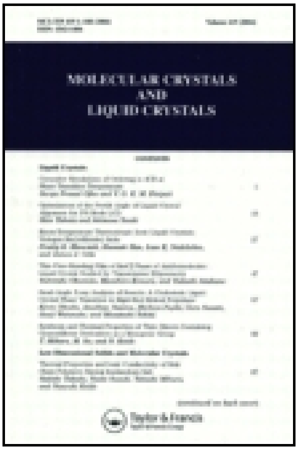

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Determination of the Insertion Loss and Refractive Index Anisotropy in Nematic Liquid Crystal Materials Using a V-band Waveguide Transmission Cell

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Version of record first published: 18 Oct 2010

Mol. Cryst. Liq. Cryst., Vol. 409, pp. 199–207, 2004

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400490431273

DETERMINATION OF THE INSERTION LOSS AND REFRACTIVE INDEX ANISOTROPY IN NEMATIC LIQUID CRYSTAL MATERIALS USING A V-BAND WAVEGUIDE TRANSMISSION CELL

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Large electrooptic effects based on the reorientation of liquid crystal molecules are expected in the high frequency electromagnetic wave region. However, there is only limited information about the optical and/or dielectric properties of the liquid crystal (LC) materials except for the visible and very low frequency region. Here, we try to determine the loss parameter and refractive index anisotropy of the commercially available nematic liquid crystal materials in the millimeter wave (MMW) region by using a V-band (50 GHz – 75 GHz) rectangular waveguide test cell. Loss parameters are determined by fitting the theoretical data based on the multiple reflection phenomena to the measured transmission spectra. Refractive index anisotropy is derived from the phase difference between the horizontal and the vertical LC molecular orientation states. It is found that the usual nematic LC materials are transparent in the millimeter wave region and the refractive index anisotropy is still large.

Keywords: loss properties; millimeter wave; nematic liquid crystal; refractive index anisotropy

INTRODUCTION

Optical properties of liquid crystal (LC) materials in the visible frequency region are well investigated due to the large demand for the display applications. However, large electrooptic effects can also be expected in other electromagnetic wave spectra. Recently, there has been enormous

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technological progress and improvement in the information technology field for utilizing a higher frequency region reaching to the millimeter wave (MMW). LC materials may have a potential applications in the telecommunication technology field as well as in the visible region. Thus far, there have been some LC research works based on the microwave technologies for the higher frequency region. The microstrip-line-type phase modulators [1–3], waveguide-type phase modulators [4–6] and controlling devices for the propagation of electromagnetic wave through space [7,8] have been reported so far. Although the possibility of the LC as an excellent material in the high frequency region has been shown, precise material data such as a complex refractive index are necessary to design the actual devices for the next research phase.

In this work, we are trying to investigate some commercially available nematic liquid crystal materials in the MMW. A V-band (50–75 GHz) rectangular waveguide is used to prepare the test LC cell. Since there is a large MMW reflection by the glass window on the both ends of the waveguide cell, we adopt a multiple reflection model similar to the optical thin film in order to determine the loss parameter which is related to the imaginary part of the refractive index. The refractive index anisotropy in the real part is determined from the phase difference between the parallel and the perpendicular molecular orientation states. Measured data are compared with the data in the visible region and the potential applications of LC materials in the high frequency region are discussed.

MEASUREMENT AND DATA ANALYSIS

A rectangular waveguide is used for the test LC cell since data for the fundamental electromagnetic mode (TE_{10}) is simple to analyze. Both ends of the waveguide (40 mm long) are sealed with thin glass windows (0.1 mm in thickness) and the nematic liquid crystal is filled within the cell as shown in Figure 1. Molecular alignment direction is determined by the external magnetic field using a pair of permanent magnets (5 kG). The molecular alignment direction can be changed by rotating the magnets between the parallel state (V: LC molecules are aligned parallel to the MMW E-field) and the perpendicular state (H: LC molecules are aligned perpendicular to the MMW E-field). The transmission properties are measured using a vector network analyzer (HP8510) within the frequency range from 50 GHz to 75 GHz (V-band).

Figure 2 shows the calculation model for the LC test cell used for data analysis. Both thin glass plates are ignored and two symmetric boundaries are assumed. There was observed to be considerably large reflection in our test cell, so we take account of the multiple reflection phenomena in the

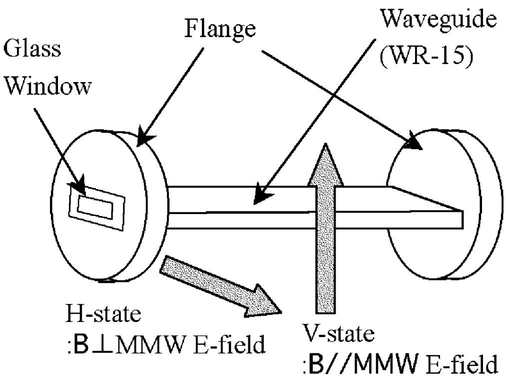

FIGURE 1 Transmission test cell.

calculation. Here, amplitude transmission and reflection coefficients are indicated by t, t', r and r'. The coefficients t, t' and r' can be expressed by r. A pass length of the LC layer is ℓ, and the loss parameter is indicated by A which causes an amplitude attenuation by $exp(-A\ell)$ for each pass of the LC layer. Incident MMW is partly reflected at the both boundaries and comes out as an n_{th} output as indicated by T_{n}. Next output $T_{\mathrm{n+1}}$is created from the output T_{n} by adding two times reflection and the phase shift with some loss while traveling twice the LC layer. Total of the output T_1 through

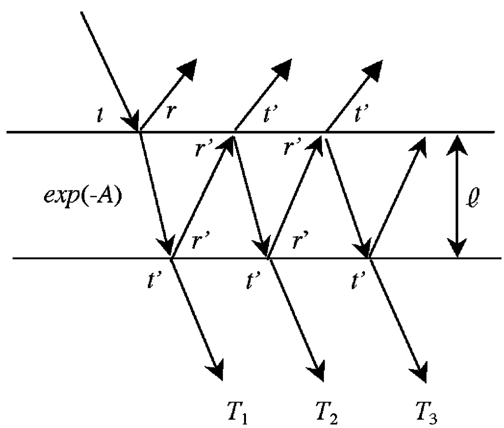

FIGURE 2 Calculation model of the transmission test cell based on the multiple reflection phenomena.

output T_n ($n \to \infty$) gives the actual transmission of the sample. The transmittance can easily be obtained by the sum of the geometric series to infinity as the following:

$$Trans = \frac{(1-r^2)^2 e^{-2A}}{1 - 2r^2 e^{-2A} \cos k\Delta + r^4 e^{-4A}}$$
$$k\Delta = \frac{2\pi}{\lambda_g^n} 2\ell = \frac{4\pi}{\lambda_0} n_{LC}^* \ell \tag{1}$$

Here, k is the wavenumber which is denoted by the same form with the free space by adopting the effective wavelength in the waveguide λ_g. The effective wavelength is different from that in a vacuum and is further modulated by the refractive index of the filled LC material. Then a relationship between the effective wavelength and the refractive index of the LC material can be described as a next equation by introducing an effective refractive index n_{LC}^*.

$$\lambda_g^n = \frac{\lambda_0}{n_{LC}^*}, \quad n_{LC}^* = \sqrt{n_{LC}^2 - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{2}$$

Basically, the refractive index of the LC materials can be determined from the phase data. However, since there may be some uncertainty of $2\pi \times \mathrm{m}$ (m: integer) in the phase data, the absolute refractive index value is difficult to determine from the phase measurement at this stage. We tried to determine the refractive index anisotropy by measuring the phase difference between the molecular orientation states which corresponds to n_e and n_o, because the phase change exceeding 2π can be followed by changing the LC molecular orientation direction continuously. Although the amplitude of the transmission MMW is also modified during the rotation, the number of the phase jump can be followed within a sufficiently slow variation.

The loss parameter can be determined from the amplitude data. Here, we take into a consideration of multiple reflection phenomena, because the loss of the LC tends to be overestimated without the consideration. There are three unknown fitting parameters 1. reflection: r, 2. loss parameter: A and 3. refractive index: n, and the measured transmission spectra is fitted by using the Eq. (1). The refractive indices calculated form the phase data are used for this fitting. Because there is no effect on the fitting even though the uncertainty of 2π m is included. The validity of this determination method is confirmed by using an empty test cell. By choosing the fitting parameters properly, data fitting by Eq. (1) can be successfully achieved, although there is a considerably large reflection coefficient of $r = 0.5$.

EVALUATION OF LC MATERIALS

Typical measurement results of the MMW transmission spectra (K15:BDH) are shown in Figure 3(a) and (b), where the LC alignment direction is parallel and perpendicular to the electric field of the MMW, respectively. Closed circles show the measurement data and solid lines are fitting curves. It is seen that the periodic fluctuation in the data can be successfully be fitted as shown in Figure 3(a). Since there is some dispersion in the measured data, fitting parameters are determined by minimizing the sum of the square of the error. Sometimes it is difficult to get a sufficient fitting for the small fluctuation of the data especially in the low transmission case as shown in Figure 3(b), but that causes no fatal problem to determine the

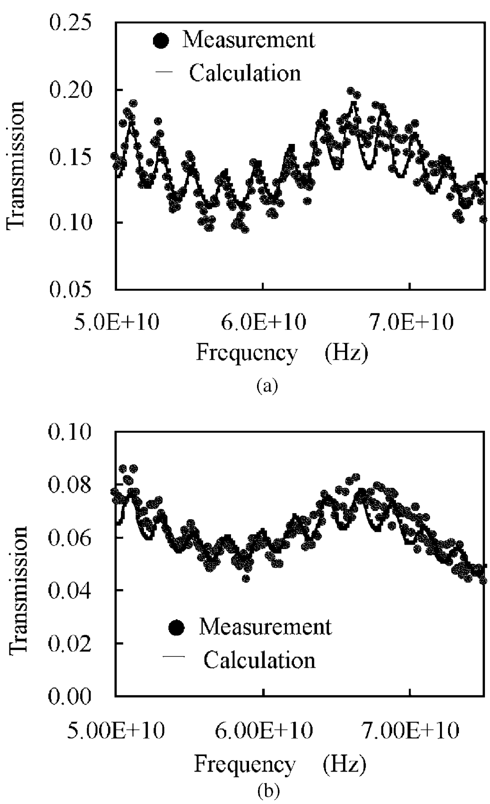

FIGURE 3 Transmission properties of K15 (a) V-state:molecular alignment direction is parallel to the MMW E-field, (b) H-state:that is perpendicular to the MMW.

loss parameter. It is seen that the transmission loss along the direction parallel to the LC molecular long axis is smaller than that along the direction perpendicular to the molecular axis. The loss parameter is small about 10^{-1}(cm^{-1}), but there is a considerably large anisotropy.

Typical phase spectra measured for K15(BDH) is also shown in Figure 4 (a) and (b). While the magnetic field is rotating from the H-state (4(b)) to the V-state (4(a)), the phase value tends to decrease with some jump up from $-\pi$ to π. This means that the phase value along the direction parallel

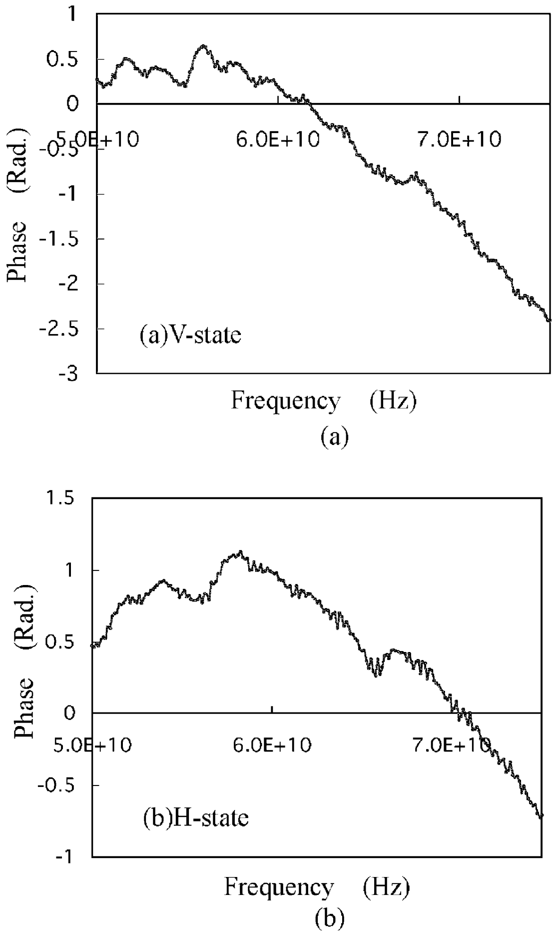

FIGURE 4 Phase properties of the K15 (a) V-state: molecular alignment is parallel to the MMW, (b) H-state: molecular alignment is perpendicular to the MMW.

to the LC molecular axis (Fig. 4(a)) is smaller than that along the perpendicular direction (Fig. 4(b)). Larger k gives a reduction of the phase value by the conventional determination of the phase sign in the microwave research field. The measured data using the network analyzer are also following the notation. Then, the results in Figure 4 show that the LC material has a positive refractive index anisotropy in the MMW region as in the visible region.

There is some uncertainty of $2\pi \times m$ between the data taken with the magnetic field direction parallel and perpendicular to the molecular alignment direction. We determined the integer m by counting the number of phase jumps during the magnetic field rotation, and calculated the anisotropy of the refractive index. Before and after the correction of the refractive index anisotropy data (Δn) are shown in Figure 5. The cause of the small data fluctuation in the figure is not clear in this stage, however there may not be large absorption and dispersion within this frequency band. It is also seen that the LC material has a considerably large Δn, although the value tends to become smaller than that in the visible region.

Determined refractive index and loss parameters for some nematic LC materials at 60 GHz are summarized in Table 1. It seems that the fluorinated LC material (ZLI5092:Merck) has a smaller loss property in comparison with other materials. The loss along the direction perpendicular to the LC molecules is larger than that along the direction parallel to the molecules for all materials as observed in the submillimeter wave region [9].

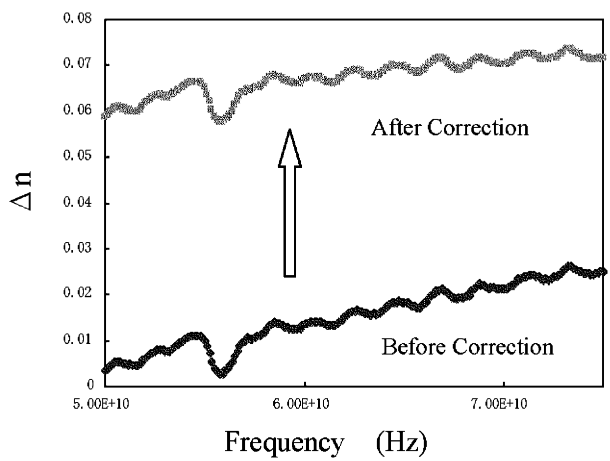

FIGURE 5 Refractive index anisotropy before and after the correction of the phase jump.

TABLE 1 Loss and Refractive Index Properties for Various LC Materials at 60 GHz. α is the Loss Parameter and $\Delta\alpha$ is Defined as α (V) $-$ α(H)

60 GHz	Alignment	$\alpha(\mathrm{cm}^{-1})$	Im(n)	$\Delta\alpha$	Δn
E44	V	2.0	1.0×10^{-4}		
	H	0.30	1.6×10^{-4}	-0.10	0.068
K15	V	0.19	9.9×10^{-5}		
	H	0.27	1.4×10^{-4}	-0.08	0.067
	B = 0	0.22	1.1×10^{-4}		
	Isotropic	0.25	1.3×10^{-4}		
ZLI5092	V	0.12	6.4×10^{-5}		
	H	0.17	9.2×10^{-5}	-0.05	0.039

The transmission loss is much smaller than that in the submillimeter wave region, and the imaginary part of the refractive index becomes about one-tenth.

Determined value are influenced by the dispersion in the measured phase and amplitude data. Comparing among the repeated experimental results, there may be a certainty about ± 0.02 both in the determined value of Δn and loss parameter. However, since the difficulty of the sample preparation tends to cause larger dispersion of the results, improved measurement method should be attained to increase the reliability.

Unfortunately, the refractive index anisotropy tends to decrease to be around $1/2 \sim 1/3$ of the value in the visible region, however it still has a large value on the order of 10^{-2}. The order of the refractive index anisotropy among the measured materials in the MMW region is the same with the order in the visible region. The LC materials which have a large refractive index anisotropy in the visible region can be expected to have a large refractive index anisotropy in the MMW region.

CONCLUSIONS

The refractive index anisotropy and the loss parameter of the common nematic LC materials are successfully determined by using a rectangular waveguide test cell in the MMW region (V-band:50 GHz–75 GHz). Although a glass window which seals the LC material inside the waveguide causes a large reflection of MMW, the measured data can be well fitted considering with the multi reflection phenomena.

It is found that the LC materials are transparent in the MMW region, but the direction perpendicular to the LC molecular axis has a larger loss property. Fluorinated material tends to show smaller loss and smaller loss anisotropy. The refractive index anisotropy becomes around $1/2-1/3$ of the visible value, but the value is still large and is on the order of 10^{-2}.

There should be a dielectric dispersion band between the MMW (or sub-MMW) region and visible region considering with the degradation of Δn. This is supported by the fact that there are usually absorption bands around the infrared region. Increase fraction of the polarization may unfortunately reduce the anisotropy of the LC materials in the MMW region.

In this work, although we have successfully determined the anisotropy of the refractive index by the magnet rotating method, determination of the absolute value of the refractive index is also very important to design the actual devices and to understand the dielectric dispersion phenomena around the very high frequency region. Then a new determination method for the absolute value is under investigation.

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