Estimation of Birefringence and Absorption Losses of hydrogen-bonded Liquid Crystal with Alkoxy Chain in Terahertz region

Ryota Ito[1], Hayato Sekiya[1], Michinori Honma[1] and Toshiaki Nose[1]

r_ito@akita-pu.ac.jp
[1] Akita Prefectural University, 84-4 Ebinokuchi, Tsuchiya, Yurihonjo, Akita 015-0055, Japan
Keywords: Terahertz, Liquid Crystal, Hydrogen-bonding.

ABSTRACT

Liquid crystal (LC) device 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.

1 INTRODUCTION

Terahertz waves have attracted significant attention for many years, mainly because of their promising applications including communication technologies, security checking, and nondestructive testing [1]. Recently, there has been an extensive effort to investigate terahertz wave control devices. Liquid crystal (LC) materials are well known as excellent electro-optic materials, and they are strong candidates for high-performance terahertz wave control devices because of their controllability at low drive voltages and their low power consumption. Up to now, many groups have reported optical properties of LCs in the terahertz region. Nose et al. reported that LCs also exhibit birefringence in the terahertz frequency range by using an optically pumped far-infrared gas laser [2]. Since then, several groups have reported the refractive indices of LCs in the terahertz range by using terahertz time-domain spectroscopy systems [3–13]. Based on these substantiated and attractive terahertz properties of LCs, they have attracted attention for a variety of terahertz wave control devices. Pan et al. developed a terahertz tunable LC phase shifter [14–15]. Koch et al. developed a tunable LC filter [16]. Several other groups also reported LC-based tunable terahertz wave control devices such as a reflection type phase shifter [17], an LC tunable metamaterial absorber [18], an LC phase grating [19], and an LC-based vortex beam generator [20].

Since terahertz waves have longer wavelengths than visible light, a thick LC layer is often needed for an LC-based terahertz wave control devices. However, in general, the LC layer should be as thin as possible to allow fast operation. For this purpose, LC materials exhibiting high birefringence in the terahertz range have been reported [21–23]. However, almost all previously developed LC materials exhibit dichroism in the terahertz range [2, 3, 6–13, 21–23] (i.e., the terahertz wave absorption varies depending on the polarization of the incident terahertz wave). This dichroism can cause unwanted variations in the intensity of the LC-base terahertz wave control devices. In our previous work, we confirmed that hydrogen-bonded LCs do not exhibit dichroism at 2.5 THz. Furthermore, hydrogen-bonded LC exhibit higher birefringence in the terahertz range than in the visible range [24].

In this study, we estimate the birefringence and absorption losses of hydrogen-bonded LC with alkoxy chain at 2.5 THz. The transmittance of homogeneous alignment cell was measured by using an FIR CW laser and the birefringence and absorption losses of the hydrogen-bonded LC with alkoxy chain was estimated by using Jones matrix calculations.

2 EXPERIMENT

Figure 1 shows structure of homogeneous alignment cell for terahertz measurements. The LC material 6380 (LCC, Japan) was injected into a sandwich cell. To keep the high transmittance of the terahertz wave, we used quartz substrates. The 6380 contains the dimer of 4-alkoxybenzoic acid as shown in Fig. 2. Both 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 thickness of the LC layer was 800 μm for terahertz operation.

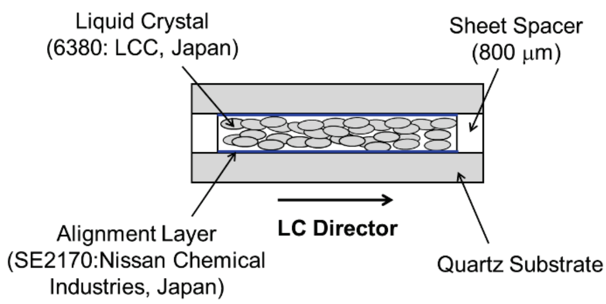

Fig. 1 Structure of homogeneous alignment cell for terahertz measurements

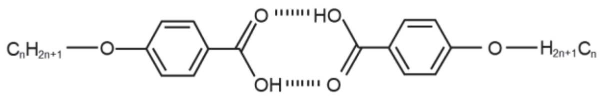

Fig. 2 Molecular structure of hydrogen-bonded liquid crystal.

Figure 3 shows the experiment setup. In this study, the terahertz wave intensity profiles were measured by using an FIR CW laser as a signal source. This laser was the major source of a coherent CW with a powerful terahertz radiation above 0.3 THz. Here a CO_2 laser was used for pumping the CH_2F_2 gas, and a frequency of 2.5 THz was used for our measurements. The LC device was placed between two wire-grid polarizers, and the intensity of the terahertz wave was detected by a pyroelectric detector.

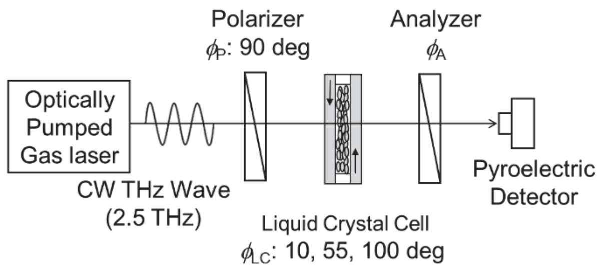

Fig. 3 Experimental set up.

3 RESULTS and DISCUSSION

Figure 4 shows the experimental and calculated terahertz transmittance of homogeneous cell using 6380 at 2.5 THz. The graph shows the transmittance as a function of analyzer angle ϕ_A when the direction of the polarizers ϕ_P = 90° and the direction of LC director ϕ_{LC} = 10°, 55°, and 100° as shown in Fig. 3. To evaluate the birefringence and losses of LC, we simulated transmittance of homogeneous cell by using the Jones matrix method [25]. The calculation data are relatively close to the experimental data when we set n_e" = n_o" = 0.028 and Δn = 0.19. Here, we took into account the attenuation of the two substrates by setting the absorption coefficient of the quartz substrates at α_s = 0.5 cm^{-1}.The tendency of n_e" = n_o" corresponds to the reported result of hydrogen-bonded LC [24]. However, the estimated Δn of 6380 is larger than the reported values of hydrogen-bonded LC without alkoxy chain.

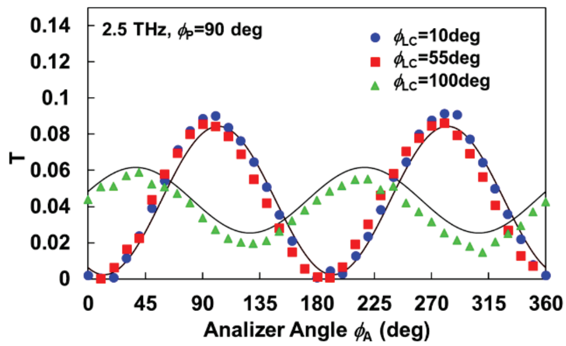

Fig. 4 Experimental and calculation terahertz transmittance of homogeneous cell using 6380 at 2.5 THz. Solid lines show the calculation results of Jones matrix method.

4 CONCLUSIONS

In this study, we evaluate the absorption losses and birefringence of hydrogen-bonded LC at 2.5 THz. Our experimental and calculation results indicate that introduction of alkoxy chain is effective to increase the birefringence in THz region.

Acknowledgement

This work was also partially supported by JSPS KAKENHI Grant Number JP20K04625.

REFERENCES

[1] M. Tonouchi, Nature Photonics 1, 97 (2007).

[2] T. Nose, S. Sato, K. Mizuno, J. Bae, and T. Nozokido, Appl. Opt., AO 36, 6383 (1997).

[3] D. Turchinovich, P. Knobloch, G. Luessem, and M. Koch, in Liquid Crystals V (International Society for Optics and Photonics, 2001), pp. 65–71.

[4] Y. Takanishi, K. Ishikawa, J. Watanabe, H. Takezoe, M. Yamashita, and K. Kawase, Phys. Rev. E 71, 061701 (2005).

[5] S. Tanaka, Y. Okada, K. Yamamoto, Y. Takanishi, M. Tani, K. Ishikawa, M. Hangyo, and H. Takezoe, in Emerging Liquid Crystal Technologies II (International Society for Optics and Photonics, 2007), p. 648708.

[6] R.-P. Pan, C.-F. Hsieh, C.-L. Pan, and C.-Y. Chen, Journal of Applied Physics 103, 093523 (2008).

[7] R. Wilk, N. Vieweg, O. Kopschinski, T. Hasek, and M. Koch, J Infrared Milli Terahz Waves 30, 1139 (2009).

[8] O. Trushkevych, H. Xu, T. Lu, J.A. Zeitler, R. Rungsawang, F. Gölden, N. Collings, and W.A. Crossland, Appl. Opt., AO 49, 5212 (2010).

[9] N. Vieweg, M.K. Shakfa, B. Scherger, M. Mikulics, and M. Koch, J Infrared Milli Terahz Waves 31, 1312 (2010).

[10] C.-S. Yang, C.-J. Lin, R.-P. Pan, C.T. Que, K. Yamamoto, M. Tani, and C.-L. Pan, J. Opt. Soc. Am. B, JOSAB 27, 1866 (2010).
[11] N. Vieweg and M. Koch, Appl. Opt., AO 49, 5764 (2010).
[12] N. Vieweg, B.M. Fischer, M. Reuter, P. Kula, R. Dabrowski, M.A. Celik, G. Frenking, M. Koch, and P.U. Jepsen, Opt. Express, OE 20, 28249 (2012).
[13] M. Reuter, K. Garbat, N. Vieweg, B.M. Fischer, R. Dąbrowski, M. Koch, J. Dziaduszek, and S. Urban, J. Mater. Chem. C 1, 4457 (2013).
[14] C.-Y. Chen, T.-R. Tsai, C.-L. Pan, and R.-P. Pan, Appl. Phys. Lett. 83, 4497 (2003).
[15] C.-F. Hsieh, R.-P. Pan, T.-T. Tang, H.-L. Chen, and C.-L. Pan, Opt. Lett., OL 31, 1112 (2006).
[16] N. Vieweg, N. Born, I. Al-Naib, and M. Koch, J Infrared Milli Terahz Waves 33, 327 (2012).
[17] L. Wang, S. Ge, W. Hu, M. Nakajima, and Y. Lu, Opt. Mater. Express, OME 7, 2023 (2017).
[18] D. Shrekenhamer, W.-C. Chen, and W.J. Padilla, Phys. Rev. Lett. 110, 177403 (2013).
[19] C.-J. Lin, Y.-T. Li, C.-F. Hsieh, R.-P. Pan, and C.-L. Pan, Opt Express 16, 2995 (2008).
[20] S. Ge, P. Chen, Z. Shen, W. Sun, X. Wang, W. Hu, Y. Zhang, and Y. Lu, Opt. Express, OE 25, 12349 (2017).
[21] N. Vieweg, M.K. Shakfa, and M. Koch, Optics Communications 284, 1887 (2011).
[22] L. Wang, X. Lin, X. Liang, J. Wu, W. Hu, Z. Zheng, B. Jin, Y. Qin, and Y. Lu, Opt. Mater. Express, OME 2, 1314 (2012).
[23] M. Reuter, N. Vieweg, B.M. Fischer, M. Mikulicz, M. Koch, K. Garbat, and R. Dąbrowski, APL Materials 1, 012107 (2013).
[24] Ito, R., Honma, M. and Nose, T., “Electrically Tunable Hydrogen-Bonded Liquid Crystal Phase Control Device,” Applied Sciences 8(12), 2478 (2018).
[25] Jones, R.C. “A New Calculus for the Treatment of Optical SystemsI. Description and Discussion of the Calculus“. J. Opt. Soc. Am., 31, 488–493, (1941).