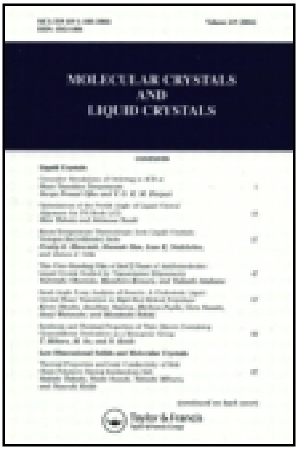

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New Approach for a Direct Measurement of Refractive Index Profile in Liquid - Crystalline Layer

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New approach for a direct measurement of refractive index profile in liquid - crystalline layer

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Abstract The prism coupler method has been applied to the investigation of refractive index profile (RIP) in liquid crystal (LC) layer. Waveguide modes have been excited in thin LC layer arranged as a planar wavequide. Modal lines of the modes excited in the waveguide are observed as evanescent in dielectric prism by tunnelling effect. Measured position of each modal line provides a mode propagation constant value. In a multimodal waveguide the set of the propagation constants creates data for RIP determination by means of M-line procedure. The usefulness of the M - line method to the investigations of LC waveguides is illustrated and verified by nematic liquid crystal (NLC) elastic response measurements.

Keywords: liquid crystal wavequide, refractive index profile, prism coupler

INTRODUCTION

The optical excitation of guided modes propagating in thin LC layer is a powerful technique to characterise the refractive index profile. Liquid-crystal-waveguide (LCWG) examination was reported earlier for MBBA (p-methoxybenzylidene-p-n-butylanine) but without clear information about LC layer aligning and the model for n(x) calculation[1]. Over recent years methods employing prism coupling of radiation into guided modes have been widely developed[2-22]. In all of them, generally, the attenuation total reflections (ATR) have been measured while excitation of the guided modes and/or surface plasmon resonance in a metal - clad liquid crystal waveguide[3, 5, 7-22]. In those methods an intensity dip of the reflected light can be observed when the coupling condition is satisfied and a guided mode is excited. The dependence of reflectivity versus angle of light incidence obtained in such a way can be modelled theoretically and, hence, in principle, information about dielectric permitivity tensor in the investigated waveguiding layer is described. The analysis of experimental results obtained in such a way is sometimes elaborate and not particularly convenient[13, 7]. One must take into account that methods of dielectric tensor modelling, as for example optical transfer matrix method, give some instabilities in calculation of the reflectivity when mixing modes are present in a waveguide[24, 8]. Besides, theoretical models of the elastic response are often not sufficient for predicting the waveguiding properties of the LC layer[12].

One of the aims of this article is an employment of the M - lines method as an additive tool for determination of a RIP. Similar method was developed earlier for RIP determination in the diffused solid waveguides[25]. To authors' knowledge the M - line method have not been applied to the investigation of liquid crystalline structures. The experimental part of the idea in the M - line method is quite similar to that in ATR but the way of the refractive indices obtaining is different one. We have shown how M - line technique can be applied to the direct RIP measurement and we discussed interpretation of the new experimental results as well.

PRINCIPLE AND SET - UP OF THE MEASUREMENTS

The measuring device (see Fig.1A) is constructed as follows: the liquid crystal layer is deposited between two prisms. Prism's bottom is coated with a layer which consist of indium tin oxide (ITO), SiO_2 , and polyimide. Thickness of this layer is chosen properly to ensure the light coupling into the waveguide[27,28]. That layer is a low index gap between prism and LC waveguide. It's refractive index value is independently measured.

Incident light excites the discrete modes for a particular θ_m angle for which the momentum of the incident photon along the interface matches the momentum of the optical mode in the waveguide. At the incidence angle θ_m the wave of proper (synchronous) phase velocity is excited. The normalised propagation constant of the m-th excited mode is equal to [29].

$$N_m = \frac{\beta_m}{k_0} = n_p \sin\left(\alpha + \arcsin\left(\frac{\sin\Theta_m}{n_p}\right)\right) \tag{1}$$

One can easily found this relation from Fig.1. The used symbols mean: β_m - phase constant of the m-th mode, k_0 - phase constant of a wave in the free -space, α - prism' angle as in Fig.1. Values of N_m^1 for m changing from 0 to M, and N_l^2 for l changing from 0 to L have been measured on both sides (both prisms) of the layer respectively. Subscripts m and l indicate number of the excited mode. The lowest number signifies the highest propagation constant of the mode. Mathematically, the wave field distributions in the waveguide are identical to those of the problem a potential well in quantum mechanics. Here the low index gaps (ITO/SiO_2/polyimide layers) play the role of the potential barriers. Hence, searched refractive index profile is the shape of the „potential well " (see scheme in Fig.1B). Calculation of this shape consists of looking for a function fulfilling the characteristic equations for the LC waveguide. Let as analyse the transverse resonance condition for a waveguide of arbitral refractive index profile like in Fig.1B.

The characteristic equation is then as follows [25,29]:

$$k_0 \int_0^{x_m} (n^2(x) - N_m^2)^{1/2} dx + \phi_{ca} + \phi_{cb} = \pi m \qquad (2)$$

In that formula we express as m - number of the mode, as x_m quasiclassic turning point for the mode defined simultaneously by $n(x_m)=N_m$ [25].The phase change during reflection ϕ_{ca} and ϕ_{cb} are given by Fresnel rule [29]:

$$\phi_{ca,cb} = -\operatorname{arctg}\left(\frac{n^2(x_m)}{n^2_{a,b}}\right)^{\rho} \sqrt{\frac{N_m^2 - n_{a,b}^2}{n^2(x_m) - N_m^2}} \qquad (3)$$

Here ρ is equal 0 for a wave polarized perpendicular to the plane of incidence or 1 for a wave polarized in plane of incidence. Measured values of the propagation constant N_m have been introduced to the system of the characteristic equations (2). In a mulitimode wavequide system of the equations (2) can be resolved with a trial function $n(x)$. From condition $n(x_m) = N_m$ the set of turning points is obtaining. Each turning point belongs to the RIP curve. In such a way RIP may be determined without aid of the theoretical model for LC layer deformation in an external field.

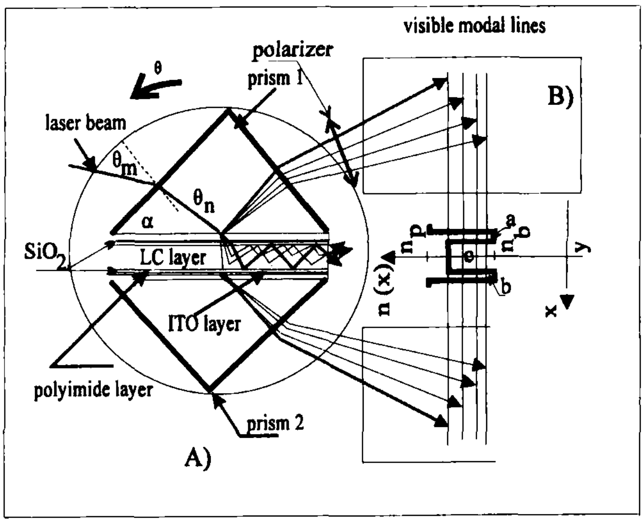


FIGURE1. The measurement device cross-section (A) and scheme of the modal lines visualisation (B) illustrating correspondence of the modal lines with an example of the refractive index profile (*x,y,z* are Cartesian co-ordinates; n_p is the refractive index value of the prism, n_b is the refractive index value of the optical buffer)

To resolve equations (2) the effective indices N_m for a mode with number m has to be measured. Such reconstruction of $n(x)$ is an inverse problem and solution has been obtained by WKB method. One can see from formula (2) that double set of the turning points should be obtained. So solution seems not to be unique. We assumed in the first term of the product a linear variation:

$$n(x) = N_k + \left(\frac{N_{k-1} - N_k}{x_k - x_{k-1}}\right)(x_k - x) \tag{4}$$

For lc with positive optical anisotropy values of n(x) are constrained by upper limit equal to n_e, and lower limit equal to n_o. Because of N_m may vary from n_o to n_e too, the second term provides solutions for n(x) which are out of constrained partition between n_e and n_o. For that reason it can not be used for turning points determination. That term is replaced during calculation by:

$$\left(N_{k-1} + N_k\right)/2 \tag{5}$$

Integrating in (2) with above assumptions results in recursive relation for x_m and x_{m-1} in which we assume that $x_0 = 0$, $n_0 = n(0)$:

$$\sum_{k=1}^{k=m}\left\{\begin{array}{l}\dfrac{1}{2\left(N_{k-1}-N_k\right)}\left[\begin{array}{l}\left(x_{k-1}-x_k\right)\left(N_k\sqrt{N_k^2-N_m^2}\right)+\\ N_m^2\log\left(\left(N_k-\sqrt{N_k^2-N_m^2}\right)\left(x_k-x_{k-1}\right)\right)\end{array}\right]-\\ \dfrac{1}{2\left(N_k-N_{k-1}\right)}\left[\begin{array}{l}\left(x_k-x_{k-1}\right)\left(N_{k-1}\sqrt{N_{k-1}^2-N_m^2}\right)+\\ N_m^2\log\left(\left(N_{k-1}-\sqrt{N_{k-1}^2-N_m^2}\right)\left(x_k-x_{k-1}\right)\right)\end{array}\right]\end{array}\right\} \tag{6}$$
$$-\left(m+\frac{1}{2}\right)\pi=0$$

For a standing wave in potential well two turning points are present for each mode. So, function describing n(x) must be even one. Each N_m is the discrete value of $n(x_m)$. The trial function n(x) obtainig in described way is used in (2) to calculate corrections for turning points. Those corrections are used in (6) to verify turning point positions. It is repeated until demanded accuracy for turning points.

EXPERIMENTAL RESULTS

Prisms in a measurement device have been made from $Bi_{12}SiO_{20}$ as square based (with faces 12mmx12mm). Both prisms worked as input and output couplers. Thickness of the optical buffer was 140±10nm. At 632,8 nm wavelength refractive index of the prism is equal to 2,545 while the SiO_2 / ITO/polyimide optical buffer's refractive index has been measured as equal to 1,49. Nematic liquid crystal (NLM) mixture W-602 (catalogue number from AWAT Poland) 6μm thick has been used in the experiment. Refractive indices of this material are equal to: n_e = 1,6494 and n_o = 1,5192.

Twisted nematic (TN) and two kinds of homogeneous alignment have been investigated versus electric field amplitude. In the first homogeneous alignment directors have been oriented along waveguide axe (z-axe), and in the second along y-axe, perpendicularly to the wave propagation in the guide.

Let us analyse the case B from the Fig.2. Guided modes propagates along z axis. Mode mixing causes that there is no pure *p* (vector of electric field in y direction) or *s* polarized (vector of electric field in xz plane) modes in the waveguide. Procedure of the M - line results in the refractive index profile like in the Fig.3. The upper refractive index value has been measured as equal to 1,6502. The lowest modal line is observed for *n(x)* equal to 1,52 in RIP computation. The perpendicularly aligned (homeotropic) region should be generated at the middle of the LC layer and it should be broadening on enlarging voltage[30]. During this deformation directors are tilted collectively in *yx* plane (see Fig.2). Hence, the modes coupling is of the same kind during directors rotation and only value of the coupling coefficient is changed causing smooth alterations in an individual mode's polarization. For this reason no sharp fluctuation has been observed in the modal lines picture. Such an observation for NLC has been reported by Elston[10] so presented results are a maintenance of that. Part of the waveguide around the middle of the layer is homeotropically aligned and the modes with polarization close to *p* - polarization exhibit higher refractive index value (1,6502). Such a mode can be supported in this region therefore. For *s* - polarization refractive index is near to 1,52 and no TE modes can be supported in the middle of the layer. The deviation from square shape of the RIP has been observed for increased voltage. The following explanation can be given. For the lowest voltage values, the mixed modes in the vicinity of the layer boundary have been almost pure p - polarized modes and the measured value of the refractive index have been close to 1,6502 in that moment. As at the higher voltages the directors have been tilted in this thick boundary layer, too, then lower value of the refractive index has been observed in the mixed mode wave field. Such an observation seems to maintain the results of investigations of B.O.Myrvold et al. [31].Those authors established, that thickness of the surface layer is of the order 0,1 - 1,0 mm. Visible change of RIP near the layer boundary suggest that the boundary layer thickness is greater than or equal to the light wavelength (~ 0,6328mm). Results for the case A from Fig.2 are shown in the Fig.5.

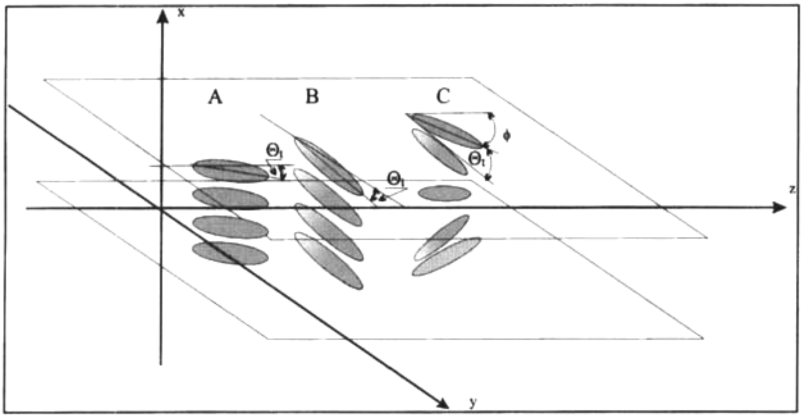
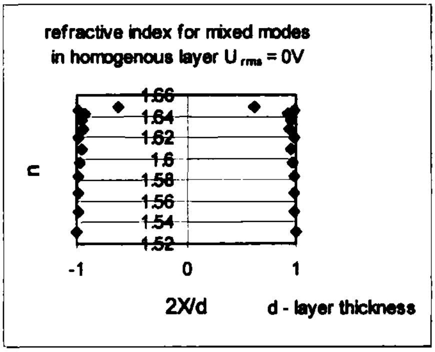


FIGURE 2. The scheme of the director alignment in the investigated layer cross - section. Cases A, B are for homogeneous alignment, and C is for twisted layer. Angle Θ_t is a pretilt angle, Φ is half of a twist angle. (Cartesian co-ordinates the same as in Fig.1).

In this case TE modes do not couples to TM modes. The *s* (TE) mode is equivalent to ordinary wave and is unchanged during electric deformation of the waveguiding layer. The *p* (TM) mode is an extraordinary wave and those modes are highly sensitive to voltage amplitude. Results of the measurement for both situations are presented in the Fig.5 and Fig.6 respectively



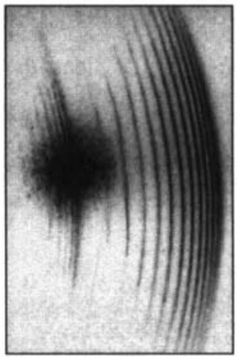


FIGURE 3. The RIP obtained in the LC layer of the thickness d and of the initial homogeneous alignment (left). Modal lines observed in CCD camera for U=0V amplitude of electric field (right).

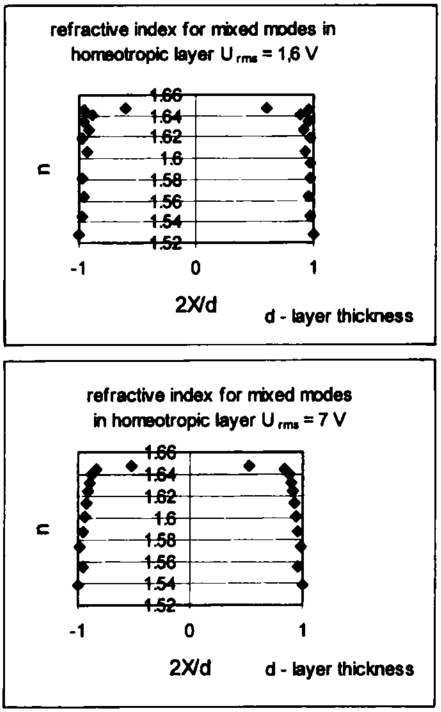


FIGURE 4. The refractive index profiles in the liquid crystal layer of the thickness d, initially homogeneously aligned for different electric amplitudes.

In both cases we have assumed that conduction processes may be neglected (resistivity is equal to 10^{12} Ωcm in liquid crystal and highest used voltage amplitude is equal to $10V_{rms}$ in the cell 6μm thick), so the ions transport cannot influence the orientation of the LC molecules in on state.

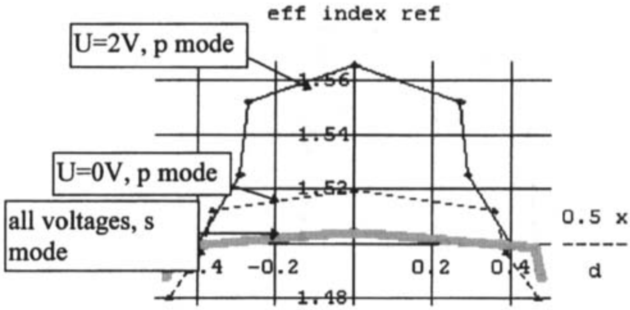
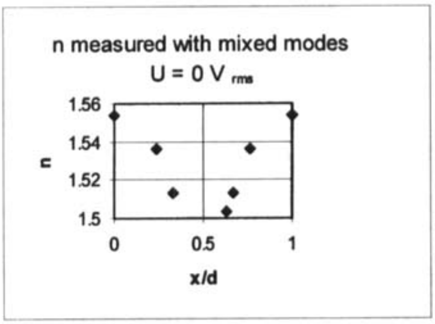
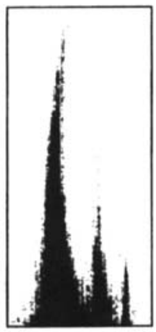
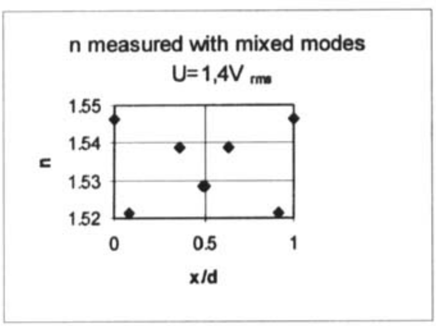


FIGURE 5. RIP profiles at voltage U=0V and voltage U=2V; homogeneous LC layer; initial optical axis alignment along waveguide, n_{eff} values measured in turning points for p modes (upper curves) and s modes (lowest curve) in the LC wavequide. Experimental points joined with line to distinguish different profiles.

Profiles measured for waveguiding layer arranged as 90^0 twisted one (TN) takes the form presented in Fig.6. The threshold value observed in the examined LC cell has been equal to $1{,}1V_{rms}$. In the experiment the visible LC layer transformations occur near to 1,2 V_{rms}. Distortions of the layer are initiated in the middle but at the layer edge changes are conspicuous, too, as the refractive index value is lowered in this zone. The number of modes is invariable for voltage amplitude between 1,2 and 1,4 V_{rms}. It allows us to suppose that coupling between the modes is of the unchanged kind, hence collective tilt of the directors supposingly preserves the twist angle. At the voltage equal to 1,4V transformations of the central area begin. In this region the directors have been previously aligned as exactly parallel to the z - axis. In the mixed mode field such a configuration provides that refractive index value is equal to ~ 1,5129. That part of the waveguide have not uphold any mode in the moment. When voltage amplitude increased to at about 1,4V the refractive index in that region increased, too, because of rotation of directors. Modes propagating in the middle part of the waveguide have been present for this voltages. Above 1,4 V_{rms} the sharp distortion of LC layer has been observed. For higher voltage the refractive index profile has tend to be more smooth and parabolic like. However it behaved like strongly influenced by boundary forces.







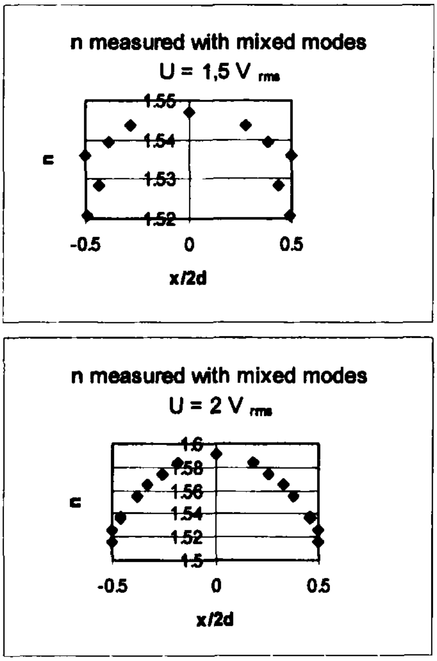


FIGURE 6. Refractive index profile for 90 ^{0} TN layer deposited with directors aligned as 45^0 between director on both layer surfaces and z-axis while a.c. voltage is applied across the layer (along x - axis) (case C from Fig.2.). Examples of the obtained modal lines picture at $U=0V_{rms}$ and $U=1{,}5V_{rms}$ are shown too.

CONCLUSIONS

The series of the measurement of the guided mode's phase constant in the nematic liquid crystal waveguide have been used as data to the M - line method. This method, known earlier in integrated optics[25] have been adapted here to the investigation of the liquid - crystalline layer properties. Obtained results seem to attest applicability of the used method to the high gradient refractive index profile determination in the LC cell. To verify results relatively well described alignments of the LC nematic layer have been chosen to investigations. The detailed analysis of RIP dependency versus external voltage has been presented for 6μm thick NLC at three different alignments. Results obtained for homogeneous alignment are similar to those reported by Elston[10]. For twisted nematic the elastic response for the driving electric field has been presented in wide voltage range. Voltage response for twisted nematic has been obtained by means of ATR by Sambles et al.[20] but only theoretical results for tilt and twist angles have been presented in accordance with earlier work of Sambles, Preist et al.[31]. In here direct experimental results have been demonstrated for this case.The advantage of the presented method is that RIP is directly measured and no aid of theoretical models of LC layer deformation is needed. So it can be applied as a verification of such a theoretical modelling. It is worthwile to point out that obtaining RIP values in set of the turning points allow us to describe RIP behaviour in the vicinity of the LC layer boundary. That area of LC layer is really hard to theoretical modelling. For example it is known that presence of surface pretilt is not detectable in conventional reflectivity measurements exploited in the ATR methods [7]. Presented method seems to be convenient and efficacious component tool of the other procedures which determines properties of liquid crystal layer by means of ATR or similar experiments. One should remember that an integer in formula (2) is taken over effective thickness of the waveguide. It results in different errors obtained for turning point position for each mode. The biggest error occuers for a first mode with an internal angle of reflection near to critical angle. Values obtained for the first mode (with lowest index m) should be rejected during RIP calculation. Another disadvantage is that M - line method can be applied only for multimode waveguides.

Refractive indices of the optical buffer placed on the bottom of both prisms must be precisely measured because it is dependent on thickness and materials used in that buffer. The sharpness and the envelope of each observed modal line are sensitive to optical buffer parameters, but their positions are not because in the turning points $n(x) = N_m$ so formula (2) is fulfilled without confinements.

The measurement accuracy depends on a precision of the prism orientation and the correctness of the incidence angle measurement. Because of the neglecting of the prism interaction in equation (2) the N_m measurements accuracy is lower than $5x10^{-4}$. Finally, in the presented experiment, one can obtain the measurement accuracy of $n(x)$ is equal to 10^{-3} and turning points position no less then 5%. Achieved accuracy can be improved.

Acknowledgments

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