5.4: Advanced Tools for Modeling of 2D-Optics of LCDs

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ABSTRACT
Liquid crystal (LC) structures in high resolution LCDs with a rapid lateral variation of optical parameters (microdisplays, multi-domain LCDs, IPS-LCDs) must be characterized taking into account the effects of light diffraction. In addition to earlier reported MOUSE-LCD, we have developed a new software allowing estimation of diffraction effects in LCD optics. This software provides the simulation of various experimental tests with fine–structure LC cells. In particular, the simulation of LCD measurements with a polarizing microscope can be performed.

1. INTRODUCTION

A fine transversal structure inherent to many kinds of modern LCDs (microdisplays, multi-domain LCDs, IPS-LCDs etc.) may give rise to a pronounced effect of light diffraction on LCD performance. In addition to earlier reported MOUSE-LCD, we have developed a new software to estimate diffraction effects in LCD optics. Along with LCD performance modeling this software permits simulation of various practical optical experiments on fine-structure LC panels.

The problem of the calculation of optical characteristics of transversally inhomogeneous LC layers allowing for diffraction effects has been widely studied. Light propagation in 2D-inhomogeneous LC layers has been simulated using Grating Method (GM) [1, 2], Finite-Difference Time-Domain method [3, 4], wide-angle beam propagation method (BPM) [5, 6], and reduced-order grating method [6, 7]. These methods provide a rather accurate solving of the corresponding electrodynamic problem. We apply the combined approach [8] using the scattering matrix technique within the framework of the grating method for the rigorous optical calculations. With this approach the multi-dimensional transmission scattering matrix characterizing 2D-inhomogeneos layers of LCD panel is calculated. From this matrix the output optical characteristics are defined using the common methods of Fourier optics and the theory of coherency [9]. The listed methods of 2D-optics are not widely used for LCD modeling now because they are very time-consuming, especially when spectral averaging is necessary. Therefore, to solve real optimization problems for LCDs, as a rule, fast approximate methods are applied, based on the optical methods developed for 1D inhomogeneous media, such as the Berreman method and various extended variants of the Jones matrix method. These 1D-opics methods are adapted for modeling of 2D- and 3D-inhomogeneous media with the use of a set of heuristic assumptions, referred to in this report as Direct Ray Approximation (DRA). Because of the heuristic nature of DRA, the question of applicability and accuracy of this approximation is very acute and should be addressed individually for each concrete case. Our software allows one to compare the results of the "precise" grating method with the results of a DRA-method. We used "electrodynamic" version of the Jones matrix method to calculate 1D-optics of LCD [10-12]. Application of this method to 2D-inhomogeneous media we call conventionally "DRA-method". In our program the LC director field configuration is calculated by using the successive relaxation method with usual division of each iteration step into two stages. The first stage is calculation of electric potential distribution at the given LC director configuration. The second stage is calculation of partial relaxation of LC director in the electric field calculated in the first stage. The "elastic" part of the task is solved with the finite difference method. The electric field distributions are calculated with the finite element method. LC-layer of the LCD modeled may have both symmetric and asymmetric boundary conditions. Real parameters of both polar and azimuthal anchoring can be taken into account.

2. VIRTUAL MICROSCOPE

One of the advantages of our software is a virtual microscope (VM). The microscopic image of an inhomogeneous LC layer with a fine transversal structure strongly depends on the observation conditions, in particular on the aperture of the condenser of the illuminating system and the aperture of the microscope objective (Fig.1). The virtual microscope allows one to model the microscopic images of LC layers observed with the polarizing microscope, with consideration for real experimental conditions.

If we are willing to have *a quantitative* evaluation of the LC layer parameters from the microscopic images (e.g. obtained with CCD camera attached to the microscope), we should be able to estimate the validity of DRA, as only within DRA one can get sufficiently simple formulas expressing explicitly the relation between the parameters and optical characteristics of the LC layer. Virtual microscope technique provides a direct reply to this question and clarifies the experimental conditions, when DRA method can be used.

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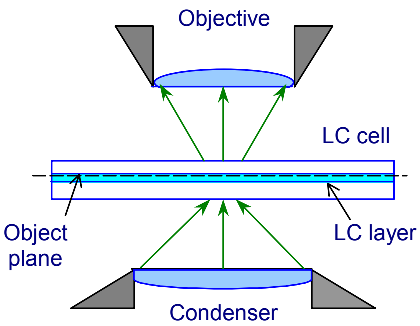


Figure 1. Options of Virtual Microscope: aperture of the condenser of the illuminating system of microscope, aperture of the objective, object plane position.

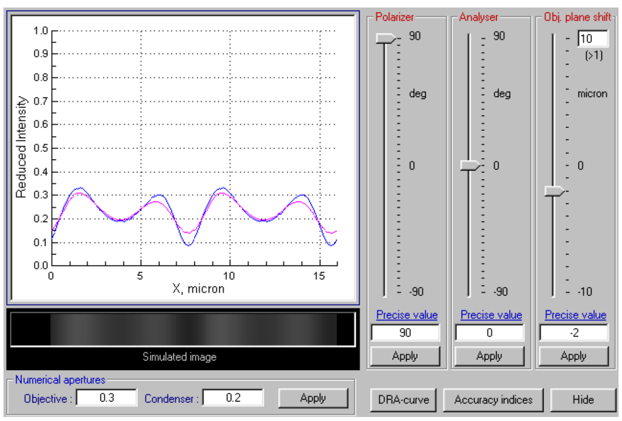
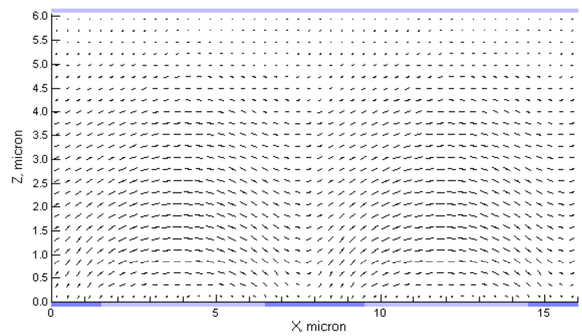


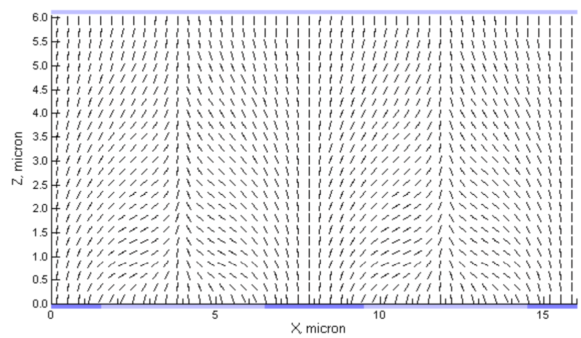
Figure 2. Virtual Microscope dialog box. The curves show the calculated dependences of the reduced intensity of the image and the normal DRA transmittance of the sample on the lateral coordinate X. We may rotate polarizer and analyzer and move the object plane and, thereby, scan the sample in depth.

Fig. 2 shows a Virtual Microscope dialog box of our program. The plot on this box shows dependencies of reduced intensity of image of the sample and its normal DRA transmittance on the lateral coordinate (x). The reduced intensity is calculated as a ratio of the intensity of the sample image to intensity of the empty field image (when the sample, polarizer and analyzer are removed) at the same point and can be easily measured in experiment. The normal DRA transmittance calculated with the DRA-method is the local transmittance of the system "polarizer – sample – analyzer" for the normal incidence of unpolarized light.

Let us provide certain examples of the possibilities of VM technique. Consider two LC cells, mentioned as IPSS and IPSVA, each having the LC layer thickness of 6.1 µm. Electrode period of both cells is equal to 8 µm, electrode width - 3 µm. IPSS cell in off-state has homogeneous structure with 88° azimuthal angle and 2° tilt angle of LC director. IPSVA cell in the off-state has a homeotropic alignment. The following parameters were used in the calculations. IPSS cell: K_{11}= 1.32·10^{-6} dyne, K_{22}= 6.5·10^{-7} dyne, K_{33}= 1.38·10^{-6} dyne, $\varepsilon_{\|}$=8.3, $\varepsilon_{\perp}$=3.1 for LC, voltage between neighboring electrodes in on-state U_{ON}=6V; IPSVA cell: K_{11}=1.32·10^{-6} dyne, K_{22}=7.1·10^{-7} dyne, K_{33}=1.95·10^{-6} dyne, $\varepsilon_{\|}$=15.1, $\varepsilon_{\perp}$=3.8 for LC, U_{ON}=8V. The calculated director profiles for the on-states are provided in Fig.3. Optical calculations were performed for a quasi-monochromatic light with a wavelength of 550 nm. Refractive indices: LC - $n_{\|}$=1.581, $n_{\perp}$=1.482; ITO layer - n_{ITO}= 2.05, aligning layers - n_{AL}=1.6, and glass substrates - n_G=1.52. Electrode thickness was taken equal to 0.03 µm. The thickness of aligning layers l_{AL}= 0.1 µm above the electrodes and l_{AL}= 0.13 µm between electrodes.



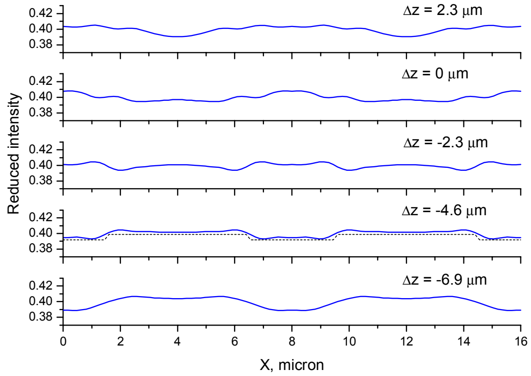
IPSS



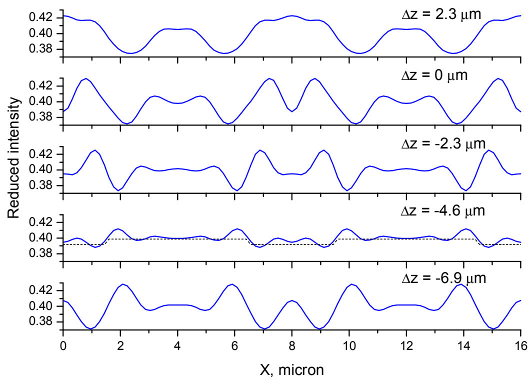
IPSVA

Figure 3. The calculated director profiles (on-state) and electrodes configurations in IPSS and IPSVA cells.

Fig.4 provides the simplest case, when the LC director is aligned uniformly throughout the layer, while the electrodes pattern is the only reason for the transversal inhomogeneity of the LC cell. The calculations were carried out in the off-state of IPSS with the analyzer and polarizer parallel to X axis. Fig.4 shows that our virtual microscope operates as a real one. Moving the objective plane we may bring the electrodes, which are located at the bottom substrate (Fig.3), into focus. The parameter Δz (on Fig.4 and below) is the difference of the current value of the working distance (D_C) (here working distance is the distance between the LC cell and the microscope objective) and its value in the case when the microscope is focused at the lower boundary of the upper glass substrate of LC cell (D_0); $\Delta z = D_C - D_0$. As in a real microscope, a sharp image can be obtained only if numerical apertures of the condenser and objective are rather large (Fig.1).



N.A.con.= 0.4

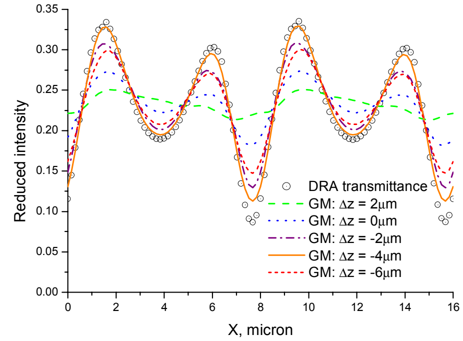


N.A.con.= 0.1

Figure 4. The virtual microscope. Scanning in depth of LC cell was simulated for various numerical apertures of the condenser N.A.con. Numerical aperture of the objective N.A.obj.=0.5. If the N.A.con. is sufficiently high, at a certain object plane position (Δz=-4.6μm) it is possible to see a sharp image of the electrodes. At this setting the curve of reduced intensity is very close to the DRA transmittance curve (dotted line). Reduction of N.A.con. blurs the image.

Fig.5 presents results for LC cells with inhomogeneous (with fast lateral LC director variation) LC layers, the layers IPSS and IPSVA (Fig.3) in their on-states, between the crossed polarizer and analyzer. We search the position of the object plane for IPSS (analyzer is parallel to X axis) and IPSVA (analyzer is at 45^0 with respect to X-axis), when the DRA transmittance curve most closely corresponds to the curve of the reduced intensity measurable with a microscope.

IPSS



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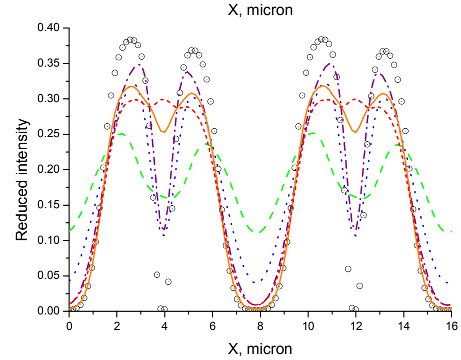

Figure 5. Virtual microscope. Scanning in depth for the LC layers with configurations shown in Fig.3. In a certain position of the object plane, DRA transmittance curve (o) rather well approximates the reduced intensity curve. N.A.col.=0.4 and N.A.obj.=0.5.

3. COLLIMATED BEAM ILLUMINATION AND DIFFUSE ILLUMINATION

One of the features of LC layers with transversal inhomogeneity is their ability to scatter light, i.e. redirect part of light flow in directions different from the propagation direction of incident light when LC layer is illuminated with a collimated light beam (Fig. 6a). On the other hand, at a diffuse illumination, LC layer can redirect towards the viewer some part of the light incident on LC panel in directions different from the viewing direction (Fig. 6b). According to our knowledge only the case of a collimated illumination was considered so far [13]. Our program allows one to model both situations.

Diffuse illumination is regarded with the help of "Illumination Mode Effect" (IME) utility of our software. This utility provides calculation and comparison of the following characteristics:

(i) Reduced LCD brightness at the diffuse illumination for a given viewing direction. The term "reduced brightness" is used to define the ratio of brightness of the light emergent from LCD in a given direction (it is an integral characteristic for the whole LCD segment under consideration) to brightness of the light source for this direction.

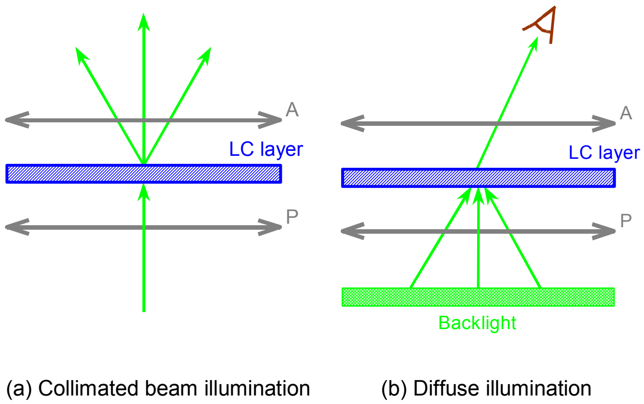

Figure 6. LCD scattering effect for collimated and diffuse light illumination. P - polarizer, A – analyzer

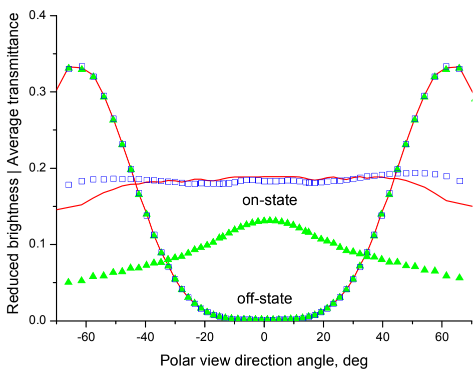

Figure 7. Optical characteristics of IPSVA LC cell for the collimated and diffuse illumination, obtained with IME tool. (Solid line - diffuse illumination by grating method, Δ - collimated beam illumination by grating method, - average transmission by DRA method).

(ii) Average LCD transmittance for the collimated light beam incident onto LCD segment towards the viewer. This average transmittance is calculated with the grating method as a ratio of intensity of the light diffracted by the LCD to the zero diffraction order to intensity of the incident light.

(iii) Calculated with the DRA-method, average transmittance of the LCD segment for the collimated beam incident on the LCD in the viewing direction.

Application of the IME tool to IPSVA LCD is demonstrated in Fig.7 (the polarizer and analyzer are oriented as in the above example corresponding to Fig.5). As can be seen from this Figure, the LC layer scattering effects (Fig. 6b) considerably influences LCD characteristics in on-state.

The IME tool provides the estimation of accuracy of DRA-method when average transmission and angular characteristics of LCD are modeled. Furthermore, this tool often allows one to define precisely status of the DRA-method results. As our calculations show, in the majority of practically important cases the LCD average transmittance calculated with DRA-method and the reduced brightness LCD for the case of the diffuse illumination (calculated with the grating method) are very close to each other for a wide range of view directions.

4. CONCLUSION

Advanced tools for modeling of 2D-optics of LCDs are presented. In addition to earlier reported MOUSE-LCD, we have developed new software, allowing for diffraction effects in LCD optics and, in particular, solving the problem of simulation of the experiments using polarizing microscopy and the illumination mode effects for LC layers with a fine transversal structure. The examples of the application of the new software tools for the evaluation of the diffraction effects, when observing the LC structures with a strong lateral variation of the director orientation are demonstrated.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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