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All-optical Integrated Switches Based on Azo-benzene Liquid Crystals on Silicon

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14. ABSTRACT Objective of this project is the design and fabrication of optically controlled switches using LC doped with azobenzene groups, with large nonlinear optical response, embedded in SiO2/Si grooves able to operate at telecom wavelengths (1500-1600 nm). Such LC mixtures are commercially available from Beam Engineering able also to synthesize custom mixtures for research purposes. In particular some fast switching mixtures are promising to obtain photonic devices with submicrosecond time responses. Multiple input multiple output devices will be designed by using CAD tools already available. Device modeling will be carried out by using finite elements and FDTD techniques. Beam propagation techniques will be employed to simulate the optical waveguide behavior. The modeling will be used to design the photolithographic masks used to fabricate the device structures whose dimensions are in the sub-millimeter scale. Fabrication will be performed at CNR laboratories to which our group has access thanks to our collaboration with Dr. Beccherelli's group. The laboratories include cleanrooms equipped with laser beam systems for mask writing, high resolution photolithography and thin film deposition equipments. Device testing will be performed in our Optoelectronic Laboratory at the Department of Electronic Engineering. In the Optoelectronics Lab, optical benches with anti-vibration pneumatic suspensions are equipped with micro- and nano-translation stages for fiber optic coupling. Instrumentation useful for the measurements requested for this project is available such as fixed and tunable wavelength laser sources operating in the fiber optic C-band, an erbium doped fiber amplifier also used as broadband source, a picometer resolution optical spectrum analyzer, near infrared photodetectors, power meters, etc. The contractor demonstrated two class of nonlinear optical waveguides controlled by an optical signal. The first consists of a commercial NLC mixture embedded in a SiO2/Si groove. The numerical simulation, obtained with an ad hoc model, confirms the experimental results obtained with characterization. An optical threshold is achieved as low as 10 mW for the nonlinear optical effects. In the other case we have a nonlinear LCW based on glass substrates. It consists in a rectangular hollow realized in SU8 photoresist two glass substrates filled with NLC. With a particular glass surface treatment (NLC alignment condition $\phi 0$) we can avoid the use of an external bias voltage, as in the upper case. By varying $\phi 0$ it is also possible to tune the optical power needed to enable the light propagation (< 1mW). These results represent an encouraging demonstration of a first step towards low driving power all-optical devices. Preliminary numerical simulations on AZO-LC V-groove clearly show that it is possible to use only an optical pump to obtain molecular LC reorientation, without the necessity of an external bias voltage. New waveguide samples including AZO-LC are in preparation.					
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1. Summary

We report on a series of optical waveguides based on liquid crystals (LC) mixtures. In particular we study the nonlinear behaviour obtained only by an optical control of the optical parameters. The working principle used for each device is connected to a modulation of the LC refractive index with an optical laser beam, fiber coupled to the device itself. The choice of liquid crystal materials is related to their large (often referred as giant) optical nonlinearities, which implies low power optical control.

2. 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].

Recently, some composite organic materials, such as azo-dye doped liquid crystals, have been engineered to obtain all-optical effects, which proved very efficient in terms of switching speed and low driving optical power [15, 16]. Light responsive materials react to external stimuli with changes in their mechanical, electrical, and optical properties [17]. In this framework, azo-dye doped Liquid Crystals (LCs) [18] and azobenzene LCs (azo-LCs) [19]

are among the most promising materials for photo-switchable devices, since azobenzene derivatives undergo reversible trans–cis isomerization process upon illumination with light (photo-isomerization), resulting in strong changes of optical properties of the material [20].

In azo-LC the nonlinear optical response is faster and stronger if compared to the one of LC doped with a non-mesogenic azo dye, such as the commonly used Methyl Red (MR) (4-dimethylaminoazobenzene-20-carboxylic acid). One more advantage of using azo-LCs is the stability and absence of irreversible “storage” effects [21].

We propose two class of devices, one based on silicon substrate and the other one based on glass substrate. For the first one we have realized a prototype and in the next paragraph we also report the numerical characterization.

3. Optically controlled Silicon V-groove: methods, assumptions and procedures

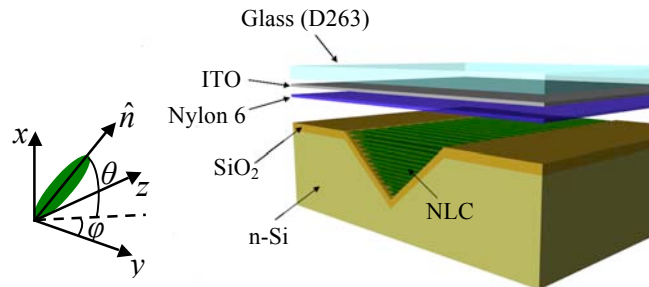


Fig. 1: Tridimensional schematic of the LCW and a representation of molecular director $\hat{n}$ with tilt (θ) and twist (ϕ) angle.

The waveguide structure, schematically illustrated in Fig. 1, consists of nematic LC (NLC) E7, often used as reference LC material, infiltrated in a recessed triangular silicon groove. The structure and the fabrication process are described in details in previous works [2,5]. The anisotropic preferential etching of Si (100) induces the characteristic V-groove. After a thermal oxidation step that produces an SiO₂ layer, the V-groove is covered by an ITO coated

borosilicate glass. A thin layer of rubbed Nylon 6 is deposited on top of the ITO layer to promote an alignment of the NLC molecules. NOA 61 UV adhesive by Norland is used to seal the input and output and to define neat interfaces with the NLC core of the waveguide. Table 1 reports refractive indices of the materials, where $n_{//}$ and $n_{\perp}$ are the two indices of refraction parallel and perpendicular to the molecular axis of the NLC respectively.

Material	Refractive index at $\lambda = 1550$
E7	$n_{//} = 1.69 \quad n_{\perp} = 1.50$
SiO ₂	$n = 1.45$
Si	$n = 3.45$
D263 glass	$n = 1.516$
NOA 61	$n = 1.5419$

Table 1: Refractive indices of silicon LCW device.

4. Optically controlled Silicon V-groove: results and discussion

The optical confinement of a laser beam at the wavelength of 1560 nm in a 15 μm width LCW, butt-coupled by a single mode fiber [6], is achieved when the effective refractive index of the LCW is higher than the glass-SiO₂ cladding refractive index. An applied voltage is used to provide an LC pretilt over the Freedericksz threshold and a further director reorientation is obtained by increasing the input power of the laser beam. The extraordinary refractive index of the NLC depends on the sum of the molecular tilt θ_V , induced by a low frequency electric field by means of an applied voltage, and the tilt θ_{op} induced by the optical electric field according to the formula:

$$n_e(\theta_V, \theta_{op}) = \frac{n_{\perp} n_{//}}{\sqrt{n_{\perp}^2 \cos^2(\theta_V + \theta_{op}) + n_{//}^2 \sin^2(\theta_V + \theta_{op})}} \quad (1)$$

Fig. 2a reports the experimental behaviour of the output power (P_{out}) versus input power (P_{in}) for different applied voltages. At voltages lower than 8 V the optical power transmission first increases linearly and then, at about only 10 mW, the behaviour becomes nonlinear due to the

dependency of the optical molecular reorientation and of the consequent LC refractive index increase from the squared amplitude of the optical electric field [7]. At higher voltages, maximum transmission is reached because maximum reorientation is already provided by the applied voltage, therefore only a linear increase of the output power is observed. The nonlinear behaviour of the LCW was modeled by considering both the electrically and optically induced molecular reorientation. The LC director orientation corresponds to the minimum free energy F reported in Equation (2), composed of the elastic $F_{elastic}$, electrostatic $F_{electrostatic}$ and optical $F_{optical}$ contribution [8]:

$$\begin{aligned}
 F &= F_{elastic} + F_{electrostatic} + F_{optical} = \\
 &= \frac{1}{2} \iiint_v \left(K_{11} (\nabla \cdot \hat{n})^2 + K_{22} (\hat{n} \cdot (\nabla \times \hat{n}))^2 + K_{33} (\hat{n} \times (\nabla \times \hat{n}))^2 \right) \\
 &\quad - \epsilon_0 \left(\Delta \epsilon_{es} (\hat{n} \cdot \vec{E}_{es})^2 + \epsilon_{\perp es} \vec{E}_{es} \cdot \vec{E}_{es} + \Delta \epsilon_{op} (\hat{n} \cdot \vec{E}_{op})^2 + \epsilon_{\perp op} \vec{E}_{op} \cdot \vec{E}_{op} \right) dv
 \end{aligned} \tag{2}$$

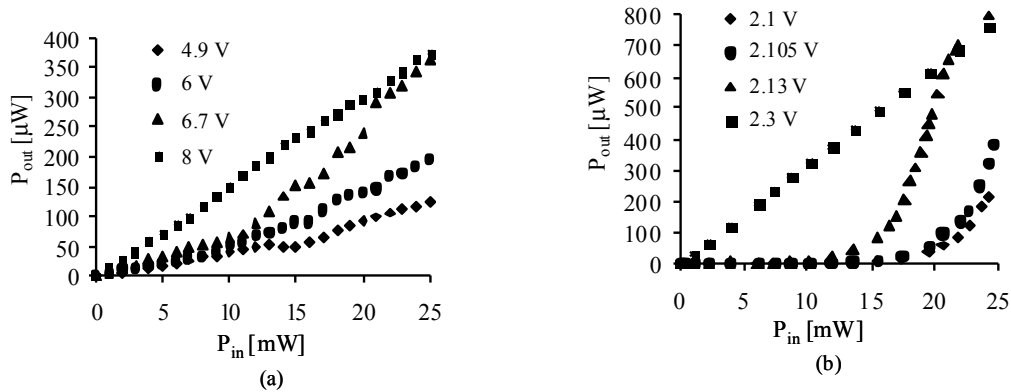


Fig. 2: Experimental (a) and simulated (b) results of output versus input power for different voltages.

The elastic energy, also known as Oseen–Frank, indicated as $F_{elastic}$, depends on K_{11} , K_{22} and K_{33} which are the elastic constants of the NLC (splay, twist and bend respectively). $F_{electrostatic}$ represents the energy contribution due to the electric field E_{es} of an applied voltage V , where $\epsilon_{\perp es}$ is the dielectric permittivity when an electric field at low frequency is applied perpendicular to the director $\hat{n}$ and $\Delta \epsilon_{es}$ is the relative dielectric anisotropy. The last

contribution $F_{optical}$ represents the energy due to the electric field referred to the optical excitation (E_{op}), where $\epsilon_{\perp op}$ and $\Delta\epsilon_{op}$ refer to the optical frequencies.

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. Moreover, a mesh made of triangular elements perfectly matches the triangular geometry of the waveguide. A detailed model for a similar LCW in a silicon groove based on a 2D finite element method is reported in [9]. The weak form method is implemented on COMSOL Multiphysics®, which uses finite element method and couples the problem of the stationary value of F with the solution of the Poisson equation for the distribution of the electric field in the structure. Strong anchoring is assumed with a pretilt of 3° at all boundaries. Lateral boundary condition and both LC tilt and twist angles are considered in the simulation. Beam propagation method is used to simulate the propagation of an optical beam at a wavelength of 1560 nm in the LCW in which the optical reorientation is induced. The effective index profile that defines the optical structure of the waveguide is extracted from the solution of the Euler-Lagrange and Poisson equations. The effect of both coupling and propagation losses of the waveguide are also taken into account [2]. Simulation results are reported in Fig. 2b.

Comparison between experimental data and simulation results shows that our model describes the nonlinear behaviour of the LCW with comparable values of both input and output power. Different voltages between theory and experiment, for which optical nonlinearity of the LCW transmission is observed, are likely due to the presence of defects on the groove walls perturbing the LC orientation. Such defects, not included yet in our model, counteract the free molecular orientation, requiring a higher applied voltage than the calculated one.

Preliminary numerical simulations on AZO-LC V-groove show that it is possible to use only an optical pump to obtain molecular LC reorientation, without the necessity of an external bias voltage.

Fig. 3 shows a preliminary simulation with a standard LC dopant methyl red.

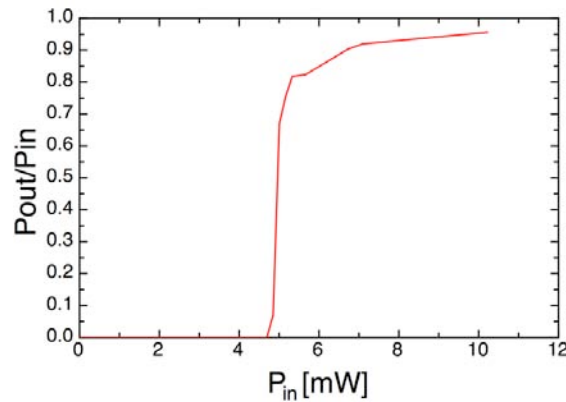


Fig. 3: Optically controlled MR:NLC optical waveguide transmission.

It can be observed that the waveguide is switched on by the optical signal with a power of just about 5 mW. Novel azo-dye LC mixtures can be also used to obtain also faster response below microsecond regime. The specific mixture considered is the NLC 1005 (provided by Beam Engineering [22]), a multi-component compound based on a series of 4-n-alkyl-40-n-alkoxyazobenzenes [23].

The rod-shaped trans-form of an azo-molecule is bent into its cis-form when absorbing radiation in the ultraviolet (UV)-green region. Absorption of radiation at longer wavelengths induces the reverse process. Accumulation of cis-isomers reduces the *LC* order parameter and can transform the *LC* mesophase into its isotropic phase [24], [25]. Varying the concentration of trans and cis isomers via photoisomerization can change the refractive index of the mixture, because of the concentration dependence in both the *LC* dielectric properties and the order parameter.

In this way, it is possible to modulate the transmittance of the LCW varying the refractive index of the NLC with an optical pump. New waveguide samples are currently in preparation to be filled with azo-LC mixtures.

5. All optical polymeric waveguide: methods, assumptions and procedure

The numerical calculations presented in this section represent a theoretical ground for an experimental realization of the rectangular liquid crystal waveguide, schematically illustrated in Fig. 4.

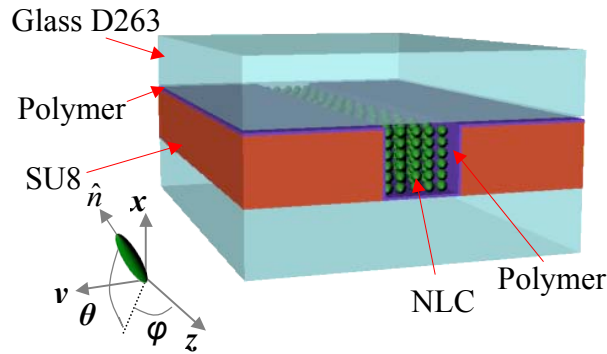


Fig. 4. Schematic of the rectangular LC waveguide with a representation of the molecular director $\hat{n}$.

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 $15\ \mu\text{m}$) is obtained by a photolithographic step. The substrate glass is a $500\ \mu\text{m}$ thick borosilicate glass D263 (Schott) with a refractive index slightly higher than the LC ordinary refractive index (see Table 2). 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.

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

Table 2: Refractive indices of device materials

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].

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

$$F = F_{el} + F_{opt} = \frac{1}{2} \iiint \left(K_{11} (\nabla \cdot \hat{n})^2 + K_{22} (\hat{n} \cdot (\nabla \times \hat{n}))^2 + K_{33} (\hat{n} \times (\nabla \times \hat{n}))^2 - \varepsilon_0 \left(\Delta \varepsilon_{opt} (\hat{n} \cdot \vec{E}_{opt})^2 + \varepsilon_{\perp opt} \vec{E}_{opt} \cdot \vec{E}_{opt} \right) \right) dv \quad (3)$$

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 $\varepsilon_{\perp opt}$ 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.

6. All optical polymeric waveguide: results and discussion

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:

$$n_e(\varphi_0, \varphi_{opt}) = \frac{n_{\perp} n_{//}}{\sqrt{n_{\perp}^2 \sin^2(\varphi_0 + \varphi_{opt}) + n_{//}^2 \cos^2(\varphi_0 + \varphi_{opt})}} \quad (4)$$

where φ_0 is the twist induced by the rubbing 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. The effective index profile that defines the optical structure of the waveguide was extracted from the solution of the Euler–Lagrange equations. In Fig. 5 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 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. 6 the molecular director reorientation is shown of the rectangular waveguide tuning the optical input power for fixed values of φ_0 .

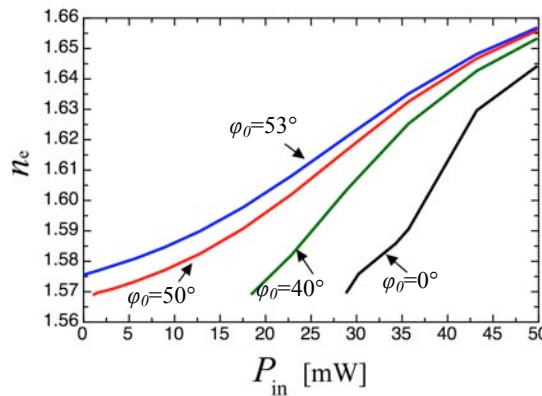


Fig. 5. Refractive index of the fundamental mode varying the input optical power for different alignment conditions.

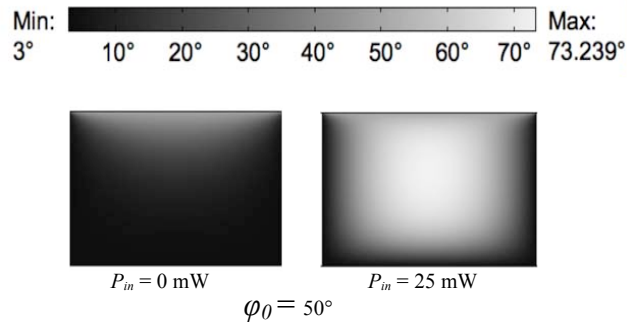


Fig. 6. Molecular director distribution for 0 and 25 mW of input optical power when $\varphi_0 = 50^\circ$.

We used E7 to compare results with the previous structure on silicon but a further reduction of driving power can be obtained by filling with AZO-LC. Fabrication of samples is in progress.

7. Conclusions

We demonstrated two class of nonlinear optical waveguides controlled by an optical signal.

The first consists of a commercial NLC mixture embedded in a SiO_2/Si groove. The numerical simulation, obtained with an ad hoc model, confirms the experimental results obtained with characterization. An optical threshold is achieved as low as 10 mW for the nonlinear optical effects.

In the other case we have a nonlinear LCW based on glass substrates. It consists in a rectangular hollow realized in SU8 photoresist two glass substrates filled with NLC. With a particular glass surface treatment (NLC alignment condition φ_0) we can avoid the use of an external bias voltage, as in the upper case. By varying φ_0 it is also possible to tune the optical power needed to enable the light propagation ($< 1\text{mW}$). These results represent an encouraging demonstration of a first step towards low driving power all-optical devices.

Preliminary numerical simulations on AZO-LC V-groove clearly show that it is possible to use only an optical pump to obtain molecular LC reorientation, without the necessity of an external bias voltage. New waveguide samples including AZO-LC are in preparation.

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