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Inline quality control of liquid crystal cells

Sergiy Valyukh, Sergei Sorokin, Vladimir Chigrinov

Abstract—Inline quality control of liquid crystal (LC) cells is usually associated with a real time non-contact characterization of moved LC cells. Such a characterization enables inspection of the products quality and helps to find in time defects. In the paper, we analyze an approach for fast evaluation of LC cell gap uniformity. The approach is based on detecting interference patterns formed by the quasi-monochromatic light reflected from a tested LC cell. To speed up the data treatment, a simple analytic expression describing the intensity of light interacting with the multilayered structure of an LC cell is derived. The results of the simplified model are compared with rigorous simulations. Two experimental setups are discussed. A CCD camera is used for detecting the interference patterns.

Index Terms—Liquid crystal (LC) cell gap, quality control, real-time measurements.

I. INTRODUCTION

THE demands on performance, quality and cost of LC devices, which have already become a part of our everyday lives, are increasing dramatically from one product generation to the next. The quality and cost of such devices depend critically on the ability to produce and control LC cells with certain specified parameters. Thickness of the LC layer, or the cell gap, is one of these parameters due to its great impact on the optical and electro-optical characteristics of finished devices. Utilization of spacers of the needed diameter enables obtaining a desired cell gap. However, the actual cell gap may vary for several reasons like the pressure difference used during assembly, the curing of the sealing glue of the displays, capillary forces during the filling of the cells, the crossovers, dust particles, the spacer concentration, etc. In order to save materials and to increase the quality of the finished items, it is important to determine defects in early stages of the production, e.g., before or just after filling the LC into cells. Therefore, a precise control of the cell gaps in a production environment is of great practical consequence.

A lot of efforts have been directed to the development of methods and the corresponding facility for determination of the parameters of LC cells [1-19]. Almost all of the proposed methods are optical methods that are divided into two categories: spectroscopic and monochromatic, relating to the spectrum of the light source used. Some of the methods are applicable for filled LC cells, and others are suited for empty

LC cells.

Being an anisotropic medium, LC affects the polarization of light passing through it. Besides the birefringence and orientation of the LC director, the change of the light polarization depends on the thickness of the LC layer. This fact is used in the majority of the techniques for filled LC cells [1-14, 17-19]. However, determination of the state of polarization of the measured light often requires mechanical rotation or movement of either some polarization components of an experimental arrangement or an LC cell to be tested. The cell gap can be derived from a fitting of simulated curves to the measured signature, or the result is found from positions of extremums, e.g., wavelengths of minima or maxima. The polarimetric methods give quite precise results for nematic and smectic LC cells, but they are inapplicable for polymer-dispersed LC cells, polymer-stabilized LC cells, and empty cells. These LC cells are usually measured by interference techniques [14-16]. By detecting the position of the maxima or (and) minima of the oscillations in the spectrum of the light reflected from or passed through a tested LC cell, it is possible to determine the optical thickness of the LC layer [14] or the cell gap, if the cell is empty [16]. In monochromatic measurements, dependence of the light intensity on the incident angle is analyzed.

Despite the variety of the proposed measuring techniques [1-19], only a few of them can be utilized for non-stop inspection of the quality control in a production line. Moreover, the majority of the developed methods are suitable for determination of a cell gap at no more than one point. In order to obtain information on uniformity of a tested LC cell, the measurements have to be done at several points. Namely such a principle was realized by one of the authors earlier in the measuring system developed for inline control [5, 6]. The same is true for other measuring tools utilized single point measurements and also installed for inline characterization. Drawback of this approach is low resolution of a map of a LC cell gap distribution. As a result, it is possible to let pass a sample with a defect zone.

In this case, information about uniformity of the cell, i.e. the cell gap distribution, is missed. There are several works dealing with two-dimension (2D) characterizations of LC cells [17, 18]. By using a CCD camera, the authors of works [17] and [18] measure the Stokes parameters spatial distribution in the light flux normally reflected from a tested LC cell. The map of the thickness distribution is obtained after mathematical treatment of the measured data. Although these methods are able to provide the needed information on LC cell uniformity with a reasonable accuracy, some of their drawbacks cause difficulties for usage in a production line. In

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particular, the methods are based on a polarizing microscope that causes some difficulties in adaptation of the measurements for moving LC cells. Moreover, certain specific orientations of the tested LC cells with respect to the microscope polarizers are required and, what can be more inconvenient for embodiment of a real time control, there is the need to rotate the analyzer and to move the quarter-wave plate.

As an alternative solution to the registration of the light flux by CCD camera is the method utilizing multi-channel registration [19] where several points in the flux of the light reflected from the LC cell are analyzed independently. This method combines spectroscopic ellipsometry with a hyperspectral imaging spectrograph [20]. The polarization in the tested points is split into p and s components by polarizing beam splitters. After that, the light energy of each component is delivered through fibers to a multi-channel spectral camera. However, to obtain a good resolution of the cell gap distribution, it is necessary to measure many points on the cell. This added complication may cause problems with parallel data treatment and leads to a rise in price.

Among the basic requirements for the measuring method to be implemented into the corresponding equipment for an inline characterization of moved LC cells are 1) ability to provide information about uniformity of the tested LC cells with sufficient accuracy, 2) ability to be adapted for different sizes of the LC cells, 3) non-contact real time measurements, and what is always desired 4) simplicity and reasonable price. In this context, a model describing the light interaction has to be sufficiently simple because the software must find a solution during no more than several seconds.

The goal of our work is to study an approach satisfying all of the above mentioned criteria for inline characterization of LC cells. After analyzing the variety of proposed methods, our attention has been stopped on the interference method where information about the cell gap is extracted from computing data of a registered light flux interacting with a tested LC cell. Two experimental arrangements utilizing a monochromatic light source will be explored below. For the sake of

of the derived results can be applied to filled LC cells too.

II. THEORETICAL BACKGROUND

In order to derive a simple approach for the determination of LC cell parameters, let us consider the multilayered structure of the LC cell (Fig.1) which consists of a pair of transparent substrates (glass or plastic), ITO layers and a layer of LC or air in the case that the LC cell is not filled.

By describing the light vector reflected from each i interface of the LC cell as $\vec{E}_i e^{j(\omega t + \varphi_i)}$, where $j = \sqrt{-1}$, ω is the angular frequency and φ_i is the relative phase and neglecting multireflections between the layers, the intensity of the reflected light can be written as

$$I = \text{Re} \left(\left(\sum_{i=0}^5 \vec{E}_i e^{j\varphi_i} \right) \left(\sum_{i=0}^5 \vec{E}_i e^{-j\varphi_i} \right) \right). \quad (1)$$

If the coherence length of the illuminated light is less than double the optical depth of the substrates, the relative phases φ_0 and φ_5 in (1) can be omitted because there is no interference between the waves reflected from the top and bottom interfaces of the LC cell. For an empty LC cell, the reflection coefficient of the interfaces of ITO-air is approximately 2.3 times higher than the reflection coefficient of the interfaces of glass-ITO. By taking into account these two facts, as well as that the thickness of the ITO is much less than the LC cell gap, (1) can be simplified to

$$I = A_0 + A_1 \cos \Delta\varphi_{23} + A_2 \cos \Delta\varphi_{13} + A_3 \cos \Delta\varphi_{14}, \quad (2)$$

where A_0, A_1, A_2, A_3 are coefficients that depend on the refractive indices of the layers included in the LC cell, the angle of incidence, α , the light wavelength, λ , and the thickness of the ITO; $\Delta\varphi_{23} = \varphi_2 - \varphi_3$; $\Delta\varphi_{13} = \varphi_1 - \varphi_3 = \varphi_2 - \varphi_4$; and $\Delta\varphi_{14} = \varphi_1 - \varphi_4$. For unfilled LC cells, I_1 and I_2 are approximately of the same value but more than five times larger than I_3 . Because of this, as well as that the thickness of the ITO is much less than the cell gap, (2) can be simplified to

$$I = I_0 + I_1 \cos(\Delta\varphi_{23} + \phi), \quad (3)$$

where I_0 and I_1 are coefficients dependent on the refractive indices of the layers included in the LC cell, α , λ and the thickness of the ITO. The phase ϕ appears due to the influence of the thin layers of the LC cell.

The phase difference $\Delta\varphi_{23}$ is expressed through the cell gap d as

$$\Delta\varphi_{23} = 2\pi \frac{2d}{\lambda} \cos \alpha + \pi. \quad (4)$$

Combining (3) and (4), we have

$$I = I_0 - I_1 \cos \left(2\pi \frac{2d}{\lambda} \cos \alpha + \phi \right). \quad (5)$$

Here I, I_0, I_1, ϕ are slowly varying functions of λ, α , and the spatial coordinates x, y , where the plane XY coincides with the plane of the LC cell. It is wise to note that Eqs. (1-5) can be applied for transmissive measurements too. In this case, the sign before I_1 must be changed to +. For reflective mode, I_0 and I_1 are approximately of the same order of magnitude,

Fig. 1. Layered structure of LC cell and electromagnetic waves reflected from the interfaces.

simplicity, we will consider an empty LC cell, but the majority

whereas for transmissive mode, I_o exceeds I_l by more than ten times. As a result, the spectral oscillations caused by the light interference or the oscillations of intensity due to a change of

Fig. 2. Fragments of the interference patterns observed from LC cells illuminated by quasi-monochromatic light.

the incident angle are much more clearly defined in the reflected light. This makes reflective mode preferable for the measurements.

The easiest way to measure spatial distribution of the intensity of the reflected light (I_o) in real-time is to use a CCD camera, or video camera, as a photodetector. The light source in this case must be quasi-monochromatic. Examples of the interference pattern detected in reflection mode for two LC cells are shown in Fig. 2.

The observed bright and dark interference fringes are fringes of equal inclination [21]. The cell gap in the places having the bright fringes corresponds to the following expression

$$d = \frac{\lambda(m+0.5)}{2\cos\alpha} - \frac{\lambda\phi}{4\pi\cos\alpha}, \quad m=0,1,2,3... \quad (6)$$

whereas the cell gap in the places having the dark fringes is

$$d = \frac{\lambda m}{2\cos\alpha} - \frac{\lambda\phi}{4\pi\cos\alpha}, \quad m=1,2,3... \quad (7)$$

In general, from (5) the distribution of the cell gap can be expressed through the functions $I(x,y,\lambda,\alpha)$, $I_o(x,y,\lambda,\alpha)$, $I_l(x,y,\lambda,\alpha)$, and $\phi(x,y,\lambda,\alpha)$ as

$$d(x,y) = \frac{\lambda}{4\pi\cos\alpha} \left(\arccos \left(\frac{I_o(x,y,\lambda,\alpha) - I_l(x,y,\lambda,\alpha)}{I_l(x,y,\lambda,\alpha)} \right) + 2\pi m - \phi(x,y,\lambda) \right) \quad m=1,2,3... \quad (8)$$

The main problem in the determination of $d(x,y)$ according to (6), (7) or (8) is non-uniqueness, because of the unknown interference order m . It is impossible to state categorically that the interference fringes belong to different m . The fringes are contours of the cell gap intervals $\pm \frac{\lambda}{2\cos\alpha}$ or, what is also

possible, two neighbouring bright or dark fringes can correspond to the same d . Such non-uniqueness causes impossibility to determinate the cell gap deviation of an LC cell having N dark or bright fringes. Even if N is quite a large number, theoretically we can face a situation when all extremums, e.g. in the images of Fig.2, correspond to the same m . This means that the maximum thickness deviation does not exceed $\lambda/4$ or even less because it is unclear if the argument of the cosine reaches $m\pi$. The thickness deviation between neighbor bright and dark fringes is $\frac{\lambda}{4\cos\alpha}$ that can be

considered as accuracy of the measuring method. If less than two extremums (a minimum and a maximum) is observed, the cell gap deviation does not exceed the mentioned value.

In order to determine m and after that d , it is necessary to measure the interferograms at different λ or α . For example, by detecting the interference extremums (it does not matter whether maxima or minima) at the angles α_1 and α_2 ($\alpha_1 < \alpha_2$), from (6) or (7) we have

$$d = \frac{\lambda}{4\pi\cos\alpha_1} \left[\frac{\phi_1 \cos\alpha_2 + \cos\alpha_1(2N\pi - \phi_2)}{\cos\alpha_2 - \cos\alpha_1} - \phi_1 \right]. \quad (9)$$

Here ϕ_1 and ϕ_2 are the phases corresponding to α_1 and α_2 , respectively, and N is the difference between the observed interference orders.

In a similar manner, it is possible to extract d from interferograms obtained at different λ :

$$d = \frac{\lambda_1}{4\pi\cos\alpha} \left[\frac{\lambda_2 N + \lambda_1 \phi'_1 - \lambda_2 \phi'_2}{\lambda_1 - \lambda_2} \right], \quad (10)$$

where ϕ'_1 and ϕ'_2 are the phases corresponding to λ_1 and λ_2 , respectively.

Although the mathematics presented above has been developed for empty LC cells, it can be adapted to filled LC cells also. In this case, $\cos\alpha$ must be replaced by $\sqrt{n_{LC}^2 - \sin^2\alpha}$, where n_{LC}^2 is the average refractive index of the LC material. Since n_{LC} is close to the refractive index of the alignment layers and does not differ too much from the refractive index of ITO, the contrast of the interference pattern of a filled LC cell is much weaker than an empty LC cell has. On the other hand, LC being an anisotropic medium affects the state of light polarization. This property can be used for evaluation of the thickness uniformity by analysing the intensity distribution when the optical arrangement includes a pair of polarizers.

III. EXPERIMENTAL SETUPS

Several possible layouts of experimental setups for real time measurements of the cell gap distribution can be proposed. Each of these setups has its own advantages and disadvantages. One such experimental setup is shown in Fig.3.

It consists of a quasi-monochromatic light source, e.g. a laser diode or a halogen lamp coupled with an interference filter, two condensers (**C1** and **C2**) that are cylindrical lenses, the LC cell to be tested, and a CCD camera connected to a computer. If the LC cell is filled, two crossed linear polarizers

(P and A) have to be included in the setup before the CCD camera and after the light source. The role of the polarizers in this case is to suppress reflection from the top substrate.

The optical layout is arranged in such a manner that the illuminated light at one side of the LC cell is projected and observed under the angle α_1 , whereas the other side of the LC cell is projected and observed under the angle α_2 . The CCD camera in this case has the LC cell image (interferogram) such that each point of the image (interferogram) corresponds to the intensity of the light specularly reflected at the angle α ($\alpha_1 \leq \alpha \leq \alpha_2$) from a certain point on the LC cell. This angle depends on the position of the point. Since the LC cell is moved in a production line, the scanned interferograms contain information about the reflections of all points of the LC cell at angles ranged between α_1 and α_2 . These interferograms can be used to determine the cell gap distribution according to (9). If the spectrum of the light source consists of two or three lines corresponding to the spectral sensitivities of the channels R, G, and B of the camera, it is possible to utilise (10).

One of the disadvantages of this setup is that the condenser C2 must be of large linear aperture to furnish relatively large range of the angles α_1 and α_2 and large LC cells. As a solution, a parabolic reflective mirror can be utilised.

The other layout for scanning the interference patterns at several angles is shown in Fig. 4. In contrast to the previous experimental setup, the focuses of the condensers C1 and C2 are matched with a line situated on the LC cell. In this case, the interference of the scanned line at the angles varied from α_1 and α_2 is projected onto the CCD camera. While the LC

Fig. 4. Experimental setup for measuring cell gap distribution. cell is moved, the CCD camera scans its whole surface.

Light sources in both experimental setups have to be points.

IV. RESULTS AND DISCUSSION

Before assembling the experimental setups shown in Fig. 3 and Fig. 4, it would be a good thing to find the optimal incident angles under which it is possible to reach the maximum accuracy of the measurements. There are several different arguments for choosing the optimal range of α . First, higher incident angles lead to higher reflectivity. In this case, it is possible to expect that $I_I(x, y, \lambda, \alpha)$, as well as the contrast of the interference pattern or the ratio signal/noise, increases when α is close to 90° . Second, the value of $\cos \alpha$, that according to (5) defines the frequency of the interference fringes, has the most

change at α being close to 45° . Finally, since there is the product d by $\cos \alpha$ in (5) and the value of $\cos \alpha$ is highest at $\alpha=0$, one can assume that the measuring system will be more sensitive to variations of d at low angles.

In order to clear up which of the three assumptions dominates, let us investigate the reflectivity of an empty LC cell as a function of the incident angle and the cell gap. Consider an empty LC cell with two glass substrates, two layers of ITO of thickness 150 nm [22] and two layers of polyimide of thickness 50 nm [22]. To calculate the reflectivity of such an LC cell, the characteristic matrix method [21] can be applied.

The obtained results are plotted in Fig. 5, where the 2-D diagram represents the distribution of the reflectivity as a function of the incident angle and the cell gap. The brighter fringes in this diagram correspond to the higher reflectivity. The top graph in Fig. 5 contains two curves representing the profiles of reflectivity versus the cell gap at incident angles of 5° and 45° . The curves in the left graph are profiles of the reflectivity versus the incident angle for the cell gaps of 6.4 μm and 6.5 μm .

Fig. 5. Distribution of reflectivity of an empty LC cell versus the cell gap and the incident angle. The curves in the top graph are profiles of the distribution at α equal to 5° and 45° . The curves in the left graph are profiles of the distribution for d equal to 6.4 μm and 6.5 μm .

Fig. 3. Experimental setup for measuring cell gap distribution.

The LC cell was illuminated by a monochromatic light source of wavelength 521 nm. This wavelength was chosen because the laser diode that we intended to utilize in the experiment has such a maximum. The coherence length of our light source is less than double the optical thickness of the

glass substrate that does not cause interference due to multireflections in the substrate. This fact was taken into account in the calculations. At the beginning, we found the characteristic matrix of the thin layers surrounded by glass and determined the reflective and transmissive coefficients of this layered system. After that, the light flux reflected from the top interface air-glass was added to the light flux reflected from the thin layers and to the light flux reflected from the bottom glass interface.

From Fig. 5, it is possible to conclude that the interference patterns obtained at both large α and small α contain information needed to obtain a unique solution. The oscillations at low incident angles are more sensitive to small variations of the cell gap than at higher incident angles. In particular, the curves in the left graph (the profiles for 6.4 μm and 6.5 μm) are almost in antiphase for small α , whereas the phase shift and, as a result, the difference between the curves become smaller and smaller with increasing α . On the other hand, it is seen from Fig. 5, as well as from (5), that it is possible to obtain similar oscillations for two cells with the

gaps' difference equal to approximately to $\Delta d = \frac{\lambda}{2} N$ for

small incident angles. However, when the range of α becomes relatively wide (more than 10°), there appears a phase shift between these oscillations that starts to be significant for large incident angles.

Taking into account the obtained results, the experimental setup shown in Fig. 4 was assembled. In our setup, the condensers C1 and C2 were identical and had the F-numbers 5.8. The achieved range of the incident angle variation ($\alpha_2 - \alpha_1$) was 38° . The minimum incident angle (α_1) in our experimental setup was 15° . The tested empty LC cell had sizes 10cm x 5cm and spacers of 6.8 μm .

Before starting the data treatment of the measured interferograms, we investigated how the results of the model presented in (1)-(10) are close to the rigorous calculations based on the characteristic matrix method [21]. Another question that had to be cleared up was how large can the phase ϕ be that appears in (5)-(10) as a corrected parameter? The results of the calculations for the simplified and rigorous models in terms of the normalized reflectivity of an empty LC cell with the cell gap 6.4 μm versus the incident angle are shown in Fig.6.

The solid curve was obtained by using the simplified model according to (5) when ϕ is zero, i.e. there are no additional thin layers like ITO and the alignment layers. The dashed curve is the result of rigorous calculations from the profile in Fig. 5. As seen from the Fig. 6, the phase shift (ϕ) between these curves reaches its maximum, which does not exceed $\pi/6$, at α close to zero and tend to zero for α more than 40° . If comparing the solid curve with the results of the rigorous simulation obtained for some other cell gap, which can be considered as an effective value and when the normalized reflectivities of both models coincide at small incident angles, it is possible to find that such effective thicknesses can be around 6.36 μm and 6.63 μm . However, opposite to the good correlation between the curves in Fig. 6 for the incident angles larger than 40° , the reflectivities corresponding to both

Fig. 6. Normalized reflectivity versus the incident angle for an empty LC cell having the cell gap. 6.4 μm . The solid curve is calculated according to (5) when $\phi=0$. The dashed curve is calculated by using the characteristic matrix method for the LC cell containing a pair of ITO layers of thickness 150nm each and a pair of polyimide layers having thickness 50nm. The dot curve is calculated according to (5) for $\phi=0.6\cos^4\alpha$.

effective thicknesses have a phase shift at large angles. Thus, the reflectivity obtained for 6.36 μm has the phase shift around $\pi/5$ and the phase shift for the reflectivity of an LC cell with a gap of 6.63 μm is close to π .

By analyzing the obtained results, it is possible to conclude that a good approximation of Eq. (5) can be achieved when the

Fig. 7. Interferogram of the tested empty LC cell when its centrum coincides with the focus of the condensers in Fig. 4.

correction phase is described by an expression like $\phi = \phi_0(\cos \alpha)^\gamma$, where ϕ_0 and γ are some constants. In our particular case, we set $\phi_0=0.6$ and $\gamma=4$. The results for I in this situation are plotted in Fig. 6 by the dot curve.

One of the interferograms measured in the experimental setup shown in Fig. 4, in particular the one that is obtained when the center of the tested LC cell has coincided with the focus of the condensers, is illustrated in Fig. 7. The curved profiles of the fringes point at the different cell gaps along Y. Higher frequency of the fringes corresponds to a larger cell gap.

To calculate the exact values of the cell gaps at this particular line (X=50mm), as well as for the other scanned

profiles, Eq. (9) with $\phi=0.6\cos^4\alpha$ was utilised. The obtained map of the cell gaps is plotted in Fig. 8. The dash-and-dot line in this figure corresponds to the interferogram from Fig. 8.

The measuring time, which coincides with the time of movement of the tested LC cell through the scanned focus line, was approximately 5s. During this time 18 screen-shots of the interferograms corresponding to different positions on the LC cell were obtained. If the speed of a production line is faster, i.e. an LC cell passes the focus of the measuring system lenses in less than 5s, utilization of a fast-speed camera will be needed.

Fig. 8. The cell gap distribution in the tested empty LC cell.

V. CONCLUDING REMARKS

In summary, we have considered the interference method for real time characterization of moved LC cells that is needed for quality control in a production line. Information about the cell gap distribution is obtained after treatment of the interferograms projected on a CCD camera at different angles. A quasi-monochromatic light source is used. To speed up the data treatment, a simplified analytical expression describing the intensity oscillations as a function of the incident angle has been derived for the multilayered structure of the LC cell. The results obtained by the simplified model and the rigorous simulations based on the characteristic matrix method have been compared. A correction for the simplified model has been done after the comparison by means of introducing a corrected parameter. Although we have studied in the work the simplest case – reflection from an empty LC cell, the considered approaches can be applied for characterization of filled transmissive LC cells too.

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