Theoretical approach of polymer stabilized blue phase beam steering

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Abstract—Nematic liquid crystal (LC)-based beam steering has been reported for wide applications. However, for conventional nematic LC beam steering the thickness is of several microns in order to have a wider deflection angle. The response time is relatively slow and the diffraction efficiency is low. In this work, novel beam steering based on polymer stabilized blue phase liquid crystal (PS-BPLC) has been designed and theoretically analyzed. This special mesophase of the chiral doped nematic LC has several advantageous characteristics, for example no need for alignment layers, microsecond response time and an isotropic voltage-off state. The results reveal control over phase retardation. The direction of the steered beam can be tuned by voltage. Depending on voltage configuration, either diffractive beam steering (0.5º deviation for 1st order) or a tunable continuous phase (tunable deviation of 0.002º) can be obtained. In the first case, the deflection angle could be tuned by stacks of samples. The second option has the same phase shift for the TE and TM modes so unpolarized light could be used.

Over the last decade, nematic liquid crystal (LC)-based phase modulators have been reported for wide applications. Some interesting proposals have produced different optical elements as tunable lenses, optical vortices, etc. One of the phase modulators with more practical applications is the LC beam steering. The spatial distributed phase shift produced in these kind of devices cause deviations in the light direction passing through them. These systems have demonstrated several advantages as light-weight, low-voltage and low cost manufacture. Moreover, complete tunability without any need of moving parts is one of the most important features. Some important applications are laser and free space communications [1-3]. To achieve this function, different proposals based on nematic LC have been made in recent years [4-6]. Despite this, for conventional nematic LC beam steering, the thickness is of several microns in order to have a wider deflection angle. The response time is relatively slow and the diffraction efficiency is low.

In this work, novel beam steering based on polymer stabilized blue phase liquid crystal (PS-BPLC) has been designed and theoretically analyzed. Polymer stabilized blue phase LC is a special mesophase of the chiral doped nematic LC with several advantageous characteristics. For example, the molecular structure gives it four important features: a microsecond response time (approximately ten times faster than NLC), optical isotropic voltage-off state due to the three-dimensional lattice structure, multi-domain voltage-on state structure and no need of alignment layers due to the self-assembly of these structures [7].

A novel structure having PS-BPLC and high resistivity layers is proposed. Earlier works have demonstrated the use of a high resistivity layer (modal control) for designing LC lenses [8] and microlenses [9], micro-axicon arrays [10], arrays of optical elements [11] and optical vortices [12]. The resistivity layer generates either a spherical or linear voltage distribution for certain values of the resistance and structural parameters. The proposed structure in this Letter can generate a linear phase profile, which is completely reconfigurable by voltage. There are two possible configurations with very different results. In one case, the device behaves like a diffractive blazed grating. In the second case, a tunable continuous phase is obtained. The fabrication cost is low, and simple (no need for alignment layers). Its application as beam steering would improve speed and simplify the fabrication process with respect to traditional proposals based on nematic LC.

The proposed device consists of two ITO coated substrates patterned with a special design and covered by a high resistivity layer. The electrode pattern consists of two striped ITO electrodes (Fig. 1 bottom). The substrates are arranged in such a manner that their electrodes are in orthogonal position with respect to each other. Several materials can be used as a high resistivity layer, for example thin films of ITO, Nickel, Titanium Oxide, or PEDOT. These materials have sheet resistances ranging from 0.1 to 10MΩ/sq. In the proposed structure, a sheet resistance of 0.1MΩ/sq has been considered (this value can only work for a theoretical device, the power consumption will be too high with this value). The applied voltage is a sine waveform with a frequency of 1kHz. The thickness of the PS-BPLC layer is 10μm. Liquid crystal

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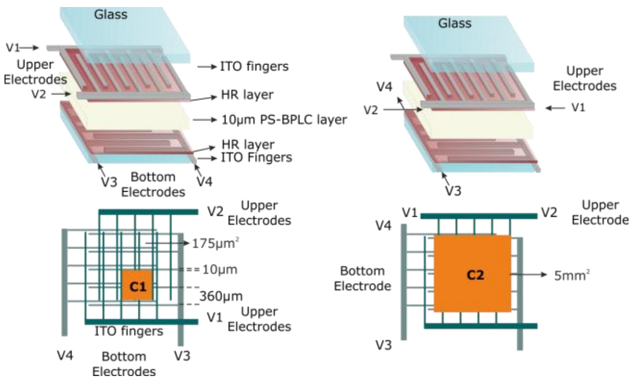

(a) (b)

Fig. 1. PS-BPLC beam steering structure. (a) Blazed grating, (b) continuous phase. The orange areas, C_1 and C_2 are the studied regions. Note: drawings are not to scale.

JC-BP01 was selected owing to its good performance. For simulation, the parameters of the PS-BPLC have been extracted from a characterized sample [13].

There are two different configurations, depending on how the voltage is applied. As can be seen in Fig. 1(a), if four different voltages are applied at each electrode, a diffractive blazed grating is obtained, henceforth this configuration is called case 1 (C_1). This results in a blazed grating with the grating period equal to the distance between finger electrodes (175μm). When only two electrodes (one in each substrate) are used [Fig. 1(b)] and the voltage is applied at the sides of these electrodes, a continuous tunable phase shift is obtained. In this case, the voltage is distributed linearly through the external ITO electrode that joins V_1 with V_2 and V_3 with V_4. This configuration is called case 2 (C_2).

The simulation program estimates the electrical field inside the structure solving the Gauss' law by using a finite element method (FEM) solver. Basically, each blue phase unit can be viewed as an optically isotropic material, and thus with an identical refractive index in each direction. When a strong electric field **E** is applied, birefringence is induced with the optical axis along the **E** vector. An isotropic initial state is considered for the permittivity. The induced birefringence, the ordinary and extraordinary refractive indices are calculated in each mesh point. Previous experimental results support this approximation [14]. Then, the induced birefringence (1), as well as the ordinary (2) and extraordinary (3) refractive indices, can be estimated by the extended Kerr model [15].

$$\Delta n = \Delta n_s \left(1 - \exp\left[-\left(\left|\overline{E}\right| / E_s\right)^2\right]\right), \tag{1}$$

$$n_o = n_i - \Delta n / 3, \tag{2}$$

$$n_e = n_i - 2\Delta n / 3, \tag{3}$$

where Δn_s is the saturated induced birefringence, E_s is the saturation field, n_i is the isotropic refractive index. The result is the induced birefringence (Δn_o) for a determined electric field ordinary (n_o) and extraordinary (n_e) refractive indices. It is important to note that most of the electric field distribution has a vertical orientation between substrates. This is produced by the high resistivity layers. The optical axis can be estimated from the electric field (4). By using these data, the effective refractive index is derived (5).

$$\theta = a\tan\frac{E_y}{\sqrt{E_x^2 + E_y^2}}, \quad \varphi = a\tan\frac{E_y}{E_z}, \tag{4}$$

$$n_{eff} = \frac{n_o n_e}{\left[n_e^2\left(\sin^2\theta\ \cos^2\varphi + \sin^2\theta\ \sin^2\varphi\right) + n_o^2\cos^2\theta\right]^{1/2}}, \tag{5}$$

With this information and adopting the extended Jones matrix, the related electro-optical properties are estimated.

The simulation indicates the amplitude of voltage required to generate specific phase profiles and beam steering directions. The parameters of liquid crystal JC-BP01 are Δn_s=0.154 and E_s=4.05V/m. Figure 2 shows the results of the phase shift produced in the C1 area. As shown, in Fig. 2(a) the applied voltages are V_1=V_2=V_3=0 and V_4=80V_{rms}, in Fig. 2(b) the applied voltages are V_1=V_3=40V_{rms}, V_2=80V_{rms} and V_4=0V_{rms}, in Fig. 2(c) the applied voltages are V_1=80V_{rms} and V_2=V_3=V_4=0, in Fig. 2(d) the applied voltages are V_1=80V_{rms} and V_2= V_3=40V_{rms}, V_4=0. As can be seen, with the changes of the applied voltage, the optical phase shift can be maintained at 2π, but the orientation changes 360º.

In case 2, the result is a continuous phase profile on the active area (C2). The results reveal a similar phase shift distribution for both TM and TE modes. This indicates that the device response is independent to the used polarization. The deflection angle can be tuned by changing the amplitude of the applied voltage in each

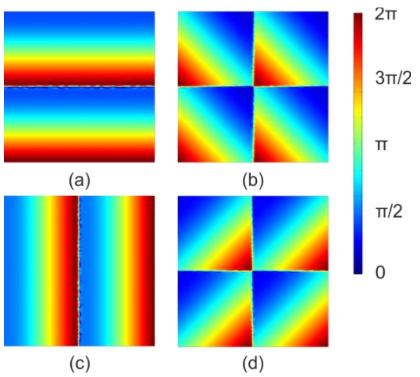

Fig. 2. Simulated results of the phase shift produced in case 1.

terminal. The main problem of this configuration is that only 2π phase shift is produced over the whole area, indicating a reduced angle in the beam steered rays. Despite this, it could be very interesting for some specific cases as long range communications based on laser sources.

The estimation of the deflection angle for both case 1 and case 2, is done by using (6) and (7), respectively.

$$\alpha_{1^{st}} = a\sin\left(\frac{\lambda}{\Lambda}\right) = 0.5^{o} \quad @1550\text{nm}, \tag{6}$$

$$\alpha_{case2} = a\sin\left(\frac{\lambda\Delta\Phi}{2\pi\Delta x}\right) = 0.002^{o} \quad @1550\text{nm}. \tag{7}$$

As commented above, in case 1 a blazed grating is obtained. The deflection angle for the first diffracted order is 0.5º. Tunable steering in the azimuth angle is obtained by changing the applied voltage. In Fig. 3, a diagram is shown with possible directions for the cases corresponding to Fig. 2. The deflection angle could be tunable by using stacks of samples [16]. In case 2, a tunable deviation of 0.002º is produced. This can be tuned so the direction and deflection angle would be tunable.

In summary, novel beam steering based on PS-BPLC was proposed and theoretically analyzed. The results reveal control over the phase retardation. The direction of the steered beam can be tuned by voltage. In some cases the deflection angle can be also tuned. In case 1, a diffractive beamsteerer is obtained (0.5º for 1st order). The second option has a continuous phase (tunable 0.002º). The phase retardation is the same for the TE and TM modes so

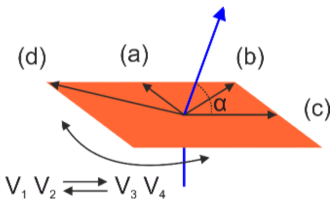

Fig. 3. Diagram of beam directions corresponding to the studied cases in Fig. 2.

unpolarized light could be used. Moreover, the proposed device has several advantages, for example no need for alignment layers, tunability, microsecond response time and an isotropic voltage-off state. It is important to note that in order to have a practical device, layers with more resistivity would be necessary in order to have reduced power consumption.

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