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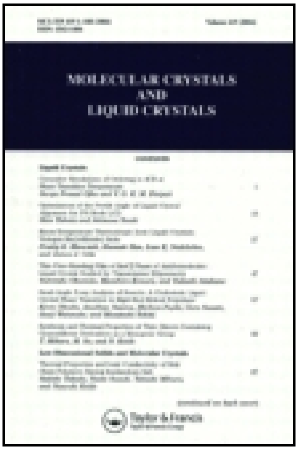
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Developments in Waveguide Studies of Director Profiles

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The most powerful optical procedures for characterising in detail the director profile in liquid crystal cells are based on the excitation of guided modes. Over the past ten to fifteen years a variety of cell geometries have been used. Most of these are not particularly suitable for the study of real commercial cells. In this study we briefly review the earlier techniques and go on to discuss recent developments. The implementation of the fully-leaky guided wave technique which uses low index coupling prisms and involves monitoring both reflected and transmitted signals with real commercial cells is discussed. In addition a further very recent modification using a convergent-beam geometry together with the fully-leaky arrangement is considered. This very latest development paves the way for detailed dynamic studies of commercial devices as well as giving potential for the exploration of single pixels.

Keywords: liquid crystal; optics; guided-mode; fully-leaky; convergent-beam

INTRODUCTION

The primary low power device for display applications is the liquid crystal cell. In such a cell a liquid crystal, in the form of a layer with a thickness of order of a few microns, is sandwiched between two glass plates (the two cell walls) which are generally coated with some transparent conductive films (e.g. ITO) on top of which are alignment layers. A detailed knowledge of the form of the director alignment in

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such cells is essential since it provides a test of model theories which, once established, leads to the ability to predict the optical response of such cells to changing external conditions. Thus the investigation of the alignment of liquid crystals in such thin film structures is fundamental to device development.

Since the early seventies a variety of optical guided wave techniques have been developed to study the refractive index profiles in thin film optical guiding structures [1,2]. These techniques utilise the fact that a series of discrete (quantised waveguide momentum) modes may be excited in thin films sandwiched between two other materials. Often the structure studied may be a true waveguide in that the surrounding media have a lower index than the layer to be explored. However this is not essential and layered structures, which support leaky modes, may also be examined. The mode spectrum is dependent upon the refractive index distribution within, and the dimensions of, the structure. It is apparent that from the optical view-point, most liquid crystal display structures comprise some form of leaky waveguide structure and may be studied using guided mode techniques.

Sprokel et al [3] appear to have been the first to have used the attenuated reflection geometry to couple light to a liquid crystal layer arranged as an almost fully guiding structure by the use of metal films as bounding mirrors. They only explored the excitation of the surface plasmon, which is a guided mode localised at the metal/liquid crystal interface. Surprisingly they did not observe the excitation of any other guided modes. Welford et al [4,5] present the first comprehensive study of the director profile in a liquid crystal cell using the guided wave technique. They discovered that it is possible to characterise in some detail the optical properties of the thin liquid crystal layer including the director profile. In their work they excited a number of different optical modes within the liquid crystal layer by varying the angle of incidence of the incoming laser beam. This variation in angle of incidence corresponds to a variation of in-plane momentum of the light. When the incident beam angle is set to excite a guided mode then the optical field profile within the liquid crystal will have an oscillation across the layer. Each different order mode has a different optical field profile and will thus be sensitive to different regions within the cell (in effect rather like a Fourier analysis) giving highly resolved (~100nm) information on the director profile. In addition, the liquid crystal is optically anisotropic (generally taken to be uniaxial). Thus when the liquid crystal director (optic axis) is twisted out of the incidence plane and/or tilted out of the plane of the cell walls then the eigenmodes in general will not be pure p (TM) or s (TE). Consequently the angle dependent reflectivity or transmissivity spectrum will show polarisation conversion which will be very sensitive to the optical axis distribution through the layer. This sensitivity to director profile is only in one dimension, through the thickness of the layer. However since a monodomain should be invariant in the plane of the cell this is exactly the sensitivity required. Indeed it is clear that this excitation of optical waveguide modes is about the only technique which is going to yield the required spatial resolution across the thickness of the liquid crystal layer.

DIFFERENT TECHNIQUES

Over recent years four somewhat different geometries have been exploited using prism coupling of light to guided modes in liquid crystals layers [6]. As already indicated the first to have been developed appears to have been the fully guiding technique.

Fully Guiding

The liquid crystal is encapsulated between metal coated glass plates with thin aligning layers on the metal coatings. One of the metal layers, the layer through which light is incident, is semi-transparent, being typically 40nm thick, of silver or gold. This thin layer not only acts as a reasonable mirror for optical waveguiding in the liquid crystal but it is also thin enough to be used as an optical tunnel barrier through which to couple incident radiation into the liquid crystal. The second metal layer may be fully opaque [4], acting as a high quality mirror, or it may be partially transmitting [5] allowing also the measurement of transmission through the cell. Using high index coupling prisms, to enhance the available in-plane momentum, Elston et al report several experiments that have helped to resolve the director profiles in bistable ferroelectric liquid crystal (FLC) cells [7-10], including studies of dynamics [11]. The fully guiding technique gives very sharp optical resonances because of the reflectivity of the metal (often silver) layer. These resonances have a typical halfwidth of order 0.1° corresponding to a propagation length of perhaps several hundred microns, requiring a beam diameter of at least this while also prohibiting the study of small pixels. However the metal layers provide the added advantage of allowing excitation of surface plasmons which, being bound to the metal surface, are sensitive

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to the director structure near to the alignment layer [4]. Unfortunately the technique has two serious disadvantages. Firstly it involves the use of thin metal layers not present in real commercial cells and secondly it is rather difficult with such soft metals as silver or gold to use rubbed polymer alignment. Even when rubbed polymer alignment has been used with gold films [12,13] the alignment created may well be different to that with rubbed polymer on ITO. To avoid the problems associated with the metal layers a technique was then developed using no metals whatsoever.

Fully Leaky (High Index Glass)

This next technique involved high index glass bounding layers. By use of a high-index coupling prism it is possible to configure a liquid crystal such that there is total external reflection at the glass/liquid crystal boundary. In this case an evanescent field penetrates the liquid crystal near the aligning surface allowing detailed information of the near surface region to be obtained. Xue et al [14] used this technique in a study of FLCs with no alignment layer.

If the angle of incidence of the optical beam is reduced in this geometry then leaky modes are excited within the liquid crystal layer. In this case the angle dependent reflectivity gives rather broad optical features which are nevertheless sensitive to the director structure in the cell. This geometry has been used [15-17] in further studies of FLC cells. By studying the polarisation conversion signal quite detailed information on director twist/tilt profiles have been obtained. However it was felt that the broadness of the leaky mode features limited the resolution of director structure. In addition while this technique easily gives refractive index information since there exist simple-to-observe critical edges in the angle dependent reflectivity data it suffers from the use of very high index glass. An improved, non-metal layer, procedure was needed, this came in the form of the half leaky guided mode technique.

Half Leaky

In the half leaky guided mode arrangement there is still a high index coupling prism but the bottom high index plate is replaced with a low index plate. This means that for a certain range of angles of incidence the optical field in the liquid crystal is totally reflected at the liquid crystal/low index plate boundary. Hence over this limited range of angles this interface acts as a perfect mirror. Consequently for angles of

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incidence up to the critical angle between the high index prism and the liquid crystal there are sharp resonant features in the angle dependent reflectivity. Fuzi Yang et al have extensively exploited this geometry for both homogeneous alignment [18,19] and homeotropic alignment [20,21]. Unfortunately, even though this technique has been used to give information on biaxiality, to test mean-field theory, to quantify variations of refractive indices and cone angle with temperature and to give details of director profiles in a range of surface aligned FLC cells it still has one severe limitation. The technique involves the use of one high index glass plate preventing the study of real commercial cells that are fabricated using low index glass.

Fully Leaky (Low Index Glass)

Since commercial cells are made with low index glass plates and contain no highly reflecting metal layers then it is clear that such cells will not be true guiding structures. These are going to be fully leaky cells. These we know give broad resonances and they had been previously considered unlikely to yield very detailed director information. In addition the use of low index glass means there will be no critical angles for simple determination of the refractive indices of the liquid crystal. However recent studies [22, 23] have shown that provided two coupling prisms are used, giving both angle dependent reflectivity and transmissivity, and the geometry of the liquid crystal cell is set to give strong polarisation conversion then detailed director profiles may be obtained

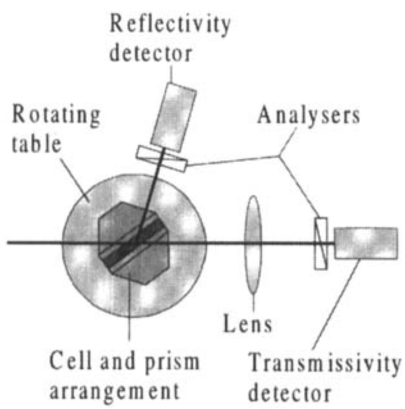

FIGURE 1 Fully leaky cell geometry with low index glass

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A schematic of the fully leaky geometry using low index glass prisms coupled with index matching fluid to a conventional cell is shown in Figure 1. Two polarizers define the input and detected linear polarizations. With a choice of settings of these polarizers we may record in total eight data sets, four in transmission, T, and four in reflection, R. In particular these include the polarization-conversion signals R_{sp}, R_{ps}, T_{sp} and T_{ps} as well as the polarization-conserving signals R_{pp}, R_{ss}, T_{pp} and T_{ss}. The polarization-conversion signals are particularly sensitive to the director twist and tilt. Further the two coupling prisms are optically attached to the cell with matching fluid which allows rotation of the cell to a position that gives optimization of sensitivity to director twist and tilt. In addition, this allows the acquisition of data for different azimuthal angle settings. By fitting to data sets taken at several azimuthal angles one further removes ambiguity in determining the director profile.

Convergent Beam

More recently the waveguiding technique, which has been almost exclusively used with a well-collimated laser beam, has seen one further development, the use of a convergent beam geometry instead. Smith and Sambles [24] have shown how with suitable optics it is possible to capture all the angle dependent data without rotation of the sample. A schematic of the geometry used to study a half leaky cell is shown in Figure 2.

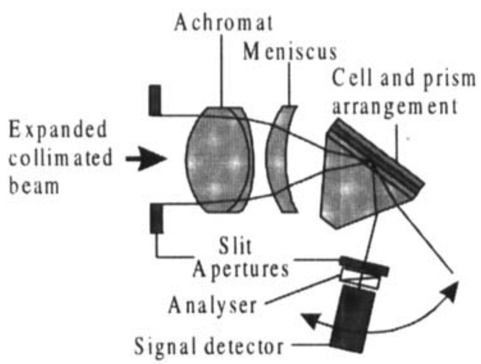

FIGURE 2 Convergent beam prism arrangement.

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It is clear that with the beam tightly focussed and stationary on the sample small area pixels may now be explored. In addition by using linear array detectors it is possible to capture the whole of the angle dependent data in less than a millisecond. This opens up potential for real-time studies of cell dynamics. A cautionary note should here be added that the focussed beam at the sample may cause heating. To avoid this the beam intensity is reduced which inevitably increases the relative noise in the final signal. Thus, in general, the data acquired using this convergent beam procedure will be of reduced quality compared with that found using the standard collimated beam arrangement.

A further adaptation of the convergent beam technique is to use, instead of coupling prisms, a pair of hemispheres. These increase the available coupling angle range and also provide a better focus at the sample. A schematic of this improved arrangement is shown in Figure 3.

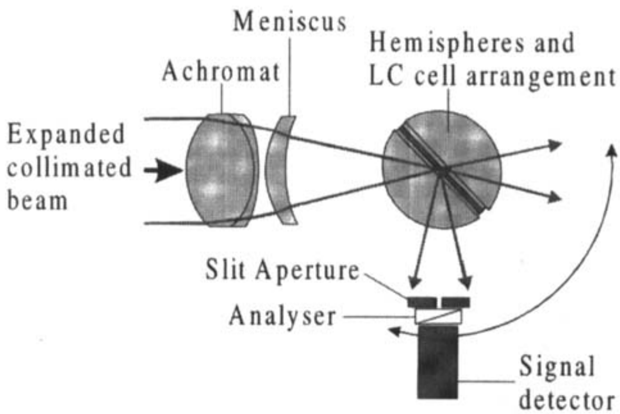

FIGURE 3 Convergent beam hemisphere arrangement

This modification, together with the use of conventional cells in the fully leaky geometry, is now being developed with a view to exploring cell dynamics and individual pixels.

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CONCLUSIONS

The use of optical guided mode excitation in the study of liquid crystal cells has been briefly reviewed. It is now established that with the development of the fully leaky mode technique this very powerful optical procedure may be used to explore commercial cells. In addition recent developments using a convergent beam variant paves the way for studies of individual pixels as well as real-time cell dynamics.

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