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Preliminary communication

Calculation of optical properties of liquid crystal devices using the transmission line matrix (TLM) method

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The TLM method uses the voltages and currents on a three-dimensional network of transmission lines to model the electric and magnetic field and loss components of Maxwell's equations. Optical fields within anisotropic media may be easily modelled and results are presented for calculation of the transmission spectra of a Fréedericksz transition liquid crystal device. The method is well suited to the calculation of transmission spectra; calculations agree well with spectrometer measurements on an actual liquid crystal device.

Optical modelling of liquid crystal (LC) devices may be carried out using one of several matrix techniques [1, 2, 3]. Alternatively, the transmission line matrix (TLM) method represents physical space as a three dimensional network of interconnected transmission lines [3, 4] and has been applied to many electromagnetic problems in waveguides [5]. The method takes into account both dielectric and magnetic anisotropy making it also readily applicable to liquid crystal devices [6].

The TLM method represents each unit cell of physical space as a node made up of two types of connection node, series and shunt, as shown in figure 1. At these nodes the differential equations describing the voltages and currents on the transmission lines are analogous to Maxwell's equations, with the inductive, capacitive and resistive properties being analogous to the permeability, permittivity and conductivity, respectively, of the region of space being modelled [3, 4]. Calculation of the voltages and current on the TLM network will directly correspond to the electric and magnetic field components within the unit cell.

One advantage of such a network is that it may be easily characterized for many frequencies simultaneously, using impulse analysis. A voltage impulse corresponding to the E-field of an E–M wave is applied to an appropriate point in space. At each iteration, the interactions of the voltage impulses with each node are calculated. Monitoring a suitable node, a case history of voltage impulses, the time domain response to an impulse, is obtained. This may be transformed to give the amplitude and phase relationship between source and monitor points at any frequency.

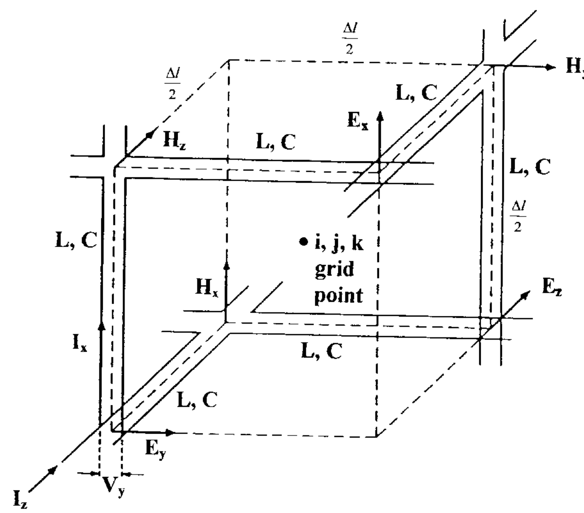

Figure 1. Transmission line matrix element unit cell made up of three series and three parallel transmission line interconnections.

At each node on the matrix, the capacitance and inductance of the transmission lines in x, y and z may be set independently, allowing ε and μ to be specified in all three dimensions for every point in the region of space being modelled. ε_{11}, ε_{22} and ε_{33} of the material's dielectric tensor are represented as ε_x, ε_y and ε_z, and more complex media with non-zero off-diagonal terms may be represented by setting appropriate values of μ. To model the dielectric constant of a liquid crystal material values of ε in x, y and z must be related to the

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refractive indices ($n_{\|}$ and $n_{\perp}$), taking into account the orientation of the liquid crystal molecules with respect to these axes. For the calculations presented here, it has been assumed that $\mu_r \approx 1$ and $n = \sqrt{\varepsilon_r}$. For a liquid crystal material with $\varepsilon_{\|}$ at an angle θ with the x axis, values of ε_x and ε_y are given by $\varepsilon_x = \varepsilon_{\|} \cos^2\theta + \varepsilon_{\perp} \sin^2\theta$ and $\varepsilon_y = \varepsilon_{\|} \sin^2\theta + \varepsilon_{\perp} \cos^2\theta$ [7].

The TLM method was used to model a simple liquid crystal device consisting of a liquid crystal with $n_{\|} = 1.65$ and $n_{\perp} = 1.51$ between two glass substrates with $n = 1.52$, as shown in figure 2. For the calculations, a cell spacing of 9 μm was assumed as this corresponded to the real device. In order to model optical propagation through the device with a field applied, the director profile of the LC must be known. For this calculation an analytical solution was used [8]. Assuming strong anchoring, the director profiles of the ECB devices were calculated for increasing applied fields. The input and output polarizations of ideal polarizers were assumed to be at 45° to the molecular long axis with no field applied, corresponding to the rubbing direction in the real device. The calculated transmission spectra clearly show the effect of birefringence. As the field is increased and the effective birefringence reduces, there is a corresponding shift in the wavelength of the maxima and minima of the spectral response, practically observed as a change in the observed colour of the device. Transmission spectra were calculated for applied fields of zero and 1.5 times the threshold field.

A test device was constructed using ITO coated glass substrates coated with rubbed nylon 6-6 alignment layers. The device was filled with the liquid crystal MLC-6200-100 having $n_{\|} = 1.65$ and $n_{\perp} = 1.51$. HN42-HE polarizing film was attached to both outer surfaces of the device at an estimated separation of approximately 9 μm, from the birefringence data. The threshold voltage was measured to be approximately 1.3 V.

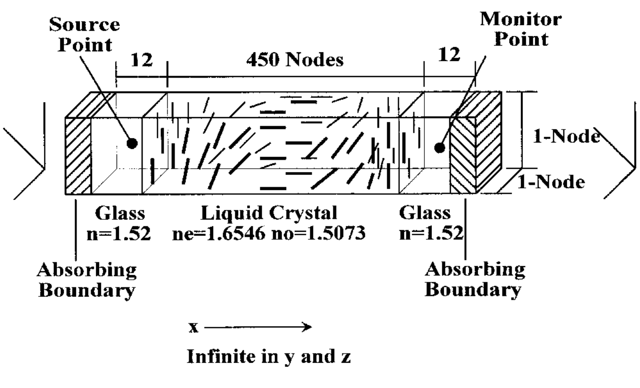
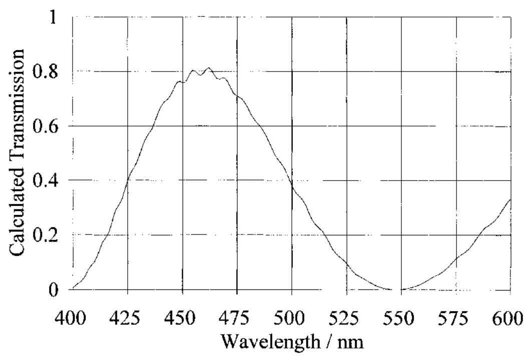


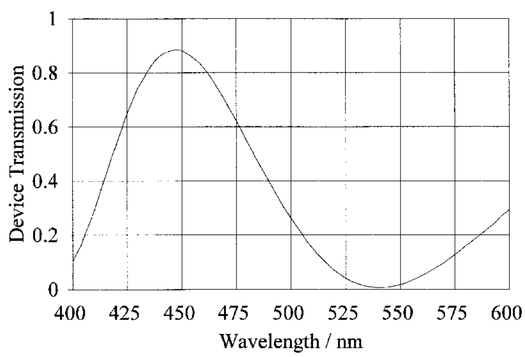
Figure 2. Simulation geometry used for the Fréedericksz transition device.

Device transmission spectra were measured over the range 400–600 nm. Parallel HN-42HE polarizers were used as a reference in the spectrometer in order to measure the transmission of the device independently of their absorption characteristics. Spectra for the device were taken with an applied 1 kHz square wave at 0.1 V intervals, and these were then compared with spectra calculated using the TLM method. Figures 3 (*a*) and 3 (*b*) show the calculated and measured spectra with no field applied, respectively. Figures 4 (*a*) and 4 (*b*) show the calculated and measured spectra with 1.5 times the threshold field and 1.9 V applied, respectively.

The measured spectra match very closely with the calculated spectra from the TLM method, well within the limitations in obtaining the material and device parameters, substrate spacing, threshold field and refractive indices. As the simulation included the refractive index of the glass, the effect of this boundary on the device transmission was taken into account directly, the predicted maxima having transmission in good agreement with measured values. At the extremes of wavelength,



(*a*)



(*b*)

Figure 3. (*a*) Calculated device transmission as a function of wavelength with no applied field. (*b*) Measured device transmission as a function of wavelength with no applied field.

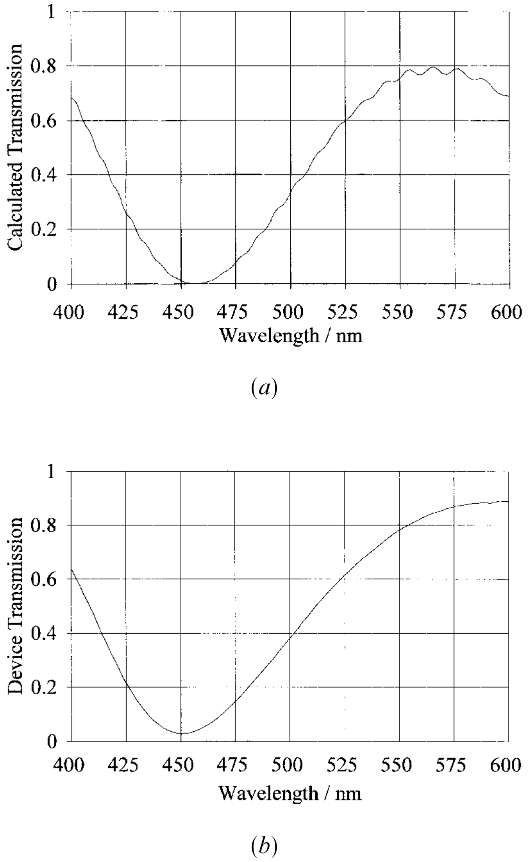


Figure 4. (*a*) Calculated device transmission as a function of wavelength with an applied field of 1.5 times the threshold field. (*b*) Measured device transmission as a function of wavelength with an applied voltage of 1.9 V.

the wavelength dependence of the refractive index begins to show some effect, for which a correction may be easily made.

In conclusion the TLM method has been shown to be capable of modelling the optical transmission of real liquid crystal devices. It has the advantages of having a very simple iterative algorithm making it fast and simple to implement even for geometrically complex problems. The generality and simplicity of the technique make it applicable to a wide range of optical modelling problems. The direct relationship between parameters required for the simulation and physical quantities make calculations straightforward to set up and the results are directly physically meaningful. The method directly calculates the electric, magnetic and conduction components of the field anywhere in the device, making it suitable for application to a wide range of field modelling problems in anisotropic materials.

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