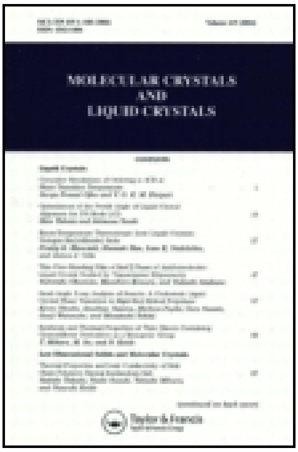

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Characterisation and Applications of Nematic Liquid Crystals in Microwave Devices

Richard James [a] [b] , F. Aníbal Fernández [b] , Sally E. Day [b] , Senad Bulja [c] & Dariush Mirshekar-Syahkal [c]

[a] Ghent University, Gent, Belgium

[b] University College London, London, U.K.

[c] University of Essex, Colchester, Essex, U.K.

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Characterisation and Applications of Nematic Liquid Crystals in Microwave Devices

RICHARD JAMES,[1,2] F. ANÍBAL FERNÁNDEZ,[2] SALLY E. DAY,[2] SENAD BULJA,[3] AND DARIUSH MIRSHEKAR-SYAHKAL[3]

[1]Ghent University, Gent, Belgium
[2]University College London, London, U.K.
[3]University of Essex, Colchester, Essex, U.K.

A method to characterise the dielectric properties of liquid crystal materials at microwave frequencies is presented that utilises a microstrip line with a layer of liquid crystal as a substrate. Accurate modelling of the liquid crystal and microwave fields is used to determine the dielectric properties of the liquid crystal from experimental measurements. The method is applied to a number of liquid crystal materials.

Keywords Dielectric properties; electromagnetic modelling; liquid crystal; microstrip; microwave

1. Introduction

Liquid crystals are attractive substrates for microwave devices. They possess a significant tuneable dielectric constant in the mm-waveband [1–3], which can be exploited in compact and reconfigurable devices such as phase shifters and antennas. When designing such devices two main problems are normally encountered. Firstly, the dielectric properties of few liquid crystals have been fully characterised in this waveband. Secondly, design tools fail to account fully for the spatial dependence of the liquid crystal orientation and its effect on the electromagnetic fields. We address the problem of characterisation using a microstrip line fabricated with a layer of liquid crystal as its substrate [4]. Standard microwave substrates are employed resulting in a practical and cost-effective characterisation device. A network analyser is used to measure the scattering parameters prior to and after filling with liquid crystal. Accurate models of the director and microwave fields are then used to set up an inverse problem that allows for the recovery of a number of liquid crystal material properties, including permittivities, loss tangents and elastic constants. Results of the characterisation are presented for a number of liquid crystalline materials.

Address correspondence to Richard James, Ghent University, St. Pietersnieuwstraat 41, 9000 Gent, Belgium. Tel.: +32 9 264 89 52; Fax: +32 9 264 35 94; E-mail: r.james@ee.ucl.ac.uk

2. Characterisation

Methods for characterizing the dielectric properties of materials at microwave materials can be broadly categorised in two classes. Firstly, there are the resonant methods that are apt to determine the properties at spot frequencies with high precision. However, it is difficult to determine the material losses accurately. A typical structure employed in this method would be a ring or patch resonator. Secondly, there are the broadband methods, which sacrifice accuracy to a degree in order to characterise both permittivity and loss tangent over some frequency range. In general, any waveguiding structure can be used for this purpose, where the liquid crystal replaces the dielectric, for example a coaxial waveguide where liquid crystal fills the space between inner and outer conductor [3].

We pursue a broadband approach, using the characterisation device shown in Figure 1. In essence it is a microstrip line; a strip electrode separated from a ground plane by a dielectric layer. However, we substitute the dielectric layer for a layer of liquid crystal. The advantage of this structure over the coaxial approach is that alignment is more controllable and it is straightforward to reorient the liquid crystal by means of an external electric field. The width of the line is 1 mm and the ground plane is of finite extent (2 mm) to ease fabrication. The microstrip line is terminated by microstrip to coplanar waveguide transitions [5]. Probes may be straightforwardly and conveniently attached to the coplanar waveguides facilitating measurement with a network analyser. The device comprises three layers of standard microwave substrate, namely the TMM series from Rogers Corporation. Maintaining a constant liquid crystal layer thickness is important and is facilitated by the rigidity of these substrates. The liquid crystal layer thickness is chosen as 101 μm so that the device contains a modest quantity of liquid crystal and to give the desired characteristic impedance. This thickness is a compromise; from the microwave point of view a thicker substrates is preferable, but this would be detrimental to achieving liquid crystal alignment. Electrical connectivity between the microstrip line and coplanar waveguides is provided by vias through the gasket.

Alignment of the liquid crystal is achieved by spin coating the upper and lower substrates with a layer of polyimide, which is subsequently annealed and rubbed. One difficulty associated with using standard microwave substrates is that they are relatively rough prior to treatment, with an r.m.s roughness of 1–2 μm. For conventional microwave devices, such surface roughness is perfectly acceptable and in no way detrimental to performance. However, achieving uniform liquid crystal alignment on such a surface is difficult. To achieve alignment the polyimide layer is made thick ($\sim$2 μm) so it acts to planarise the substrates. Subsequent to treatment an r.m.s

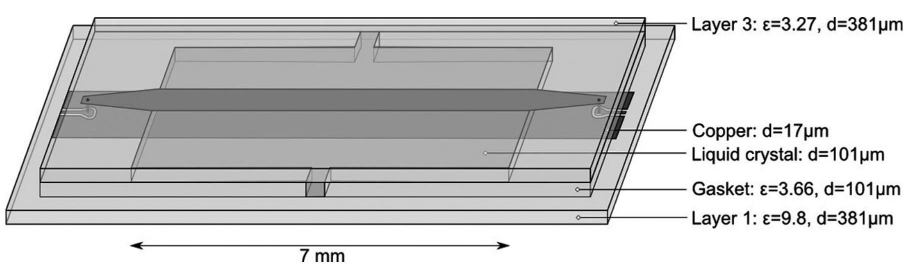

Figure 1. Characterisation device; a microstrip line with a liquid crystal substrate.

roughness of 100–200 nm results, which has been confirmed to provide good alignment by polarizing microscopy of a liquid crystal layer sandwiched between a treated substrate and a glass coverslip.

After filling the cell by capillary action, it is connected to a network analyser and the scattering parameters measured from 30 to 60 GHz. However, the measured results include the influence of the transitional regions as well. In order to ascertain the scattering parameters of the line section alone, a through-line calibration technique is employed [5]. This yields the effective permittivity of the line section. In order to get from this to the parallel and perpendicular permittivity of the liquid crystal itself, one needs to know the microwave and liquid crystal orientational fields accurately. These can be determined by means of modelling.

In modelling the liquid crystal orientation it is of interest to obtain the steady-state orientation in an efficient manner. Since the alignment is contrived to avoid defects (with rubbing parallel to the microstrip line length), it is sufficient to use the Oseen-Frank theory to determine the liquid crystal orientation. The Oseen-Frank free energy functional is supplemented by a Lagrange multiplier to enforce the unitary length of the director. From the director field, the permittivity distribution can be determined at microwave frequencies, provided $\varepsilon_\perp$ and $\varepsilon_\parallel$ are known. Once known, the microwave fields can be calculated by minimizing a variational form of the Helmholtz equation for the electric field

$$\Pi(\vec{E}) = \frac{1}{2}\int_\Omega \left(\frac{1}{\mu_r}(\nabla \times \vec{E}) \cdot (\nabla \times \vec{E})^* - k_0^2 \vec{E} \cdot \bar{\bar{\varepsilon}} \cdot \vec{E}* \right) d\Omega, \tag{1}$$

where $\vec{E}$ is the electric field, k_z the propagation constant, k_0 the free-space wave number and $\bar{\bar{\varepsilon}}$ the permittivity tensor. Since the liquid crystal orientation is invariant along the length of the microstrip line, the electric field can be assumed to vary in the longitudinal direction as

$$\vec{E}(x, y, z) = \vec{E}(x, y) \exp(-jk_z z), \tag{2}$$

which can be substituted into the variational form above to yield

$$\Pi(\vec{E}) = \frac{1}{2}\int_\Omega \left(\frac{1}{\mu_r}(\nabla_t \times \vec{E}_t) \cdot (\nabla_t \times \vec{E}_t)^* - k_0^2 \vec{E} \cdot \bar{\bar{\varepsilon}} \cdot \vec{E}* \right. \\ \left. + \frac{1}{\mu_r}(\nabla_t E_z + jk_z \vec{E}_t) \cdot (\nabla_t E_z + jk_z \vec{E}_t)^* \right) d\Omega. \tag{3}$$

Here, $\vec{E}_t$ and E_z are the transverse and longitudinal field components of the electric field respectively. This is a quadratic eigenvalue problem for the propagation constant, which we convert to a standard eigenvalue problem by linearisation. Solution is sought by means of the finite element method, using vectorial basis functions for the transverse fields in order to avoid spurious solutions and nodal shape functions for the longitudinal field [4,6]. From k_z the effective permittivity may be calculated.

Determination of the dielectric properties of the liquid crystal is an inverse problem. Firstly, we consider the experimental results at a single frequency, for instance

60 GHz, as shown in Figure 2 for E7. A bias voltage is applied across the liquid crystal layer by means of a bias tee. As a result we obtain values of the effective permittivity in the switched and unswitched states. Director fields for these two states can be calculated using the known datasheet values of the elastic constants and low frequency dielectric properties. Next, initial guesses for $\varepsilon_\perp$ and $\varepsilon_\parallel$ are made and the microwave fields modelled. This yields the propagation constant, from which the simulated effective permittivity can be determined. Finally, this is compared with experiment and the initial guess improved upon, making use of an optimisation procedure to minimize the difference between experiment and simulation. After several iterations, $\varepsilon_\perp$ and $\varepsilon_\parallel$ are recovered. Using these recovered values the simulated effective permittivity can be calculated for the intermediate voltage values. Good agreement with experiment is observed in this interval, as shown in Figure 2. This procedure is then repeated across the frequency range.

A number of test devices were fabricated and capillary filled with different liquid crystals and measured. After solving the inverse problem across the frequency range the results shown in Figure 3 are obtained. The oscillations observed are artefacts due to errors associated with the calibration procedure.

Additionally, the procedure can be applied to obtain the losses of the liquid crystal. Figure 4 shows the loss tangent for a number of liquid crystals as a function of frequency. Losses are generally low and tend to decline with frequency, which is promising from an applications point of view.

The procedure as presented assumes prior knowledge of the elastic constants and low frequency dielectric properties of the liquid crystal. For some more recently developed liquid crystals these are unavailable. In such cases our method is still applicable as the threshold and slope of the effective permittivity-voltage curve infer information about these material properties. Repeating the optimisation procedure with these material properties as additional optimisation parameters is more time consuming, as the director calculation enters the optimisation loop. Carrying out the procedure yields the elastic constants within 8% of their datasheet values

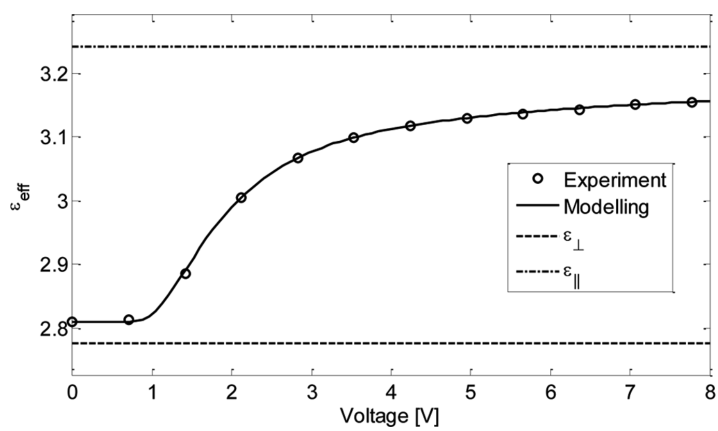

Figure 2. Modelled and measured effective permittivity of E7 as a function of bias voltage at 60 GHz. Modulation of the effective permittivity provided by the liquid crystal is diminished due to the fall-off in the electric potential within the alignment layers and the electric field that leaks into the substrates.

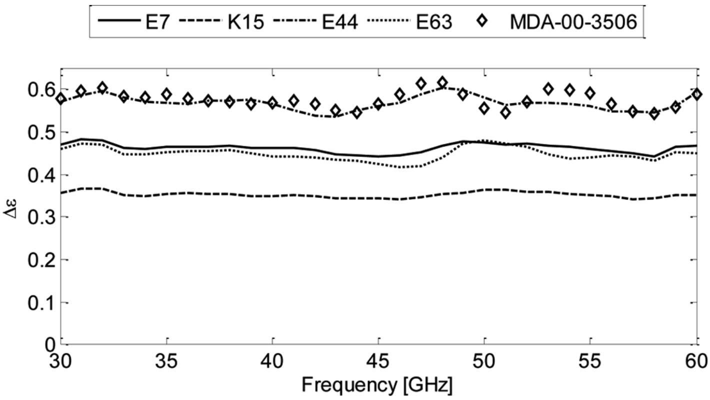

Figure 3. Dielectric anisotropy of E7, K15, E44, E63 and MDA-00-3506 as a function of frequency.

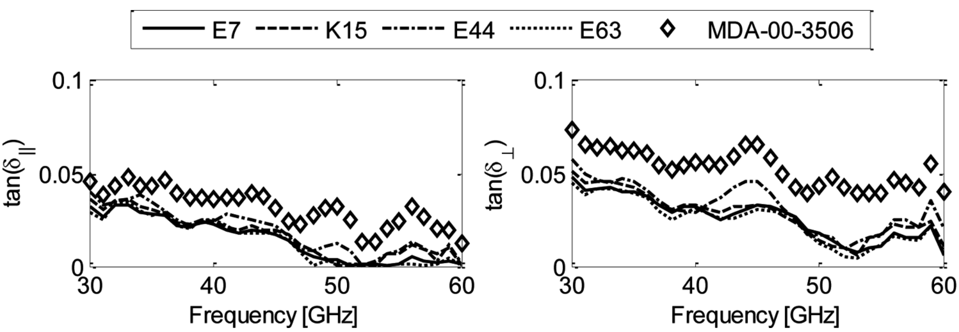

Figure 4. Parallel and perpendicular loss tangents of E7, K15, E44, E63 and MDA-00-3506 as a function of frequency.

and, more promisingly, the microwave dielectric properties within 0.1% of those found earlier.

The characterisation device is a useful microwave device in its own right. It acts a tuneable phase shifter. The amount of phase shift (and the associated loss) is proportional to the length of the microstrip line. A differential phase shift of 7.21 degrees per millimetre is achieved at a frequency of 60 GHz for E7. In order to achieve larger phase shifts in a compact device design, it is advantageous to meander the microstrip line.

3. Coplanar Waveguide

Coplanar waveguides utilise conductors situated on the same plane to support wave propagation. This is advantageous when designing microwave circuits as conductors may be straightforwardly tapered in order to connect one component to the next.

We have designed an inverted coplanar waveguide structure similar to [7], but designed to operate between 30 and 60 GHz. An 85 μm deep cavity is etched into a copper block, which is then attached to a standard microwave substrate of

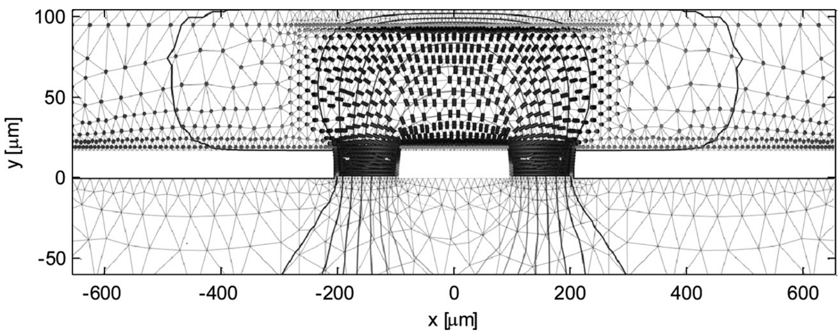

Figure 5. Director field on a cross-section through a coplanar waveguide structure with a liquid crystal substrate and with 5 V applied to the central conductor. The liquid crystal, E7, is contained by a metal cavity.

thickness 381 μm and permittivity 9.8 that has coplanar electrodes etched on its upper surface. There are three parallel strip electrodes etched on the substrate surface. The outer two electrodes make contact with the copper block and act as ground. A gap of 110 μm separates these from the central conductor, which is 190 μm wide. The cavity is capillary filled with liquid crystal.

Figure 5 shows the director field on a cross section through the coplanar waveguide structure filled with E7 and with an applied voltage of 5 V. The polyimide on the etched cavity ceiling is assumed to be 10 μm thick. Due to the thickness of the copper foil electrodes (17 μm) there is some uncertainty as to the liquid crystal alignment between the electrodes. In modelling the structure it has been assumed that the anchoring is planar degenerate in this region. Using the dielectric properties of E7 in the microwave range determined previously, the microwave fields may be calculated. The transverse components of the electric field of the dominant propagating mode are shown in Figure 6 at 30 GHz with an applied bias voltage of 5 V.

Figure 7 shows the simulated dispersion curve of the structure for a number of applied bias voltages. The slope and shape of the dispersion curve can be tuned by adjusting the electrode gaps and widths. It has been assumed that the lower substrate is anisotropic, since anisotropy is a product of the fabrication process. Parallel to the

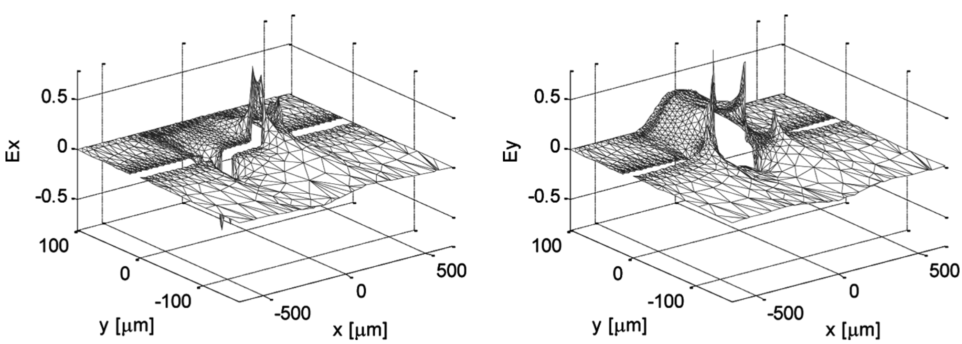

Figure 6. Transverse components of the electric field for the dominant mode of the coplanar waveguide structure at 30 GHz with an applied bias voltage of 5 V.

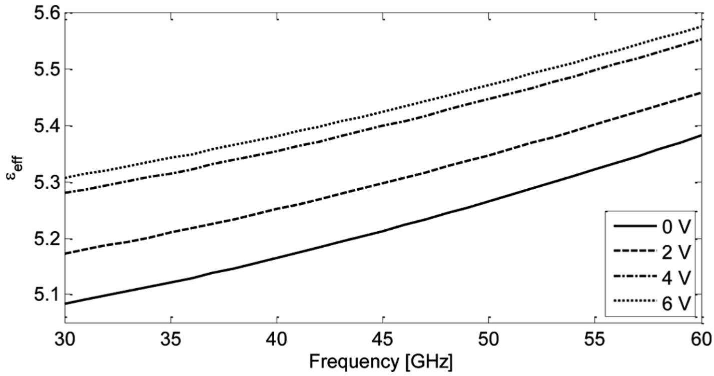

Figure 7. Modelled effective permittivity of the coplanar waveguide structure as a function of frequency for a number of applied bias voltages.

substrate surface, the permittivity has been assumed to be 10% higher, as reported by the manufacturer.

In common with the microstrip line, the coplanar waveguide can be used as a phase shifter. However, the disruption in the liquid crystal orientation caused by the electrode gaps reduces the modulation of the effective permittivity provided by the liquid crystal. Thus, the phase shift for a given length is lower. It was envisaged initially that the coplanar waveguide structure could be used for the purposes of characterisation, but the measured effective permittivity proved overly sensitive to the probe placement. Furthermore, the uncertainty in the liquid crystal alignment between the electrodes introduces an additional error that is undesirable for characterisation. An advantage to this structure over the microstrip line lies in its ease of fabrication. Additionally, the shielding of the structure eliminates radiation and reduces sensitivity to interference.

4. Conclusions

A broadband method to characterize liquid crystal materials at millimetre-wave frequencies has been demonstrated that makes use of a microstrip line with a liquid crystal substrate. The characterisation device may be measured straightforwardly using probes connected to a network analyser. By solving an inverse problem that utilises accurate modelling of the liquid crystal orientation and microwave fields, the dielectric properties of a liquid crystal can be determined. Dielectric properties and loss tangents of E7, K15, E44, E63 and MDA-00-3506 between 30 and 60 GHz have been presented, which agree well with previously published results where available. A coplanar waveguide structure has been demonstrated, which sacrifices tunability to a degree, but is more straightforward to fabricate and is shielded, making it less prone to interference.

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