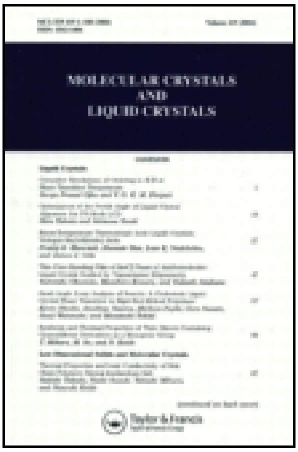

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

All Optical Tunable Nematic Liquid Crystal Waveguide

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Version of record first published: 18 Apr 2012.

To cite this article: M. Trotta, R. Asquini, A. d'Alessandro & R. Beccherelli (2012): All Optical Tunable Nematic Liquid Crystal Waveguide, Molecular Crystals and Liquid Crystals, 558:1, 204-208

To link to this article: http://dx.doi.org/10.1080/15421406.2011.654189

Mol. Cryst. Liq. Cryst., Vol. 558: pp. 204–208, 2012

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2011.654189

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All Optical Tunable Nematic Liquid Crystal Waveguide

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In this paper we theoretically investigate the nonlinear behaviour of a rectangular liquid crystal waveguide. An optical beam of a C-Band laser, fiber coupled to the waveguide, modulates the refractive index of the liquid crystal core. Light propagation is obtained when the effective refractive index of the core exceed the cladding refractive index one. The cut-off condition can be determined by the initial alignment of the liquid crystal molecules and by the laser beam itself that excites optical nonlinearity due to optically induced reorientational effect. Low power optical control could be obtained with an optimization of the molecular alignment.

Keywords All-optical waveguides; electro-optic effect; liquid crystals; nonlinear optics

Introduction

All-optical nonlinear devices are able to process fast optical signals in communication lines without electrical control. These components bring a lot of advantages for many applications, because they allow exploiting more efficiently the huge bandwidth of optical fibers [1–5]. In fact all-optical signal processing limits the need of electro-optical conversion, typical bottleneck of any photonic system. The operation principle of all-optical components is based on nonlinear optical properties of materials such as lithium niobate, III–V semiconductors, or nonlinear polymers. Goals still to be reached in the realization of all optical components are a reduction of the pumping signal power and the realization costs. Liquid crystals (LC) are interesting optical materials for their nonlinear optical properties. They are transparent from UV to IR wavelengths with low scattering losses at wavelengths typically used in optical fiber systems [6,7]. Different devices have been demonstrated based on LC waveguiding properties [8], and all optical switches have been realised [9,10].

In this paper the study of a nematic LC (NLC) waveguide (LCW) in a novel rectangular geometry is reported where a low power optical pump in C band (1530–1565 nm) causes an effective reorientation of the NLC molecules.

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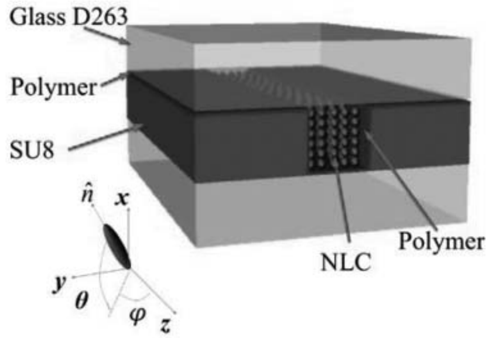

Figure 1. Schematic of the rectangular LC waveguide with a representation of the molecular director $\hat{n}$.

Optical Structure and Working Principle

The numerical calculations presented here represent a theoretical ground for an experimental realization of the rectangular liquid crystal waveguide, schematically illustrated in Fig. 1. It is based on a NLC E7 (Merck) infiltrated in a rectangular SU8 hollow on glass substrate. The NLC is the core material of the waveguide, whereas the cladding is represented by the glass and SU8 photoresist.

The rectangular gap of SU8 to be filled with the NLC (width and height of 15 μm) is obtained by a photolithographic step. The substrate glass is a 500 μm thick borosilicate glass D263 (Schott) with a refractive index slightly higher than the LC ordinary refractive index (see Table 1). A polymer is deposited by spin coating on the surfaces in contact with NLC to obtain, after an alignment process, the desired NLC molecules distribution.

The NLC is infiltrated by capillarity in the gap and next sealed by a UV adhesive NOA61 (Norland) at both input and output of the waveguide. The use of these polymer stoppers prevents formation of droplets, which cause large input and output scattering.

A rectangular hollow waveguide permits a better fiber coupling with lower coupling losses and better polarization maintaining during propagation than a V-waveguide previously reported [8].

Waveguide Modelling

The LC molecular director represents the average unit vector of the molecular orientation. Its reorientation depends on an applying external field, on the NLC characteristics and on the anchoring conditions. In this case the external field is provided by an optical laser pump emitting a wavelength of 1.550 μm with a TE polarization. The molecular director distribution was obtained with the minimization of the free energy written in its integral

Table 1. Refractive indices of device materials

Materials	Refractive index @1.55 μm
E7	$n_{//} = 1.689$ $n_{\perp} = 1.502$
Glass D263	$n = 1.575$
SU8	$n = 1.516$

form given by the Oseen–Frank equation [11]:

$$F = F_{el} + F_{opt} = \frac{1}{2}\iiint (K_{11}(\nabla\cdot\hat{n})^2 + K_{22}(\hat{n}\cdot(\nabla\times\hat{n}))^2 + K_{33}(\hat{n}\times(\nabla\times\hat{n}))^2 - \varepsilon_0(\Delta\varepsilon_{opt}(\hat{n}\cdot\vec{E}_{opt})^2 + \varepsilon_{\perp opt}\vec{E}_{opt}\cdot\vec{E}_{opt}))dv \quad (1)$$

The elastic energy, indicated as F_{el}, depends on K_{11}, K_{22} and K_{33}, which are the elastic constants of the NLC (splay, twist and bend respectively). F_{opt} represents the energy due to the electric field referred to the optical excitation ($\vec{E}_{opt}$), where ε_{opt} is the dielectric permittivity when an electric field at optical frequencies is applied perpendicular to $\hat{n}$ and $\Delta\varepsilon_{opt}$ is the relative dielectric anisotropy.

The minimization of F is achieved by solving the Euler-Lagrange equation of F. In order to solve the partial derivative equation, a finite element method is well suited since it allows the implementation of the weak form of the Euler-Lagrange equation. Strong anchoring is assumed at all boundaries for tilt (θ) and twist (φ). The tilt component is negligible considering a TE polarized beam.

Numerical Results

The effective refractive index of the waveguide can be modified by changing the twist angle by the external optical field or by the alignment conditions:

$$n_e(\varphi_0, \varphi_{opt}) = \frac{n_\perp n_{//}}{\sqrt{n_\perp^2 \sin^2(\varphi_0 + \varphi_{opt}) + n_{//}^2 \cos^2(\varphi_0 + \varphi_{opt})}} \quad (2)$$

where φ_0 is the twist induced by the alignment process and φ_{opt} is induced by the laser beam itself. Only when the effective refractive index of the LCW is higher than the SU8 one, light can propagate.

Beam propagation method was used to simulate the propagation of an optical beam at a wavelength of 1560 nm in a 5 mm LCW in which the optical reorientation is induced.

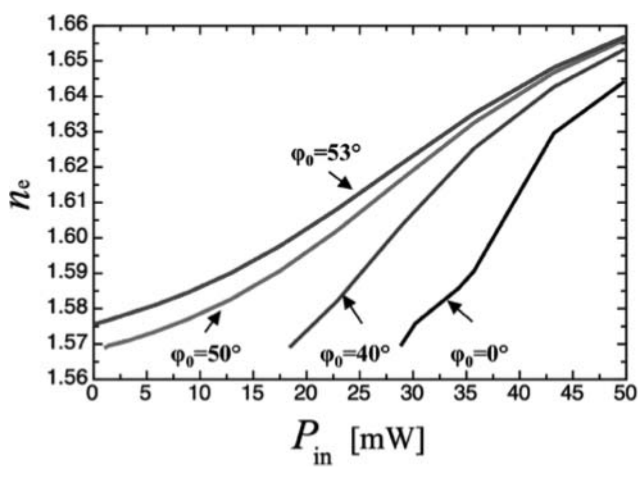

Figure 2. Refractive index of the fundamental mode versus the input optical power for different alignment conditions.

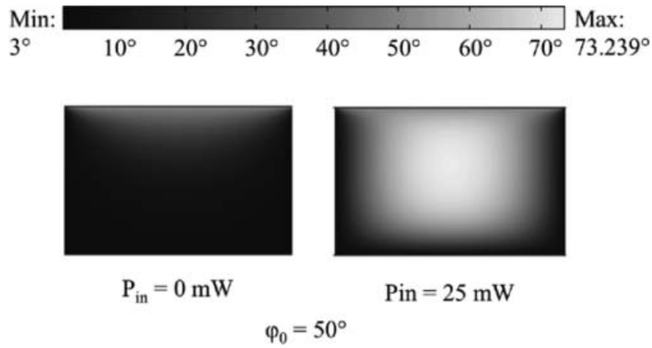

Figure 3. Molecular director distribution for 0 and 25 mW of input optical power when $\varphi_0 = 50^\circ$.

The effective index profile that defines the optical structure of the waveguide was extracted from the solution of the Euler–Lagrange equations. In Fig. 2 the effect of the optical beam on the effective refractive index of the fundamental mode is shown for different alignment conditions. The larger φ_0 the less power is required to obtain a guiding mode. With a power of about 1 mW and $\varphi_0 = 50^\circ$ it is possible to switch from a cut-off condition to a guided mode. Increase of φ_0 induces an increase of the effective refractive index of the LCW (2) and in the nonlinearity of the NLC [12].

In Fig. 3 it is shown the molecular director reorientation of the rectangular waveguide tuning the optical input power for fixed values of φ_0.

Conclusion

A nonlinear optical LCW made of a commercial NLC mixture on a glass substrate is theoretically demonstrated. It consists in a rectangular hollow realized in SU8 photoresist with height and with of 15 μm between two glass substrates filled with NLC. By varying the alignment condition (φ_0) of the NLC it is possible to tune the optical power needed to enable the light propagation. In particular with $\varphi_0 = 50^\circ$ it is possible to obtain a guided mode with optical power of about 1 mW. These preliminary results represent an encouraging demonstration of a first step towards low driving power all optical devices.

Acknowledgments

This research has been supported by the Air Force Office of Scientific Research, Air Force Material Command, U.S. Air Force, under grant FA8655-10-3070.

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