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Characterization of the alignment of a nematic liquid crystal using half leaky guided modes

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The excitation of half leaky guided optical modes to characterize fully the optical tensor profile in a thin liquid crystal layer has been used to evaluate the effect of rubbed polyimide aligning layers on the alignment of a nematic liquid crystal. A cell fabricated with rubbed polyimide alignment surfaces was studied at a wavelength of 632·8 nm. The liquid crystalline layer is sandwiched between a high refractive index top glass plate and a low refractive index glass substrate. Angular dependent reflectivities are recorded using a coupling prism and matching fluid with the same index as the top glass plate. Careful fitting of the predictions from multilayer optics theory to the observed angle dependent polarization conversion and reflectivity data yields the director profile within the liquid crystal layer in great detail.

1. Introduction

Studies of liquid crystalline materials rely heavily on optical microscopy. This technique will yield much information about domain structure; however, in general it is rather insensitive to details of the director profiles through the cell, since it provides an integral of the optical response of the system.

Other techniques have been developed to study the director profile across the cell and in particular the use of optically excited guided modes that propagate along the aligned liquid crystalline layer has proved to be a valuable probe [1–3]. A number of experimental geometries have been used for the excitation of guided modes and these will be outlined before describing the half leaky guided mode geometry employed in this study.

The first of these geometries uses the method of attenuated total reflection which allows the excitation of both a surface plasmon resonance (for transverse magnetic, *p*, polarization) and waveguide modes in a thin crystal layer bounded by two metallized surfaces [1, 2]. These modes manifest themselves as sharp dips in the reflectivity data taken as a function of the angle of incidence. A model of the optic tensor profile, together with a general anisotropic multilayer optics modelling program, produces theoretical predictions that are compared to the observed data. Since the optical electric field profiles through the liquid crystal layer are different for different guided modes, the careful fitting of all the mode minima yields detailed information about the director profile through the cell. The surface plasmon resonance supported for *p* polarized radiation at the liquid crystal–alignment layer–silver interface is particularly sensitive to the director profile near the cell surface. This technique however has limitations. The use of metallic layers to give sharply resonant modes and to support the surface plasmon resonance prevents the study of commercial cells and also practical devices, since rubbed polymer surface treatments used commercially cannot be applied to the thin metallic layers without causing damage.

A second technique was developed to overcome these limitations by dispensing with the metallic layers, thus enabling rubbed polymer alignment to be studied [3]. Now, without the strongly reflective metallic layers, the guided modes that propagate are fully leaky and result in broad features in the observed angular dependent reflectivities. This means that fitting the data using this technique is nothing like as sensitive to the details of the director profile as the fully guided technique.

Recently a better optical guided wave technique has been developed that will reveal the detailed nature of the director profile within an aligned liquid crystal layer. This technique uses half leaky guided modes and was first used to measure the refractive index and thickness of isotropic fluid layers [4], being developed further by Yang and Sambles to characterize anisotropic liquid crystalline layers [5]. It is a technique that can be used to study a liquid crystal cell fabricated as a commercial device, allowing detailed determination of the director profile.

The chosen geometry (shown in figure 1 (*a*)) consists of a high refractive index glass top plate and a low refractive

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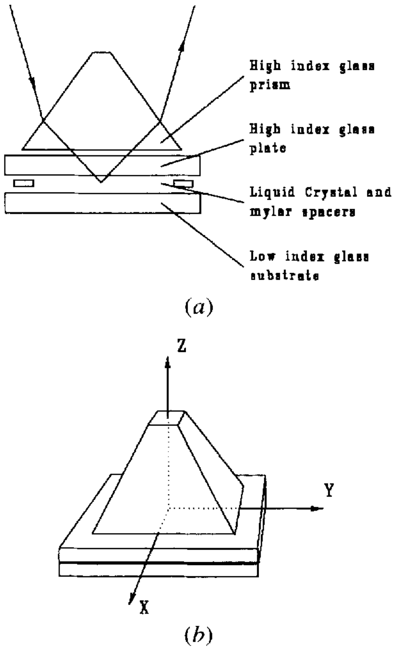

Figure 1. Schematic of the experimental geometry used: (*a*) shows the half leaky cell coupled to the prism with the alignment in the plane of incidence and (*b*) labels the orthogonal axes.

index substrate where ideally the lowest and the highest liquid crystal indices are bounded by those of the glasses. Numerical analysis of this geometry and experimental observation shows there to be a range of incident angles over which half leaky guided modes are excited from a real critical angle between the high index top glass plate and the low index substrate to a pseudo-critical angle associated with the high index glass and the effective index of the liquid crystal. Within this angular window, the probing optical field is fully reflected at the liquid crystal substrate boundary, propagating in the liquid crystal layer and being evanescent in the substrate.

The aim of this study is to examine the effect of polyimide alignment for the first time using this sensitive technique and to quantify accurately the director profile and particularly the surface tilt which such an alignment mechanism produces in an ordinary nematic liquid crystal.

The homogeneously aligned cell under study was filled with E7 nematic liquid crystal and probed using a wavelength of 632·8 nm with the alignment direction approximately in the plane of incidence and also rotated clockwise out of the plane of incidence by 5° and 10°. If the director profile within the cell is twisted out of the plane of incidence, then a *p* to *s* (transverse magnetic to transverse electric) conversion signal is observed whose amplitude increases with azimuthal twist. The comparison of the angular dependent reflectivities obtained experimentally with those predicted by multilayer optics theory [6] yields the optic tensor configuration within the liquid crystalline layer.

2. Experimental

An approximately 8 μm thick cell was constructed from two dissimilar glass pieces. The substrate glass has a low refractive index ($n = 1{\cdot}457$) and the top plate a high refractive index ($n = 1{\cdot}733$). Both glass pieces had a rubbed polyimide surface treatment which is known to give a low surface tilt homogeneous alignment. The polyimide (Probimide 32) was dissolved in *N*-methylpyrrolidinone to form a 10 per cent solution of the polyimide monomer. A few drops of the monomer solution were placed on to the glass surfaces and spun at approximately 3000 rpm to produce a thin uniform coating. This layer was then flash dried to limit shrinkage before being hard baked at 300 ± 5°C for 3 hours. These polyimide layers were then rubbed by passing the glass plates slowly under a cloth-coated, 95 mm diameter, spinning drum rotating at 400 ± 5 rpm. The rubbing directions were aligned antiparallel to endeavour to give a uniform bulk director tilt and, using mylar as a spacer, the glass plates were sealed together with ultraviolet curing glue. Finally the cell was filled with E7 under vacuum at 80°C.

The top glass plate of the cell was optically matched to the base of a high index ($n = 1{\cdot}730$) glass pyramid with a suitable matching fluid. Then the cell and pyramid were clamped together in a gimbal that allows the cell to be azimuthally rotated on the base of the pyramid about the Z axis (see figure 1 (*b*)). This apparatus was enclosed in a temperature controlled insulated box and stabilized at 23·0 ± 0·1°C. The box is slotted to allow entry and exit of the probing laser beam.

Experimental data were taken in the form of reflectivity as a function of angle of incidence of the linearly polarized (p or s) probing laser beam. This was achieved by mounting the sample and oven assembly on a computer controlled rotatable table that controls both the angular position of the sample and that of the detector. The probing light was a monochromatic HeNe laser beam mechanically chopped at 1·7 kHz. Modulating the beam allows the use of phase sensitive detection to give a high signal to noise ratio. In order to allow for any source intensity fluctuations, a weak reference beam (approximately 4 per cent) is taken out of the input beam just before it enters the sample. This reference is used to monitor and thereafter to correct for changes in the intensity of the incident laser radiation.

The incident beam may be pure p-polarized (TM) or pure s-polarized (TE) and by placing a polarizer in front of the detector it was possible to record not only the R_{ss} and

R_{pp} reflectivities but also any p to s conversion with the R_{sp} and R_{ps} reflectivies.

Reflectivity data were taken with the cell at different azimuthal orientations and with the alignment direction in the plane of incidence (azimuthal angle, $\phi \approx 0°$) and rotated clockwise out of the plane of incidence by 5° and 10°. The plane of incidence is the *XZ* plane as shown in figure 1 (*b*).

3. Analysis and results

The angular dependant reflectivities obtained were corrected for the reflections at the entrance and exit faces of the pyramid and normalized to the absolute input intensity of the laser source.

Typical experimental data (crosses) compared to the theoretical predictions with beam divergence, 0·02°, included (solid curve) are shown in figure 2. In this case the cell is orientated such that the alignment direction is twisted 5° out of the plane of incidence. This gave rise to very strong s to p or p to s conversion signals R_{sp} or R_{ps} which appear as a series of peaks on a null background at those angles where the incident beam momentum propagating along the *X* axis can excite the half leaky guided modes.

Theoretical reflectivity curves were generated using the scattering matrix method [7] for multilayer media. Fitting these theoretical models to the observed R_{ss} reflectivity with the alignment direction in the *XZ* plane ($\phi \approx 0°$) yields a value for the dielectric permittivity perpendicular to the director axis of the liquid crystal. In this case, the incident propagating electric field senses only the ordinary refractive index of the liquid crystal since there is negligible twist and it is totally insensitive to director tilt. Therefore the guided mode cut-off momentum is dictated almost exclusively by the value of this dielectric permittivity, whilst the angular positions of the lower momentum modes are sensitive to the liquid crystal layer thickness. The value of 1·5190 ± 0·0002 obtained for the ordinary refractive index is in agreement with a previously recorded value of 1·518 [8]. It is only with this orientation and geometry that the probing laser beam is insensitve to the director details. Fitting R_{sp}, R_{ps}, R_{pp} and R_{ss} data for the other orientations gives a degeneracy between the twist, tilt and the dielectric permittivity parallel to the director.

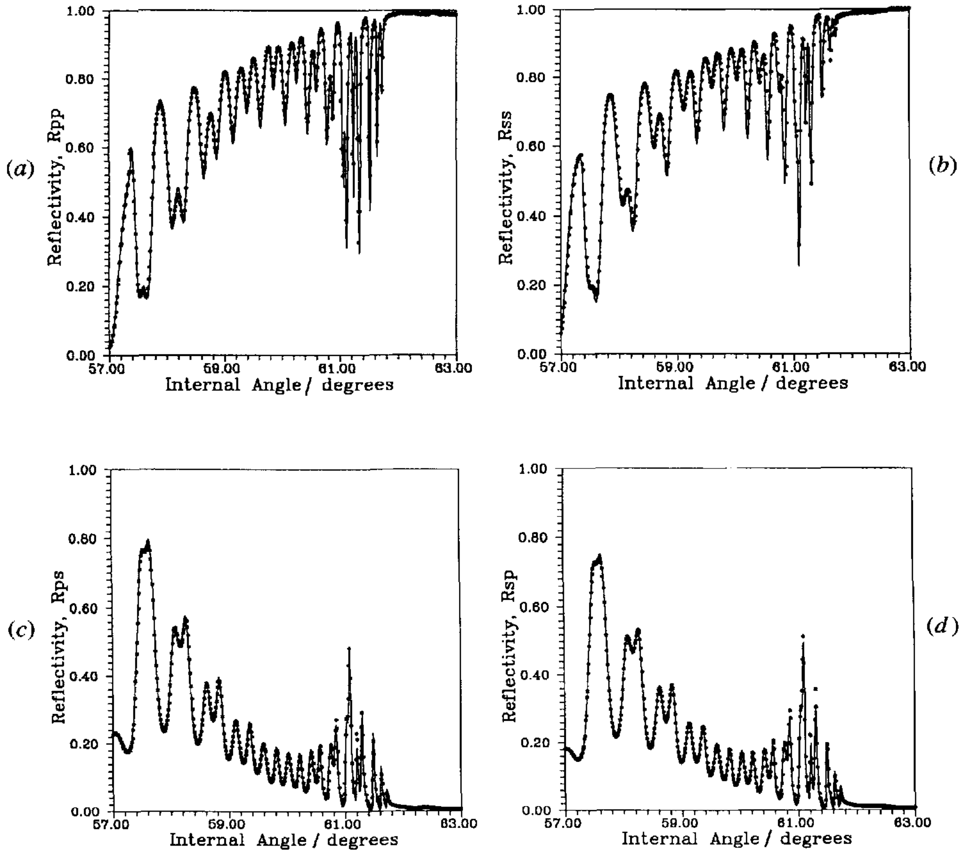

Figure 2. The recorded reflectivity scans (crosses) showing R_{pp}, R_{ss}, R_{ps} and R_{sp} as a function of angle of incidence ((*a*), (*b*), (*c*) and (*d*) respectively) when the alignment direction is rotated approximately 5° out of the plane of incidence compared with theory (solid lines).

Table 1. Modelled liquid crystal layer parameters for 0°, 5° and 10° twist.

$\epsilon_\perp$	$\epsilon_\parallel$	Twist (± 0·2°)	Tilt (± 0·2°)	E7 thickness (± 0·05 μm)
2·3074 + 0·00007*i*	—	—	—	8·33
2·3071 + 0·00007*i*	3·017 + 0·001*i*	4·9 to 4·9	8·2 to 7·3	7·97
2·3078 + 0·00009*i*	3·014 + 0·001*i*	9·3 to 9·2	8·0 to 7·5	8·60

This parameter degeneracy is resolved by fitting data taken with the cell rotated to different azimuthal orientations. From this fitting, a small range of values for the extraordinary refractive index was obtained, giving a mean value of 1·736 ± 0·002, in close agreement with a previously measured value of 1·734 [8]. The results from each orientation are averaged and presented in tables 1 and 2.

The effect of increasing the azimuthal twist angle between the plane of incidence and the alignment direction from 5° to approximately 10° on the s to p conversion signal can be seen in figure 3. The transverse electric-like first half leaky guided mode is excited at an increasingly higher angle of incidence as the angle of azimuthal rotation increases. By twisting the liquid crystal alignment direction out of the plane of incidence, the probing transverse electric optical field becomes increasingly more sensitive to the dielectric permittivity parallel to the director, because the oscillating electric field is sensitive to the permittivity in the *ZY* plane. As a result, the effective index of the liquid crystal layer increases as the angle of azimuthal rotation increases, since this material has positive optical anisotropy. Therefore the pseudo-critical edge between the high index prism and the effective index of the liquid crystal layer moves to a higher angle of incidence with increasing azimuthal twist, thus widening the angular window over which half leaky guided modes maybe excited.

From our modelling of the experimental data, it soon became apparent that the observed half leaky guided modes with the higher propagating momenta were considerably broader than model theory suggests. This discrepancy between theory and experiment is readily attributed to laser beam divergence. Correction for this is achieved by convoluting the theoretical prediction with a normalized gaussian to mimic the effect of the non-ideal source beam with a divergence of 0·02°. With this included in the modelling we may turn to the task of obtaining the details of the director profile within the cell.

Table 2. Layer parameters used for the multilayer optics theory.

Layer name	ϵ	Thickness
Prism	2·9949 + 0·0000*i*	Semi-infinite
Top plate	2·9949 + 0·0000*i*	2·00 cm
Polyimide	3·09 + 0·00*i* ($\epsilon_\perp$) 3·09 + 0·12*i* ($\epsilon_\parallel$)	20·0 ± 0·1 nm
Substrate plate	2·1253 + 0·0000*i*	Semi-infinite

Although the alignment layers were carefully assembled with their rubbing directions antiparallel, there exists a small twist of less than 0·2° in the director profile that was introduced during the fabrication of the cell and which is clearly indicated by the p to s conversion signal taken with the alignment direction in the plane of incidence ($\phi \approx 0°$). However, the reflectivity data R_{sp} and R_{ps} taken

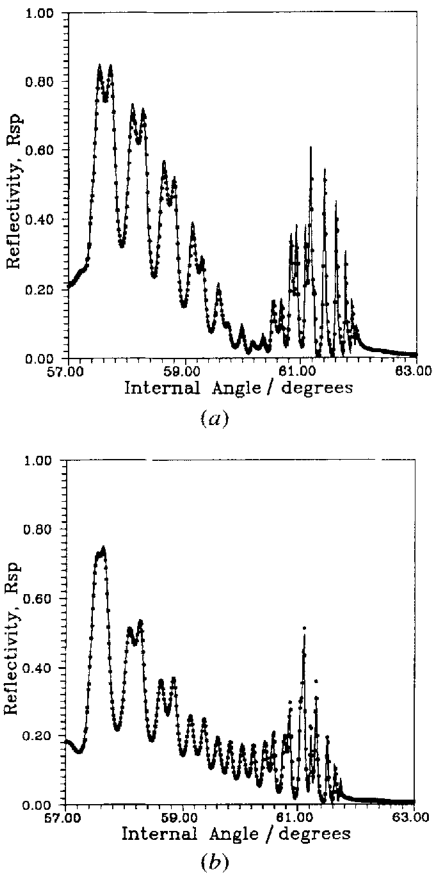

Figure 3. Two s to p conversion reflectivity scans showing the effect of azimuthal rotation of the alignment direction out of the plane of incidence by approximately 10° and 5° ((*a*) and (*b*), respectively) on the mode structure in the angular window where the half leaky guided modes can be optically excited. The solid lines are the fitted theory to the experimental data (crosses).

with the alignment direction in the plane of incidence ($\phi \approx 0$) were not fitted to theory. This was because the s to p and p to s conversion signals at $\phi \approx 0°$ were not much bigger than the leakage signal through the non-ideal polarizers. In general the director profile was modelled with a tilted director axis twisting through the liquid crystalline layer. Calculation of the Gibbs free energy associated with the liquid crystal alignment having different surface tilt angles at the top and bottom layer interfaces shows that a director profile that is linear in tilt through the cell should be expected [9]. Similarly, even quite large surface twists will result in a director twist profile that closely follows linear behaviour through the cell.

In order to rotate the cell azimuthally on the base of the prism about the Z axis the pressure required to hold the cell in place and to retain the matching fluid must be momentarily reduced within the gimbal mount. Then, due to the nature of the glue used to seal the cell the liquid crystal layer thickness may vary slightly between the different orientational data sets. It was also noted that the cell relaxes somewhat during the course of the experiment. In the case shown in figure 2, the R_{pp} data scan was recorded first and the R_{ss} data scan last, and the respective fitted thicknesses are $7{\cdot}985 \pm 0{\cdot}005\,\mu m$ and $7{\cdot}930 \pm 0{\cdot}005\,\mu m$—a relaxation of 55 nm in thickness.

In obtaining these final parameter sets, the optical characteristics of the top and bottom polyimide layers were assumed to be identical, but the alignments they induced within the liquid crystal layer were fitted as independent parameters. It should be noted that the polyimide layers were found to be only 20 nm in thickness, which makes the optical characterization of these layers difficult.

It is clear that the twist and tilt profiles for the different azimuthal orientations are in close agreement. Azimuthal rotation of the cell means that the probing laser beam does not sample exactly the same region in the liquid crystal layer and this may account for the small discrepancies. The implication could be that the surface tilt and twist resulting from the polyimide layers is slowly varying throughout the cell.

4. Conclusions

By using the half leaky guided mode technique to examine the optical tensor profile of a liquid crystalline layer aligned with rubbed polyimide surfaces, it has been possible to determine the resulting director profile.

The rubbed polyimide alignment layers induce a surface tilt of approximately 8° which appears to vary slowly across the cell by approximately 0·5°. The top and bottom alignment layers produce slightly different surface tilt angles and there is also a small degree of twist (less than 0·2°) in the cell. This twist and tilt profile varies linearly through the liquid crystal layer from the top alignment surface to the substrate. The director profiles that have been deduced independently from the observed reflectivity data taken with the alignment direction in the plane of incidence and rotated azimuthally out of the plane of incidence by approximately 5° and 10° are in excellent agreement. It should be noted that a thinner liquid crystal layer, closer to that of a commercially fabricated cell, would not support as many half leaky guided modes leading to simpler p to s and s to p conversion and reflectivity scans. However, despite the complex shape of the observed angular dependent p to s and s to p conversion and reflectivity scans the modelled data compare remarkably well.

This technique is unable to provide a precise characterization of the optical properties of the alignment layers because they exhibit low absorption. This appears to be the limiting factor in the determination of the director profile, but it has been shown that it is quite possible to resolve detail in the liquid crystal alignment down to ± 0·1°.

This sensitive technique can be used to study cells fabricated commercially to resolve the subtleties in the alignment of liquid crystalline materials. The only proviso is that the liquid crystalline layer is sandwiched between high and low refractive glass plates.

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