Thin Solid Films xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Polarization modulation polarimeter for measuring two-dimensional distribution of five cell parameters of a twisted nematic liquid crystal display

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ARTICLE INFO

Available online xxxx

Keywords:
Polarimeter
Twisted-nematic liquid crystal device
Cell gap
Pretilt angle
Rubbing angle
Twist angle
Untwisted phase retardation

ABSTRACT

In this study, an intensity-sensitive polarization modulation polarimeter (IPMP) was proposed and set up in order to measure the cell parameters of a *twisted-nematic liquid crystal display* (TNLCD). Both Yeh and Gu's transfer matrix and Lien's transfer matrix of a TNLCD are used and they are able to characterize all five cell parameters of a TNLCD including the cell gap, pretilt angle, rubbing angle, twist angle and untwisted phase retardation simultaneously. The optical setup is based on a single CCD camera and the ratio of p- and s-linear polarization intensity signals whereas we rotate a calibrated quarter wave plate to produce the polarization modulation during measurement. Thus, all five cell parameters are determined numerically by use of the least square curve fitting algorithm between the measured data and theoretical prediction following Yeh & Gu's and Lien's models of a TNLCD at same time. Finally, the advantages of this proposed IPMP are discussed.

1. Introduction

Five cell parameters of a *twisted nematic liquid crystal display* (TNLCD), which are the cell gap, twist angle, rubbing angle, untwisted phase retardation and pretilt angle, are critical to the performance of the image of a *liquid crystal display* (LCD). Those parameters are highly sensitive to the contrast ratio, brightness and viewing angle. Thus we need a method that can be able to precisely measure the cell parameters of an LCD in order to assure high quality image display during manufacturing process.

Ellipsometer applies an oblique linearly polarized light to a tested thin film in order to measure the film thickness and refractive index via two ellipsometric parameters. The state of polarization of the reflected light wave is analyzed in terms of the ratio of the amplitudes and *phase retardation* of the electric fields of p- and s-linearly polarized light beams. Accordingly, ellipsometer can be used to characterize an LCD as well. However, an oblique incident beam onto an LCD in ellipsometer produces an elliptical beam spot size on specimen that introduces uncertainty in an LCD characterization for two-dimensional (2-D) display. In order to solve this problem, a normal incident of the laser beam onto the LCD is preferred. Recently, an interferometric polarimeter has been demonstrated enabling to measure the cell parameters of a TNLCD precisely [1–3]. Tsai et al. [4] proposed the phase-sensitive heterodyne interferometer to detect the cell parameters of a TNLCD via differential phase detection of the heterodyne signal. However, their method lacks the ability to measure the pretilt angle of a TNLCD and only for single point detection. In contrast, Wei et al. [5] proposed an amplitude-sensitive heterodyne polarimeter (ASHP) which is able to measure the cell parameters of a TNLCD via amplitude detection of the heterodyne signal. However, 2-D distributions of cell parameters are available and they are based on scanning the tested sample properly. Similarly, the pretilt angle is still not available in their method because of being based on Yeh and Gu's transfer matrix of TNLCD [6]. Liu et al. [7] proposed the equalization of Yeh and Gu's transfer matrix and Lien's transfer matrix [8] of a TNLCD in ASHP and all five cell parameters of TNLCD are obtained numerically at the same time by use of the least square curve fitting algorithm. However, the 2-D distributions of cell parameters of a TNLCD based on CCD are not applicable either.

In this study, we propose an intensity-sensitive polarization modulation polarimeter (IPMP) which uses polarization modulation method via a rotating quarter wave plate (QWP) that 2-D distributions of all five cell parameters of a TNLCD are available at the same time by using a CCD camera. A series of CCD images of p- and s-polarization components are collected separately versus the rotation of a calibrated quarter wave plate (QWP) during measurement. Then, all five cell parameters can be calculated numerically by using a least square curve fitting algorithm whereas the equality between Yeh and Gu's transfer matrix and Lien's transfer matrix is developed. In order to

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0040-6090/$ – see front matter
http://dx.doi.org/10.1016/j.tsf.2013.12.040

simplify the experimental setup, an analyzer or a polarization beam splitter is inserted in front of CCD in order to select p- or s-polarization component independently in this setup where a single or a pair CCD is arranged for measurement. As results, IPMP not only becomes a simplified optical setup at normal incident but also able to measure all five cell parameters of a TNLCD numerically and simultaneously. To best fit the developed theory of a TNLCD which is based on the ratio of intensity of p- and s-polarization components, with using the measured data by a CCD camera, IPMP can characterize a TNLCD in terms of all five cell parameters in 2-D distribution precisely.

2. Working principle of intensity-sensitive polarization modulation polarimeter

IPMP as shown in Fig. 1 uses a linearly polarized light normal incident onto a continuously rotating QWP for polarization modulation. A tested TNLCD is located after the QWP hence 2-D images of p- and s-polarization components of the emerging beam from the TNLCD are detected separately via a properly adjusted analyzer or a polarizing beam splitter (PBS) by using a CCD camera. The CCD camera continuously records the detected intensity corresponding to the different polarization states at different orientations of QWP within 360° under 1°/s of rotation speed during measurement. Hence two sets of series CCD images with respect to p- and s- polarization components are recorded independently which can be used for all five cell parameters characterization precisely.

At first, a QWP is calibrated by considering the QWP to be an elliptical wave plate instead of a linear wave plate by that two orthogonal elliptical polarization Eigen states instead of two linear polarization Eigen states that are presented in the QWP as shown in Fig. 2. A_x and A_y are the amplitudes of the fast elliptical Eigen polarization along the x and y axes, respectively. We assume that the transmittance of two orthogonal elliptical polarization Eigen states satisfies $T_f = T_s = 1$ and the transmission transfer matrix M_{QWP} of a QWP is described by [9–11].

$$M_{QWP} = \begin{bmatrix} \cos^2\beta + \left(\sin^2\beta\right)e^{-i\gamma} & \sin\beta\cos\beta\left(1-e^{-i\gamma}\right)e^{i\delta_f} \\ \sin\beta\cos\beta\left(1-e^{-i\gamma}\right)e^{i\delta_f} & \sin^2\beta + \left(\cos^2\beta\right)e^{-i\gamma} \end{bmatrix}, \quad (1)$$

where β is the direction angle of fast Eigen-polarization of the QWP with respect to the x axis and γ is the phase retardation between fast and slow elliptical Eigen-polarizations and also δ_f is the phase difference between x and y components in each elliptical Eigen-polarization.

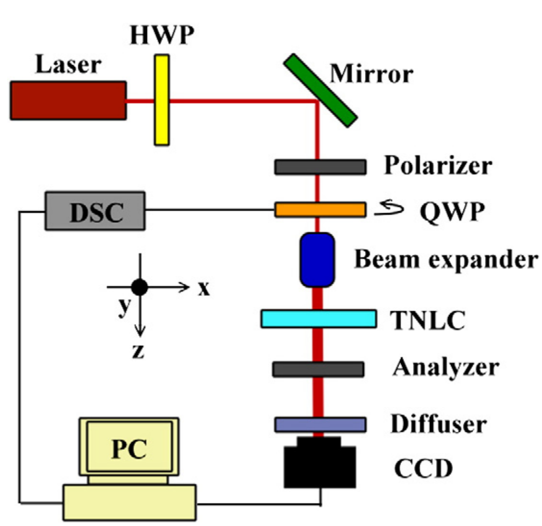

Fig. 1. Schematic of the intensity-sensitive polarization modulation polarimeter.

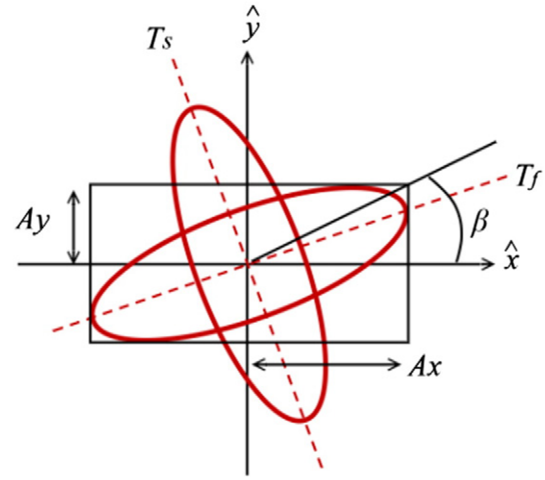

Fig. 2. Elliptical Eigen-polarizations of an elliptical wave plate.

In general, the transmission transfer matrix of TNLCD (M_{TNLC}) which is non-absorbing medium can be written as

$$M_{TNLC} = \begin{bmatrix} A & B \\ -B^* & A^* \end{bmatrix} = \begin{bmatrix} a+ib & c+ie \\ -(c-ie) & a-ib \end{bmatrix}. \quad (2)$$

The physical model of a TNLCD based on Yeh and Gu derived transmission transfer matrix is M_{Yeh} in which three cell parameters of TNLCD are included. They are twist angle (ϕ), rubbing angle (α) and untwisted phase retardation (Γ) [5]. Hence,

$$M_{Yeh} = \begin{bmatrix} a+ib & c+ie \\ -(c-ie) & a-ib \end{bmatrix} = \begin{bmatrix} p\cos\Phi + qr\sin\Phi - iqs\cos(2\alpha+\Phi) & -p\sin\Phi + qr\cos\Phi - iqs\sin(2\alpha+\Phi) \\ p\sin\Phi + qr\cos\Phi - iqs\sin(2\alpha+\Phi) & p\cos\Phi + qr\sin\Phi + iqs\cos(2\alpha+\Phi) \end{bmatrix}, \quad (3)$$

where $p = \cos\chi, q = \sin\chi, r = \Phi/\chi, s = \Gamma/2\chi$ and $\chi = \sqrt{\Phi^2 + (\Gamma/2)^2}$ are defined. Meanwhile, if using Lien's transfer matrix for a TNLCD at the same time, it can provide three cell parameters, the cell gap (d), twist angle (ϕ) and pretilt angle (θ) in a range from 0° to 30° explicitly [8]. Thus,

$$M_{Lien} = \begin{bmatrix} a+ib & c+ie \\ -(c-ie) & a-ib \end{bmatrix}, \quad (4)$$

where

$$a = \frac{1}{\sqrt{1+u^2}}\sin\Phi\ \sin\left(\sqrt{1+u^2}\Phi\right) + \cos\Phi\ \cos\left(\sqrt{1+u^2}\Phi\right), \quad (5)$$

$$b = \frac{u}{\sqrt{1+u^2}}\cos(\Phi+2\alpha)\sin\left(\sqrt{1+u^2}\Phi\right), \quad (6)$$

$$c = \frac{1}{\sqrt{1+u^2}}\cos\Phi\ \sin\left(\sqrt{1+u^2}\Phi\right) - \sin\Phi\ \cos\left(\sqrt{1+u^2}\Phi\right), \quad (7)$$

$$e = \frac{u}{\sqrt{1+u^2}}\sin(\Phi+2\alpha)\sin\left(\sqrt{1+u^2}\Phi\right), \quad (8)$$

where $u = (\pi d/\lambda\Phi)(n_{eff} - n_o)$ and $n_{eff}(\theta) = \left(n_e n_o/\sqrt{n_o^2\cos^2\theta + n_e^2\sin^2\theta}\right)$, n_o and n_e are the ordinary and extra-ordinary refractive indices of the liquid crystal molecules in a TNLCD respectively. Theoretically, both transfer matrices are equal to each other for a TNLCD. The rubbing angle in both transfer matrices is assumed to be equal that all five cell parameters of a TNLCD can be obtained numerically with using the least square fitting algorithm properly.