode and also LC devices. Here, we expect the easiness of constructing the test cell for introducing LC materials because it is easy to introduce a usual sandwich type cell structure by only mounting a small piece of glass substrate on it.

2. Principle of Measurements

Some measurement methods for refractive indices and loss parameters have been proposed by injecting the test materials to coaxial or waveguide transmission line. If we adapt some variable function of the propagation length in the test sample, unwanted affection except by test sample such as a connector loss and some imperfection of waveguide can be eliminated, and accurate evaluation of refractive indices and loss parameters can be achieved. Figure 1 shows a method by using the rectangular waveguide, which has a moving reflector on the upper end of the test cell, and the reflection difference during the propagation length change of the test sample

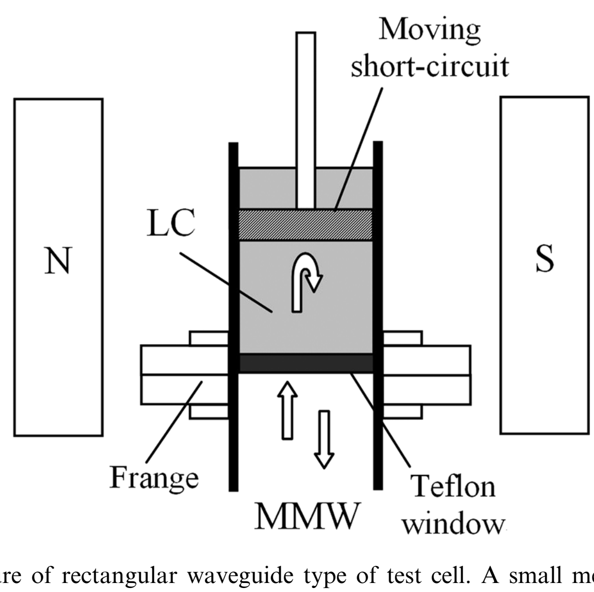

Figure 1. Structure of rectangular waveguide type of test cell. A small metal tip is inserted from the upper opening as a moving short which acts as an excellent reflector.

can be extracted for the accurate evaluation. Electric field direction of the propagating electromagnetic waves is uniformly along the short-circuit wall in the rectangular waveguide, and ordinary and extraordinary refractive indices can be separately evaluated by changing the applied magnetic field direction used for LC molecular orientation. Bottom end is sealed with Teflon window and the upper opening is actually advantageous for elimination of remaining bobble problem in case of the liquid like sample. However, transmission frequency of the waveguide is usually limited to be narrow band depending on their size, and considerably large amount of sample is necessary to fill up inside the waveguide even though the MMW region.

On the other hand, CPW has both signal and ground electrodes on the same surface of dielectric substrate, and it becomes easy to introduce usual planar cell structure on it. Since the electromagnetic wave propagates near the surface of the substrate, the wave is affected by the dielectric and loss properties of the induced materials into the cell and then the material parameters can be evaluated by measuring the change in the propagation of the electromagnetic wave. In this case, the cell is basically planar structure, and the necessary amount of test sample can be reduced extremely comparing with the bulky waveguide test cell. Furthermore, CPW has usually quite large propagation frequency range, and it becomes possible to evaluate in the wide range by using the same test cell. However, some kind of moving short-circuit must be introduced for adapting the same accurate measurement technique as waveguide test cell.

Structure of the test cell using a CPW substrate is shown in Figure 2, where sandwich cell structure is introduced by mounting a small piece of glass substrate with suitable spacer as usual LC cell. From the right side opening, thin metal plate with the same thickness as spacers is inserted as a sliding short-circuit electrode which shorts between signal electrode and both side ground electrodes and is expected to work as an excellent reflector. When we slide the metal plate by a distance of Δx, propagation length of the sample can be changed by $2\Delta x$. The change in the propagation properties of electromagnetic waves is directly related to the sample length $2\Delta x$, where unexpected disturbance by the connection part with outer

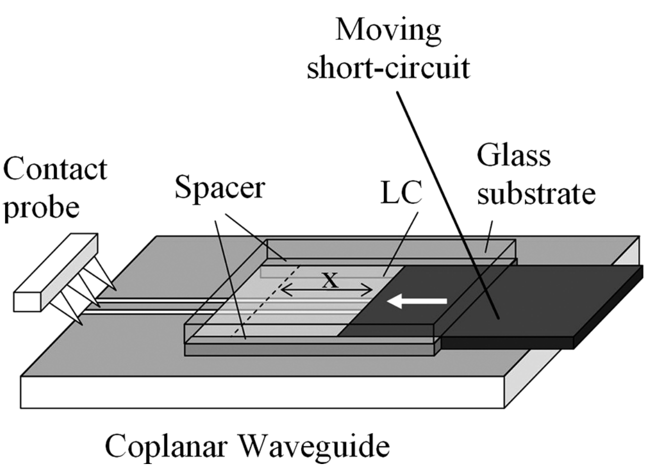

Figure 2. Structure of the CPW type of test cell. A thin metal plate is inserted from the right hand side opening as a moving short.

equipments, discontinuity appearing at the edge of the glass and so on can be basically eliminated. Assuming that the typical sample length is 5 mm (propagation change is 10 mm), necessary sample quantity is about 35 ml for V-band rectangular waveguide (50 GHz–75 GHz). On the other hand, the quantity is extremely reduced to be less than 7.5 μl, if we adapt 100 μm cell thickness in the CPW type of test cell. In our study, we adapt a signal electrode width of 340 μm, gap width between electrodes of 85 μm and the cell thickness of 100 μm, where the substrate is made of Teflon composite and its dielectric permittivity is 2.17. Phosphor-bronze metal is used as a short-circuit electrode and injected nematic LC (K15:Merck) is measured by using Vector Network Analyzer (Anritsu).

3. Results and Discussion

3.1. *Evaluation of Loss Properties*

Figure 3 shows typical measurement result of the reflection properties in the test cell, where the propagation length of the LC layer is changed from the initial position ($2\Delta x = 0$) up to 10 mm. It is seen that there are some dip structures probably affected by some unknown reflection phenomena, the general gradient of the curves tends to decrease as increasing the propagation length of the sample and the decrease reflects the loss of test sample.

Based on the measurement results in Figure 3, transmission properties are plotted as a function of propagation length of the LC layer as shown in Figure 4. There are almost linear relations in wider frequencies, and the gradient tends to increase as increasing the frequency. Here, we estimate the loss parameter α by using the following relation

$$|S_{11}|^2 = \exp(-2\alpha x), \tag{1}$$

where x is the length of the sample and left side of this equation $|S_{11}|^2$ is corresponding to the transmittance. Loss parameter α is estimated from the gradient of the logarithmic plots as shown in Figure 4.

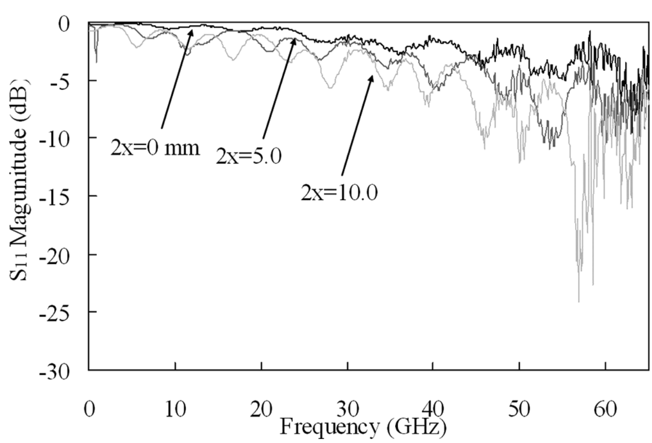

Figure 3. Reflection properties (S_{11}) as a function of frequency. Here, the reflectance contains information of transmission properties during twice travel through the test sample.

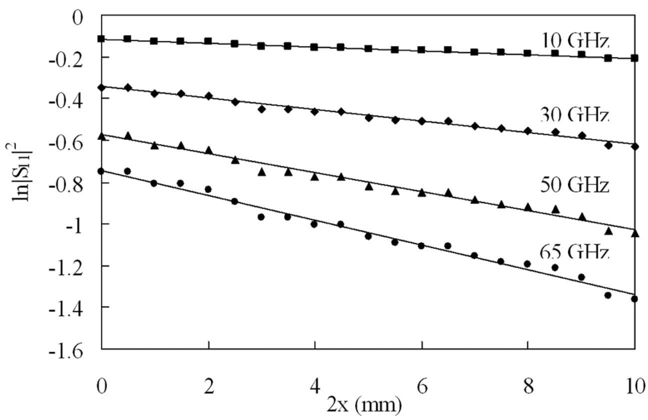

Figure 4. Logarithmic plot of the transmittance as a function of the traveling length through the test sample.

Estimated loss parameters of the LC material for various frequencies are summarized in Table 1. Evaluated data using rectangular waveguide are shown in the table for comparison, where α_e and α_o correspond to the loss parameters along the direction parallel and perpendicular to the molecular axis, respectively. Since there was no molecular alignment treatment on the CPW cell in this stage, mean loss values are estimated in our experiment and are indicated here by α_{eff}. Comparing the measurement data with those by using rectangular waveguide in our previous work, both values at 50 GHz and 65 GHz become a little larger, which are affected by the loss of the CPW test cell. Propagating electromagnetic waves on the CPW basically feel every existing material around the electrode not only the test material but also the Teflon composite substrate, upper glass substrate and so on. Although we tried to estimate the loss of the LC material by subtracting the loss of the empty cell, evaluated value of $\Delta\alpha$ may be over estimated by some error influenced from the large intrinsic loss of the test cell. The loss of the test cell is too large to measure accurately the low loss sample like LC materials in this stage. Reduction of the intrinsic loss is necessary for the accurate measurement by optimizing the cell and electrode structures, dielectric materials of the CPW substrate and so on.

Table 1. Evaluated loss parameters using the CPW test cell and those obtained by using rectangular waveguide for reference

	Rectangular waveguide		CPW test cell		
Frequency (GHz)	α_e	α_o	α_{eff} (with LC)	α^*_{eff} (Empty)	$\Delta\alpha_{eff}$
10	—	—	0.009	0.009	0.000
30	—	—	0.028	0.026	0.002
50	0.019	0.036	0.046	0.043	0.003
65	0.015	0.024	0.060	0.056	0.004

3.2. *Evaluation of Refractive Indices*

Refractive indices can be estimated by measuring the phase change of the propagating electromagnetic waves contrary to the amplitude measurements for the loss evaluation. By measuring the difference in the phase data during the propagation length change, it becomes possible to pick up the data of test sample by eliminating some unexpected affections. In this case, the phase change $\Delta\theta$ is denoted by the following relation as a function of propagation length $2x$ and frequency

$$\Delta\theta = -\frac{2\pi}{c} n_{eff} \cdot 2x \cdot f, \tag{2}$$

where c is light speed in space and n_{eff} shows the effective refractive index including the affection of dielectric properties of substrate, upper glass and so on.

Figure 5 shows the measurement phase properties for various propagation length changes from the initial position of $2x = 0$. Although there is a little deviation from the ideal liner relation which is probably caused by some unknown influence of reflection, it is obviously seen that the absolute phase values increase as increasing the propagation length.

Based on the phase measurement data, phase difference for different propagation length is plotted in Figure 6. Measured phase data usually contain uncertainty of every $\pm\pi$ radian, and then we unwrap the data at every discontinuity and almost linear relations can be obtained. Refractive indices can be evaluated by the gradient of the line through Eq. (2), and the estimated refractive indices are summarized in Table 2. It is known that there are not any dispersions around this frequency region in the usual nematic LC materials, and almost linear relation is observed in Figure 6. Here, we estimated the refractive index from the gradient of the line because the small fluctuation in Figure 6 is probably caused by some noises phenomena.

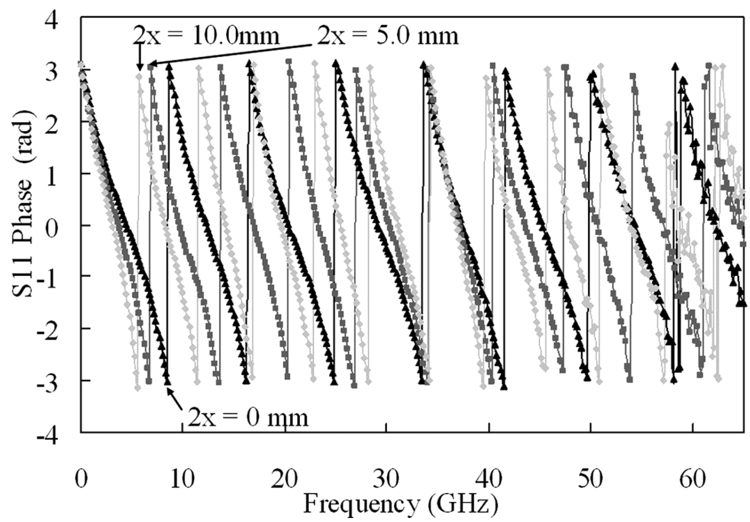

Figure 5. Phase properties of the transmission electromagnetic waves, which also contain the refractive index information of test sample.

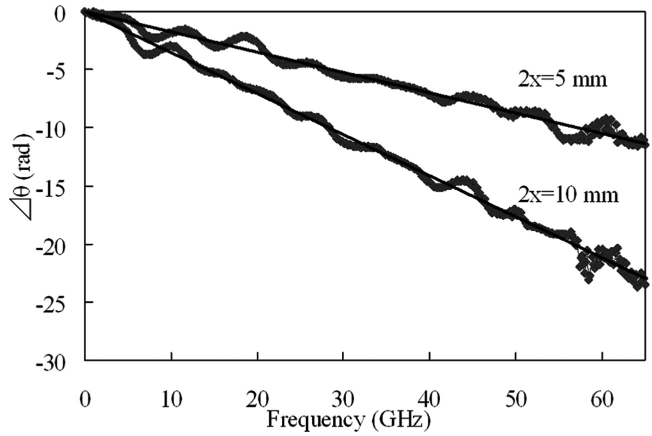

Figure 6. Differential evaluation of the phase properties for various propagation length of test sample, where the phase data are unwrapped at their jump points.

Measurement of the frequency dispersion is also important issue as actual measurements, and it is basically possible to evaluate the refractive index dispersion by the change in gradient, but the small fluttered deviation from the linear relation in Figure 6 is probably caused by some measurement error. More accurate measurement will be possible to attain the refractive index by estimating from the phase properties as a function of propagation length Δx for each frequency. 2π phase period becomes easy to detect by using high permittivity substrate, and the method is now undergoing for improving the accuracy. Evaluated effective refractive index of the empty cell is also indicated in Table 2, which is corresponding to the air sample, and the actual value of the LC is calculated as mean value from the measurement data using the rectangular waveguide. Evaluated values using the CPW test cell become larger than those in the actual values, because they include some influence of the test cell. Since the refractive indices of test cell components such as substrate and glass substrate is comparable with the LC materials, the influence probably tends to increase. The influence is not so simple and we have to construct accurate calibration relation between the measured effective values and actual material indices for the accurate evaluation. Alignment of the LC molecules is the important issue for evaluating the anisotropy of the LC materials. Although there was no alignment treatment here for the experimental easiness, it is possible to introduce surface alignment as normal sandwich cells. However, the alignment will be broken by sliding the metal short-circuit during the measurements. We are now trying another method of

Table 2. Evaluated refractive index by the CPW test cell and the comparison with actual value

Test material	Actual refractive index	Measurement value
Air	1	1.36
K15	1.65 ($n_e = 1.71$, $n_o = 1.62$)	1.70

sliding the upper glass substrate for changing the propagation length of LC layer, and the reflecting short-circuit is initially fabricated on CPW substrate as a fixed circuit in this case. Although the intrinsic loss and phase properties of CPW must be measured accurately before the sample measurements, alignment surface will be reusable in this method. Although there still remains such a problem to overcome for accurate evaluation of LC materials, it is obvious that the measurement method using the CPW is sensitive enough to the extremely small amount of LC test sample.

4. Conclusions and Perspectives

New evaluation method of complex refractive index in the super-high frequency region is investigated for LC materials by using CPW substrate in order to reduce the necessary quantity of test sample extremely. By introducing a moving short-circuit to the LC cell constructed on the CPW substrate, a potential as a novel evaluation method of refractive index and loss parameter is demonstrated by the differential measurements during the propagation length change. There remain some problems for the accurate measurement, because the propagating electromagnetic wave tends to be affected not only by the LC materials but also by the surrounded cell structural materials and then the measurement data become basically effective values. However, the change in the amplitude and phase of propagating electromagnetic wave is sufficiently sensitive to the extremely small amount of test sample less than a few μl, and the very wide coverage of measurable frequency region is advantageous for the investigation of dielectric dispersion in various LC materials. Although some calibration method and nondestructive moving short-circuit for molecular alignment are necessary for improving the accuracy, high sensitivity and wider frequency band are very attractive for the material research in the super-high frequency region.

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