Measuring Liquid Crystal Permittivity With High Accuracy

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In this paper three methods for the characterisation of dielectric properties of Liquid Crystal (LC) are presented. Their main properties as well as results obtained by each method are discussed. The knowledge of these properties are interesting in microwave, millimetre-wave and terahertz applications due to the low dispersion and low losses in these electrically and magnetically tuneable, anisotropic materials.

1. Introduction

Liquid crystals (LC) are a class of anisotropic liquid dielectric materials well-known in the field of display technology since the 1970s. Recently, they have been the subject of various investigations from the microwave through to the terahertz range. Their unique property to exhibit local anisotropy allows for tuning using chopped electric fields (DC) and for building various types of tuneable components, e.g. phase shifters.

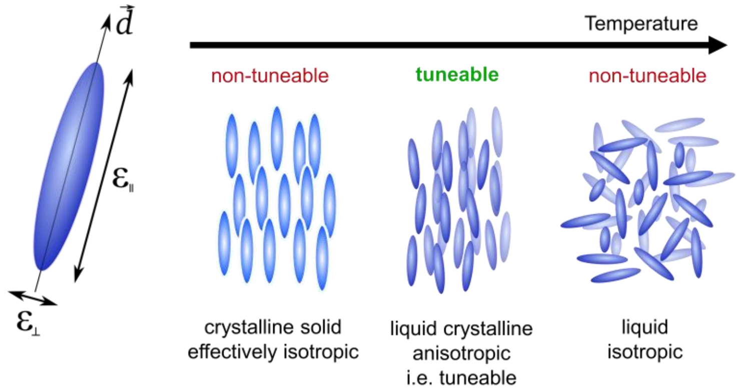

Fig. 1. Director Model of Liquid Crystal and respective material phases over temperature

Both loss angle, $\tan\delta$, and permittivity, ε_r, can be expressed as tensors with respect to the director (i. e. ordinary axis) as

$$\tilde{\varepsilon}_r = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix} \text{ and } \widetilde{\tan\delta} = \begin{pmatrix} \tan\delta_\perp & 0 & 0 \\ 0 & \tan\delta_\perp & 0 \\ 0 & 0 & \tan\delta_\parallel \end{pmatrix} \quad (1)$$

$$\text{with the loss angle } \tan\delta = \Im\underline{\varepsilon}_r / \Re\underline{\varepsilon}_r$$

respectively, with typically $\varepsilon_\parallel > \varepsilon_\perp$ and $\tan\delta_\parallel < \tan\delta_\perp$. Accurate characterisation of these properties on a macroscopic level is essential for material system optimisation and can reveal information about phase transitions if carried out over a wide frequency range. Determining the anisotropic properties of LCs requires two measurements with well-known field expressions.

2. Non-resonant methods

Non-resonant line methods have been employed to characterise LCs up into the region of 50 GHz, a prominent one being the coaxial line approach [1].

2.1 Coaxial Line

The parallel permittivity, $\varepsilon_{\parallel}$, and loss, $\tan\delta_{\parallel}$, are determined using a static voltage between an inner conductor and ground as depicted in Fig. 1. Since the RF field contains radial components only, $\varepsilon_{\text{eff}} = \varepsilon_{\parallel}$ holds.

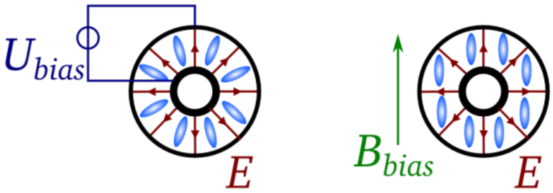

Fig. 2. Biasing arrangement in the two stages of a coaxial line measurement

In a second measurement, an external homogeneous magnetic field orders all directors in parallel so that a simple consideration of symmetry yields $\varepsilon_{\text{eff}} = (\varepsilon_{\parallel} + \varepsilon_{\perp})/2$. A simple vector network analyser (VNA) measurement is needed to obtain data over a wide frequency range. There are several ways of obtaining permittivity and loss data from the S parameters obtained in a VNA measurement. The method employed here is the reflection-transmission method, where the following assumptions and relations hold:

$$S_{11}=S_{22}=\frac{\underline{r}(1-\underline{z}^2)}{1-\underline{r}^2\underline{z}^2},\quad S_{21}=S_{12}=\frac{\underline{z}(1-\underline{r}^2)}{1-\underline{r}^2\underline{z}^2}$$
$$\text{with}\quad \underline{z}=e^{-i\frac{2\pi f}{c_0}L_{\text{line}}\sqrt{\varepsilon_r}}\quad\text{and}\quad \underline{r}=\frac{\underline{\varepsilon_r}^{-1/2}-1}{\underline{\varepsilon_r}^{-1/2}+1} \tag{2}$$

With this method, the permittivity of E7, a common and commercially available LC, has been determined in the range of 10 to 50 GHz with $\varepsilon_{\parallel} = 2.96, \tan\delta_{\parallel} = 9.36 \cdot 10^{-3}$, $\varepsilon_{\perp} = 2.61$ and $\tan\delta_{\perp} = 24.90 \cdot 10^{-3}$ [1].

A downside of this method is that the determination of material losses is limited. If approximately $\tan\delta < 10^{-2}$, metallic losses and mismatch become more important than material losses, especially at higher frequencies.

2.1 Free Space

In the terahertz range, where metallic resonators are currently not envisaged, one falls back to a transmission line method as described above (coaxial line). The measurements are taken with a quasi-optical setup in transmission. Time Domain Spectroscopy (TDS) Systems provide a transient signal that – once transformed into the frequency domain – serves as data for fitting material parameters. Permittivities are determined using the signal phase shift with respect to an empty measurement. Once the phase is known, loss can be determined by comparing the transmissivity of the empty measurement with that of the sample. Data is obtained over a wide frequency range (from 250 GHz up to several THz, depending on the system). Here, a very good agreement of the permittivity values between THz measurements and results from a resonant cavity has been observed. The materials exhibit almost flat permittivity curves up to 1.5 THz with values of $\varepsilon_{\parallel} = 3.19, \tan\delta_{\parallel} = 17.5 \cdot 10^{-3}, \varepsilon_{\perp} = 2.34$ and $\tan\delta_{\perp} = 28.6 \cdot 10^{-3}$ for Merck's GT3-23001 [2]. Much like in the coaxial line approach, losses are well resolved only if they are comparatively large. The present method did not resolve these very well. Resonant methods offer an elegant solution for this issue.

3. Resonant Methods: Cavity Perturbation

Using magnetic biasing, the LC is oriented along the central axis of a cylindrical cavity. If the perturbed resonant modes of the cavity are considered, two adjacent modes can be found that are almost rigorously orthogonal in E-field orientation with respect to each other [3].

Two examples of such modes are TM010 and TE111, where the E-field of the first contains only z-components while the latter contains only $\boldsymbol{\rho}$ and $\boldsymbol{\varphi}$-components. TM010 is therefore used to determine $\boldsymbol{\varepsilon}_{\parallel}$ and $\mathbf{tan}\,\boldsymbol{\delta}_{\parallel}$ which is done through a variation of the said parameters in a numerical model of the cavity. Knowing the parallel components, TE111 is used to extract the other components $\boldsymbol{\varepsilon}_{\perp}$ and $\mathbf{tan}\,\boldsymbol{\delta}_{\perp}$.

This approach is limited by fabrication tolerances and sample sizes. The LC is injected into a quartz tube of 750 µm diameter. The use of higher frequencies therefore enforces the introduction of higher order modes. Currently, a higher-order cavity for 60 GHz is investigated. It offers two adjacent, quasi-orthogonal modes TE111 at 57 GHz and TM020 at 60 GHz. A dielectric tuning element is introduced in order to separate the modes in the desired way. 3 GHz are chosen to ensure reliable data fitting.

A VNA measurement provides the transmission data. Lorentzians are fitted on both resonance peaks and yield an estimate for $\boldsymbol{f}_{\mathrm{res}}$ and $\boldsymbol{Q}$ (quality factor). A numerical model of the resonator provides the means of varying the aforementioned material parameters such that the estimates are met. A simple, yet not particularly efficient method is to optimise using CST Studio Suite's solver. Another way is calculating the eigenmodes and their parameters manually exploiting the symmetries of a cylindrical cavity which reduces model complexity. Depending on the quality factor, $\boldsymbol{Q}$, loss angles as small as $\mathbf{10^{-4}}$ can be determined.

4. Conclusion

We have compared three methods of obtaining permittivity data of uniaxially anisotropic liquids, namely LCs. A large frequency range has been covered in order to understand and model the materials accurately. Non-resonant techniques proved to be suited for wideband characterisation of permittivity but not so much for losses – at least at higher frequencies, i. e. larger than 60 GHz. Resonant methods resolve losses very well and if taken to higher-order modes with high quality factors still perform well at 60 GHz.

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