Research Article

Electro-Steering Tapered Fiber-Optic Device with Liquid Crystal Cladding

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The paper presents the results of design, manufacturing, and characterization of a hybrid broad band in-line fiber-optic device. It uses nematic liquid crystal as cladding with electro-steering properties in a biconical optical fiber taper structure. Liquid crystal mixtures denoted as 6CHBT and E7 are designed for electric as well as temperature control of electromagnetic wave propagation in a broad wavelength range. The applied taper with 10 ± 0.5 μm diameters has losses lower than 0.5 dB in whole investigated spectrum range. Three kinds of initial liquid crystal molecules’ orientations (parallel, orthogonal, and twist) in relation to the light beam propagating in a taper were applied. The performance of a tuned cladding was studied at an electric field of the range of 0–190 V and the temperature range from 20°C up to 42°C and 59°C for 6CHBT and E7, respectively. The induced reorientation of liquid crystal molecules was measured at a broad wavelength range (550-1550 nm).

1. Introduction

Nowadays, the world without liquid crystals’ (LCs) technology is difficult to imagine. They have a lot of applications, for example, in LC displays [1], programmable lasers [2], and LC tunable filters [3]. Day by day the interest of electronic industry in LC increases that makes this field of studies also very interesting for scientists. Except for a small dimension of molecules, the additional benefit of LC devices is a relatively low cost of manufacturing. It is well known that by the electrical voltage it is possible to reorient LC molecules in a predicted way [4, 5]. When director of an LC device is reoriented, its optical properties change regarding refractive index changes from ordinary to extraordinary value [6]. The above phenomena are investigated in this paper. Structure of tapered telecommunication fibers was placed in an LC between two electrodes with a different rubbing orientation in order to monitor with an oscilloscope (dynamic response) or an optical spectrum analyzer (wavelength response) changes of optic power after it passes through LC devices with a modulated electric voltage.

Tapered fibers are created in a slow stretching process at a melting temperature of the fiber. Biconical-tapered fiber created in this process is adiabatic and characterized by low losses and long taper waist. The main reason for these phenomena is a reduction in diameter of the optical fiber core and cladding and ensuring that the whole volume of a taper waist is used by the light beam [7, 8]. In this case, difference in the refractive index between the core and the cladding in this volume is irrelevant, thereby air surrounding the taper becomes its cladding [9–11]. As a result, this specific property makes modification of the boundary conditions of the electromagnetic wave propagation possible [11].

Authors’ previous studies were performed only in a visible wavelength range; however, modifications of the LC device allowed to extend measurement to the infrared range.
In this paper, the influence of using a low melting liquid mixture denoted as 6CHBT (4-[(trans-4′-n-hexylcyclohexyl]-isothiocyanatobenzene) and E7 synthesized in the Chemistry Department MUT has been described. First LC consists of a single chemical compound; the second one is a mixture of biphenylic chemical compounds [12]. Moreover, the refractive indices of these two LCs are different. For 6CHBT the maximum value of an ordinary refractive index is equal to \( n_o = 1.518 \) and an extraordinary refractive index equals \( n_e = 1.672 \), whereas for E7, \( n_o = 1.523 \) and \( n_e = 1.739 \) [12], and they are temperature dependent as shown in Figure 1. As one can see above, such critical temperature for both LC mediums are isotropic medium and steering them by electric field is impossible.

2. Materials and Methods

Tapered fibers were manufactured on the dedicated device named Fiber-Optic Taper Element Technology (FOTET) which schema is presented in Figure 2. This set-up is equipped with an automatic stretching system connected to a special antigravitation unit. Tapering process is
performed under a low-pressure burner supplied by a propane-butane-oxygen gases mixture. FOTET allows to set many different parameters, e.g., elongation velocity, flame movement, or its distance from the tapering fiber [11, 13]. Basic parameters of the tapering process, such as length and velocity of elongation, are controlled and monitored by the dedicated computer program steering the step motors’ work.

For the needs of this paper, two types of taper length of elongation were obtained, $L_{6CHBT} = 30.50 \pm 0.16 \, \text{mm}$ and $L_{E7} = 20.20 \pm 0.16 \, \text{mm}$, which correspond to the taper waist diameter, $d_{6CHBT} = 6 \pm 0.5 \, \mu\text{m}$ and $d_{E7} = 12 \pm 0.5 \, \mu\text{m}$. After the fabrication process, both taper structures have losses less than 0.5 dB for the wide spectrum range from 550 to 1550 nm. In Figure 3, there are presented photos of the bare standard telecommunication optical fiber and the tapered fiber with an elongation of 20 mm.

The prepared optical fiber taper was put on a specially prepared glass electrode covered with alignment layer and ITO (see Figure 4(a)). Furthermore, the tapered fiber has been placed close to the electrode without touching it. It is very important because the glass with ITO layer has a much higher refractive index than optical fiber ($n_{glass} = 1.46$ and $n_{ITO} = 1.98$) [14]. In order to perform measurements, three different LC cells have been prepared which differ by initial LC molecules’ orientation regarding the tapered fiber. They are called orthogonal, parallel, and twist as shown schematically in Figure 4(b). The initial LC molecules’ orientation is obtained by applying rubbing technology to a glass plate with alignment layer. For the orthogonal structure (Figure 4(b) pictures on the left side), rubbing direction is the same for the top and the bottom glass plates but orthogonal to the tapered/fiber axis. Hence, without electric field, the molecular director of the LC structure, as well as the optical axis of LC structure, is orthogonal to the taper axis. For the second one, called parallel (middle pictures in Figure 4(b)), rubbing allayment is set in two glass plates parallel to the axis of the tapered/fiber, and in this case without electric field the LC molecules’ director is parallel to the taper. For the last one, named twist (pictures on the right side in Figure 4(b)), the top glass plate has rubbing direction orthogonal whereas the bottom one parallel to the axis of a tapered/fiber. In this case without electric field the director of LC molecules continuously changes from orthogonal to parallel in respect to the tapered/fiber axis. In all three cases, after switching on the electric field, the director of LC molecules reorients to the direction which is orthogonal to surrounding substrates as shown schematically in the bottom pictures in Figure 4(b). Physically, by changing the molecules’ orientation, the different refractive index of a waveguide cladding (LC medium around tapered fiber) is achieved, which has been steering by external electric field that is investigated in the next section. It should be noticed that in our investigation we were writing about averaged refractive index, as well as averaged LC molecules’ orientation. One of the problems on which we are working is that the first line of LC molecules is always orthogonally attached to the taper. Diameter of the mentioned layer is smaller than wavelength, and we will not take it under investigation in this paper.

Thickness of the created cell is approximately equal to $d = 50 \, \mu\text{m}$ which is connected with the averaged orientation of molecules and the diameter of taper waist. Taper waist is placed in the middle between two electrodes. Additionally, to the data presented in Figure 1, Table 1 shows the properties of used LCs. According to the literature data, 6CHBT has a nematic-isotropic transition temperature equal to $T_{iso} = 40^\circ\text{C}$ [15, 16], and for 6CHBT synthesized at MUT it is equal to $T_{iso} = 43^\circ\text{C}$. In case of E7 mixture, the nematic-isotropic transition temperature is equal to $T_{iso} = 61 - 62^\circ\text{C}$ [17, 18] and synthesized at MUT $T_{iso} = 60^\circ\text{C}$.

Measures were performed in two measuring systems. The first one was used to the spectral analyzer and therefore was equipped with supercontinuum source SC450 (Fianium) and optical spectrum analyzers OSA-AQ6375 (Yokogawa) which cover the wide wavelength range from 350 nm to 2400 nm. Electric signal was triggered by generator DG-1032 (RIGOL), then amplified 20 times using amplifier A400D (FLC). The second measuring system designed to measure time response used laser, detector, and oscilloscope DSO-X 2012A (Agilent). Electric signal was triggered in the same way as in the first measuring system.

3. Results and Discussion

Applied voltage to the LC device causes reorientation of the director of LC molecules changing simultaneously the refractive index of the whole LC cladding material. Change of refractive index influences boundary condition which can
be observed as a changing output power. At $U = 0\, \text{V}$ leaking wave from the taper waist one can see the LC with a much higher refractive index than the tapered fiber. Additionally, most of the optical power is radiating out from the optical fiber due to the law of total internal refraction. Under applied electric voltage, the molecule director changes its direction to the parallel relative to the electric field lines. Furthermore, the refractive index of LC is reduced, thereby the light beam stays inside the tapered fiber. It also should be noticed that despite decreasing the refractive index, its value is still higher than the refractive index of taper waist material. In this case, we can observe a band gap propagation scheme.

Described in the previous paragraph, three kinds of rubbing of ITO alignment layer were investigated below.

**Table 1: The properties of 6CHBT and E7.**

| Name | Structure | $T_{\text{iso}}$ (°C) | $n_0^*$ | $n_e^*$ | $\varepsilon_{||}^{**}$ | $\varepsilon_{\perp}^{**}$ |
|------|-----------|---------------------|---------|---------|-------------------|------------------|
| 6CHBT | $\text{C}_6\text{H}_{13}$ | 43 | 1.518 | 1.672 | 12.0 | 4.3 |
| E7 | $\text{CN}_5\text{H}_{11}$ | 60 | 1.523 | 1.739 | 6.0 | 19.7 |

*Measured at 25°C for sodium line D; **measured for $f = 1\, \text{kHz}$ at 25°C.
Depending on applied rubbing, the wavelength range changes even from the infrared (IR) to the visible (VIS) part. Therefore, the measurements of spectrum have been performed for two ranges IR ($\lambda = 1300-1550$ nm) and VIS ($\lambda = 550-1050$ nm). Figure 5 presents the spectral dependences of LC device with 6CHBT and E7 for orthogonal, parallel, and twist molecules' orientation. For all figures, 190 V current with and without modulation of 2 Hz have been applied.

For orthogonal rubbing of the ITO layer, at the initial state with $U = 0$ V, the long axes of the molecules stay orthogonal to the tapered fiber and the light beam propagated in it. In this case, refractive index of cladding in averaging can be treated as $n_e$ of LC. For this type of rubbing, the measured wavelength contains in the telecommunication range of 1300-1550 nm for both fillings of liquid crystal 6CHBT and E7. The use of parallel or twist rubbing causes damping of the signal with a different degree, depending on the type of LC applied in cell. The measured wavelength range for E7 is shifted to VIS range and near IR range. Compared with the E7 mixture, the 6CHBT mixture causes a high attenuation of both ranges VIS and IR which make it impossible to record any signal (see data presented in Table 2). Therefore,

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**Table 2: Signal attenuation for two used LC mixtures for LC cells without applied voltage.**

| LC mixture | Device type | $P$ for $\lambda = 530$ nm (dBm) | $P$ for $\lambda = 1550$ nm (dBm) |
|------------|-------------|---------------------------------|---------------------------------|
| 6CHBT      | Orthogonal  | -4.50                           | -36.30                          |
|            | Parallel    | -14.00                          | -60.00                          |
|            | Twist       | -17.30                          | -60.00                          |
|            | Orthogonal  | -0.21                           | -9.72                           |
| E7         | Parallel    | -32.70                          | -36.50                          |
|            | Twist       | -22.50                          | -18.20                          |

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Figure 5: Spectral analysis for LC device: (a) orthogonal device contained 6CHBT; (b) orthogonal device contained E7; (c) twist device contained E7; (d) parallel device contained E7.
all measurements were performed only for orthogonal 6CHBT and orthogonal, parallel, and twisting E7 cells. As it can be observed for all cases, the applied modulation causes a decrease of power in a time of switching on reorientation of about 5-10 dBm which corresponds to switch on and off of a LC mixture described earlier.

What is interesting in the construction of optical fiber devices proposed by authors, the response of device is being
observed for low electric voltage values of $U = 60\,\text{V}$. Based on the previous spectrum analyses, appropriate light sources were selected for all types of LC devices. Changes of the output optical power in LC devices were measured (for a light beam wavelength $\lambda = 1550\,\text{nm}$ and power $P = 1\,\text{mW}$) using the oscilloscope. Figure 6 presents the results for 6CHBT and E7 cells with orthogonal rubbing for the voltage range of $U = 60-190\,\text{V}$ and different modulation from 1 Hz to 10 Hz. As it can be observed, due to increasing applied voltage, the power of propagated wave is also increasing to the level of 190 V. Over this voltage the increase output power is very small. We can also observe that for all modulation LC molecules reproduce the applied signal very well.

As mentioned before, during the measure time response of twisted and parallel cells, it was necessary to change the light emitters for the visible range. Figures 7 and 8 show the obtained results for two different types of cells.

Increasing of the electric voltage also like in orthogonal orientation causes an increase of the output optical power after passing through an LC device. The highest power has been reported for E7 twisted cell and it was equal to $P_t = 4.5\,\text{V}$ for voltage $U = 190\,\text{V}$. For the paralleled LC device filled with E7, the reported power is about 100 times lower and it is equal to $0.045\,\text{V}$. In both cases, LC molecules introduced smaller delay in answer courses than in orthogonal. In most courses, there can be an observed additional perturbation which can be a result of multimodal propagation of a visible wave in a standard telecommunication fiber. Comparing the results of the orthogonal cell, the registered level of output signal measured of the LC device

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**Figure 7:** Response of the LC device filled with E7 having parallel rubbing for different frequency of electric field: (a) 1 Hz; (b) 2 Hz, (c) 5 Hz, and (d) 10 Hz for voltage contained in the range of 6–190 V. The laser with $\lambda = 532\,\text{nm}$ has been applied.
Figure 8: Response of the LC filled with E7 having twist rubbing for different frequency of electric field: (a) 1 Hz; (b) 2 Hz, (c) 5 Hz, and (d) 10 Hz for voltage in the range of 60–190 V.

Figure 9: Courses of answer/response of LC device showing the delay of switching on and off the modulation (a) and answer/response of different shape of modulation square, sine, and ramp (b).
filled with 6CHBT are 8 times higher than the one filled with E7 and equal to $P_{6CHBT} = 0.71 \text{ V}$ and $P_{E7orthogonal} = 0.092 \text{ V}$, respectively.

As can be observed in Figure 9, the applied frequency of electric field has a “destructive” influence on the LC. The signal decreases comparing to the signal without applied frequency of voltage modulation as shown in Figure 9(a). In Figure 9(b), there are presented answers of LC device for different shapes of modulation ramp, square, and sinusoidal. It can be noticed that for ramp modulation acquired signal is much higher than for ramp and sinusoidal. For ramp and sinusoidal orientation, the delay of switching on and switching off is not observed. Additionally, at the obtained curves, the changes in the shape of the signal can be observed. For modulations equal to 1 Hz and 2 Hz, the shape of the answer signal follows the modulated signal. On the other hand, for modulations contained within the range of 5 Hz to 10 Hz, the response time curve becomes smaller. For all modulation frequency, the time response of LC devices was calculated and presented in Table 3 and in Figure 10.

It can be observed from above that for parallel and twist initial rubbing the modulation in the range of 1–10 Hz is very well mapped by the LC device. As it was expected, the response time shows decreasing trend with increasing frequency modulation of switching on and switching off times. The longest response time was reported for the orthogonal

### Table 3: Calculated time response of LC devices.

| Liquid crystal device | 1 (Hz) On | 1 (Hz) Off | 2 (Hz) On | 2 (Hz) Off | 5 (Hz) On | 5 (Hz) Off | 10 (Hz) On | 10 (Hz) Off |
|-----------------------|----------|-----------|----------|-----------|----------|-----------|-----------|-----------|
| 6CHBT Orthogonal      | 12.8     | 7.23      | 11.7     | 7.20      | 10.3     | 5.17      | 7.83      | 5.17      |
| Orthogonal Parallel   | 5.41     | 7.67      | 4.83     | 7.67      | 3.96     | 3.83      | 3.90      | 5.43      |
| E7 Parallel           | 2.50     | 5.00      | 2.33     | 3.00      | 1.67     | 2.33      | 1.10      | 2.23      |
| Twist                 | 5.40     | 5.00      | 4.17     | 5.00      | 1.67     | 2.17      | 1.70      | 1.43      |

*Measurement error is below 5%.

![Figure 10: Response time of LC device.](image-url)
initial orientation of LC molecules filled with 6CHBT and E7. The twisted cell has the shortest response time of the proposed type of orientation.

4. Conclusions

In this paper, the LC device based on optical fiber taper was shown. Three kinds of ITO alignment layer orientation named orthogonal, parallel, and twist were investigated. From the results, it can be noticed that depending on applied rubbing, the wave range changes. Orthogonal LC device works in the infrared range, and for parallel and twist LC devices the operation range is shifted to the visible region. Measurement mixture 6CHBT works only for orthogonal rubbing; for others, we do not observed any propagation. For E7 mixture, the shift described above was observed. Also, it can be noticed that depending on rubbing orientation and applied LC mixture, a different value of transmitted light, value of attenuation is obtained. For a device with 6CHBT mixture, a higher output power than for E7 mixture was observed. This is the result of better fitting the refractive index of this mixture to the fiber. In all cases, propagation in this device is provided by the bend gap phenomenon. Refractive index of LC mixtures is higher than refractive index of taper waist. Also, modulation frequency influences time delay for LC device. Increasing frequency in all kinds of applied rubbing, delay time of switching on and switching off is decreasing. For parallel and twist initial orientation of molecules decreasing is much smaller than for orthogonal. The relatively high saturation cutoff voltage is connected with a relatively high LC cell width (50 μm). However, because the steering voltage for LC cell decreases with square of reduction of its width, we believe that for optimized cell thickness equal to 20 μm it should be in a range of 30 V.

This paper shows the possibilities of new kinds of hybrid devices in which the wave propagated in an optical fiber can be modulated and changed by cladding exchange in a taper waist. Selection of different LC mixtures with matched refractive indices and attenuation for chosen wavelength allows manufacturing new kinds of devices for transmission wave or different factors’ detection.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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