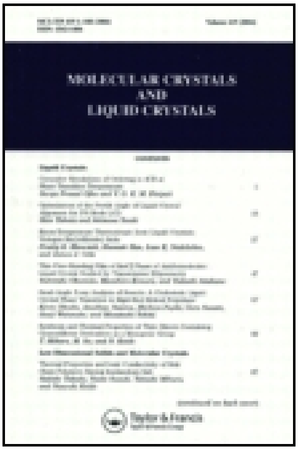

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

Diffraction Gratings, Liquid Crystals and Guided Modes

J. Roy Sambles [a] & Emma L. Wood [a b]

[a] Thin Film Photonics, Department of Physics, University of Exeter, Exeter, EX4 4QL

[b] DERA, St Andrews Rd, Great Malvern, WR14 3PS

Version of record first published: 24 Sep 2006

To cite this article: J. Roy Sambles & Emma L. Wood (1998): Diffraction Gratings, Liquid Crystals and Guided Modes, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 321:1, 349-358

To link to this article: http://dx.doi.org/10.1080/10587259808025101

Mol. Cryst. Liq. Cryst., Vol. 321, pp. 349–358
Reprints available directly from the publisher
Photocopying permitted by license only

Diffraction Gratings, Liquid Crystals and Guided Modes

J. ROY SAMBLES, AND EMMA L. WOOD[a]
Thin Film Photonics, Department of Physics, University of Exeter, Exeter EX4 4QL; [a] now at DERA, St Andrews Rd, Great Malvern, WR14 3PS

Abstract The use of optical excitation of guided modes to study the director profile in thin liquid crystal layers is well established. The most commonly used coupling geometry is that of prism-coupling, the prism providing the required extra in-plane momentum to allow coupling between the external radiation and the guided modes in the liquid crystal layer. A second coupling arrangement involves the use of a grating to provide the extra in-plane momentum by diffraction. Optical modelling of grating structures with liquid crystal layers is by no means as easy as modelling the planar prism-coupled system. In this article we examine both experiments involved with, and the theoretical modelling of, grating coupling to guided modes in liquid crystals.

Keywords: liquid crystals; diffraction gratings; waveguides

INTRODUCTION

There exist in the literature a large number of studies of the director profile in liquid crystals using optical excitation of waveguide modes. These may be fully guided techniques[1-5], where metal layers are used as mirrors to confine the optical field within the liquid crystal layer, they may be fully leaky techniques[6-8], where the liquid crystal is confined between high index prisms and no true waveguiding is observed, or they may be half-leaky structures[9-14], where the liquid crystal is trapped between high and low index prisms. In all of these experiments the incident radiation has it's in-plane momentum enhanced by the use of prism coupling. This facilitates direct matching of the incident photon in-plane momentum to the in-plane momentum of the optical guided mode in the liquid crystal layer. By varying the angle of incidence of the incoming radiation it is apparent that the in-plane momentum is varied and hence coupling to different momenta guided modes is achieved. This results in reflectivity minima in the angle dependent reflectivity. By fitting this angle dependent reflectivity data to modelling theory it is then possible to obtain details of the director structure in the liquid crystal waveguide, the cell. Using different input and output polarisations, generally either p (TM) and s (TE), it is then possible to establish a detailed picture of the director profile in the cell. Because the system under study is comprised of a set of planar layers it is relatively straightforward to model the optical response of even the most elaborate liquid crystal layer provided it has no in-plane variation. An optical multilayer modelling procedure may be utilised based upon the 4x4 matrix approach[15-17]. While this may appear complicated if complex director tilt/twist profiles, biaxiality and absorbance are correctly included, it is exact and relatively easily implemented as a computer code. This is not true for the alternative procedure commonly used to couple radiation into a waveguide, that of grating coupling. Here the surface of the sample is either corrugated or it has a periodic index profile such that it can diffract the incident radiation. Then the in-plane momentum of the photon can be enhanced by integer multiples of the grating momentum allowing coupling to guided modes without the use of coupling prisms. While this may provide a better device geometry - the coupling prisms are often bulky - the optical modelling of such systems is much more demanding. Only recently have workers started to combine rigorous grating modelling codes with liquid crystal layers[18-20] to predict their optical response. We now go on to explore recent results in this emerging area of liquid crystal optics.

THEORY

There are a number of possible approaches to solving the problem of combining anisotropic materials with a grating. The case of a bare surface relief grating made of a uniaxial material has been investigated[21] using a conformal transformation in the plane of symmetry of the grating. This work was restricted to considering the optic axis of the anisotropic material only in the mean plane of the grating, which rather limits its usefulness as far as liquid crystal structures are concerned. Harris et al [18] presented a slightly more general theory based on the transformation of coordinates as first formulated by Chandezon et al[21], but they limited their study to the optical axis lying in the symmetry plane with the plane of incidence also being the symmetry plane. Nevertheless their multilayer formalism allows for the modelling of grating coupled systems in which the direcor tilt varies through the cell thickness. More recently Harris et al[19] have developed a general version of their earlier work allowing for conical diffraction thereby opening up the study of grating coupling to liquid crystal layers without the need for the optic axis, the director, or the grating vector to lie in any specific plane. Models of conical diffraction based upon Chandezon's approach were first developed for isotropic materials by Popov and Mashev[23] and then Elston et al[24]. Li[25] and Preist et al[26] provide improvements which Harris et al[19] incorporate.

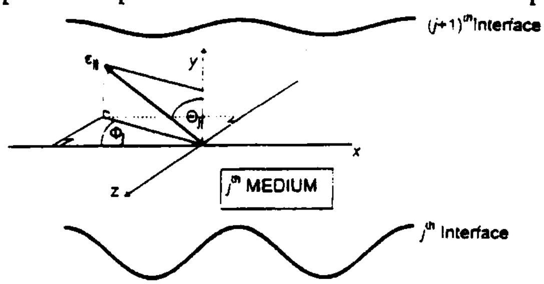

FIGURE 1 Geometry for the model calculation of Harris et al [19].

The system considered by Harris et al[19] is illustrated in Fig. 1. This comprises a multilayer grating structure containing interfaces of the same periodicity but allowing for different amplitudes. The optic axis or, in the case of a uniaxial liquid crystal, the director, is defined by the angle Θ with respect to the grating normal (y-axis) and the angle Φ , the azimuthal angle, with respect to the x-y plane. The k vector of the incident photon is defined similarly by two angles θ and φ. Then using a transformation to non-orthogonal curvilinear coordinates Maxwells equations are solved. Because of the transformation the boundary conditions on the corrugated interfaces are made simpler but this is offset by the requirement that the optical fields are expanded as a set of partial waves in the transformed frame. This set and the mathematical representation of appropriate functions of the differential of the surfaces present in the system are both in principle infinite. However in practice an extremely good approximation to modelling the optical response of such a system is obtained with a truncated order series. For gratings with amplitudes no greater than their pitch good convergence (the predicted reflectivity does not change by more than 0.1% by increasing the order by 1) is found for less than $\sim\pm 15$ orders. The details of the rather difficult mathematics associated with this modelling is to be found in Harris et al's[19] paper and we will not reproduce it here. The essential point is that there is now a modelling program available with which to compare the measured optical response of grating-coupled liquid crystal waveguides, however complex the director profile may be, with theoretical predictions. This then allows grating-coupling to be used in a similar manner to prism-coupling. In addition it opens up potential for predicting the optical response of new types of device structures which incorporate the controllability of liquid crystals with diffractive optics. We now go on to explore some of the experiments which have used gratings and liquid crystals.

EXPERIMENTS

There exists much work on the diffraction of light by liquid crystals but this is primarily concerned with Bragg diffraction from the helical pitch of cholesteric nematics which is not the problem of interest here. There is also a body of work on grating alignment of liquid crystals, indeed one of the earliest theories of the manner in which homogeneous alignment was achieved on rubbed surfaces explored the influence of a simple surface corrugation upon the elastic deformation energy of a nematic liquid crystal[27]. In subsequent years grating alignment of liquid crystals has been explored for various grating pitches and depths[28-31]. While we are not specifically concerned with the alignment by gratings here it is worth noting that gratings are one of the few readily characterised and controllable surfaces which lend themselves to good surface anchoring energy measurements[32].

Here however we wish to focus on the combination of gratings and liquid crystal waveguides. Provided the refractive index of the glass surrounding a liquid crystal layer is lower than at least one of the indices of the liquid crystal then the thin film of liquid crystal may be set up to act as a waveguide. If both n_e and n_o of the liquid crystal are smaller than the index of the glass then the liquid crystal layer is always capable of supporting guided modes regardless of the director orientation or the radiation polarisation. One of the earliest studies of grating coupling to fully guiding modes explored a homogeneously aligned nematic layer with the director aligned along the grating groove direction[33]. The liquid crystal was aligned homogeneously using evaporated silicon oxide and thin silver layers acted as strongly reflecting boundaries. Because of the absence of an adequate modelling theory at the time all that Wood et al[33] could do was to explore the variation of mode momentum with the twist angle of the plane of incidence, showing that it corresponded to that expected for such an aligned slab of liquid crystal. In a later study[34] of homeotropically aligned 5CB, one of the silver layers was removed, the geometry being that shown in Fig. 2.

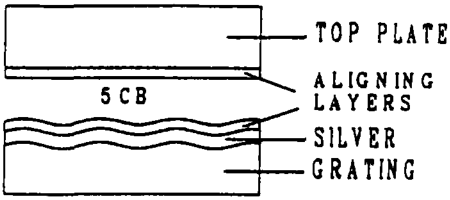

FIGURE 2 The half silvered grating cell geometry.

The angle dependent reflectivity for a monochromatic plane parallel p-polarised light beam of wavelength 632.8nm for $\varphi = 0$ is shown in Fig. 3. There are a number of interesting features. On the left, labelled (1) is the critical momentum for guiding of the first order (+1) diffracted modes, for higher angles, to the right in this figure, are sharp first order diffracted guided modes having their cut-off momentum designated by (2). Beyond this angle there exists a surface plasmon resonance coupled to by first order diffraction, this is the broad background minimum labelled (3). The point labelled (4) is the guided mode cut-off for the second order (-2) diffracted modes and (5) shows the position of the corresponding surface plasmon minimum.

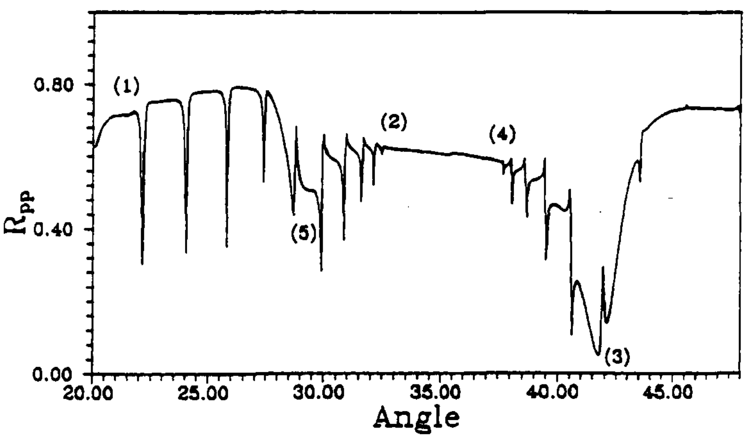

FIGURE 3 p-polarised reflectivity for a homeotropic cell as in Fig. 2.

If a homogeneously aligned cell is rotated so that the director does not lie in the plane of symmetry then the guided modes are no longer pure TM or TE and polarisation conversion is recorded in the reflected signal. Such a signal is shown in Fig. 4.

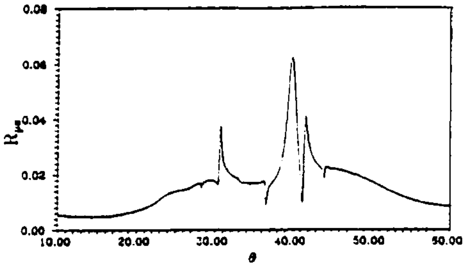

FIGURE 4 p to s polarisation conversion reflectivity signal for a homogeneous cell as in Fig. 2, with a rotation of 45^0.

Of course with a grating this is not the only possible mechanism for polarisation conversion, the grating itself will also cause this phenomenon unless the grating vector lies in or perpendicular to the plane of incidence. For a hybrid, homeotropic/homogeneous sample, of 5CB it has been shown[35] that sharp p to s conversion modes are available which are readily moved in angle by the application of a small field. This opens up the potential for high contrast switching using planar geometry with grating-coupling to liquid crystal waveguides. It also leads to the possibility of accurate measurements of pre-transitional Kerr effects[36]. Studies by Bryan-Brown et al[37,38] have briefly explored the potential for using such grating-coupled liquid crystal waveguides as fast switches both with nematic and ferroelectric liquid crystals. However, as mentioned all these studies were limited in that exact modelling comparisons with theory could not be undertaken. With the subsequent theoretical development[19] this limitation has now been overcome and we have available the predictive capability required for looking at future device potential. The manner in which the new model theory compares with data is shown in Fig. 5. This data was recorded for a 2.5 μm thick cell of 5CB with homogeneous alignment almost exactly along the grating grooves with thick silver coating the bottom, grating, surface of the cell. Clearly visible are sharp guided modes between 16.5^0 and 20^0, coupled to by first order diffraction, with second order modes between 22^0 and 25^0. The broader feature at 28^0 is the first order surface plasmon. The full lines, the theoretical predictions based upon Harris et al's[19] theory are in excellent accord with the data.

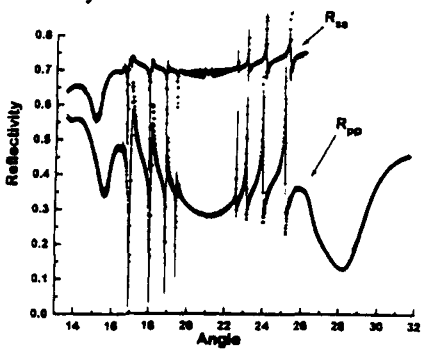

FIGURE 5 Fits (full lines) to experimental data (crosses) for R_{pp} and R_{ss}.

CONCLUSIONS

In recent years there have been a number of advances in our ability to model the optical response of systems incorporating diffractive surfaces. This, combined with a thorough knowledge of waveguiding in thin liquid crystal layers, is providing a springboard from which new combinations of diffractive optics with liquid crystals may be explored and possibly exploited. Already it has been shown that structures may be fabricated which show fast switching and, when used as p to s converters, high contrast[35]. Recently[39] the possibility of bistable nematic alignment with gratings has been realised which also opens up further device potential. certainly the low voltage control of diffractive optics using liquid crystals and gratings is now in a strong position to be developed both from the scientific perspective and technologically.

Acknowledgements

The authors acknowledge the support of the EPSRC and DERA Malvern.

References

[1.] K.R. Welford, J.R. Sambles and M.G. Clark, *Liq. Cryst.*, **2**, 91 (1987)
[2.] S.J. Elston, J.R. Sambles and M.G. Clark, *J. Mod. Opt.*, **36**, 1019 (1989)
[3.] S.J. Elston and J.R. Sambles, *Mol. Cryst. Liq. Cryst.*, **200**, 167 (1991)
[4.] Mengnang Gong and J.R. Sambles, *Liq. Cryst.*, **13**, 637 (1993)
[5.] S. Ito, F. Kremer, E. Aust and W. Knoll, *J. Appl. Phys.*, **75**, 1862 (1994)
[6.] C.R. Lavers, P.S. Cann, J.R. Sambles and E.P. Raynes, *J. Mod. Opt.*, **38**, 1451 (1991)
[7.] C.R. Lavers and J.R. Sambles, *Jpn. J. Appl. Phys.*, **30**, 729 (1991)
[8.] C.R. Lavers and J.R. Sambles, *Ferroelectrics*, **113**, 339 (1991)
[9.] Fuzi Yang and J.R. Sambles, *J. Opt. Soc. Am.*, **B10**, 858 (1993)
[10.] Fuzi Yang and J.R. Sambles, *Liq. Cryst.*, **13**, 1 (1993)
[11.] Fuzi Yang, J.R. Sambles and G.W. Bradberry, *Phys. Rev.*, **E50**, 2834 (1994)
[12.] Fuzi Yang, G.W. Bradberry and J.R. Sambles, *Phys. Rev.*, **E53**, 674 (1994)
[13.] Lizhen Ruan, J.R. Sambles and J. Seaver, *Liq. Cryst.*, **19**, 133 (1995)
[14.] Lizhen Ruan, J.R. Sambles and J. Seaver, *Liq. Cryst.*, **21**, 909 (1996)
[15.] D.W. Berreman, *J. Opt. Soc. Am.*, **62**, 502 (1972)
[16.] R.M.A. Azzam and N.M. Bashara, *Ellipsometry and Polarised Light*, (North Holland, Amsterdam, 1979)
[17.] D.Y.K. Ko and J.R. Sambles, *J. Opt. Soc. Am.*, **A5**, 1863 (1988)
[18.] J.B. Harris, T.W. Preist and J.R. Sambles, *J. Opt. Soc. Am.*, **A12**, 1965 (1995)
[19.] J.B. Harris, T.W. Preist, E.L. Wood and J.R. Sambles, *J. Opt. Soc. Am.*, **A13**, 803 (1996)
[20.] J.B. Harris, E.L. Wood, T.W. Preist and J.R. Sambles, *J. Mod. Opt.*, **43**, 1379 (1996)
[21.] R.A. Depine and M.E. Inchaussandague, *J. Opt. Soc. Am.*, **A11**, 173 (1994)
[22.] J. Chandezon, M.T. Dupuis, G. Cornet and D. Maystre, *J. Opt. Soc. Am.*, **72**, 839 (1983)
[23.] E. Popov and L. Mashev, *J. Opt. Paris*, **17**, 175 (1986)
[24.] S.J. Elston, G.P. Bryan-Brown and J.R. Sambles, *Phys. Rev.*, **B44**, 6393 (1991)
[25.] L. Li, *J. Opt. Soc. Am.*, **A11**, 2816 (1994)
[26.] T.W. Preist, N.P.K. Cotter and J.R. Sambles, *J. Opt. Soc. Am.*, **A12**, 1740 (1995)

[27.] D.W. Berreman, *Phys. Rev. Lett.*, **28**, 1683 (1972)
[28.] D.C. Flanders, H.I. Smith, H.W. Lehmann, R. Widmer and D.C. Shaver, *Appl. Phys. Lett.*, **32**, 112 (1978)
[29.] J. Cheng and G.D. Boyd, *Appl. Phys. Lett.*, **35**, 444 (1979)
[30.] A. Sugimura, N. Yamamoto and T. Kawamura, *Jpn. J. Appl. Phys.*, **20**, 1343 (1981)
[31.] Y. Kawata, K. Takatoh, M. Hasegawa and M. Sakamoto, *Liq. Cryst.*, **16**, 1027 (1994)
[32.] E.L. Wood, G.W. Bradberry, P.S. Cann and J.R. Sambles, *J. Appl. Phys.*, accepted for publication (1997)
[33.] E.L. Wood, J.R. Sambles and S.J. Elston, *J. Mod. Opt.*, **38**, 1385 (1991)
[34.] E.L. Wood, Ph.D. Thesis, University of Exeter (1992)
[35.] E.L. Wood and J.R. Sambles, *J. Mod. Opt.*, **40**, 493 (1993)
[36.] E.L. Wood, J.R. Sambles and S.J. Elston, *Mol. Cryst. Liq. Cryst.*, **222**, 1 (1992)
[37.] G.P. Bryan-Brown, J.R. Sambles and K.R. Welford, *Liq. Cryst.*, **13**, 615 (1993)
[38.] G.P. Bryan-Brown, J.R. Sambles and K.R. Welford, *J. Appl. Phys.*, **73**, 3603 (1993)
[39.] G.P. Bryan-Brown, C.V. Brown, J.C. Jones, E.L. Wood, I.C. Sage, P. Brett and J. Rudin, *SID Digest*, **28**, 37 (1997)