Wave guiding with liquid crystals

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ABSTRACT

Optical waveguides are widely used in the telecom industry for long distance data transport. Glass fibers are designed to have minimal losses. Different functionalities have been integrated in waveguides, such as wavelength filtering, amplitude modulation and routing. Liquid crystals are promising, because their optical properties can be modified by applying a small voltage or by illumination with light. The variation in optical properties can be exploited in different kinds of waveguide systems.

It is possible to generate a wave guide in bulk liquid crystal by modulating the director orientation in an appropriate pattern. Some guided modes in such pure liquid crystals are discussed. Because the liquid crystals are anisotropic, the modes have some unusual properties. The influence of light can lead to director reorientation and modify the waveguiding properties. This optical non-linearity determines largely the light propagation. In hybrid waveguides, liquid crystal are used in combination with a material with higher (in the core) or lower (in the cladding) refractive index. Silicon on insulator waveguides are convenient components to study the tuning possibilities in combination with liquid crystals.

Keywords: liquid crystals, waveguide, non-linearity, solitons

1. INTRODUCTION

In direct-view liquid crystal displays, the pixels dimension is in the order of $100 \times 100 \mu\text{m}^2$ and the liquid crystal layer does not influence the wave vector of the incident light, only the polarization state. There are several ways to obtain fast lateral variations in the incident light by using liquid crystals. One way is to realize smaller pixel sizes, in the order of only a few μm . Switchable one-dimensional optical phased arrays, based on liquid crystal between glass substrates, can be used for beam steering. Devices with two-dimensional arrays of pixels are usually based on the liquid crystal on silicon (LCOS) technology. With such spatial light modulators (SLM) in combination with laser light, Fourier images or beam steering in two dimensions can be realized [1,2,3]. When ferro-electric materials are used the switching times can be in the order of μs . Another approach is to implement the lateral variation in the structure of the substrate, in such a way that the thickness of the liquid crystal layer changes with the position. With this approach switchable Fresnel lenses can be produced.

In the above examples, the light is incident from above or below a liquid crystal layer, and we call this transversal propagation [4]. In the following, we will focus on devices in which the light travels parallel with the liquid crystal layer, so called lateral light propagation. The interaction between the light and the liquid crystal occurs over a larger distance and many architectures become possible.

2. 1D WAVEGUIDES IN LIQUID CRYSTAL

2.1 Wave equation and solution

In this section we will develop the theory for anisotropic one-dimensional slab waveguides. This involves solving the equations of Maxwell (time dependency $e^{j\omega t}$) for a dielectric tensor which depends only on the x-coordinate:

$$\begin{aligned}\nabla \times \vec{E} &= -j\omega\mu_0\vec{H} \\ \nabla \times \vec{H} &= j\omega\epsilon_0\vec{\epsilon} \cdot \vec{E}\end{aligned}\tag{1}$$

We are looking for solutions of these equations that are propagating in the z-direction and are independent of the y-coordinate:

$$\begin{aligned}\bar{E}(x, z) &= \bar{e}(x) \exp(-jk_0 n_{\text{eff}} z) \\ \bar{H}(x, z) &= \bar{h}(x) \exp(-jk_0 n_{\text{eff}} z)\end{aligned}\quad (2)$$

With k_0 the wave vector in vacuum and n_{eff} the effective refractive index for the solution. Substituting these solutions in the equation of Maxwell yields:

$$\begin{aligned}jk_0 n_{\text{eff}} e_y &= -j\omega\mu_0 h_x \\ -jk_0 n_{\text{eff}} e_x - \frac{\partial e_z}{\partial x} &= -j\omega\mu_0 h_y \\ \frac{\partial e_y}{\partial x} &= -j\omega\mu_0 h_z \\ jk_0 n_{\text{eff}} h_y &= j\omega\epsilon_0 (\epsilon_{xx} e_x + \epsilon_{xy} e_y + \epsilon_{xz} e_z) \\ -jk_0 n_{\text{eff}} h_x - \frac{\partial h_z}{\partial x} &= j\omega\epsilon_0 (\epsilon_{xy} e_x + \epsilon_{yy} e_y + \epsilon_{yz} e_z) \\ \frac{\partial h_y}{\partial x} &= j\omega\epsilon_0 (\epsilon_{xz} e_x + \epsilon_{yz} e_y + \epsilon_{zz} e_z)\end{aligned}\quad (3)$$

Now we make another assumption about the anisotropic material in order to separate the set of 6 equations into two sets of 3 equations. We will only consider anisotropic materials which have mirror symmetry with respect to the xz plane, leading to $\epsilon_{xy} = \epsilon_{yz} = 0$. In this case the equations containing e_x, h_y, e_z describe the so-called TM polarization:

$$\begin{aligned}-jk_0 n_{\text{eff}} e_x - \frac{\partial e_z}{\partial x} &= -j\omega\mu_0 h_y \\ jk_0 n_{\text{eff}} h_y &= j\omega\epsilon_0 (\epsilon_{xx} e_x + \epsilon_{xz} e_z) \\ \frac{\partial h_y}{\partial x} &= j\omega\epsilon_0 (\epsilon_{xz} e_x + \epsilon_{zz} e_z)\end{aligned}\quad (4)$$

Elimination of the electric field vectors leads to a second order differential equation for the magnetic field in the y-direction, in which the components of the dielectric tensor are functions of the x-coordinate [4]:

$$\epsilon_{xx} \frac{\partial^2 h_y}{\partial x^2} - 2jk_0 n_{\text{eff}} \epsilon_{xz} \frac{\partial h_y}{\partial x} + k_0^2 \left[(\epsilon_{xx} \epsilon_{zz} - \epsilon_{xz}^2) - n_{\text{eff}}^2 \epsilon_{zz} \right] h_y = 0 \quad (5)$$

Finding solutions of this differential equation is not evident. In this paper we will use a matrix method and assume a piecewise constant dielectric tensor. If the tensor is constant in an interval of the coordinate x, the solution of the differential equation can be written as:

$$h_y(x) = A \exp(-jk_0 n_a x) + B \exp(-jk_0 n_b x) \quad (6)$$

Substituting this solution into the differential equations yields two different refractive indices:

$$n_{a,b} = -n_{eff} \frac{\epsilon_{xz}}{\epsilon_{xx}} \pm \sqrt{\epsilon_{xx} - n_{eff}^2} \frac{\sqrt{\epsilon_{xx}\epsilon_{zz} - \epsilon_{xz}^2}}{\epsilon_{xx}} \quad \text{for } \epsilon_{xx} \geq n_{eff}^2$$

$$n_{a,b} = -n_{eff} \frac{\epsilon_{xz}}{\epsilon_{xx}} \mp j \sqrt{n_{eff}^2 - \epsilon_{xx}} \frac{\sqrt{\epsilon_{xx}\epsilon_{zz} - \epsilon_{xz}^2}}{\epsilon_{xx}} \quad \text{for } \epsilon_{xx} \leq n_{eff}^2$$
(7)

As long as $\epsilon_{xx} > n_{eff}^2$ the two refractive indices are real and the resulting solution is a plane wave with propagation vector in the xz plane (with $n_a > n_b$):

$$\bar{H}(x, z) = A \exp[-jk_0(n_{eff}z + n_ax)] + B \exp[-jk_0(n_{eff}z + n_bx)]$$
(8)

The propagation vector $\bar{k}_{a,b}$ makes an angle $\zeta_{a,b}$ with the z-axis, as can be seen in figure 1:

$$\tan \zeta_{a,b} = \frac{n_{a,b}}{n_{eff}},$$
(9)

and the vector of Poynting makes an angle $\alpha_{a,b}$ with the z-axis:

$$\tan \alpha_{a,b} = \frac{n_{a,b}\epsilon_{xx} + n_{eff}\epsilon_{xz}}{n_{eff}\epsilon_{zz} + n_{a,b}\epsilon_{xz}}$$
(10)

Fig. 1. Illustration of the orientation of the director (tilt angle θ), propagation vector with angle ζ (negative in this figure), and Poynting vector with angle α with the z-axis.

In the case $\epsilon_{xx} < n_{eff}^2$ the refractive indices have an imaginary part and the resulting solutions are a so-called evanescent wave, with the A-wave exponentially decreasing in the +z direction (and B increasing in the -z direction).

When liquid crystals are used, the equations can be formulated by using the ordinary and extra-ordinary refractive indices. For a liquid crystal layer with the director making an angle θ with the z-axis (tilt angle) we have:

$$\begin{aligned} \epsilon_{xx} &= n_o^2 \cos^2 \theta + n_e^2 \sin^2 \theta \\ \epsilon_{xz} &= (n_e^2 - n_o^2) \sin \theta \cos \theta \\ \epsilon_{zz} &= n_o^2 \sin^2 \theta + n_e^2 \cos^2 \theta \end{aligned}$$
(11)

The angle of the propagation vector with the z-axis $\zeta_{a,b}$ can also be found from its projection on the z-axis, equal to $k_0 n_{eff}$:

$$\frac{\cos^2(\theta - \zeta_{a,b})}{n_o^2} + \frac{\sin^2(\theta - \zeta_{a,b})}{n_e^2} = \frac{\cos^2 \zeta_{a,b}}{n_{eff}^2}$$
(12)

2.2 Matrix calculation method

The relation between the TM fields in two neighboring slabs is determined by the boundary conditions. The tangential components of the electric and magnetic fields h_y , e_z must be continuous at the border between two slabs. Immediately this implies that the effective refractive index should be the same in both layers. For e_z this leads to the continuity of:

$$\frac{\epsilon_{xx} \frac{\partial h_y}{\partial x} - jk_0 n_{eff} \epsilon_{xz} h_y}{\epsilon_{xx} \epsilon_{zz} - \epsilon_{xz}^2} \quad (13)$$

With the solution in a certain layer i written as:

$$h_{yi}(x) = A_i \exp(-jk_0 n_{ai}(x - x_i)) + B_i \exp(-jk_0 n_{bi}(x - x_i)), \quad (14)$$

with x_i the coordinate of the interface with layer $i-1$. Expressing the continuity of the two expressions leads to a relation between the coefficients of adjacent layers. For the coefficient A in layer i we find for example:

$$A_i = \left(n_{bi} \epsilon_{xxi} + n_{eff} \epsilon_{xzi} - \frac{\epsilon_{xxi} \epsilon_{zzi} - \epsilon_{xzi}^2}{\epsilon_{xxi-1} \epsilon_{zzi-1} - \epsilon_{xzi-1}^2} (n_{ai-1} \epsilon_{xxi-1} + n_{eff} \epsilon_{xzi-1}) \right) \frac{\exp(-jk_0 n_{ai-1}(x_i - x_{i-1}))}{(n_{bi} - n_{ai}) \epsilon_{xxi}} A_{i-1} \\ + \left(n_{bi} \epsilon_{xxi} + n_{eff} \epsilon_{xzi} - \frac{\epsilon_{xxi} \epsilon_{zzi} - \epsilon_{xzi}^2}{\epsilon_{xxi-1} \epsilon_{zzi-1} - \epsilon_{xzi-1}^2} (n_{bi-1} \epsilon_{xxi-1} + n_{eff} \epsilon_{xzi-1}) \right) \frac{\exp(-jk_0 n_{bi-1}(x_i - x_{i-1}))}{(n_{bi} - n_{ai}) \epsilon_{xxi}} B_{i-1} \quad (15)$$

And:

$$B_i = \left(n_{ai} \epsilon_{xxi} + n_{eff} \epsilon_{xzi} - \frac{\epsilon_{xxi} \epsilon_{zzi} - \epsilon_{xzi}^2}{\epsilon_{xxi-1} \epsilon_{zzi-1} - \epsilon_{xzi-1}^2} (n_{ai-1} \epsilon_{xxi-1} + n_{eff} \epsilon_{xzi-1}) \right) \frac{\exp(-jk_0 n_{ai-1}(x_i - x_{i-1}))}{(n_{ai} - n_{bi}) \epsilon_{xxi}} A_{i-1} \\ + \left(n_{ai} \epsilon_{xxi} + n_{eff} \epsilon_{xzi} - \frac{\epsilon_{xxi} \epsilon_{zzi} - \epsilon_{xzi}^2}{\epsilon_{xxi-1} \epsilon_{zzi-1} - \epsilon_{xzi-1}^2} (n_{bi-1} \epsilon_{xxi-1} + n_{eff} \epsilon_{xzi-1}) \right) \frac{\exp(-jk_0 n_{bi-1}(x_i - x_{i-1}))}{(n_{ai} - n_{bi}) \epsilon_{xxi}} B_{i-1} \quad (16)$$

Or in short notation:

$$\begin{pmatrix} A_i \\ B_i \end{pmatrix} = \begin{pmatrix} M_{i1,1} & M_{i1,2} \\ M_{i2,1} & M_{i2,2} \end{pmatrix} \begin{pmatrix} A_{i-1} \\ B_{i-1} \end{pmatrix} \quad (17)$$

For a stack with many layers, the amplitudes A and B in the last layer can be expressed as a function of the amplitudes in the first layer, by multiplication with all the matrices of the layers in between:

$$\begin{pmatrix} A_{i\max} \\ B_{i\max} \end{pmatrix} = \begin{pmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2} \end{pmatrix} \begin{pmatrix} A_{i\min} \\ B_{i\min} \end{pmatrix} \quad (18)$$

2.3 Finding the modes in a waveguide

A mode is a solution which is bound to the waveguide, which means that the waves in the first and last layer should be exponentially damped in the direction away from the stack. This implies that $\epsilon_{xxi\min}, \epsilon_{xxi\max} < n_{eff}^2$ and that only the damped exponential is different from zero:

$$A_{i\min} = B_{i\max} = 0 \quad (19)$$

This means that a mode is obtained when the coefficient $M_{2,2}$ of matrix for the entire stack is equal to zero. As the matrix M depends on the effective refractive index n_{eff} , the condition $M_{2,2} = 0$ determines the existence of a mode. The number of modes in a waveguide increases with the thickness of the stack and the contrast in the refractive indices. Each mode has its effective refractive index n_{eff} .

2.4 Homogeneous LC slab waveguide

As an example, we consider a homogeneous slab waveguide between two glass plates. For the examples presented in this paper we use data listed in Table 1.

Table 1. Important parameters used in the calculations (the liquid crystal used is E7).

n_o	1.5038
n_e	1.6954
n_s	1.516
K	$12 \cdot 10^{-12} \text{ N}$
ϵ_o	5.1
ϵ_e	19.6
λ	$0.98 \mu\text{m}$

Fig. 2 (left) gives the relation between the thickness of the slab and the effective refractive index of the modes for a given tilt angle (45°). The second graph shows the relation between the liquid crystal tilt angle and the effective refractive index for a mode for a given slab thickness of $2 \mu\text{m}$.

The field H_y at a given time can be calculated as a function of the z and x coordinates. This is illustrated in Fig. 3 for the modes TM0 and TM1. Note that the wave fronts are not perpendicular to the propagation direction (the z -direction) of the mode. This is due to the anisotropy of the liquid crystal. When the liquid crystal has a positive tilt angle (in this case 45°), the wave fronts are typically directed downward.

Fig. 2. Calculated modes (TM0 and TM1) in a waveguide as a function of the thickness d and the effective index, for a slab liquid crystal with 45° mid-plane tilt (left). Calculated modes (TM0, TM1 and TM2) in a waveguide as a function of the mid-plane tilt angle and the effective index for a slab liquid crystal with thickness $2 \mu\text{m}$ (left).

Fig. 3. Distribution of the magnetic field H_y as a function of the x and z coordinate. The waveguide is a homogeneous liquid crystal slab with tilt angle 45° and thickness $2\mu\text{m}$. There are two guided modes in this waveguide, with effective refractive indices 1.589 (TM0) and 1.553 (TM1).

2.5 LC slab waveguide with variation in the tilt

As an example, we consider a liquid crystal waveguide in which the director varies sinusoidally between the two glass plates. Fig. 4 (left) gives the relation between the thickness of the slab and the effective refractive index for a given maximum tilt angle. Fig. 4 (right) gives the relation between the liquid crystal tilt angle and the effective refractive index for a given slab thickness.

Again, the field H_y can be calculated as a function of the z and x coordinates. This is illustrated in Fig. 5 for the modes TM0 and TM1. As the tilt angle is now varying along the x -axis, the angle of the wave-fronts also depends on x . In the mid-plane, the tilt is 90° and the wave front are parallel again.

Fig. 4. Calculated modes in a waveguide as a function of the thickness d and the effective index, for a liquid crystal with sinusoidal variation of the tilt (90° mid-plane tilt) (left). Calculated modes in a waveguide as a function of the mid-plane tilt angle and the effective index for a liquid crystal with sinusoidal variation of the tilt and with thickness $2\mu\text{m}$ (left).

Fig. 5. Distribution of the magnetic field H_y as a function of the x and z coordinate. The waveguide is a liquid crystal slab with sinusoidal variation of the tilt (90° mid-plane tilt) and thickness $2\mu\text{m}$. There are two guided modes in this waveguide, with effective refractive indices 1.656 (TM0) and 1.565 (TM1).

2.6 Director orientation in 1D liquid crystals

The orientation of the liquid crystal director depends on the applied voltage, and, if the light is intense enough, also on the electric field of the light inside the waveguide. For a liquid crystal with positive anisotropy, the director prefers to align with the electric field in order to minimize the electrical energy. For static electric fields, the static anisotropy of the electric permittivity $\Delta\epsilon^s$ has to be used. To describe the alignment of the liquid crystal with the electric field direction of polarized light, the anisotropy in the permittivity at optical frequencies $\Delta\epsilon$ is required. For a one elastic constant (single K) approximation and assuming that the electric field of the light (E_x) is mainly in the x -direction, the equilibrium of torques yields [5]:

$$K \frac{\partial^2 \theta}{\partial x^2} + \frac{1}{2} \epsilon_0 \sin 2\theta \left(\Delta\epsilon^s \left| \frac{\partial V}{\partial x} \right|^2 + \Delta\epsilon |E_x|^2 \right) = 0 \quad (20)$$

If the light intensity is negligible, the director orientation is determined by the above equation, together with the boundary conditions for the director (planar anchoring with 2° pretilt), leading to the well-known director pattern distribution. For low voltages the liquid crystal does not switch, and for higher voltages the tilt angle in the middle of the liquid crystal tends to 90° as illustrated in Fig. 6.

Fig. 6. Distribution of the tilt angle as a function of the x -position in the liquid crystal layer for different applied voltages.

This director pattern can be compared with the director pattern under the influence of light, in the absence of a voltage. Assuming that the light wave has a Gaussian distribution with a width of $3\mu\text{m}$ and is located in the center of the liquid

crystal layer (with thickness $75\mu\text{m}$), we find the director pattern shown in Fig. 7. As there is no torque in the regions without illumination, the director tilt is linear with x . The simultaneous presence of a voltage and a light beam leads to an intermediate situation, as illustrated in Fig. 8.

Fig. 7. Distribution of the tilt angle as a function of the x -position in the liquid crystal layer for different illumination intensities (0, 30, 110, 240, 420, 660 and 950 mW/mm). The thickness of the cell is $75\mu\text{m}$.

Fig. 8. Distribution of the tilt angle as a function of the x -position in the liquid crystal layer for different illumination intensities (0, 30, 110, 240, 420, 660 and 950 mW/mm) and for an applied voltage of 1V. The thickness of the cell is $75\mu\text{m}$.

2.7 Propagation of light in an LC waveguide

The modes in a 1D LC waveguide that we discussed before are valid for sufficiently weak intensities. For a (slightly) higher intensity of the beam, the modified TM₀ mode (invariant along the z -axis) will obtain a (slightly) different director distribution and light distribution. It is not a true mode anymore, as it is intensity dependent and it will interact with other modes if excited simultaneously. It is also difficult to excite such a modified mode, because it requires an excitation with appropriate beam shape.

In the regime where non-linearities are important, the variation of the beam as a function of the coordinate in the propagation direction (z -axis) is determined in a different way. Starting from the $z=0$ plane, the director pattern and the light beam are calculated step by step. A beam propagation method is used to determine the light distribution in the next plane ($z = \text{constant}$), and the corresponding director distribution is calculated from the equilibrium of torques. In this way the distribution of the light beam and the director are determined going from left to right. The simulation method is described elsewhere in more detail [6]. An example of a simulation result is given in Fig 9. If the intensity of the beam is high, the light beam increases the index in its path by the director reorientation effect. When the intensity is sufficiently high, the increase in the refractive index can compensate the diffraction and a non-deforming beam is formed. Such a beam is called a spatial soliton, or, in nematic liquid crystals, a nematicon [7-10].

Fig. 9. Illustration of beam propagation of a 1D beam in a planar liquid crystal layer. (a) Structure of the cell with dimensions. (b) Propagation in the absence of voltage or non-linearity. (c) Waveguiding (multimode) if a voltage of 1V is applied in the absence of non-linearity. (d,e,f) For a voltage of 1V with 30, 110 and 240 mW/mm applied.

2.8 Application of linear 1D LC waveguides

In a linear one-dimensional nematic LC waveguide the TM polarized light is trapped in the region of the LC layer with the highest tilt. The number of modes in the LC slab waveguide depends on the thickness of the waveguide, the ordinary and extra-ordinary refractive indices and the tilt of the molecules. The effective refractive index and the speed of the TM₀ mode depends on the applied voltage. By changing the voltage along the y axis, a y-dependent phase delay can be built in the waveguide. This can be used for beam steering over large angles [11].

3. 2D WAVEGUIDES IN LIQUID CRYSTAL

In two-dimensional configurations the director orientation and optical field vectors depend on both x and y. These situations are much more complicated and it becomes hard to obtain insight in the theory by analytical modeling. The numerical simulations involve some approximations, by neglecting the smaller terms in the anisotropy. A beam propagation model has been presented [12]. We will not go deeper into the theory but present a number of simulation results.

3.1 2D LC waveguides with non-linearities

In a similar way as in the 1D case, the 2D liquid crystal can also shown non-linear behavior by director reorientation if the intensity of the laser beam is sufficiently high. If the intensity of the beam is such that the non-linearity is strong enough to maintaining the waveguide pattern, this beam is again called a soliton [7].

Fig. 10. Illustration of the distribution of the light distribution in the xy plane, for three values of the z coordinate: $z=0$ (a,d), $z=200 \mu\text{m}$ (b,e) and $z=400 \mu\text{m}$ (c,f). The intensity in (a,b,c) is very low and a linear behavior is observed. In (d,e,f) the intensity of the beam is 5.07 mW, which is the value for which a soliton is formed. The thickness of the LC cell is 75 μm and a voltage of 1 V is applied over the cell.

The path of the soliton beam in thick cells (50-100 μm) shows a nearly sinusoidal transverse undulation along the thickness [8]. In thick cells, steering over large angles at the exit of the liquid crystal layer can be achieved by changing the period of this undulation [10]. The change in period can be achieved by changing the applied voltage. The undulation can be used to change the propagation of the beam in the vertical direction if there is an output window on the right side.

Fig. 11. Simulated propagation of a spatial soliton in a thick nematic liquid crystal cell for an optical power of 3.5 mW. The beam exhibits a sinusoidal undulation along the thickness. The initial angle is due to the anisotropy of the liquid crystal and the tilt angle induced by the voltage.

Fig. 12. Experimental measurement of the angle of a beam coming out of a liquid crystal cell as a function of the voltage. The beam inside the liquid crystal cell is a soliton and the length of the cell is 4 mm.

3.2 Multimode 2D LC waveguides

A simple example of a 2D LC waveguide is the case of LC sandwiched between a planar electrode and a strip electrode. In this case, the liquid crystal below the strip will tilt more under influence of a voltage and a waveguide is created. The electrical potential distribution and the resulting tilt distribution in the xy plane are illustrated in Fig. 13. The waveguides in this case are rather wide and therefore multimode. By increasing the optical power however, the optical director reorientation can increase the confinement of the beam.

Fig. 13. Illustration of the distribution of the potential and the tilt angle distribution in the xy plane, between a strip electrode (top) and a homogeneous electrode (bottom).

We have demonstrated that it is possible to deflect light using a voltage addressed two-dimensional waveguide by using strip electrodes on one substrate and a planar electrode on the other one [9].

Fig. 14. (a) Sketch of a configuration with a waveguide induced by a strip electrode on one substrate and a planar electrode on the other. By addressing electrodes with different angles, the direction of a soliton beam can be altered, as shown in (b) for 0° and in (c) for 6° . The optical power is 3.0 mW.

4. 2D HYBRID LIQUID CRYSTAL WAVEGUIDES

There is extensive literature on waveguide systems in which liquid crystals are used to realize tunability. In such hybrid systems, the liquid crystal can serve as the core, when it is surrounded by a low-refractive index material [13] or as (part of) the cladding. The liquid crystal can be used as an overlay material for silicon on insulator (SOI) [14] or silica-titania glass [15] waveguides. Typically, by applying the voltage over the liquid crystal, the effective index of the waveguide is slightly modified and this effect can be used to engineer tunable filters. In two-dimensional photonic crystal waveguides, the holes can be filled with liquid crystal to obtain tunability.

4.1 Example: SOI with LC overlay

As an example of a hybrid waveguide device using liquid crystal, we present a Silicon on Insulator device, using thin and narrow Si waveguides on a SiO_2 layer. This technology is commonly used for photonic devices, but tunability is not easily obtained in this material. By using a liquid crystal overlay, and applying a voltage between the Si wafer and the ITO electrode on the glass substrate, a tunable device can be realized. By switching the liquid crystal from the planar orientation to a high tilt angle, the light in the Si waveguide experiences a slight change in the effective refractive index. The wavelength shift of the Fabry-Perot interference peaks has been measured for this device.

Fig. 15. Structure of an SOI waveguide with LC overlay. The liquid crystal is switched by a voltage. The light in the Si waveguide is partially reflected at the facets of the waveguide and the orientation of the LC modifies the effective refractive index. The bottom figure shows the measured wavelength shift of the interference peaks as a function of the cell voltage.

5. CONCLUSION

In this paper we have presented waveguides based on liquid crystal. The focus is on waveguiding in bulk liquid crystal. The theory for light propagation in one-dimensional anisotropic media has been treated in detail, to illustrate the effects of anisotropy on modes in homogeneous and inhomogeneous LC waveguides. The field patterns are clearly different from the isotropic case, with the wave vector, the Poynting vector at an different angles with the z-axis. The effect of the light on the orientation of the director leads to non-linearities and in some cases to soliton waves, which do not change their shape as they propagate through the liquid crystal. There exists an extensive literature on hybrid waveguides in which the LC plays a role of an electrically tunable cladding layer. As an example an SOI device with LC overlay was discussed.

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