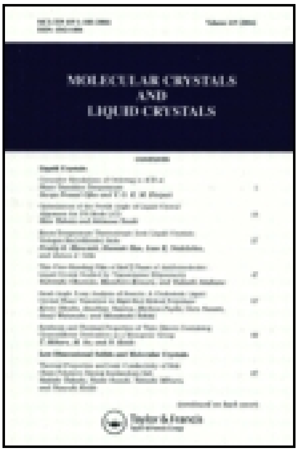

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Tunable Optical Filtering Techniques in Waveguides Using Liquid Crystals and Composites

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Published online: 14 Jun 2013.

Mol. Cryst. Liq. Cryst., Vol. 576: pp. 141–150, 2013

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2013.789718

Tunable Optical Filtering Techniques in Waveguides Using Liquid Crystals and Composites

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We present several approaches to make integrated optic filters, which include either liquid crystals or composite structures including polymers. The presence of liquid crystals allows tunability of the filters controlled by means of low power electric signals. All-optical tuneable filters are also presented in which optical nonlinear properties of liquid crystals are deployed to drive the device.

Keywords Optical filters; waveguides; nonlinear optics; liquid crystals; polymers

1. Introduction

Electrical and optical control of liquid crystal (LC) refractive index allows the realization of reconfigurable optical devices. Several device geometries can be created to get a modulation of the index of refraction, which can be deployed to perform optical filtering. Furthermore the possibility to confine light beams in LC allows for designing and fabricating integrated optical tunable filters by using several approaches. One of the main motivations which justifies the use of LC is related to the low power signals required to activate molecular reorientation implying a refractive index change. Moreover LC can be combined with other soft materials to realize periodic microstructures or other resonant structures, which act as main part of optical filters. Several features of LC can be deployed to make low driving power and low cost photonic devices for different fiber optic systems. In fact LC are transparent to near infrared wavelengths of low loss optical fibers spectrum (1500–1700 nm) with low scattering losses which scale as $\lambda^{-2.39}$ [1]. LC large electro-optic effects provide driving voltages of a few volts with negligible current absorption determining submilliwatt electrical driving power. Another interesting feature of LC is their high optical nonlinear effects, which provide low threshold all-optical devices. In fact in centro-symmetric media the simplest nonlinear response is modeled by changes in refractive index n proportional to the local intensity I, i.e., $\Delta n = n_2 I$, with n_2 the Kerr coefficient [2]. In lithium niobate n_2 is of the order of 10^{-14} cm^2/W, in LC is typically 10^{-5} cm^2/W [1], and nematic cyanobiphenil 5CB doped with a small amount of the azo-dye methyl red (MR) can exhibit a nonlinear coefficient higher than 1 cm^2/W [3]. A number of mechanisms have been discovered in the last two decades, resulting in optical nonlinearities characterized by n_2 in the range $10^{-3} \div 10^3$ cm^2/W. For $n_2 > 1$ cm^2/W, they have been called supra-optical nonlinearities, and for

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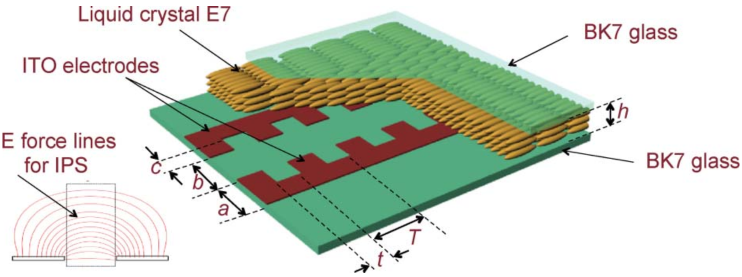

Figure 1. LC Bragg reflector obtained by applying a voltage between comb-like electrodes. The inset shows the applied electric field E force lines, which induce in-plane switching (IPS).

$n_2 > 1000\ cm^2/W$, they have been called colossal nonlinearities. In all cases, they involve introducing a photosensitive dye or molecular dopants to mediate, facilitate and enhance the reorientation process. Corresponding to these dramatic improvements in n_2, the laser power required to create observable nonlinear optical effects has also dropped dramatically to the mW, μW and even nW levels [4–13].

Several approaches were implemented to make tuneable filters by using LC. Simple nematic LC (NLC) have been used in Fabry-Perot etalon [14] and a smectic LC has been used to obtain fast tuning in the range of μs regime response time [15]. Waveguided filters using Bragg gratings modulated by electrically controlled LC have been used [16]. Tunable filters have been experimentally demonstrated in which optical signals travelling in glass waveguides are filtered by the action of electrically controlled Bragg gratings made of microstructured alternating stripes of polymers and NLC's to form the so-called POLICRYPS (POlymer LIquid CRYstal Polymer Slices) [17–19].

In this paper waveguided LC based optical filters using different approaches are reviewed. In section 2 an electro-optic grating based tuneable Bragg reflector in a NLC is reported for wide tuning range in the spectrum of near infrared wavelengths. In section 3 a whispery gallery mode based resonator using glass waveguides and sapphire microsphere is proposed for high-Q performance, where LC are used for tuning the resonant wavelength. In section 4 integrated optics tunable filters using POLICRYPS structures, which can be controlled either optically or electrically, are reported and compared.

2. An NLC Bragg Reflector

Optical reflectors are made usually by using Bragg phase gratings. Tuning can be implemented mainly through thermo-optic effect, mechanically, electrically, acusto-optically, electro-optically and opto-optically. Several technological solutions have been proposed by employing different materials and structures such as polymers [20–24] silicon-on-insulator (SOI), [25–31] hollow capillaries, [32–35] lithium niobate [36–38], metal-insulator-metal [39,40], silica for fiber Bragg gratings [41–45] and LC [46–50]. An optical slab LC waveguide layer can be controlled electrically by using several possible electrode patterns. Fig. 1 shows a device configuration in which a periodic LC molecular reorientation can induce a Bragg grating inside the waveguiding LC layer by applying a voltage to periodically patterned coplanar ITO electrodes. The shape of the electrodes is determined by the geometrical parameters *a, b, c, t,* and *T*, being *a* the maximum width of a single coplanar electrode, *b* the minimum electrode distance, *c* the variation of the width for each electrode,

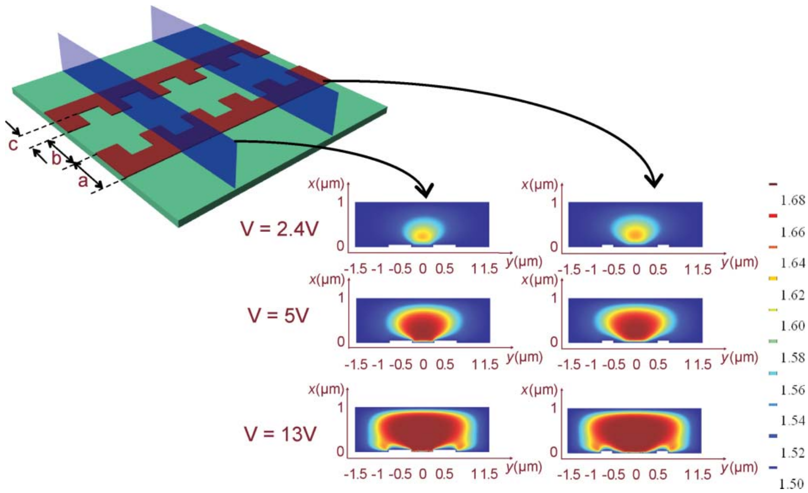

Figure 2. Contour maps of the refractive index distribution, for three voltages in two cross sections of the device. The left-hand side maps are related to the closer electrode fingers at distance b and the right end side maps refer to wider electrode separation $b + 2c$.

t the length of the narrower electrode section for each period, and T the electrode period respectively, as shown in Fig. 1. In fact the different distance between the two comb-like patterned electrodes create a periodic value of the in-plane electric field. The design of the device was optimised including the LC mixture E7 infiltrated between ITO patterned BK7 glass substrates with a cell gap h.

The device behaviour and simulation can be obtained by minimising the Frank-Oseen free energy of the LC including the optical anisotropy [51]. Both dielectric and elastic energy contributions were included in the calculations. The LC orientation and the related refractive index spatial distributions were obtained by solving the Poisson equation.

Fig. 2 shows the refractive index distribution in two cross sections with different electrodes distances, b and $b + 2c$ respectively for three voltage values. The results refer to the following optimised design values: $h = 1\ \mu$m, $t = 250$ nm, $T = 500$ nm, $a = b = 500$ nm, $c = 250$ nm. Calculations show that the index modulation reaches its maximum at 5 V, because the NLC director is entirely reoriented perpendicularly to the electrodes in the regions with minimum inter-electrode separation (b) and no further reorientation is induced by increasing the voltage. On the other hand, the LC is only partially reoriented where the electrodes are separated by $b + 2c$, hence a further increase of the voltage above 5 V induces a reorientation of the LC in this region but resulting in a progressive reduction of the index modulation.

Fig. 3 shows that such a device configuration shows an impressive performance in terms of tuning range, which reaches 104 nm in the near infrared regions between 1.52 nm and about 1.625 nm with a reflectivity of 50% by changing voltage between 2.9 V and 10.2 V.

The selectivity of the device in terms of FWHM is below 2.3 nm in the tuning range for a length of 1.5 mm corresponding to 3000 periods. These results indicate that this device is able to ensure Bragg reflection and spectral filtering in the whole C + L band for optical fiber systems.

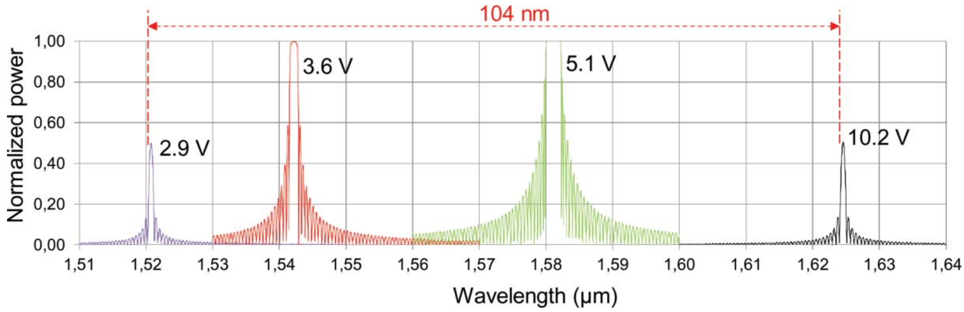

Figure 3. Voltage tuned spectral reflectivity and propagation over 1.5 mm.

3. Tunable Whispering Gallery Mode Resonators

In his work "The problem of the whispering gallery" published in 1912, Lord Rayleigh demonstrated the very efficient propagation of acoustic waves along the internal surface of the dome of St. Paul's Cathedral in London [52].

The acoustic modes propagating in the dome were called whispering gallery modes (WGM's) because they allowed a listener positioned in one end of the dome to listen perfectly the words pronounced by a speaker located on the opposite side of the dome without the need to speak aloud. The same principle can be applied to optical waves to make WGM based optical resonators with very high Q factor (defined as the ratio between stored energy over lost energy per unit cycle in the resonator). For a perfectly smooth sphere, Q would ideally be limited by the absorption loss in the material. If the sphere is made of a material with low absorption losses, the high Q and the elevated spatial confinement of the wave make such device of great interest for several applications such as microlasers [53], filters based glass [54] and silicon [55] microspheres, switches [56], high resolution spectroscopy applications [57] and Raman sources [58]. Polymer [59,60] and glass [61] spheres placed on glass optical fiber half couplers, have been used by using evanescent wave coupling. Later, tapered optical fibers [62] and channel waveguides [63] have also been used for coupling light into the spheres. A narrowband electrically tunable filter based on a sapphire microsphere, a glass optical waveguide and LC as tuning medium for telecommunication applications in the near-infrared was proposed [64].

Fig. 4 shows a tuneable hybrid resonator using WGM's coupled in a sapphire microsphere. The resonating modes are excited by evanescent coupling of light propagating in a single-mode double ion-exchange $K+/Na+$, $Ag+/Na+$, waveguide [65] on a BK7 glass substrate. Patterned PDMS (polydimethylsiloxane) is used to create the basis to place the sphere with a gap to be filled with an NLC. Coplanar ITO electrodes are used to reorient the NLC molecule inducing a refractive index change, which tuned the optical spectrum of the resonator. Light is coupled in and out of the glass waveguide by butt-coupling single mode optical fibers. Critical parameters are refractive indices of the materials of the various device components and some geometrical features. In particular the width of the aperture of PDMS where the microsphere is located and its distance from the glass surface determine important design rules of the device. The device can be designed so that the resonator is on or off resonance according to the voltage applied to the coplanar electrodes.

Before applying voltage the NLC are aligned along the waveguide by using a rubbed Nylon 6 alignment layer deposited on the glass surface. NLC molecules are tilted after applying voltage. Fig. 5 shows that a tuning range of 0.5 nm can be obtained by changing

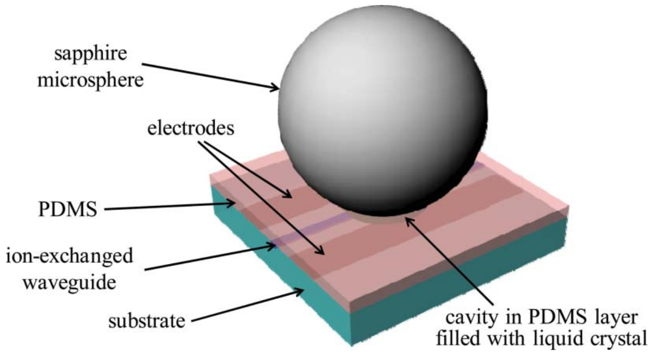

Figure 4. Tunable WGM resonator based on a sapphire microsphere placed on top of ion-exchanged channel waveguide. Tuning is provided by electrically LC placed in PDMS cavity between the microsphere and the waveguide.

voltage from 0 to 11 V with a free spectral range (FSR) of 1.5 nm. In the calculations, the waveguide width was 6 μm with an effective refractive index of 1.5108, the PDMS thickness was 4 μm with a refractive index of 1.406 at 1550 nm. The sapphire microsphere had a refractive index of 1.7 and a radius of 150 μm. The NLC considered is E7 (with ordinary refractive index $n_{\perp} = 1.5$ and extraordinary refractive index $n_{//} = 1.689$ at 1550 nm). The dips in the transmitted spectra are at approximately −44 dB, with 3 dB line-widths of only 0.2 pm (25 MHz), when calculated with a wavelength step as narrow as 0.1 pm. Hence, the quality factor $Q = \lambda/\Delta\lambda_{FWHM}$ of the filter is approximately 8×10^6, even after tuning. Such results suggest that this device is suitable especially for optical sensor system applications. In fact it is possible to replace the NCL with a fluid whose refractive index can shift the spectrum of the resonator, allowing to use the device as a very sensitive microfluidic sensor.

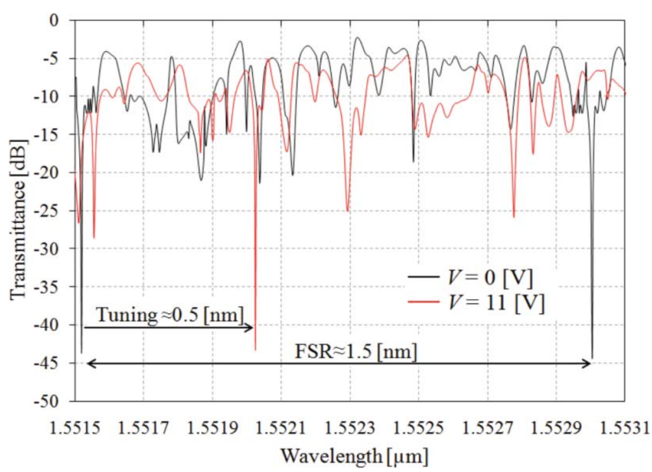

Figure 5. Optical response of an NLC tunable WGR hybrid resonator using a sapphire microsphere and a double ion exchanged waveguide.

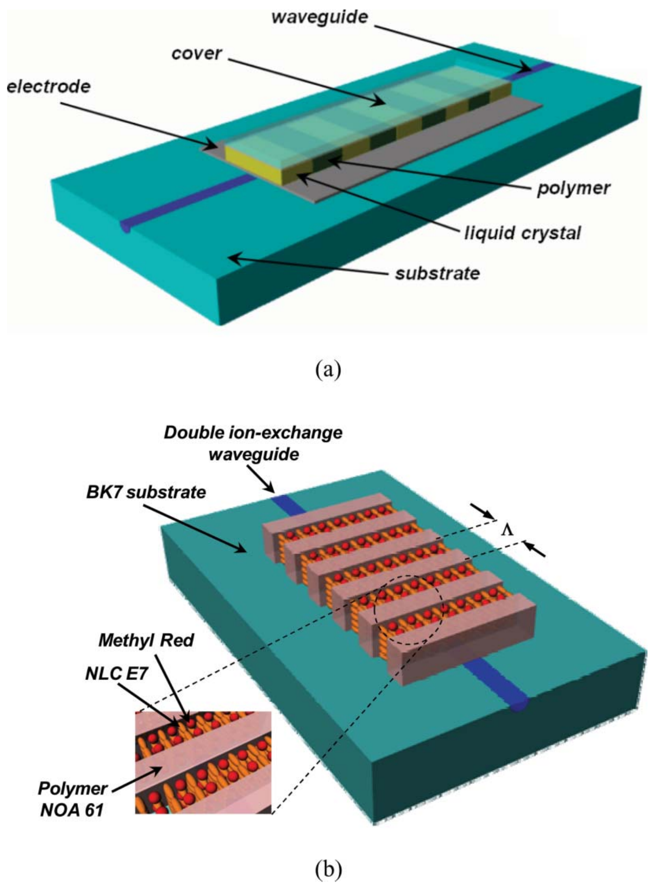

Figure 6. POLICRYPS based electrically (a) [74] and optically tuneable (b) integrated optical filters using double ion-exchange waveguides in BK7.

4. POLICRYPS Integrated Tuneable Filters

POLICRYPS, acronym for POlymer LIquid CRYstal Polymer Slices, are very well-known microstructures made of alternated microstripes of cured polymer and NLC [17–19]. They are a good alternative to HPDLC (Holographic Polymer Dispersed Liquid Crystals) [66,67] to make switchable gratings. In fact POLICRYPS have been designed [68,69] realized [17,70] and characterized [18,71] in order to improve the main limitation of HPDLC optical and electro-optical characteristics. In fact strong scattering of light occurs when the average size of NLC droplets in HPDLC is comparable to the wavelength of the impinging light. Many applications were demonstrated in which POLICRYPS gratings can be used as free space electro-optic [72] and all-optical device [73]. Furthermore it was demonstrated that POLICRYPS are considered as a basic microstructured template for a variety of uses and applications including also lasing device by replacing NLC with a cholesteric LC. In particular POLICRYPS can be also integrated with channel waveguides to obtain tunable waveguided filters, which can be driven either electrically [49] [74] or optically [75]. Fig. 6 shows both an electrically driven (Fig. 6a) and an optically driven (Fig. 6b) integrated optical tuneable filter for comparison. In both devices a 6 μm wide single mode double

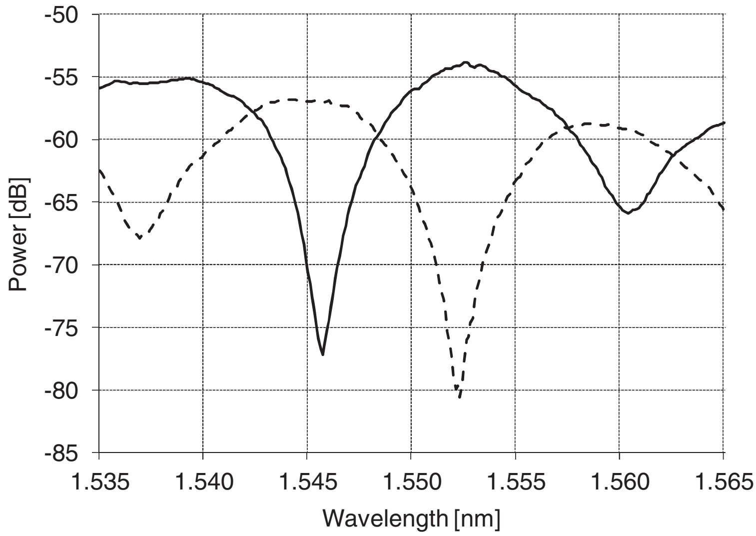

Figure 7. Optical transmission spectra of the NOA61/MR:E7 POLICRYPS based optical filter when no driving signal is applied (solid line) and when a 45 mW laser beam at 532 nm impinges on the grating (dashed line).

ion exchange K+-Na+/Ag+-Na+ waveguide in a BK7 substrate is used to confine light beams whose wavelengths can be selected by the Bragg diffraction due to the overlaying POLICRYPS grating. In both devices the grating is embedded between the substrate, which includes the waveguide, and a cover made of the same glass BK7. Both gratings use NOA61 polymeric stripes alternated to the NLC E7 in the electro-optic filter and to the methyl red (MR) doped E7 (MR:E7) in the all-optical version of the grating. In the electro-optic type filter the tuning is provided by the electro-optically induced molecular reorientation due to the electric field applied to the coplanar electrodes. In the all-optical filter, no electrodes are required since the MR:E7 can be reoriented by using green light (at the wavelength of 533 nm). In fact the trans-cis conformal transformation due to the photo-isomerization of MR under illumination breaks the homeotropic alignment of the NLC between the polymeric stripes. Both the electrically and the optically induced reorientation implies a variation of the average refractive index seen by a quasi-TE polarized light propagating into the optical channel waveguide.

The refractive index change implies a tuning of the Bragg wavelength $\lambda_B = 2n_{eff}\Lambda$ where n_{eff} is the effective refractive index of the waveguide affected by the grating index modulation, being Λ the pitch of the grating. Grating pitch was 2.55 μm in the electro-optically controlled filter and 1.55 μm in the optically driven version. In both cases the grating thickness was 1.1 μm. The devices were designed to operate in the 1.55 μm region.

Fig. 7 shows the transmission optical band of the all-optical filter measured by an optical spectrum analyzer. The filter output optical signal is collected by a single mode optical fiber when a broad band spectrum optical signal generated by an erbium doped fiber amplifier, used as a white source, is fiber-coupled to the input of the filter glass waveguide.

The spectrum is tuned by 6.6 nm when 45 mW laser beam at 532 nm is applied. Similar tuning of about 4 nm is obtained for the electro-optical filter when a voltage of 40 V is applied to the coplanar electrodes but with overall sub-milliwatt driving power due to the negligible current absorption.

The switching times for both filters are in the range of few tens of ms as typically measured for E7 NLC standard cell with the same thickness. In both filters temperature tuning can be also obtained. As an example a tuning range over 15 nm by changing temperature of 4°C was measured for the filter using the NOA61/MR:E7 grating, as expected for the thermo-optical properties of E7.

5. Conclusions

We have demonstrated several tunable filters operating in the typical third window spectral band, centered at 1.55 μm, used in most of fiber optic systems. The devices, conceived by using different kinds of resonant structures, can be divided in two categories.

In a first category an optical beam travels into an NLC electro-optical grating created by patterned electrodes. Modulation of electric field along the direction of propagation induce a phase grating acting as an optical filter which can be tuned over 100 nm. In principle, such structures can be also driven optically by deploying the optical nonlinearities of the NLC. Main advantages are structure simplicity and compactness, but insertion losses, especially coupling losses, can be significant and must be assessed in the fabricated samples.

A second category is based on resonant structures acting on the optical beams travelling in channel waveguides. We have shown how to obtain tuneable filters using glass channel waveguides carrying the optical beams to be filtered acting with two examples of resonant structures. In a first example sapphire microspheres select resonant wavelengths by WGM's, which can be tuned by electrically reorienting a NLC between the microsphere and the glass waveguide. In a second example POLICRYPS gratings on top of the waveguide act as wavelength selecting element. For this kind of filters we have shown that either the electrical or the optical driving technique can be used. The glass waveguide devices have shown good coupling with optical fibers with low driving power in the milliwatt or even submilliwatt range.

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