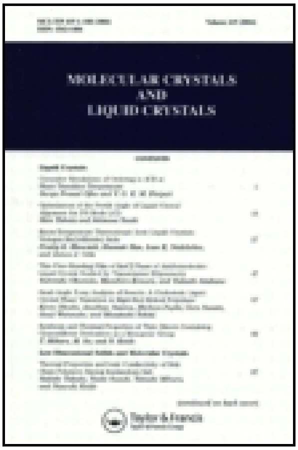

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Tunable Liquid Crystal Fiber-Optic Polarizer and Related Elements

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A new in-line type tunable liquid crystal fiber-optic device is presented. The main idea is to obtain anisotropic waveguide structure based on biconically tapered isotropic fiber core and anisotropic liquid fiber clad. As the liquid-crystalline clad, the nematic mixture 1110-10C_3 made by Dąbrowski's group has been used. The special construction of a device with square cross-section secures a possibility to change molecular orientation of the liquid-crystalline clad by external field. Thus, different polarising action has been obtained depending on fulfilment waveguide condition of the structure.

Keywords: liquid crystal devices; tapered optical fiber; polarisation phenomena; tunable optical devices; electro-optical effect

I. INTRODUCTION

Recently a growing interest in fiber-optic elements using polarisation phenomena is observed [1]. Generally, those devices are used in telecommunication domain and different optical fiber sensors for controlling light interaction. An application of electro-optical effect *via* special layer of liquid crystal (LC), gives a possibility to obtain electric driving of active elements, which are characterised by compact size, low cost, and low power consumption. The main configuration for such element is a construction based on face-to-face element connection with external ferrules as for example: polarisation controller [2], Mach-

Zehnder directional coupler [3], Fabry-Perot tunable filter [4] or different types of light modulator [5].

However, the main disadvantage of above constructions is open-bulk device architecture, then for single mode operation they might introduce additional losses. From this reason other type of device, so called in-line, has been proposed. Normally side-polished fiber structures with additional layer of LC are used as fiber-optic polarizer [6], dropping filter [7], and other tunable components [8]. All above elements use tunable anisotropic properties of liquid crystal for controlling its fundamental properties. Moreover, they need very good quality of polished surface for secure low transmission losses. Recently, the anisotropic fiber using LC material in elliptical core has been reported [9], but its polarising properties are fixed, and structure is multimode.

In this paper, we present a new idea of an action of fiber-optic polarizer and related elements, based on biconical taper of single-mode fiber. The taper region is suitable placed in liquid-crystalline layer that acts as fiber clad. The external electrical field gives a possibility to change molecular orientation in a direction perpendicular to the taper axis. The application of such structure as fiber-optic polarizer with tunable orientation of polarizer axis is presented and discussed.

II. IDEA OF MAIN STRUCTURE

The fundamental law of waveguide operation is the condition of total inner reflection. It seems that refractive index of guiding material (fiber core) must be higher than refractive index of a surrounding one (fiber clad). Moreover, the polarisation properties of single-mode fiber depend on angular symmetry of refractive index along propagation direction [10]. If symmetry is perfect, the fundamental mode of the structure is degenerated on two mutually orthogonal, linear polarised modes (LPM). Any perturbation of this symmetry mixed LPM and randomly changes output state of polarisation (SOP). Thus broken angular symmetry, fixed along propagation direction, is the best way to obtain fixed SOP of guided light. The above idea is realised in so-called polarisation maintaining or high-birefringent fiber. On the other hand, to obtain linearly polarised light in standard single-mode fiber, a fiber polarizer is used. Its action bases on attenuation or radiation of one of two LPMs [1]. However, all those methods give only fixed SOP, because asymmetry in polarizer structure is unchanged.

The structure, schematically shown in Figure 1, contains a circular fiber core surrounded by the liquid crystal clad, giving a possibility of polarizer action switching. To get LC material access to light propagating in fiber core, the biconical taper technology (Figure 1a) [11] has been used. As one can see from Figure 1c, the LC material with ordinary (n_o) and extraordinary (n_e) refractive indices below and above refractive index of the fiber core (n_f), respectively, has been applied. Physically in taper region, the refractive index profile in extraordinary direction of LC does not support waveguide condition ($n_f<n_e$) for proper LC molecule orientation (Figure 1b). Hence fundamental LPM polarised in this direction is radiated. Waveguide condition exists in ordinary direction of LC ($n_f >n_o$), and structure guides LPM polarised in this direction, only. Then, the classic polarising action by radiation of one of LPMs exists for such structure.

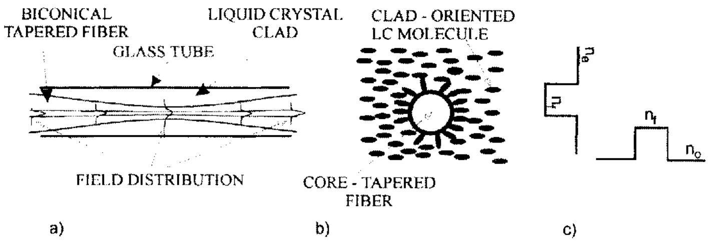


FIGURE 1 Scheme of polarizer structure: a) general view of biconical fiber taper with LC cladding, b) LC molecule orientation around taper in its cross-section, c) refractive index profile in taper cross-section.

The solution of the suitable wave equation has been used for a calculation of polarizer extinction ratio [11]. Obtained relationship between the extinction/loss ratio and the length of the elongated taper region for standard single-mode fiber is shown in Figure 2. The 680 nm wavelength and suitable clad-core refractive index difference (Δ) have been used for calculation. It can be seen that despite smooth changes of the fiber diameter in the elongation process, the extinction/loss ratio of polarizer has oscillating disturbances connected with the existence of the transverse resonance conditions. Additionally, the maximum value of the extinction/loss ratio strongly depends on core/clad refractive index difference and generally needs the longer taper for smaller core/clad difference. In the polarizer with high extinction ratio and low insertion loss taper elongation equal 6, 9, 14 mm should be used for Δ equal 0.01, 0.008 and 0.005, respectively.

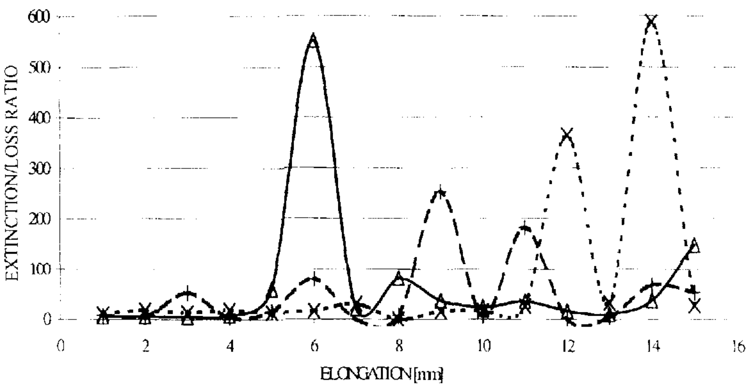
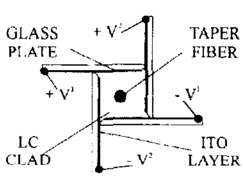


FIGURE 2 Influence of the elongation length on the extinction/loss ratio. Parameter Δ equal: 0.01 – (Δ), 0.008 – (+), 0.005 – (x).

Because taper cross-section retains circular symmetry, the orientation of output polarisation depends on clad anisotropy axis direction. As one can see from Figure 3, using electrical field and suitable initial orientation of LC layer it is possible to obtain linearly polarised light with switchable direction. Electrically driven LC molecules orientation depends on LC anisotropy, so switching direction is different for optically positive and negative LC materials. However, two pairs of electrical connection and suitable LC molecules initial orientation (see scheme shown in Figure 3), secure a possibility of output polarisation switching for both material types.



	OUTPUT LINEAR SOP ORIENTATION (n_e - IN TAPER ($\Delta\varepsilon>0$) or IN PERPENDICULAR ($\Delta\varepsilon<0$) DIRECTION)		
	$V^1=V^2=0$	$V^1=0, V^2\neq0$	$V^1\neq0, V^2=0$
$\Delta\varepsilon>0$	NO POLARISING ACTION	LINEAR SOP VERTICAL	LINEAR SOP HORIZONTAL
	$V^1=V^2=0$	$V^1=0, V^2\neq0$	$V^1\neq0, V^2=0$
$\Delta\varepsilon<0$	NO WAVEGUIDE CONDITION	LINEAR SOP HORIZONTAL	LINEAR SOP VERTICAL

FIGURE 3 Scheme of device cross-section and polarising action for different electrical driving.

III. EXPERIMENTAL RESULTS

We used a new nematic LC 1110-10C$_3$ mixture (made by prof. Dąbrowski's group from MUT) having nematic properties in room temperature as liquid-crystalline material. Its refractive indices at room temperature are 1,460 and 1,5014 for ordinary and extraordinary 589 nm wavelength, respectively. The biconical taper of single mode optical fiber operated at 680 nm wavelength with clad/core refractive index equal 1.458/1.468 has been elongated by 10 mm. In the taper region, fiber diameter was about 40 μm with refractive index 1.459. The experimental investigation had to be made at temperature 33 Celsius where ordinary refractive index of on 1110-10C$_3$ mixture decreases to 1.455. The fiber taper has been mounted between parallel glass plates separated at 125 μm by fiber-optic diameter. Such high thickness of LC layer has been the main cause of high voltage (1 kV) driving. The measured polarising properties of such structure (by rotation of linear SOP on input to investigated element) are shown in Figure 4.

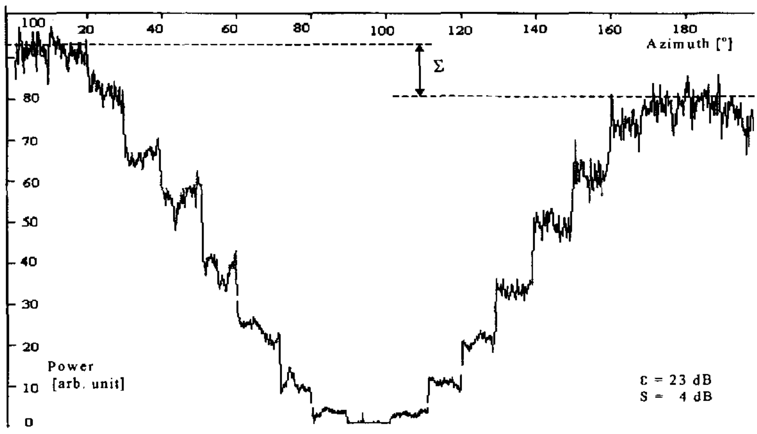


FIGURE 4 The profile of power changes on a detector placed behind the element. The azimuth of input polarization has been changed with 10-degree step.

An oscillating character of this graph is caused by the temperature instability of the structure - so-called 'flotation' of the power. Influence of this factor demonstrates itself in a difference Σ between maximums of the graph shown in Figure 4. Above-mentioned results are consistent with the theoretical relationship: $\cos^2(\phi)$, where: ϕ is an angle of a linear input polarization azimuth. This measurement has given polarizer extinction ratio equal 23 dB with 3 dB insertion loss, that it is similar to properties of classic fixed fiber-optic polarizer for this wavelength.

An application of two pairs of such plates, mounted according to the scheme shown in Figure 3, secures polarisation switching by electrical signal. Because LC mixture used was optically negative ($\Delta\varepsilon<0$), then the initial molecular orientation have been nearly perpendicular to the glass surface. It was made by special aligning technique. For square cross-section of the device, those molecular orientation given circular symmetry with clad refractive index larger than this one of core, thus the device switches off light, because it does not fulfil waveguide condition. When voltage is applied to suitable parallel plates (see Figure 3), the LC molecules have been reoriented in one direction perpendicular to electrical field. Then polarising action with direction of linear output SOP switchable by electrical field (see table in Figure 3) has been obtained (see Figure 5).

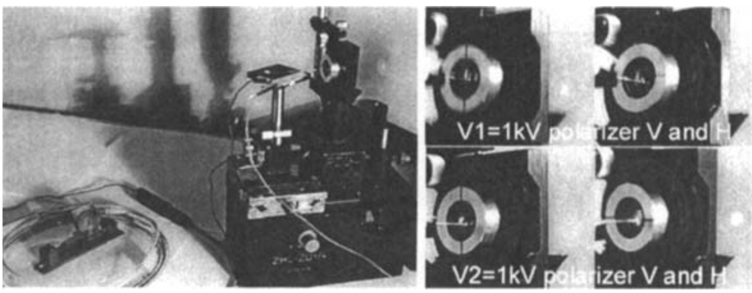


FIGURE 5 General view of experimental set-up (left) and linear output SOP switching effect (right). V – vertical, H – horizontal.

The above described element is the three-state device working as light switch-off, and two directional polarizer – all due to changes of supplying electrical signal. It is worth mentioning that the main technical difficulty has been connected with an assurance of uniform reorientation of molecules by electrical field. If initially molecular orientation is exactly perpendicular to the bonded glass plates, then in electrical field part of molecules will be reoriented parallel to the taper direction. The partially linear polarising action has been obtained in this situation.

IV. SUMMARY AND CONCLUSIONS

The idea and initial experimental results of tunable fiber-optic polarizer with NLC material have been presented. The condition of circular optical symmetry of the core, moreover changeable anisotropy of LC clad have given possibility of tunable and/or switchable device action. The above behaviour depends on LC material optical anisotropy type and element geometry. The in-line polarizer with 23 dB extinction ratio and 4 dB insertion loss has been obtained for 1110-10C_3 mixture fiber-clad, while operated at wavelength of 680 nm.

Used 1110-10C_3 material is multicomponet nematic mixture based on cyclohexane esters derivatives. This very stable material has been designed to work at room temperature. Its ordinary refractive index, equal to 1.460 for mercury source, has been the least one, which can be obtained technologically for this wavelength. Therefore, the practical construction of described elements for this wavelength should use the special fiber with refractive index increased by 0.01 as for core as clad. Dr. Wójcik team (from UMCS-Lublin) currently prepares such fibers based of MCVD and OVD technologies. Then two-order smaller driven voltage is expecting for proper element action. This problem is less pronounced for standard telecommunication wavelengths (1300 or 1550 nm) due to dispersion of LC refractive indices.

The described element can be used as the basis for different fiber-optic devices such as:

- two- or three-stage polarisation switcher – (by application optically positive or negative LC materials, respectively), demonstrated in paper
- polarisation scrambler – for element electrically supplied by random value as well as direction signal,
- polarisation state modulator – for cascade of two polarizer switchers; the second of them driven by one directional signal.

All of them have potential application for telecommunication (mainly in coherent transmission systems and transport networks) as well as sensing systems, for example, in optical fiber system for shape measurement by fringe projection.

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