An Electrically Controlled Nematic Liquid Crystal Core Waveguide With a Low Switching Threshold

M. R. Shenoy, Mukesh Sharma, and Aloka Sinha

Abstract—**We demonstrate an electrically-controlled liquid crystal (LC) core waveguide, using 4-cyano-4′-pentylbiphenyl (5CB) nematic liquid crystal, fabricated on a glass substrate. A negative photoresist, AZ15nXT layer was coated on the glass substrate to realize a channel waveguide of core thickness 4.8 μm. The LC core waveguide exhibits strong differential attenuation for propagation of the TE- (horizontal) and TM-like (vertical) polarizations of light. The experimental results show that the output power suddenly drops down by several dB at an applied voltage of 1 V, for a waveguide of length 10 mm, due to the re-orientation of the LC molecules. The waveguide can be used as an optical switch, as well as an optical attenuator.**

Index Terms—**Electrooptic devices, liquid crystals, liquid crystal devices, optical switching devices.**

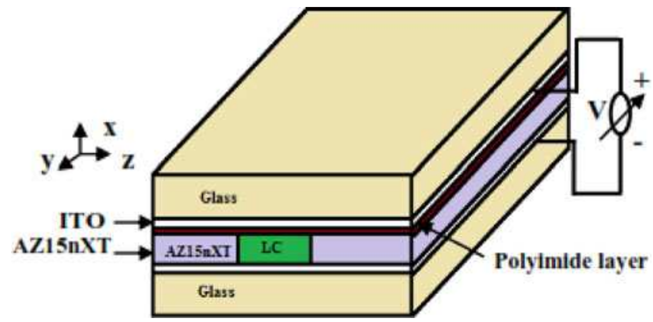

Fig. 1. Schematic of the fabricated LC core waveguide.

I. Introduction

LIQUID crystal (LC) optical waveguides have become increasingly important in integrated optics because liquid crystals can change their optical properties under the influence of a small applied voltage, as compared to conventional electro-optical materials, in the waveguide configuration [1], [2]. Several properties of LCs such as high birefringence, high transmission, large electrooptic effect, low driving power, and low power consumption also make them a promising material to fabricate integrated optical devices, like planar and channel waveguides [3]–[6], optical switches [7]–[13], attenuators [14], [15] and polarization controllers [16] that are useful in fiber optic communication systems [17]. Nematic liquid crystals have several advantages: they are inexpensive, have better mechanical properties, and easily regain their original alignment when the field is switched off. LC based optical switches do not need mechanical moving components, and therefore they have longer life, low operating voltages and less power consumption, compared to traditional electro-mechanical switches [18]. d'Alessandro *et al.* [5] demonstrated the first channel waveguide using E7 nematic liquid crystal in SiO_2–Si V-grooves. Donisi *et al.* [13] reported an integrated optical switch based on liquid crystal waveguide that required a threshold voltage of 2 V for switching ON the waveguide. However, the waveguide exhibits higher coupling losses. Maksimochkin *et al.* [3], [4] reported electrically-controlled switching of light beams in the plane of liquid crystal layer through total internal reflection at a threshold voltage of 4 V. Wang *et al.* [19] reported electrically tunable liquid-crystal-core-channel waveguide in semicircular grooves on a glass substrate with a threshold voltage of 4 V. These structures were complex in shape and their fabrication process was expensive; also, waveguidance in the liquid crystal required high voltages, and showed lower switching response in terms of change in light intensity. In this paper, we present a simple electrically-controlled LC core waveguide, fabricated on a glass substrate, with a low threshold voltage of 1 V_{pp}. The nematic LC 5CB (4-Cyano-4′-pentylbiphenyl), from Sigma-Aldrich, USA, is used as the core layer of the waveguide, and the negative photoresist AZ15nXT (from Microchemicals, Germany) is used, instead of spacers, to obtain the required thickness of the waveguide. The design, fabrication process, and the effect of applied electric field on light propagation are presented.

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II. Device Design and Fabrication

The proposed device structure consists of a high-index guiding LC layer sandwiched between two glass plates of lower refractive index. Schematic diagram of the proposed waveguide device is shown in Fig. 1. The nematic liquid crystal 5CB is used as the waveguide core material and indium tin oxide (ITO) coated glass plates, which is made of Corning Gorilla glass, are used as upper and lower cladding layers. The ordinary (n_o) and extraordinary (n_e) refractive indices of the LC are 1.53 and 1.71 (at the wavelength of 633 nm), respectively [20]; the upper and lower ITO coated glass plates have a refractive index of 1.51. The ITO layer is a conducting layer which is used as the electrodes to apply electric field to the LC core waveguide. The refractive index and the thickness of the ITO layer are 1.858 [21] at 633 and 150 nm, respectively. The refractive index of the negative photoresist AZ15nXT is 1.60 at 633 nm.

The fabricated waveguide structure is a rectangular core waveguide with a guiding layer of thickness 4.8 μm, width 2 mm and length 10 mm. For fabrication of the rectangular core

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region, the negative photoresist AZ15nXT is first spin-coated on an ITO-coated glass substrate, which is followed by UV exposure, and then developed to realize the rectangular channel. The photoresist layer determines the thickness of the waveguide. A polyimide layer, which is used as an alignment layer to align the LC molecules in a certain orientation, is spin-coated over another ITO-coated glass substrate and is rubbed along the direction of the channel for homogeneous alignment of the liquid crystal molecules. It is then placed on the first glass plate with the photoresist layer (with the fabricated channel in it). The channel is then filled with the liquid crystal 5CB. The 5CB LC is infiltrated into the LC core waveguide by the capillary force. During the LC-infiltration procedure, the substrate was placed on a hot plate, which is maintained at 50 °C; at this temperature, the 5CB is in its isotropic phase, with a much lower viscosity. A small drop of the LC was then placed at the edge of the glass plate with the help of a needle such that the LC fills the core region in the required alignment direction by the capillary force. After filling, the sample was cooled down to room temperature. The top and bottom ITO-coated glass substrates are used as electrodes to apply electric field to the waveguiding LC layer. The voltage applied to the electrodes is in the transverse direction to the aligned LC molecules. Since the width of the waveguide is much larger than the thickness, the structure essentially behaves like a planar waveguide. The number of modes supported by the waveguide depends on the V-parameter of the waveguide. The V-parameter of a symmetric planar waveguide is given by [22]

$$V = \frac{2\pi d}{\lambda}(n_1^2 - n_2^2)^{1/2} \tag{1}$$

where d is the thickness of the waveguide, λ is the operating wavelength, n_1 and n_2 are the refractive indices of the LC core and the (glass plate) cladding, respectively. Nematic LCs are uniaxial crystals and hence they exhibit two refractive indices, $n_x = n_y = n_o$ and $n_z = n_e$. Due to their shape and polarization anisotropy, LC molecules exhibit different properties for light traveling with the electric field parallel and perpendicular to the director. The optical anisotropy is characterized by $\Delta n = n_e - n_o$, and is called as the "birefringence." Light with electric field polarization perpendicular to the director sees the ordinary refractive index (n_o), and light with electric field polarization parallel to the director of molecules sees extraordinary refractive index (n_e). The 5CB nematic liquid crystals have positive birefringence property (i.e. $\Delta n > 0$; $n_e > n_o$); the molecules tend to align along the direction of the applied electric field.

The threshold voltage is given by [1]

$$V_{th} = \pi\sqrt{K_{11}/\varepsilon_0\Delta\varepsilon} \tag{2}$$

where "K_{11}" is the elastic constant for deformation, "$\Delta\varepsilon$" is the dimensionless dielectric anisotropy parameter and "ε_0" is the free space dielectric permittivity. The parameter used to calculate the threshold voltage for 5CB LC are [1] $K_{11} = 9.5\,\text{pN}$, $\Delta\varepsilon = 11$ and $\varepsilon_0 = 8.85\,\text{pF/m}$. From Eq. (2), the threshold voltage is calculated as 0.98 V. In the LC core waveguide, the number of propagating mode fields and their distribution will change due to change in the refractive index. This is because the V-parameter of the waveguide changes with the change in refractive index. The V-parameter values are calculated using (1) as $V \approx 3.74\,\pi$ for $n_1 = n_o$ and $V \approx 12.17\,\pi$ for $n_1 = n_e$, the implications of which are discussed in Section IV.

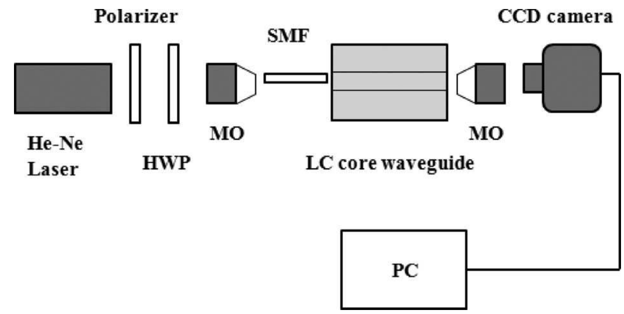

Fig. 2. Schematic diagram of the experimental setup—SMF: single mode fiber; HWP: Half-wave plate; MO: Microscope objective (20×).

III. Experiment

A schematic of the experimental setup is shown in Fig. 2. In the experiment, a He–Ne laser is used as the light source at the wavelength of 632.8 nm; a single mode fiber (SMF SM600, $\text{NA} = 0.13$, 4.3/125 μm) of length 12 cm is used to couple light into the LC core waveguide by the butt-coupling technique. In the experiment, we placed the SMF in a straight position on a V-groove so that the linear state of polarization is least affected. The input light polarization is controlled by a half-wave plate (HWP) and a polarizer. The half-wave plate is used to convert the input vertical polarization into horizontal polarization when required. The output of the waveguide was collected by a 20× microscope objective (MO), and imaged on to a CCD Camera (Lumenera Infinity 2.0, 1616 × 1216 pixels) which is interfaced with a computer for mode field analysis.

To measure the output power, the CCD camera was replaced by a photodetector head, which is connected to an optical power meter. In order to observe the light propagation through the waveguide, the CCD camera was setup above the LC core waveguide to image the top surface. A variable square voltage signal of frequency 1 kHz is applied across the upper and lower electrodes of the waveguide to study the transmission characteristics of the LC core waveguide.

IV. Results and Discussion

A. Light Guidance Inside the LC Core Waveguide

In the first experiment, we have studied the light guidance inside the LC core waveguide and the effect of an applied electric field. Initially, light is guided inside the LC core waveguide because n_o of the core layer is more than the refractive index of the top and bottom glass plates. In this case, the output power of the waveguide is maximum, since the guided mode of the optical fiber excites the TE/TM modes of the LC core waveguide. Fig. 3 shows a top view of light propagation inside the LC core waveguide, as captured by the CCD camera. At the interface of single mode fiber and the LC core waveguide, and near the

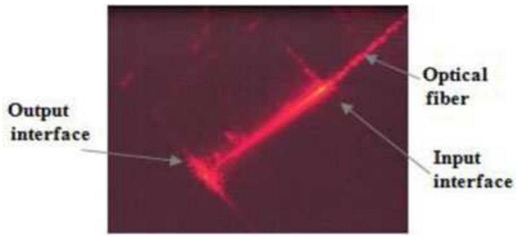

Fig. 3. Light guidance inside the LC core waveguide.

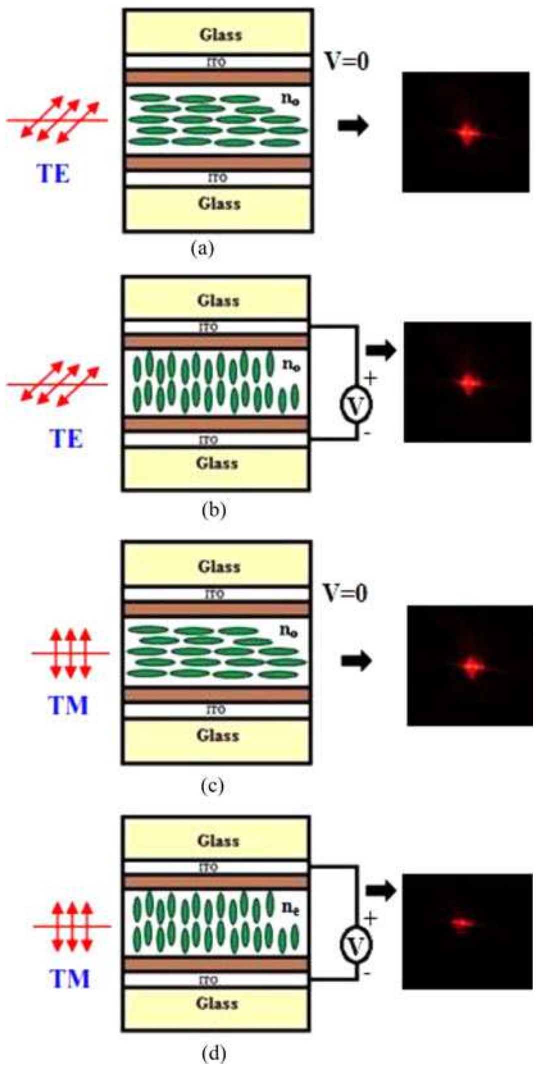

Fig. 4. Transmission of light (a) when input polarization is horizontal and $V = 0\,\mathrm{V}$, and (b) when $V = 1\,\mathrm{V_{pp}}$; the output intensity does not change with the applied voltage; (c) when input polarization is vertical with $V = 0\,\mathrm{V}$, and (d) with $V = 1\,\mathrm{V_{pp}}$; output intensity is reduced in the presence of the applied voltage.

output end, scattering of light can be observed. The scattering losses can be minimized by using appropriately polished input and output faces of the waveguide.

In the presence of the electric field, the LC molecules re-orient in the (vertical) direction of the field (see Fig. 4). The two orthogonal polarization components of the light see two different refractive indices. The vertically polarized input light

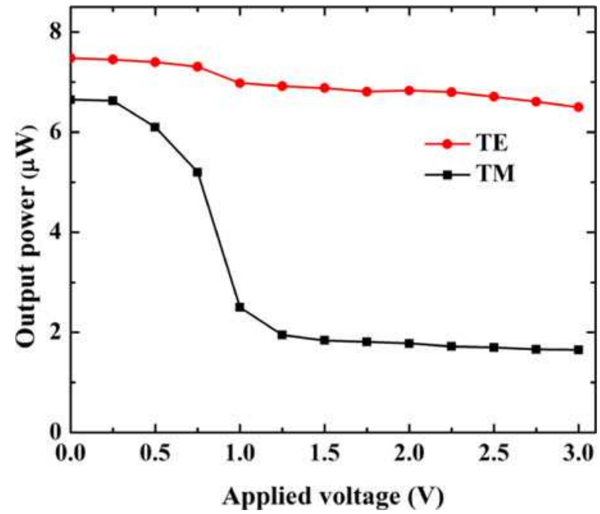

Fig. 5. Effect of input state of polarization on the output power of the LC core waveguide.

would now see the extraordinary refractive index (n_e), and the resultant V-parameter increases to 12.17π (from $V = 3.74\,\pi$). The LC core waveguide then supports more TE/TM modes for vertically polarized light, while the horizontally polarized light would continue to see the ordinary refractive index, and therefore would support the same number of modes as before (application of the field).

B. LC Core Waveguide as an Optical Switch

In the second experiment, the optical switching properties of the LC core waveguide, due to an applied electric field, are studied. Light from a linearly polarized laser is coupled through a small length of single mode fiber into the LC core waveguide. Fig. 4(a)–(d) illustrates the behavior of LC molecules and the output intensity pattern in the presence of applied electric field for linearly polarized input light.

When the voltage is applied across the electrodes, the LC molecules re-orient in the direction of the applied electric filed. In the first case, as shown in Fig. 4(a) and (b), the input polarization of light is in the horizontal direction (TE polarization). In this case, light continues to see the ordinary refractive index (n_o) and the output intensity pattern shows hardly any variation with the applied field, as shown in Fig. 4(b).

When the input light is in (vertical) TM polarization, the light coupled from the fiber excites TM modes of the LC core waveguide, and with the applied filed, the input light now sees the extraordinary refractive index of the liquid crystal (see Fig. 4(c) and (d)). The LC core waveguide is now converted from a few moded waveguide into a highly multimoded waveguide due to the increase in the V-parameter. The output light intensity is reduced significantly for an applied voltage of $V = 1\,\mathrm{V_{pp}}$ as shown in Fig. 4(d). This threshold voltage compares very well with the theoretical calculated value as discussed in Section II.

The measured output power variations for both TE and TM polarizations with applied voltage are shown in Fig. 5. As can be seen from the figure, there is very little change in the output

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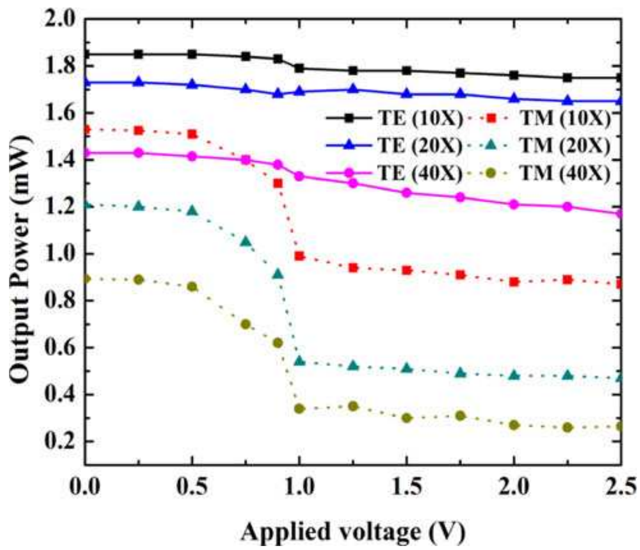

Fig. 6. Output power variation with applied voltage when the input power is coupled with 10× MO, 20× MO, and 40× MO.

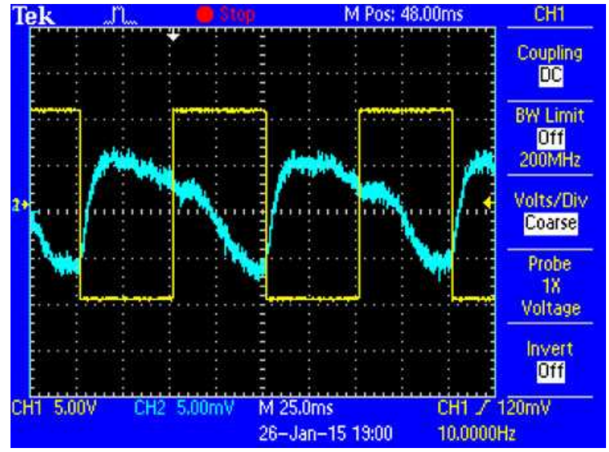

Fig. 7. Time response of the LC core waveguide optical switch.

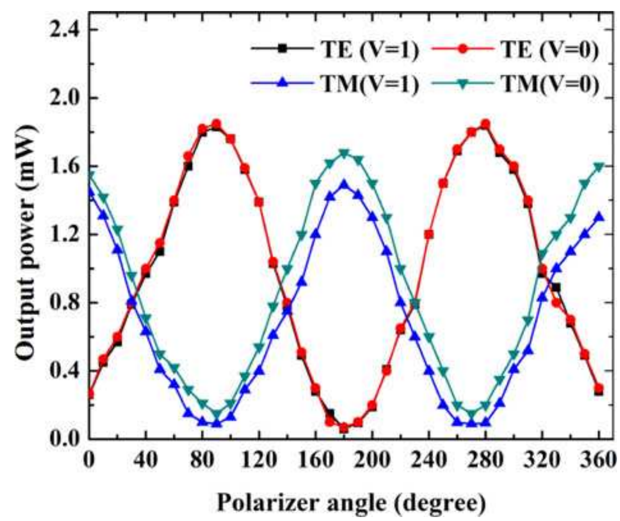

Fig. 8. Output power variation with the polarizer angle (at the output interface) for TE and TM polarizations for applied voltage $V = 0$ and $V = 1\,\mathrm{V_{pp}}$.

power for the TE polarization while the output power drops sharply when the applied voltage exceeds 1 $\mathrm{V_{pp}}$ for the TM polarization.

The coupled power in the TM polarization is distributed among the various modes, and the output power drops significantly at the threshold voltage. This is primarily due to higher absorption coefficient of the TM modes in the metal-clad waveguide [23], [24]. The absorption losses in the ITO layer depend on the spatial extent of the propagating modes. Also, the losses for the higher order modes are much greater than those for the lower order modes. Thus, effectively, the loss for TM polarization is greater than the loss associated with the TE polarization. Due to both these effects, the output power of the LC core waveguide drops down sharply for TM polarization at the threshold voltage. The measured extinction ratio between TE and TM polarizations is >7 dB for a waveguide of length 10 mm. For an applied voltage $\geq 1\,\mathrm{V_{pp}}$, the power in the TM polarization drops by ∼5 dB. Therefore, the LC core waveguide works as an electrically-controlled optical switch/ attenuator for TM polarization of the light with a threshold voltage of 1 $\mathrm{V_{pp}}$. The insertion loss for the LC core waveguide is estimated as $10\log(P_{\rm out}/P_{\rm in}) = -17.93\,\mathrm{dB}$; where "$P_{\rm in}$" is the output power at the end of the SMF, and "$P_{\rm out}$" is the power decoupled by the MO at the LC core waveguide end. The insertion loss would be the sum of the coupling loss and the propagation loss.

Fig. 6 shows the variation of output power with applied voltage for direct excitation (without the SMF) using three different microscope objectives (MOs) of numerical apertures 0.25 (10×), 0.45 (20×) and 0.65 (40×), respectively. In all the cases, the attenuation of the TM modes is more than TE modes, with no applied voltage. In the case of excitation by 40× MO, the fractional power coupled into the higher order modes is larger due to a higher numerical aperture. Higher order modes are more lossy in metal-clad waveguides (see Section IV-C). In the case of coupling with the 10× MO, the difference between the output power of TE and TM modes, with no applied voltage, is less in comparison to excitation by 20× and 40× objectives. This is due to excitation of lower order modes with low numerical aperture 10× MO, as shown in Fig. 6. In all cases, when the voltage is applied, the output power in the TM polarization is reduced due to the increased V-parameter, as explained above.

The response time for the LC core waveguide optical switch has been experimentally measured. The rise and fall time for the switch are 10 and 28 ms, respectively. Fig. 7 shows the time response of the LC core waveguide optical switch when an input variable square voltage signal of frequency 10 Hz is applied. The calculated fall time using parameters corresponding to 5CB [25] turns out to be 30.7 ms, which again compares well with the measured value. It is also known that the rise times are much shorter than the fall time [25].

Fig. 8 shows the output power variation with angle of the pass axis of the polarizer for input TE and TM polarizations (using SMF) with $V = 0$ and $V = 1\,\mathrm{V_{pp}}$. In the experiment, the polarizer was placed at the output of the LC core waveguide.

In the case of TE polarization, the change in output power is negligible with change in the applied voltage (from $V = 0$ to $V = 1\,\mathrm{V_{pp}}$) whereas in the case of TM polarization, the output power is reduced when the applied voltage is changed from $V = 0$ to $V = 1\,\mathrm{V_{pp}}$. The sinusoidal variation of power with the angle of the polarizer also shows that the LC core waveguide maintains the input state of polarization at the output.

C. Estimation of the Attenuation Coefficients

In this section, the attenuation due to the ITO coated substrate glass plates is estimated. The ITO (metallic) layer is lossy at the optical wavelengths, and therefore the guided waves are attenuated when they interact with the ITO layer. In waveguides with a metal cladding, the attenuation of TM modes is greater than TE modes, and the attenuation coefficients of the higher order modes are larger (as compared to those for lower order modes) [26], [27]. For most metals, dielectric constant ε_r is negative and $|\varepsilon_r|$ is larger than ε_i at optical frequencies, where ε_r and ε_i are the real and imaginary parts of the dielectric constant of the metal. By considering $|\varepsilon_r| \gg \varepsilon_i$, the attenuation coefficients for the TE and TM modes are approximately given by [24]:

$$\alpha_{\mathrm{TE}m} \approx \frac{(m+1)^2\pi^2}{n_f k^2 d^3}\left(\frac{\varepsilon_i}{\left(n_f^2-\varepsilon_r\right)^{3/2}}\right) \tag{3}$$

$$\alpha_{\mathrm{TM}m} \approx \frac{(m+1)^2\pi^2}{n_f k^2 d^3}\left(\frac{\varepsilon_i\left(2n_f^2-\varepsilon_r\right)}{n_f^2\left(n_f^2-\varepsilon_r\right)^{3/2}}\right) \tag{4}$$

where "*m*" is the mode number, "n_{f}" is the refractive index of the LC film, and "*d*" is the thickness of the LC film. Using the numerical values $\varepsilon_r = -3.46$ and $\varepsilon_i = 0.22$ (for the ITO layer) at 633 nm [28], the calculated attenuation coefficient for the TE and TM modes (from (3) and (4)) are given by

$$\begin{aligned}\alpha_{\mathrm{TE}m} &= 0.093\,(m+1)^2(\mathrm{cm}^{-1}),\\ \alpha_{\mathrm{TM}m} &= 0.324\,(m+1)^2\ (\mathrm{cm}^{-1}).\end{aligned} \tag{5}$$

In this case, the attenuation coefficient of TM modes is $\sim$3.5 times greater than that for the TE modes, which is consistent with the measured differential output between TE and TM modes, with no applied voltage (see Fig. 5).

With input TM polarization, when the applied voltage is $\geq 1\,\mathrm{V_{pp}}$, the LC molecules re-orient in the vertical direction (see Fig. 4(d)) and the V-parameter of the waveguide increases. This results in the propagation of more number of TM modes, and since higher order TM modes (i.e., for higher values of m) are more lossy, the overall loss in the waveguide increases, resulting in a drop in the output power as seen in Fig. 5. Further, both TE and TM higher order modes (i.e., for larger values of "m") are more lossy, and therefore the output power is lower for excitation by an MO of higher NA even when there is no applied voltage, as seen in Fig. 6. The fabricated device in this work is a multimode LC core waveguide. With 5CB as the cladding layer, by reducing the width of the waveguide using lithography, it would also be possible to fabricate a single mode LC core waveguide for the extraordinary polarization. In this case, the performance of the optical switch is expected to improve in terms of extinction ratio. Further, optimization of the thickness of the AZ15nXT photoresist layer and the ITO layer could also lead to a better extraordinary ratio.

V. Conclusion

A simple fabrication process to realize nematic LC core waveguide, on ITO coated glass substrate has been reported. The conventional spacers are replaced by a negative photoresist (AZ15nXT) layer whose thickness can be controlled to realize the designed waveguide parameter. It is experimentally shown that with the application of 1 $\mathrm{V_{pp,}}$ the refractive index distribution of the LC core waveguide changes due to the reorientation of LC molecules. This results in a change in the V-parameter of the waveguide, and the waveguide supports more number of modes. The vertical (TM) polarization suffers higher attenuation as compared to the horizontal (TE) polarization on propagation through the LC core waveguide. Therefore, this waveguide structure can be used as an electrically-controlled optical switch, as well as an optical attenuator. The proposed LC core waveguide has advantages in terms of simple fabrication process at low cost, and a low switching voltage of 1 $\mathrm{V_{pp}}$.

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