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Determination of the permittivity of nematic liquid crystals in the microwave region

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Two 3 mm thick microscope glass plates, having one face plus their two long edges coated by a thick metallic film, are spaced 75 μm apart by mylar spacers. Because of the metallic coatings on the inner faces the structure acts as a single metallic slit. The space between the two coated plates is filled with aligned nematic liquid crystal (E7, Merck/BDH) and the cell is inserted in an absorber aperture. This single metallic slit geometry supports resonant modes when microwaves are incident with their polarization (E-field) perpendicular to the slit. The structure gives a set of Fabry–Perot-like resonant transmission frequencies. These frequencies move when a voltage is applied between the two plates, the liquid crystal being first aligned homogeneously, then realigning homeotropically with the applied field. By minotoring these changes a fast and easy to use procedure for determining the permittivity and its anisotropy for nematic liquid crystals in the microwave region has been developed. The parameters determined for E7 are $\varepsilon_e = 3.17$ ($n_e = 1.78 \pm 0.01$) and $\varepsilon_o = 2.72$ ($n_o = 1.65 \pm 0.01$), ($\Delta n \approx 0.13$) in the 40.0–60.0 GHz region.

1. Introduction

In recent years, the requirement for new compact, low cost, low voltage and low power consumption microwave modulation devices in commercial and military communications, surveillance and navigation technologies, etc. has pushed research into new materials. Thermotropic liquid crystals (LCs) have a large birefringence in the visible region, the basis of low voltage-driven LC displays. This birefringence may be maintained through into the microwave range [1] and thus such materials may provide a low voltage control technology for microwaves. Indeed some microwave modulation devices involving microstripline [1], zero order metallic gratings [2] or waveguides [3–5] have already been reported. To select a suitable LC material for device design, the determination of the anisotropic microwave permittivity (refractive indices) of these LC materials is vital. However, to measure these parameters in the microwave region some technique, as for example mentioned in [3, 5], is required. This may need a quite complex experimental set-up, including perhaps the fabrication of a Mach–Zehnder interferometer. It will also generally require the use of quite substantial quantities of LC materials, to fill a waveguide for example. The aligning of the LC material is also quite difficult. A fast and easy-to-use procedure which utilizes small amounts of LC would be welcome.

Over the past few years a substantial body of experimental and theoretical work has shown strongly enhanced transmission of electromagnetic radiation through thin slits in otherwise opaque metallic samples [6, 7] and also very small hole arrays [8, 9]. Substantially enhanced transmission through the slit-type structures has been attributed to the resonant excitation of coupled surface plasmon polaritons (SPPs) within each thin cavity [6]. A clear explanation for the origin of the extraordinary transmission from metallic slit gratings has been given by Takakura [10] who theoretically analysed the interaction between TM-polarized waves and a sub-wavelength metallic slit quantifying the Fabry–Perot-like behaviour obtained. The conclusion from [10] is that for sufficiently thick conductors, transmission from a single sub-wavelength slit leads to maxima at certain frequencies which can be identified with the resonance peaks observed when a periodic array of such slits is examined. The 'strongly enhanced transmission' created in such metallic slit gratings is the result of constructive interference of

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the signals arising from each Fabry–Perot-like resonance localized in the separate cavities. If in addition the periodicity of the grating surface is such as to create a grazing diffracted wave (which will be a standing wave) then the resonant transmission may be further enhanced. In our recent work [11] transmission through a very narrow (as compared with the microwave wavelength used) single metallic slit inserted in a wavelength aperture has been experimentally investigated. The transmission spectrum does indeed have a Fabry–Perot-like character and there is quite strong transmission even though there is no grating structure. By using this geometry a fast and easy-to-use technique for determining the permittivity tensor of LCs in the microwave region was experimentally demonstrated [12]. However, the fabrication of samples for that study required that one surface of each metallic plate be very carefully polished to give the very high quality surface conditions needed for the LC alignment. This is a rather time consuming procedure.

In this present study standard glass plates, as used to build commercial LC display cells, with very high surface quality form the cell walls. Thereby standard procedures for fabricating a LC cell can still be used, the only difference being that one face and the two long edges of the glass plates are pre-coated with thick (> 100 nm) metallic films. This, when the metallized faces are placed adjacent, allows these metal-coated plates to act equivalently to the single metallic slit as used for the previous microwave transmission experiment. Then the single metallic slit, the LC cell, is filled with aligned nematic LCs (aligned by rubbed polyimide layers) and inserted in a wavelength aperture at the microwave region. Variation of the voltage applied across the slit changes the orientation of the LC director. Thus resonant frequencies of the Fabry–Perot-like transmission maxima shift as the voltage changes leading directly to the determination of the ordinary and extraordinary permittivities of the LC at microwave frequencies.

2. Experimental

As shown in figure 1, a very narrow (compared with the wavelength used) single slit is formed from a pair of metallized glass plates with mylar spacers at each short end. The dimensions of the plates are: length $L = 60.00$ mm, width $T = 20.00$ mm and thickness $D = 3.00$ mm. The crucial thickness of the mylar-spaced gaps is only $W = 75.0\,\mu$m. The area occupied by the slit is thus 1/81 $[= W/(2D + W)]$ of the whole area of the front or back faces of the sample. This very narrow gap may be readily filled with a relatively small amount of NLC using capillary filling to form a monodomain sample. To make the slit 'metallic' in the microwave region one large face and the two long edges of each glass plate are metallized. To give a robust coating the plates are first coated with a Ni film to a thickness of several nanometres to provide a 'sticking' layer. On top of this is deposited an approximately 300 nm thick aluminium film, as shown in figure 1. For aligning the liquid crystals two surfaces, the walls of the slit cavity, are individually spin-coated with a polyimide (AL 1254). They are baked and unidirectionally rubbed parallel to the short edge direction of the plates to provide homogeneous alignment of the liquid crystal molecules. The polyimide layers also act as ion barriers preventing ions entering the thin liquid crystal layers when a field is applied. The two treated plates are then face-to-face packed together with mylar spacers placed at the two short edges, this forms a single 'metallic' slit which is then capillary filled with NLC (E7, Merck/BDH). The two plates are also connected to an a.c. voltage source (10 kHz) allowing the application of voltage across the cell as shown in figure 1. This single 'metallic' slit sample is then inserted in an absorber aperture and examined for its microwave transmission properties.

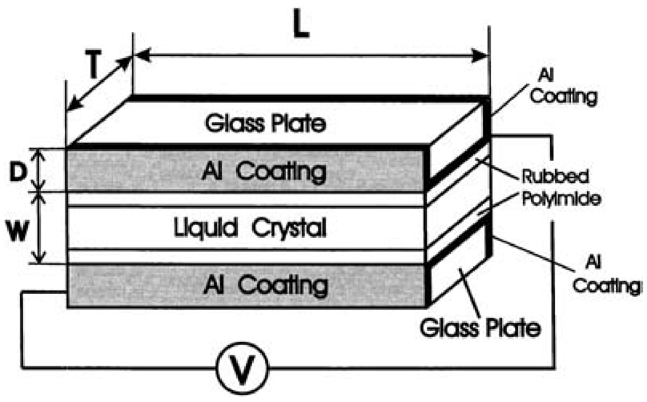

Figure 1. Schematic of the sample.

The experimental set-up is shown in figure 2. The whole geometry mentioned above is placed between a generator and a detector. A horn antenna fed by a variable frequency microwave generator (40.0–60.0 GHz) with emitting power about 10.0 mW is set a distance about 50.0 cm from the sample to direct an approximately plane wave at the slit front surface. The zero order transmitted beam is collected by the horn antenna of the detector, which is set a distance of about 30.0 cm from the slit

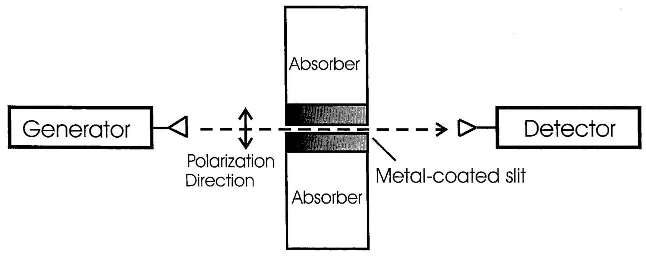

Figure 2. The experimental set-up.

to collect enough transmitted signal. This in turn is connected to a scalar network analyser. Because the sample is quite close to the detector horn, the whole sample geometry is rotated a little such that the incidence angle is $\alpha \sim 18.0^{\circ}$ to avoid strong interference between the surfaces of the 'metallic' part of the sample and the horns. Only linearly polarized microwaves are incident with the electric vector lying perpendicular to the slit direction, i.e. the incident beam of radiation is TM-polarized. As expected there is no transmission for radiation polarized along the slit direction.

3. Results and discussion

Transmission data were taken as a function of frequency and also of the voltage applied across the liquid crystal filled slit. Figure 3 shows typical frequency- and voltage-dependent transmission spectra. Data sets were recorded for 22 voltages from 0.0 to 30.0 V, however, for clarity only nine curves corresponding to the voltages: 0.0, 1.2, 1.4, 1.6, 1.8, 2.0, 3.0, 5.0 and 30.0 V are shown from the bottom to the top in figure 3. This data has been normalized with respect to the signal obtained in the absence of the slit in the aperture. There is a clear set of resonant transmission peaks, with almost one mode step in frequency being encompassed by changing the voltage over this range. The most rapid movement of the modes occurs between 1.2 and 3.0 V. This indicates that E7 is a suitable NLC material for a voltage-controlled wavelength selector at the microwave region.

As mentioned in our earlier work [12] there are two essential aspects for the use of this technique in characterizing the permittivity of LCs at microwave frequencies. Firstly the transmission spectrum of the single metallic slit has a very clear Fabry–Perot-like signature, which depends on the dimension of the slit and the refractive

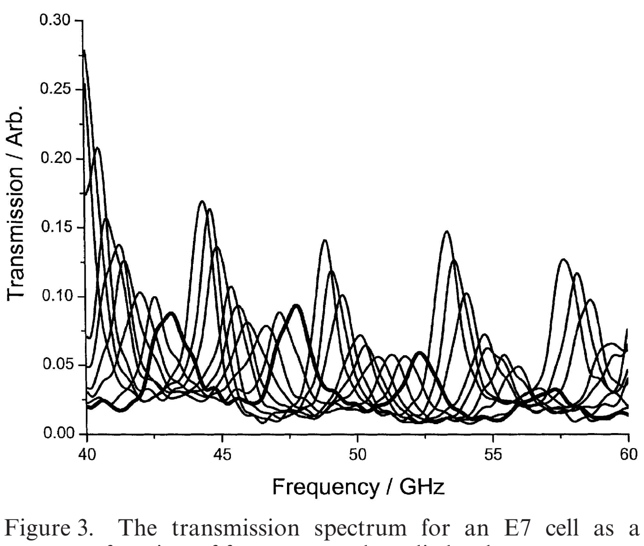

Figure 3. The transmission spectrum for an E7 cell as a function of frequency and applied voltage.

index of the material in the slit. Secondly the transmission signals through the very narrow slit are strong enough to be easily recorded. To achieve these two requirements theoretical analysis and experimentation [10–12] show the key point to be that the very narrow single slit is 'metallic' enough to allow the support of surface plasmon polaritons. At microwave frequencies aluminium has a permittivity with a very large negative real part ($\sim -10^4$) and may be considered as almost perfectly conducting [13], thus the fields of the electromagnetic waves are excluded from the metal. The aluminium layer does indeed support a surface wave or surface plasmon at this frequency. With the skin depth of the aluminium much less than the 300 nm aluminium layer thickness then each coated glass plate acts as an almost ideal metal as required. A secondary point is that the LC should not be too strongly absorbing at these frequencies.

According to the analyses of Takakura's work [10] if W/λ (λ is wavelength of the radiation) is small enough (for our situation the value of W/λ is less than 0.01) then the transmission spectrum from a metallic slit will exhibit Fabry–Perot-like behaviour. However, there is a fundamental difference between a real Fabry–Perot and a narrow metallic slit: in the latter case, additional wavelength-dependent terms in the denominator are responsible for small shifts of the resonant wavelengths, expressed as [10]:

$$\lambda_{\text{shift}}/\lambda_{\text{FP}} = 2(W/T)[\ln(\pi W/\lambda_{\text{FP}}) - 3/2] / \{2(W/T)[\ln(\pi W/\lambda_{\text{FP}}) - 1/2] - \pi\} \quad (1)$$

where λ_{FP} is a Fabry–Perot wavelength. For the case presented here W/T and W/λ_{FP} are very small (of order 10^{-2}–10^{-3}), and thus $\lambda_{\text{shift}}/\lambda_{\text{FP}}$ is positive and very small. The relative deviation of the wavelength shift calculated from equation (1) is less than 1.0%, so the transmission maxima will closely satisfy the simple Fabry–Perot equation even when the gap is filled with a liquid crystal.

If the mode positions from the recorded data are introduced into the Fabry–Perot equation, $\lambda_{\text{FP}} = 2nT\cos\alpha/N$, then the mode order numbers can be calculated. For example, from left to right of the bottom curve (thick solid line for no applied voltage) in figure 3, they are $N = 9$, 10, 11 and 12 and for the top line they are $N = 10$, 11, 12 and 13, respectively. In the calculation no index dispersion of the material over the frequency region has been found, agreeing with the results of [2]. The corresponding effective refractive index as a function of voltage is also obtained as shown in figure 4 as solid circles. From figure 4 we can see that there is a fast change of index with voltage between 1.2 and 3.0 V, after this the change appears to saturate. This is simply because at these voltages the LC director is almost completely homeotropically aligned throughout the slit.

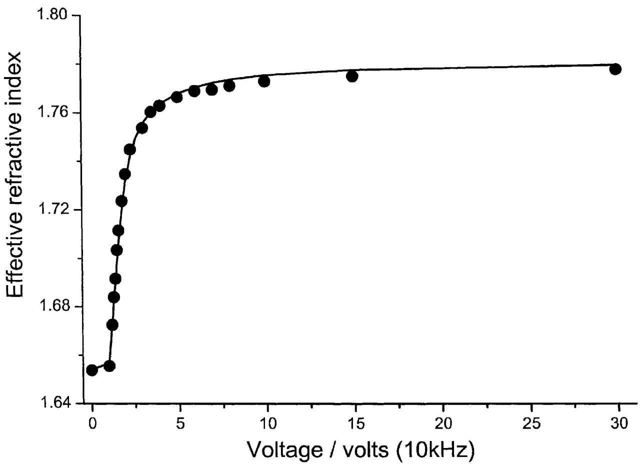

Figure 4. Variation of the effective index as a function of the a.c. applied voltage.

From this we then deduce that the indices obtained at 0.0 V, $n = 1.65$ (± 0.01) and at 30.0 V, $n = 1.78$ (± 0.01) are effectively the ordinary index, n_o and a value very close to the extraordinary index, n_e of E7, over this frequency region. Then the anisotropy of the E7 is about $\Delta n \approx 0.13$ over 40.0–60.0 GHz; this also accords well with the results of [1, 2, 12]. In addition, from the amplitude and width of the resonant peaks in the transmission spectrum the anisotropy in the absorption of this material over the microwave region can be estimated. The absorption anisotropy ratio of E7 is estimated from the widths of the resonances for zero field and at high field to be 1.4 (± 0.1), with less absorption when the director is aligned parallel to the polarization direction.

For intermediate voltages the situation is a little more complex. Now the director tends to homeotropic alignment at the centre of the slit while remaining homogeneous at the walls. Thus the radiation experiences a distribution of refractive index (permittivity) across the slit, the highest (guiding) index being at the centre. However because W/λ is very small the microwave field distribution may be treated as quasi-uniform. The effective index for each mode is then, to first order, the average calculated from the spatial profile of the director field. We use continuum elastic theory [14] to model the tilt angle, θ distribution with the parameters of E7: $\varepsilon_{\parallel} = 19.50$, $\varepsilon_{\perp} = 5.40$, $k_{11} = 1.15 \times 10^{-11}$ N and $k_{33} = 1.46 \times 10^{-11}$ N. From this the effective local index is calculated using:

$$n_{\text{eff}} = n_o n_e / (n_e^2 \cos^2\theta + n_o^2 \sin^2\theta)^{1/2} \qquad (2)$$

with $n_e = 1.78$ ($\varepsilon_e = 3.17$) and $n_o = 1.65$ ($\varepsilon_o = 2.72$). Then finally, by integrating across the liquid crystal layer, we find the average effective index as a function of applied field. This is shown as the solid line in figure 4. The agreement between the solid line and data is very good. It serves to confirm that the resonant mode shifts are in accord with the simple model of the low voltage-induced reorientation of the LC.

4. Conclusions

In conclusion, based on the behaviour of the transmission of radiation through a sub-wavelength single metallic slit, a fast and easy technique for determining the permittivity tensor of NLCs in the microwave region has been developed and experimentally demonstrated. The parameters determined for E7 are $n_e = 1.78$ (± 0.01), $n_o = 1.65$ (± 0.01) ($\Delta n \approx 0.13$) in the 40.0–60.0 GHz region. A simple model which treats the slit as a Fabry–Perot fits the data obtained rather well. Combining this with an elastic continuum model for the response of the liquid crystal director fully explains all the mode positions and their variation with voltage.

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