Optik 126 (2015) 917–922

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Predicting wavelength dependency of optical modulation of twisted nematic liquid crystal display in the visible range

Ghaith Makey, Moustafa Sayem El-Daher*, Kanj Al-Shufi

Higher Institute for Laser Research and Applications, Damascus University, Airport Highway, Damascus, Syria

ARTICLE INFO

Article history:
Received 2 February 2014
Accepted 12 February 2015

Keywords:
Spatial light modulators
Optoelectronics
Simulation
Holography

ABSTRACT

One of the main problems in liquid crystal spatial light modulators (LC-SLM) is the prediction of their optical modulation behavior for different wavelengths; this coupled phase/amplitude modulation can be hard to measure for specific wavelengths and setups, yet it is required to be included in the study of a number of SLM's applications. This work proposes a simulation model to predict the phase/amplitude modulation for different twisted nematic liquid crystal displays (TN-LCD) optical setups, this model incorporates the effects of wavelength in addition to other parameters which already have been studied before like twist angle as internal parameter and polarizers angles, we verified the accuracy of our model compared to results of previously published work.

1. Introduction

Extensive work have been dedicated to the topic of twist nematic liquid crystal displays (TN-LCD) modeling and simulation [1,2], yet the individual papers in this field could not answer clearly a key question required for many users of TN-LCD when used as SLM, namely at an arbitrary wavelength what is the coupled amplitude-phase modulation for each grayscale value in a pixel? This question is quiet important to be answered by a simulation model specifically when the measurements of the associated modulation is hard to carry out (e.g. when working on holography's experiment with amplitude mostly setup and need to predict the values of coupled phase modulation). By keeping the previous question in mind, let us review quickly related work.

In 2000 Marquez et al. [3] presented distinctive characterization of edge effects in TN-LCDs; their analysis was supported by measurements taken at 4 wavelengths. In 2001 Marques et al. [4] used the results of [3] to extend their work and gave a quantitative prediction of the modulation behavior of TN-LCD, again the measurements were limited to 4 wavelengths and their analysis requires specific measurement for each wavelength at which they want to predict TN-LCD modulation behavior.

In 2005 Kim and Lee [5] measured the parameters of TN-LCD with no ambiguity by fitting the theoretical predictions to the intensity of transmittance, then they predicted the phase modulation and verified the results experimentally; their work was limited to the study of one wavelength. In the same year, Wan and He [6] proposed new model for the director distribution of TN-LC cell but again the work did not include a study of wavelength dependency.

Results which describe the optical modulation properties of TN-LCD without the need to know LCD's internal structure parameters do exist [7–9]; however these studies did not include a study of wavelength dependency.

In this paper we will use the equations derived and listed very neatly in Refs. [3,5], and we will incorporate extended Cauchy equations [10] to propose one unified mathematical model that can be used to predicted phase and amplitude modulation of TN-LCD at any visible wavelength and without the need for any measurement at this wavelength. We will also use the experimental results of [3,4,11–13] to verify our simulation results.

2. Mathematical model

In this section we will discuss the mathematical models for two main TN-LCD SLM setups: the first one is a system composed of SLM sandwiched between two polarizers (System A) and the second is a system composed of polarizer-SLM-quarter wave plate-polarizer (System B). Fig. 1 shows the differences between two setups.

* Corresponding author. Tel.: +963 1133920683.
E-mail addresses: ghaith.maki@yahoo.com (G. Makey), eldaherm@scs-net.org (M. Sayem El-Daher), kalshoufi@gmail.com (K. Al-Shufi).

http://dx.doi.org/10.1016/j.ijleo.2015.02.072
0030-4026/

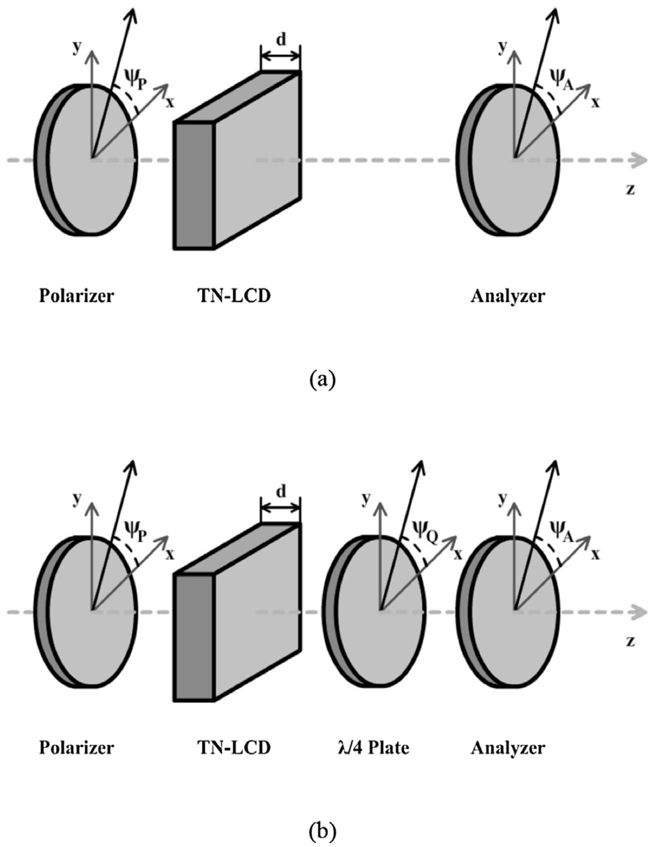

Fig. 1. Different optical setups for TN-LCD as SLM, (a) System A, (b) System B [5].

2.1. Mathematical model for System A

We will start directly with the following equations [5] for System A:

$$\tilde{T} = f\cos(\psi_A - \psi_P) + h\sin(\psi_A - \psi_P) - ig\cos(\psi_A + \psi_P) - ij\sin(\psi_A + \psi_P) \quad (1)$$

$$\delta = \beta - arg(\tilde{T}) \quad (2)$$

$$t = |c\tilde{T}|^2 \quad (3)$$

where $\tilde{T}$ is the normalized transmission coefficient, δ is the phase delay which represents phase modulation, and t can be used to predict analytically intensity transmittance which represents amplitude modulation.

ψ_A, ψ_P are the angles of the analyzer and the polarizer, respectively, (refer to Fig. 1a).

c is a constant represents the loss factor of TN-LC cell (which can be considered unity by normalizing the transmission or can be measured in similar manner to [5]).

f, g, h, and j are Jones parameters for TN-LC cell with edge effect taken in account (this effect arises when applying voltage to the cell):

$$f = \left[1 - \frac{\beta_{\text{center}}}{\alpha}\cot(\alpha)\sin(2\beta_{\text{edge}})\right]\frac{\alpha}{\gamma}\sin(\gamma)\sin(\alpha) + \cos(2\beta_{\text{edge}})\cos(\gamma)\cos(\alpha) \quad (4)$$

$$g = \left[\cos(2\beta_{\text{edge}}) + \frac{\gamma}{\beta_{\text{center}}}\cot(\gamma)\sin(2\beta_{\text{edge}})\right] \times \frac{\beta_{\text{center}}}{\gamma}\sin(\gamma)\cos(\theta_E + \theta_S) \quad (5)$$

$$h = -\left[1 - \frac{\beta_{\text{center}}}{\alpha}\tan(\alpha)\sin(2\beta_{\text{edge}})\right] \times \frac{\alpha}{\gamma}\sin(\gamma)\cos(\alpha) + \cos(2\beta_{\text{edge}})\cos(\gamma)\sin(\alpha) \quad (6)$$

$$j = \left[\cos(2\beta_{\text{edge}}) + \frac{\gamma}{\beta_{\text{center}}}\cot(\gamma)\sin(2\beta_{\text{edge}})\right] \times \frac{\beta_{\text{center}}}{\gamma}\sin(\gamma)\sin(\theta_E + \theta_S) \quad (7)$$

$$f^2 + g^2 + h^2 + j^2 = 1 \quad (8)$$

θ_S, θ_E are angles of the extraordinary axis of the liquid-crystal molecules at the entrance and exit surfaces of TN-LC cell, in respect.

α is the twist angle:

$$\alpha = \theta_E - \theta_S \quad (9)$$

γ is given by:

$$\gamma = \sqrt{\alpha^2 + \beta_{\text{center}}^2} \quad (10)$$

β, β_{center}, and β_{edge} are very important parameters which include wavelength and voltage dependency (and even temperature dependency which is out of our focus in this paper); β is the birefringence of the TN-LCD and it reaches its maximum value in the case of voltage absence:

$$\beta_{max} = \pi\frac{d(n_e - n_o)}{\lambda} = \pi\frac{d\Delta n_{\max}}{\lambda} \quad (11)$$

where d is the thickness of the cell (the liquid crystal part only). λ is the wavelength of the incident light in vacuum. n_e, n_o are extraordinary and normal refractive indices, respectively, and $\Delta n_{\max}$ is refractive indices difference ("max" subscript stands for Δn value when no voltage is present). From the first look at Eq. (11) one can deduce that $\beta_{\max}$ is changing linearly with $1/\lambda$ but that is not right experimentally [3,13] because $\Delta n_{\max}$ is changing with λ as well. We will return to this point after completing the definitions of β_{center}, β_{edge}.

When applying voltage greater than the threshold of TN-LC cell, edges effect appears [3] and the extraordinary refractive index changes [14]; in this case β will equal to:

$$\beta = \beta_{\text{center}} + 2\beta_{\text{edge}} \quad (12)$$

where β_{edge} is the birefringence at each edge area ("edge" is also referred as "surface"). β_{center} is the birefringence of the center area ("center" is also referred as "bulk") whose molecule's rotation is not constrained by edge effect;

$$\beta_{\text{edge}} = \pi\frac{d_{\text{edge}}\Delta n_{\max}}{\lambda} \quad (13)$$

where d_{edge} is the depth of the area affected by each edge.

$$\beta_{\text{center}} = \pi\frac{(d - 2d_{\text{edge}})\Delta n(V)}{\lambda} \quad (14)$$

where Δn(V) emphasizes the dependency of Δn on the applied voltage to each TN-LC cell.

Now let us take a look at the equations from a practical point of view, in the case of the absence of applied voltage β_{edge} will equal to zero. And if α and θ_s are known, we only need to know the value of $\beta_{\max}$ to predict amplitude and phase modulation for each