Estimating the Birefringence and Absorption Losses of Hydrogen-bonded Liquid Crystals with Alkoxy Chains at 2.5 THz

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SUMMARY Liquid crystal (LC) device has high tunability with low power consumption and it is important not only in visible region but also in terahertz region. In this study, birefringence and absorption losses of hydrogen-bonded LC was estimated at 2.5 THz. Our results indicate that introduction of alkoxy chain to hydrogen-bonded LC is effective to increase birefringence in terahertz region. These results indicate that hydrogen-bonded LCs are a strong candidate for future terahertz devices because of their excellent properties in the terahertz region.

key words: Terahertz, liquid crystal, hydrogen bonding, optically pumped gas laser.

1. Introduction

Terahertz waves have attracted significant attention for many years, owing to their promising applications including communication technologies, security checking, and nondestructive testing [1]. Recently, there have been extensive efforts to investigate terahertz wave control devices. Liquid crystals (LCs) are well known as excellent electro-optic materials and are strong candidates for high-performance terahertz wave control devices owing to their low power consumption and controllability at low drive voltages.

A material’s properties in the terahertz frequency range must be fully understood before it can be used for terahertz applications. Researchers have thus aimed to clarify the optical properties of LCs in the terahertz region. For example, Nose et al. [2] reported that LCs exhibit birefringence in the terahertz frequency range by using an optically pumped far-infrared gas laser. Many others have since used terahertz time-domain spectroscopy systems to demonstrate the refractive indices of LCs in the terahertz range [3–15]. Based on these substantiated and attractive terahertz properties, LCs have attracted attention for usage in a variety of terahertz wave control devices. Pan et al. [16–19] developed a terahertz-tunable LC phase shifter, whereas Koch et al. [20] developed a tunable LC filter. Other reported LC-based tunable terahertz wave control devices have included a reflection-type phase shifter [21], an LC tunable metamaterial absorber [22], an LC phase grating device [23], and an LC-based vortex beam generator [24]. Since terahertz waves have longer wavelengths than their visible light counterparts, a thick LC layer is often needed for LC-based terahertz wave control devices. However, in general, the LC layer should be as thin as possible to allow fast operation and high birefringence LCs are effective to decrease the thickness of the LC layer. As such, LC materials exhibiting high birefringence in the terahertz range have been reported [25–27]. However, almost all previously reported LC materials exhibit dichroism in the terahertz range (i.e., the terahertz wave absorption varies depending on the polarization of the incident terahertz wave) [2–4, 8–13, 25–27]. This dichroism can cause unwanted variations in the intensity of the LC-based terahertz wave control devices. In our previous work, we confirmed that hydrogen-bonded LC with alky chain does not exhibit dichroism at 2.5 THz [28]. Nevertheless, the birefringence of this LC was not large as reported high-birefringence LCs [25–27]. In this study, we focus on hydrogen-bonded LC with alkoxy chains and estimate the birefringence and absorption losses at 2.5 THz. Here, the transmittance of the homogeneous alignment cell is measured using an optically pumped gas laser and birefringence and absorption losses of the hydrogen-bonded LC with alkoxy chains is estimated by using Jones matrix calculations.

2. Experimental

2.1 Measurement Methods

Figure 1 shows structure of a homogeneous alignment cell for terahertz measurements. To maintain a high transmittance of the terahertz wave, we used z-cut quartz substrates. The LC material 6380 (LCC, Japan) was injected into a sandwich cell. The 6380 contains the dimer of 4-alkoxybenzoic acid as shown in Figure 2. Both of the inner surfaces of the substrates were treated with antiparallel rubbing after coating the planar alignment layer with polyimide (SE2170, Nissan Chemical Industries, Japan) to obtain homogeneous alignment. The cell thickness was determined by using sheet spacers. The LC layer was 800 μm thick.

Figure 3 shows the experiment setup. In this study, the terahertz wave intensity profiles were measured using an optically pumped gas laser as a terahertz source, as shown...
in the experimental setup that is summarized in Figure 3. This laser is a coherent continuous wave source and delivers powerful terahertz radiation above 0.3 THz. A CO₂ laser was used to pump the CH₃F₂ gas, and a frequency of 2.5 THz was used for the measurements. The LC device was placed between two wire-grid polarizers. To minimize the influence of laser power variation when measuring the intensity of the terahertz wave, two pyroelectric detectors were used. Thus, an accurate transmittance was obtained by normalizing the intensity of pyroelectric detector 2 by that of detector 1 (see Figure 3).

The birefringence and absorption losses of the LC were evaluated by calculating the transmittance of the homogeneous cell using the Jones matrix method [28, 29]. Since the LCs have absorption loss in the terahertz region, we consider the influence of absorption loss in the Jones matrix calculation as follows [28]. Here, the electric field of the terahertz wave passing through the homogeneous cell can be written as

\[ \begin{bmatrix} E_x \\ E_y \end{bmatrix} = P_A Q W Q \begin{bmatrix} \cos \Psi_p \\ \sin \Psi_p \end{bmatrix}, \]

where \( P_A, Q, \) and \( W \) represent the Jones matrices of the analyzer, z-cut quartz substrate, and homogenous cell, respectively, and \( \Psi_p \) is the angle of the analyzer. Here, \( P_A \) is calculated as

\[ P_A = R(\Psi_p) \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} R(-\Psi_p), \]

where \( \Psi_p \) is angle of the analyzer and \( R(\Psi) \) is the rotation matrix,

\[ R(\Psi) = \begin{bmatrix} \cos \Psi & -\sin \Psi \\ \sin \Psi & \cos \Psi \end{bmatrix}. \]

Further, the Jones matrix of the z-cut quartz substrate (i.e., \( Q \)), is written as

\[ Q = \exp \left( -\frac{2\pi n'' d}{\lambda} \right) \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \]

where \( d \) and \( n'' \) are the thickness and imaginary part of the refractive index of the z-cut quartz substrate, respectively, and \( \lambda \) is wave length of the terahertz wave. The Jones matrix of the homogeneous cell (\( W \)) is written as follow.

\[ W = R(\Psi_{LC}) \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix} R(-\Psi_{LC}). \]

Here, \( a \) and \( b \) are written as

\[ a = \exp \left( -\frac{\mu e}{2} \right) \exp \left( -\frac{2\pi n'' d_{LC}}{\lambda} \right), \]

\[ b = \exp \left( \frac{\mu e}{2} \right) \exp \left( -\frac{2\pi n'' d_{LC}}{\lambda} \right), \]

where \( d_{LC} \) is the thickness of LC layer, \( n'' \) are the imaginary part of the extraordinary and ordinary refractive indices of the LC, respectively, and \( \lambda \) can be calculated as

\[ \lambda = \frac{2\pi n d}{\lambda}. \]

where \( \Delta n \) is the birefringence of the LC.

3. Result and Discussion

Figure 4 shows the experimental and calculated terahertz transmittance values of the homogeneous cell using 6380 at 2.5 THz. The graph shows the transmittance as a function of analyzer angle \( \Psi_p \) when the direction of the polarizers \( \Psi_p = 90 \) deg and the direction of LC director \( \Psi_{LC} = 0, 45, 90 \) deg as shown in Figure 3. The measured and calculated data were in good agreement when \( n'' = 0.028 \) and \( \Delta n = 0.19 \). Here, \( n'' = 0.0005 \), corresponding with \( \alpha = 4\pi n'' / \lambda = 0.5 \) cm⁻¹, and is consistent with previously reported values [30]. The tendency of \( n'' = 0.028 \) is consistent with reported results of hydrogen-bonded LCs without alkyl chains [28]. The estimated \( \Delta n \) of LC 6380 was 0.19, slightly greater than the reported value of 0.17 in a hydrogen-bonded LC without alkyl chains [28]. The incensement of birefringence in the terahertz region by introducing alkyl chain has been reported in LCs without hydrogen bonding [11]; the results presented here thus indicate that alkyl chains can enhance birefringence in hydrogen-bonded LCs, as well. Further, the lower \( n'' \) value (i.e., 0.028 vs. 0.035 by [28]) is attractive for the development of future LC-based terahertz wave control devices. More-detailed measurements are in progress to characterize the broadband terahertz properties of hydrogen-bonded LCs.
4. Conclusions

The absorption losses and birefringence of a hydrogen-bonded LC at 2.5 THz were measured by using optically pumped gas laser. The experimental and calculated results indicate that the introduction of an alkoxy chain can increase the birefringence and ensure no dichroic absorption at 2.5 THz. Furthermore, the absorption loss of the hydrogen-bonded LC with alkoxy chains is lower than that of hydrogen-bonded LCs with alkyl chains. This work thus represents a significant step toward the development of LC-based terahertz wave control devices used in terahertz applications, which require no dichroism, low losses, and high birefringence.

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References


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