Tapered fiber liquid crystal hybrid broadband device

J E Mos1 ©, K A Stasiewicz1 ©, K Garbat2, P Morawia1k, W Pieck1 and L R Jaroszewicz1

1 Military University of Technology, Institute of Technical Physics, Warsaw, Poland
2 Military University of Technology, Institute of Chemistry, Warsaw, Poland

E-mail: karol.stasiewicz@wat.edu.pl

Received 19 April 2018, revised 21 September 2018
Accepted for publication 10 October 2018
Published 6 November 2018

Abstract

This paper presents the results of design, manufacturing and characterization of a hybrid broadband filter based on taper technology and liquid crystalline structure using a standard single mode fiber. A liquid crystal mixture, denoted 1550*, was designed for the electrically driven modulation of an electromagnetic wave at visible range. The main reason for using a biconical optical fiber taper as a core is surrounding it by a liquid crystalline medium providing the possibility to control an effective refractive index of fiber cladding. Two kinds of rubbing, orientation parallel and orthogonal to the taper axis, were applied. The performance of a tuned optical fiber taper technology is relatively easy and gives the possibility for continuously monitoring the changes in the light propagation through the fiber during element manufacturing [12]. The tapering process allows for changes to the optional boundary condition of fibers without needing a new one to be drawn. The theoretical and experimental investigation of changing core and cladding diameters, change of optical beam parameters, as well as a refractive index profile along the taper region [8] shows that there is the possibility to use a biconical optical fiber taper as a basic element to manufacture advanced devices [13–16]. Commonly known studies on the tapered optical fiber with liquid crystal cladding require high voltage driving (over 350 V), which was the result of a reasonable cells’ gap of over a dozen micrometers [3]. All measurements reported were made at a single wavelength.

Since the taper process allows a diameter of the waist below a few microns with acceptable propagation losses in the range of 0.2–0.5 [dB] to be obtained, the possibility of connecting such a modified optical fiber, with a liquid crystal structure and operating at a voltage range much below 200 V, another way to obtain satisfactory results is to implement the optical fiber taper technology [8–12]. Compared to PCF technology, the tapering technology is relatively easy and gives the possibility for continuously monitoring the changes in the light propagation through the fiber during element manufacturing [12]. The tapering process allows for changes to the optional boundary condition of fibers without needing a new one to be drawn. The theoretical and experimental investigation of changing core and cladding diameters, change of optical beam parameters, as well as a refractive index profile along the taper region [8] shows that there is the possibility to use a biconical optical fiber taper as a basic element to manufacture advanced devices [13–16]. Commonly known studies on the tapered optical fiber with liquid crystal cladding require high voltage driving (over 350 V), which was the result of a reasonable cells’ gap of over a dozen micrometers [3]. All measurements reported were made at a single wavelength.

In previous decades the development of optical fiber technology provided the possibility to manufacture small active functional elements with a diameter as small as several micrometers [1]. The fundamental requirement for all above elements is protection of light propagation inside the structure and highly replicable element manufacture. In this way, such in-line elements are very useful, especially for the miniaturization of a designed system. There are many ways in which such results can be obtained, including the widely described investigations that focused on photonic crystal fibers (PCF) [2–5]. Unfortunately, this technology is still expensive due to the cost of PCFs. It also requires the use of advanced technology to make the connection of a PCF with the most of the standard measurement equipment available [5]. Much of the work in PCF technology has concentrated on filling the air holes with different types of materials, like liquid crystals [6], but it also requires an additional set-up for filling holes [7].
gives a new opportunity to develop advanced photonic devices incorporating light guiding elements.

This paper presents the results of design, manufacturing and characterization of a tunable broad band filter based on a biconical optical fiber technology [8] and dedicated liquid crystals’ (LCs) structures [9, 10]. The manufactured device is made with a low cost technology using a standard single mode fiber. The construction of an LC cell which allows the taper waist to be placed inside the cell, has been developed at the Institute of Applied Physics of the MUT. As the main problem, which has been solved, was protection against the mechanical damage and reduction of attenuation for a structure which is placed in a liquid crystal cell with gap below 30 μm. For a structure of such dimensions, a smaller value of electric field occurs, which is necessary for reorienting the molecules. In the first part of the paper the applied technology of manufacturing optical fiber tapers, as well as properties of the used LC are presented. The second part describes an LC tunable filter device with its experimental investigation of transmission characteristics in a wide range of wavelengths, between 350 and 2400 nm. Supercontinuum as a source and optical power meter and optical spectrum analyzer as detectors were used. In this part an investigation of device speed operation for changes of the electric field is presented at the full temperature domain, as well. The conclusions of the presented experimental results contain additional information about the advantages and future research of devices which should be provided.

The set-up for the manufacturing of an advanced optical fiber taper elements used a fiber elongation process with the assistance of a low-pressure gas burner. The process of elongation is conducted at a melting temperature that is obtained by heating part of the fiber region in a propane-oxygen flame. The fiber elongation is made by an axial stretching at two points located symmetrically to the heating point. Figure 1 presents the functional scheme of the set-up named FOTET II (Fiber-Optic Taper Element Technology) which was developed at the Institute of Technical Physics, Military University of Technology (MUT).

The main advantage of this arrangement in comparison to commercially available stations, is the possibility of manufacturing different biconical tapers (with the length of the taper main region from points up to 200 mm, and the waist diameter below a single micrometer) [8] for all types of fibers, including standard telecommunication fibers, photonic crystal fibers, as well as plastic ones.

The process of fiber elongation can be controlled by the flame movement connected with the speed of two stretching engines. The system of a taper elongation was designed to avoid damage to the fiber (especially breaking) and to get a perfect biconical taper. This was achieved by permanent monitoring of the light propagation through the fiber and by the application of a special anti-gravitation unit for controlling the distance of the flame from the taper.

For the purpose of our investigation, the most interesting tapers are those with a long taper waist region [8]. For the manufacturing of a tunable broad band liquid crystal devices, a taper that has a whole length of elongation equal to 20.3 ± 0.5 mm was tapered. The diameter of the waist region was below 15.0 ± 0.5 μm.

Manufactured tapers characterized by very low insertion losses can be achieved by the proper shape of the whole taper region (adiabatic type), including the area of connection of an upstretched fiber with the taper waist region. The achievement of manufactured tapers were ranged from 0.2 to 0.5 [dB].

The presented idea of using tapered single mode fiber immersed in LC medium is a possible way to control losses at broad band wavelengths’ range by the applied electric field acting on an LC medium schematically presented in figure 2. For investigation, two types of glass with ITO allayment layer were used. The first LC driven element, the so-called orthogonal (ORT) one, was fabricated with a rubbing direction set orthogonal to the taper/fiber axis. In the case where there is no electric field, the molecular director of the LC structure (hence optical axis of this LC structure) is orthogonal to the taper axis. In this case, without an electric field, the molecular director as well as optical axis of the LC structure are orthogonal to the taper axis. The second is called parallel (PAR), where the rubbing allayment is set parallel to the axis of a taper/fiber, and in this case without electric field, the director is parallel to the taper (see figure 2). In both cases, after switching on the electric field the director reorients to the direction orthogonal to surrounding substrates.

The main factor affecting the parameters of light propagation in a tapered waveguide is a spatial distribution of the molecular director (hence the spatial distribution of optical indicatrix) of the LC medium. The LC director can be driven (reoriented) by the external electric field E, as well as temperature. In the manufactured device, the special LC mixture, denoted as 1550° [10], exhibiting smectic phase of B type (SmB) and the nematic one (N), at their mesogenic behavior
was used. This mixture was synthesized at the Institute of Chemistry of the MUT [10]. Important LC parameters are presented in table 1.

The LC under study was selected for the device due to its low ordinary refractive index \(n_o = 1.4618\) and low optical anisotropy \(\Delta n = 0.068\). These parameters are directly connected with taper parameter—refractive index of taper waist.

In optical fiber tapers of a micrometer size, the penetration depth of light in the cladding increases with a decrease of the whole structure diameter. As a result of this taper technology, a part of the light power is reflected with a higher frequency along the taper which causes the leaking out of the light beam outside the structure of the taper. Moreover, a reasonable part of the guided light power propagates outside of the core as an evanescent field [1]. The core diameter of tapers reported here are not large enough to propagate mods, so the whole structure of waist became a core. The surrounding liquid crystalline medium fulfills the role of a taper cladding and influences parameters of the light propagation. In this way, the opportunity to change the light propagation parameters by using a driving electric field or temperature for reorientation of LC molecules and changing the refractive index affected by a leaking light was created.

As mentioned above, two kinds of rubbing orientation PAR and ORT were used. Initial orientations of the molecular director in both cases will demonstrate different effective refractive indices which can be modulated with the external electric field \(E\). Transmission characteristics for the applied LC 1550° [10], which operates at a visible 500–750 nm and near infrared 750–1200 nm ranges without absorption bands in two LC structures of ORT and PAR, are presented in figures 3 and 4.

It is worth noting that for a PAR structure the graph shape for low voltage is unmodulated (see figure 4). A driving voltage over 80 \(V\) and applying to the liquid crystal cell causes reorientation of the molecular director what induces arising of damped and strengthened bands in the whole range of 550–1200 nm. This can be seen in a form of a curve modulation. A shape of the observed bands is driven with an LC structure affected with the applied voltage. For an ORT structure, the obtained narrow transmission range of 550–950 nm exhibits a steep decrease of the transmitted beam power with increasing wavelength. At a driving voltage over \(c.a. 80 \, V\), an ORT cell starts to transfer modulation of applied electric field.

For both investigated structures (ORT and PAR), the driving of the molecular director can be observed at the threshold voltage of 80 \(V\). The threshold voltage is mainly connected with the taper cell gap and diameter.

The second part of the study was devoted to an observation of the simultaneous influence of temperature and electric field on the light transmitted through the proposed devices.

In figures 5 and 6, an influence of distribution of the molecular director in the LC cladding regarding temperature at constant electric field applied to devices can be observed.

---

**Table 1. The electro-optical properties of 1550° mixture [9, 10].**

| Property                     | Symbol, units | Value          |
|------------------------------|---------------|----------------|
| Melting temperature          | \(T_m\) (°C)  | \(<−16\)       |
| Isotropic temperature        | \(T_{iso}\) (°C) | 79.2           |
| Dielectric anisotropy        | \(\Delta \varepsilon\) (1 kHz) | 3.1            |
| Parallel permeability        | \(\varepsilon_{||}\) (1 kHz) | 5.25           |
| Perpendicular permeability   | \(\varepsilon_{\perp}\) (1 kHz) | 2.15           |
| Optical anisotropy           | \(\Delta n\) (589 nm) | 0.068          |
| Ordinary reflective index    | \(n_o\) (589 nm) | 1.4618         |
| Extraordinary reflective index| \(n_e\) (589 nm) | 1.5276         |

---
As one can see, temperature change does not significantly influence transmitted power because, simultaneously, the courses shape is preserved.

Transmission of the applied modulated frequency is observed for both ORT and PAR structures. At lower temperatures, a PAR LC structure transfers strongly the modulation of applied electric filed, whereas for an ORT structure its oscillations are not significantly visible. At higher temperatures, the modulation of transmitted power gets stronger. At the PAR structure, driving electric field oscillations are transferred at all temperatures which is apparently connected with the value of the refractive index of the LC structure. This is observed in a form of the pronounced modulation of the light transmitted through the fiber and taper. For the PAR structure, it can be seen that a modulated waveband is broader at the lowest temperatures (450 nm—700 nm at 20 °C), while it expands to over 1150 nm at the highest temperatures (c.a. 50 °C). For the ORT structure over 40 °C (close nematic—isotropic phase transition, where Δn strongly decreases) the propagating wave range is between 470 nm to 1130 nm. At lower temperatures (below 30 °C) the waveband of the modulated transmission ends below c.a. 1000 nm.

Generally, a higher transmitted power (by c.a 10 dBm) is observed in the case of the ORT structure what is strictly connected with the special distribution of LC medium properties. The LC structure apparently influences the wave range. When the temperature increases, the refractive index anisotropy of the LC medium declines what influences broadening of a transmitted wavelength. This effect is mostly observed close to the clearing temperature T_{isc}. When temperatures are higher than T_{isc} the LC medium is at the isotropic state and the electric field modulation is not transferred to the power transmission through the taper.

In figures 7 and 8 time courses of devices are presented in response to the applied electric field.

As it can be noticed in the ORT structure (LC cell with a taper) the received answer possesses a time delay regarding the applied filed in both switch on/off times, while at the PAR structure the time delay in the signal answer is much shorter.

Based on the observations mentioned above, one can conclude that there is the possibility to build a tunable filter in a wide wavelength range steered by low electric field. The proper initial molecules’ orientation (parallel or orthogonal) protected a different operation wavelength for the device, as well as the power level of transmitted light. The results obtained confirm that for the PAR structure, the filter gives the best results and exhibits the shortest switching-on/off times. The shortening of the switching time and the reduction of driving voltages of the ORT and PAR structures can be done by lowering of the cell gap. Such results can be obtained simply, in taper technology, by reducing the taper waist diameter to below 10 micrometres. Applied in the experiment, the LC mixture secures the proper filter operation for an electric field with an 80 V amplitude range. Additionally, thermal characteristics showed the possibility that structure losses could be minimalized by the proper choice of the operation temperature range. From our observation and earlier research, we can conclude that there is the possibility to make such device that operates in a chosen wavelength range by applying special LC mixtures on a thin taper.

**Acknowledgments**

This work was carried out in 2017 under the financial support of the Polish Ministry of Sciences and Higher Education Statutory task PBS-23-652 and National Science Centre task Miniatura 2017/01/X/ST7/00860, PBN 07-160.
References

[1] Sumetsky M and Tong L 2010 Subwavelength and Nanometer Diameter Optical Fibers (Zhejiang: Zhejiang University Press) pp 4–11
[2] Birks T A, Knight J C, St P and Russell J 1997 Endlessly single-mode photonic crystal fiber Opt. Lett. 22 961–3
[3] Veilleux C, Lapierre J and Bures J 1986 Liquid-crystal clad tapered fibers Opt. Lett. 12 773–5
[4] Magi E C, Steinvurzel P and Eggleton B J 2004 Tapered photonic crystal fibers Opt. Express 12 776–84
[5] Zhu S, Pang F and Wang T 2011 Single-mode tapered optical fiber for temperature sensor based on multimode interference SPIE—OSA-IEEE 8311 83112B
[6] Wolinski T R, Szaniewska K, Ertnan S, Lesia P, Domanski A W, Dabrowski R, Nowinowski-Kruszelnicki E and Wojcik J 2006 Influence of temperature and electrical fields on propagation properties of photonic liquid crystal Meas. Sci. Technol. 17 985–91
[7] Przybysz N, Marć P, Tomaszewska E, Grobelny J and Jaroszewicz L R 2017 Pure and Au nanoparticles doped higher alkanes for an optical fiber temperature threshold sensor Proc. SPIE 10231 1023125–31
[8] Stasiewicz K A, Krajewski R, Jaroszewicz L R, Kujawińska M and Świłło R 2010 Influence of tapering process on changes of optical fiber refractive index distribution along a structure Opto-Electron. Rev. 18 102–9
[9] Kędzierski J, Garbat K, Raszewski Z, Kojdecki M A, Kowionski K, Jaroszewicz L R, Miszczyk E, Dąbrowski R, Zieliński J and Piecck W 2014 Optical properties of a liquid crystal with small ordinary and extraordinary refractive indices and small optical anisotropy Opto—Electron. Rev. 22 162–5
[10] Dąbrowski R, Garbat K, Urban S, Wolński T R, Dziaduszek J, Ogrodnik T and Siarkowska A 2017 Low-birefringence liquid crystal mixtures for photonic liquid crystal fibres application Liq. Cryst. 44 1–18
[11] Dąbrowski R, Dziaduszek J, Stolarz Z and Kędzierski J 2005 Liquid crystalline materials with low ordinary index J. Opt. Technol. 72 662–7
[12] Birks T A and Li Y W 1992 The shape of fiber tapers J. of Lightwave Techn. 10 432–8
[13] Kieu K Q and Mansuripur M 2006 Biconical fiber taper sensors IEEE Photonics Technology Lett. 18 2239–41
[14] Lu P, Men L, Sooley K and Chen Q 2009 Tapered fiber Mach–Zehnder interferometer for simultaneous measurement of refractive index and temperature Appl. Phys. Lett. 94 131110
[15] Harun S W, Lim K S, Damanhuri S S A and Ahmad H 2011 Microfiber loop resonator based temperature sensor J. European Opt. Soc. 6 11026-1-11026-4
[16] Tian Y, Wang W, Wu N, Zou X and Wang X 2011 Tapered optical fiber sensor for label-free detection of biomolecules Sensors 11 3780–90