ISSN (e): 2250 – 3005 || Volume, 05 || Issue, 09|| September – 2015 ||
International Journal of Computational Engineering Research (IJCER)

A Review on the Progression in Liquid-Crystal Optical Fibers and Their Uses in Photonics

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Abstract: *The aim of this paper is to review and demonstrate a recent progress in liquid-crystal optical fibers and their applications in photonics. The review starts from early works with classical optical fibers modified with liquid crystals and ends up with the latest achievements in the field of photonic liquid crystal fibers (PLCFs). Potential applications and future perspectives of PLCFs are shortlysummarized.*

Index Terms: *Liquid crystals, Optical fiber devices, Optical fiber sensors*

I. INTRODUCTION

LIQUID crystals (LCs) have been successfully usedforthelast decades both in fiber optics and photonicstoinfiltrateinitially hollow-core optical fibers [1] and then microstructured photonic crystal fibers (PCFs) [2].

Optical fibers with liquid crystals belong to complex mediums that proved to be greatly attractive for various applications because these materials present unusual anisotropic physical properties. Scientists have reported liquid crystal optical fibers (LCFs) of different forms of construction in respect of geometry as well as material distribution. LCFs may consist of liquid crystals either in the fiber core [1], [3] or in the cladding of the fiber [4]–[6]. High optical and electric anisotropies of liquid crystals make them perfect materials in a wide range of applications and in particular in electric field sensing as the macroscopic optical properties of liquid crystals can be altered under the influence of an external electric field [7], [8].

Optical wave-guiding in a PCF is governed by one of two principal mechanisms responsible for light trapping within the core [9]. While the first one is a classical propagation effect based on the so called "index guiding" phenomenon, which is well known and similar to the wave guiding effect within a conventional fiber, the second one, referred to as the photonic band gap (PBG) effect, occurs if the refractive index of the core is lower than the mean reflective index of the cladding region.

Submitted on……

The authors gratefully acknowledge support of the Polish National Science Center under the Grant NCN 2015/19/B/ST7/03650. K.R. would like to acknowledge support from the Polish National Science Centre under the grant no. DEC-2013/11/B/ST7/04330.

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Infiltrating the air-holes with different materials allows for creation of a special class of infused PCFs with enhanced optical properties. In this context, the application of liquid crystals has gained particular attention, resulting in new highly-tunable photonic structures, called photonic liquid crystal fibers (PLCFs) [10]–[12], in which light propagation conditions are determined by both: a LC “guest” material and by a PCF “host” structure. PLCFs benefiting from a merger of passive PCF host structures with active LC guest materials are responsible for the diversity of new propagation, spectral, and polarization properties.

Light guiding dynamics, including switching between both mechanisms of propagation, can be simply achieved in PLCFs thanks to the unique properties of an infiltrating LC. Due to high electro-, magneto-, and thermo-optic responses of LCs, their refractive indices may be relatively easily changed either by temperature or external physical fields. In this context, thermal and electrical tuning along with unusual spectral and polarization properties of PLCFs have been studied over the last few years [12]–[20].

After demonstration of tunable PBGs using thermo-optic tuning of the LC [2], one of the most spectacular phenomena was the successful realization of temperature-induced switching between two mechanisms of light propagation [13].

Due to high sensitivity to external conditions, PLCFs were also used for switching and sensing applications, e.g. [21]–

[23] when subjected to the influence of temperature, electric field, or hydrostatic pressure. The resultant devices can find potential applications as threshold sensors, in birefringence measurements, as temperature and pressure sensors, all-optical multi-parameter sensors, tunable filters and all-fiber attenuators. For this purpose, PCFs infiltrated with doped nematic LCs (including cholesteric dopant mixtures, azo- compounds, dyes, and nanoparticles) can be also successfully used [24].

Moreover, intensive work on long-period fiber grating sensors based on LC micro-structures has been initiated [25], [26].

In addition, research on high-index-glass-based PLCFs has been also performed [27]. It allows for index-guiding propagation in a wide range of LC guest materials and enables continuous and repeatable broad-band birefringence tuning, as well as continuous adjustment of polarization-dependent losses (that can be potentially used for the development of a new type of all-in-fiber polarization controllers).

The aim of this paper is to review and demonstrate progress in liquid-crystal fiber optics and photonics, in particular the most spectacular features of liquid crystal-core fibers and photonic liquid crystal fibers that over the last decades have been used for dynamically controlled and tunable photonic devices.

The paper is organized as follows: Section II presents liquid-crystal guest structures for optical and microstructured fibers whereas Section III will discuss classical optical fibers modified with liquid crystals including optical fibers with liquid-crystal cladding and with liquid crystalline cores. A special attention is devoted to polarization properties of optical fibers with an elliptical liquid-crystalcore.

Section IV will discuss in details the progress in fabrication methods of photonic liquid crystal fibers, mechanisms of light propagation, spectral properties of photonic liquid crystal fibers, electrical tuning of polarization properties, all-optical modulation in photonic liquid crystal fibers, and nanoparticles-enhanced photonic liquid crystal fibers.

Potential applications including prospective photonic devices on PLCFs and future perspectives (Section V) will summarize the paper.

II. LIQUID-CRYSTAL (LC) GUEST STRUCTURES FOROPTICAL AND MICROSTRUCTUREDFIBERS

Liquid crystals belong to a special class of organic materials sharing the properties of solid crystals and liquids [28], [29]. Among the four main groups of liquid crystals discovered so far, which are: thermotropic, lyotropic, photochromic and polymeric LCs, the first one has been studied the most extensively and their practical applications have reached a mature stage. Thermotropic LCs are achieved during the heating process of some specific compounds or mixtures going through a series of phase transitions from solid through liquid crystalline phases and reaching eventually an isotropic liquid state. They can exist in nematic and smectic phases: as well in their chiral modifications.

Nematic liquid crystals (NLCs), exhibiting long-range molecular orientational are the most widely used in photonic applications and they are typical guest structures for optical and microstructures fibers. The average molecular orientation in NLCs is described by a dimensionless unit vector $\boldsymbol{n}$, called the director. Typical NLC textures to be achieved in a confined cylindrical geometry that could be considered for component capillaries and fibers themselves are: planar, radial, and escaped radial (known also as axial or splay-type). Such anticipated equilibrium configurations are strongly dependent on capillary geometry (size), director orientation along cylindrical boundaries, anchoring strength, and material properties of LC. It has been experimentally proven that in capillaries with the radii of few microns, which is typical for PCF structures, that planar texture, with NLC molecules aligning along the fiber axis, is commonlyachieved.

NLCs are characterized by significant inherent anisotropy of physical properties, as well as capability of changing their molecular orientation with the use of external fields and factors. Their physical properties, such as e.g. refractive indices, dielectric and elastic constants as well viscosities strongly depend on temperature. Particularly, in the proximity of the clearing point, which corresponds to the nematic/isotropic phase transition, the thermo-optic coefficient is significantly high, which is a great advantage in the sense of thermal tunability of NLC-based photonic devices. On the other hand, reorientation of LC molecules under the application of an electric, magnetic or optical field (above the Fredericks transition threshold in specific configurations [29]) may result in significant changes in LC optical properties due to the substantial birefringence of LCs. It means that the field- induced director reorientation may cause a large phase change in an optical field propagating through a LC. It may be manifested as pure phase modulation without changing the polarization state, phase retardation or polarization rotation, depending on the initial and resultant alignment of the director. Dramatic changes in light propagation may be also achieved due to nonlinear effects related to reorientational and/or thermal mechanisms of nonlinearities in NLCs [30], [31]. Importantly, nonlinear effects can be observed in NLC even with CW laser sources, at variance with many other nonlinear dielectrics often requiring pulsedexcitations.

All above-mentioned features of NLC make them perfect candidates as constituent elements and components for multifunctional, highly-tunable photonic devices. In particular, the main advantage of NLCs application in fiber optics stems from (i) the possibility of dynamical changes in light propagation by applied fields and factors obtained due to adjusted diffraction and dispersion properties and (ii) enhanced nonlinear properties, typical ofNLCs.

The ceaseless progress in the synthesis of novel LC materials results in compounds and mixtures with revised physical and chemical parameters, such as e.g. lower viscosity and higher birefringence, extending thus tunability and applicability of fiber-based photonic devices. New materials, characterized by unique chemical and physical properties, provide additional possibilities of potential applications. Apart from nematics, other possible materials in the form of polymer-stabilized, dye- and nanoparticle-doped LCs, as well as blue phases, are on the way of further development and progress in liquid-crystal fiber optics and photonics.

III. CLASSICAL OPTICAL FIBERS MODIFIED WITHLIQUID CRYSTALS

A. *Optical fibers with liquid crystallinecores*

In modern optical fiber systems there has been a general tendency to replace optical bulk elements by equivalent all- fiber realizations. A significant advantage of fiber-optic liquid-crystal devices is the fact that an optical signal can be held all the time inside an optical path whereas the modulation of intensity, phase or polarization can be accomplished due to the presence of a liquid crystal. In addition, the predominant feature of liquid crystals is that they are extremely sensitive to any external fields and perturbations. Consequently, over the last decades much research effort has been devoted to exploring the combined use of optical fibers and liquid crystals. In initial studies of waveguide structures, liquid crystals were used both as the fiber core [4] and fiber cladding [6].

Hollow-core fibers were initially used as a guest medium for liquid crystal infiltration. Early experimental demonstration of light propagation in liquid crystal-core optical fibers (LCFs) obtained by infiltrating hollow-core fibers (capillary tubes of radii between 5 and 30 microns) with a low-birefringence nematic liquid crystal (cat. No. 1100, Military Univ. of Technology, Poland) was reported two decades ago [32]. In theory, the propagation properties of the TE01 and TM01 modes have been analyzed in the waveguide composed of a low-birefringence nematic liquid crystal acting as an optical-fiber anisotropic core characterized by an index ellipsoid. It was shown that for smaller diameters of the liquid crystal-core, the TE01 mode was guided while TM01 was the leaky mode although for bigger diameters the differences between both modes decreased. The experimental results were compared with theoretical calculations in view of some typical optical fiber parameters such as e.g. numerical aperture (NA), suggesting a great potential of liquid crystal-core fibers for environmental sensing. Since the liquid crystalline-core fiber is characterized by an index ellipsoid, it can serve as a fiber with easily controlled birefringence. Consequently, external stresses modify propagation properties of the liquid crystalline fiber due to reorientation of liquid crystal molecules resulting in sensing possibilities. The LCF was used for high pressure sensing in an all-optical configuration, where light did not leave the waveguide path[3].

B. *Cylindrical waveguides with liquid-crystalcladding*

An interesting approach to cylindrical waveguides with liquid crystals was studied both theoretically and experimentally in [5], [6]. A low-birefringence nematic liquid crystal mixture (Merck, cat. No 14616) was characterized by refractive indices tuned to core and cladding indices of a single-mode fiber operating at the 633 wavelength as follows. The core and cladding had diameters of 4 and 125 μm and refractive indices of 1.462 and 1.458, respectively. The ordinary index and extraordinary index were given as 1.457 and 1.5037, respectively, at a wavelength of 509 nm and a temperature of 25°C. The geometry of the fiber cell is shown in

Fig.1.
The authors [6] studied the propagation behavior of the four lower-order modes, HE11, TE01, TM01, and HE21, in a radially

TE01 mode was separated from the leaky HE11, TM01, and HE21modes.

The use of liquid-crystal cladding has a significant advantage in comparison to liquid crystal-core fibers since in the first case light is being propagated in the glass core thus limiting losses that are present in liquid crystalline cores. That is why future new liquid-crystal infiltrated fibers based on photonics crystal fibers that have appeared since 2003 [2] are using generally solid-core PCFs and the role of LCs is to modify/tune the parameters of the propagating light with a limited influence on fiber losses.

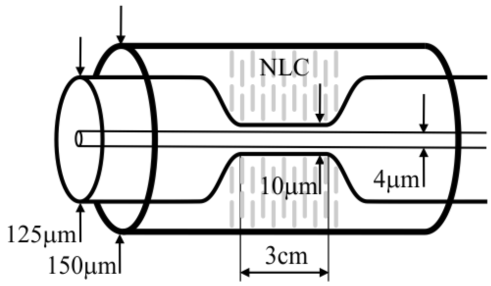

Fig. 1. A single-mode fiber operating at the 633 wavelength with liquid-crystal cladding: a short section (3 cm) of the stripped fiber was etched and clad with a low-birefringence nematic liquid crystal (Merck, cat. No 14616) (as described in[6]).

C. Polarization properties of elliptical liquid-crystal core optical fiberwaveguides

In order to control the polarization properties of the lowest- order LP modes within a liquid crystal-core optical fiber, an elliptical-core cylindrical waveguide was proposed and manufactured [33]. The elliptical-core (4*x*18μm, Fig. 2) optical fiber was filled with specially designed low- birefringence liquid crystals with a homogeneous transverse orientation of the LC molecules. The low-birefringence LC mixtures (cat. nos. 1333 and 1335-1) synthesized for the first time at the Military Univ. of Technology, Warsaw, Poland had their ordinary (no) refractive indices below the refractive index (n = 1.4580 at λ = 583 nm) of the fused silica in a certain temperature range. Since both refractive indices (ordinary and extraordinary) of the LC are thermally dependent, at a certain temperature range the elliptical-core LCF could propagate only the light polarized along the major x-axis of the ellipse. Consequently, the elliptical-core LCF exhibited single- polarization propagation due to the fact that the modes associated with polarization along the major y-axis of the ellipse are radiated out of the fiber (the LC ordinary refractive index was lower than the refractive index of silicacladding).

anisotropic cylindrical waveguide with liquid crystal cladding. The effective cylindrical waveguide constituted a doubly-clad fiber with an isotropic core and inner cladding and a radially anisotropic outer cladding made of low-birefringence nematic liquid crystal. It was theoretically demonstrated and experimentally confirmed that in such a structure the guided

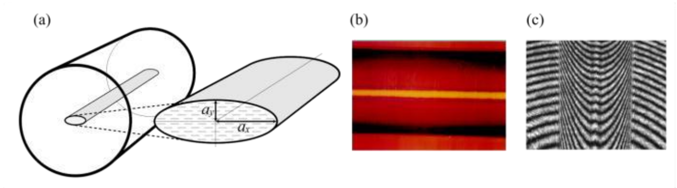

Fig. 2 Elliptical-core liquid crystal fiber a) LC molecules transversely oriented inside the core; b) observation under polarizing microscope between the crossed polarizers confirming uniformity of the molecular orientation within the LCF; c) interferogram of the core area [33]

Specially drawn hollow-core fibers were initially treated by a polyimide solution (PI TH-20) then heated and cured, and finally filled by a long-term capillary action with a low- birefringence liquid crystal mixture. The whole fill-up process was controlled under the polarizing microscope. Fig. 2b presents photographs of the LCF under the polarizing microscope between the crossed polarizers indicating the homogenous orientation of the molecules perpendicular to the fiber axis (*z*) and Fig. 2c presents an interferogram that confirmed transverse molecular distribution within the elliptical core of the LCF.

The elliptical-core liquid crystal fibers were subjected to the influence of an external electric field, temperature, and hydrostatic pressure and their experimental polarization characteristics were obtained. The results indicated a possibility of single-polarization propagation within the liquid crystal fiber suggesting a great potential of liquid crystal-core fibers for multi-parameter sensing. The elliptical-core LCF is a unique example of a single-polarization multimode optical fiber.

I. PHOTONIC LIQUID CRYSTALFIBERS

A. Fabrication methods

There is a very large diversity of types of photonic crystal fibers and microstructured optical fibers [9], [34], [35]. In general, almost any of them can be successfully applied to obtain photonic liquid crystal fibers (PLCFs) with the only exception of all-solid photonic crystal fibers [36] which have no holes that could be filled with an LC. In this sense, any microstructured fiber that can be relatively easy filled with LCs, allows for producing a new type of fiber with modified guiding properties and usually capable of dynamic tuning. In practice, most of the experimental work done on PLCFs is based on solid-core isotropic photonic crystal fibers made of silica glass (including the first experimental work in this area [2], but also most of the other papers cited in this review). However, there were also attempts to use hollow-core PCFs [16], [37] and solid-core fibers made of polymers [38], [39] and other glasses, including soft-glasses [40], [41] and high- index glasses [27].

The process of infiltration of the microstructured fibers with LCs is quite simple, as usually it is sufficient to immerse one end of the fiber into a container with a liquid crystal and the fiber would be filled due to capillary force (or more adequate, due to capillary pressure). The dynamics of such process can be approximately described by the well-known Washburn's equation [42] in which the infiltration length is a square root function of time, parameterized by the capillary radius, contact angle and viscosity of the liquid. Strict calculations for anisotropic liquids such as LCs would be more complicated if a full tensor of viscosity and orientation effects had to be considered, however some simplified models can be also successfully used for calculations [43]. In practice, infiltration speed can be increased by creating an additional pressure difference, either by applying external pressure to a container with LCs or by applying vacuum to the not immersed end of thefiber.

Even if the above-described process of the infiltration with liquid crystals is relatively simple, it is not so easy to obtain a good and repeatable alignment of the molecules within microchannels. In general, the long axis of the molecules in the central part of the microcapillaries are aligning parallel to the fiber axis due to the flow-induced orientation. The molecular alignment at the capillaries interiors depends on the interaction between the molecules and the surfaces. Typically planar (Fig. 3a) or splay (Fig. 3b) alignment of the molecules inside PCFs microchannels can be easily obtained; however, to ensure high stability and repeatability of such molecular orientations it is necessary to provide special aligning layers inside the microchannels, before the PCF is filled with LC. The lack of such orienting layers results generally in a low order parameter of the created alignment, causing thus higher propagation losses due to increased scattering and in a less effective electric tuning in suchfibers.

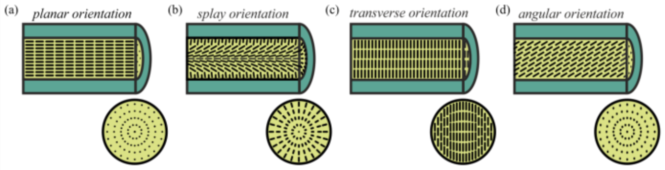

Fig. 3. Typical alignments of the LC molecules observed inside PCFs microchannels: a) planar; b) splay (also known as axial or escaped radial); c) transverse; d)transverse-tilted.

The simplest method to obtain at hin film of aligning layer inside a microcapillary of PCF is to fill it with some material/solution and then pull it out with high-pressure air. The latter action is often assisted with high temperature to promote evaporation of the solvent. Recently it has been demonstrated that the pre-treatment of the microchannels with lecithin enforces homeotropic molecular alignment, whereas planar anchoring can be obtained by applying 3- glycidoxypropyltrimethoxysilane as an orienting layer [44], [45]. It is also possible to use polymer solutions, like SE-1211 and SE-130 (Nissan Chemical Industries, Ltd) which are typically used in LCDs technology, but can be also used to enforce homeotropic and planar anchoring in capillaries [46], [47].

A more complex but also more universal method for LC orientation control is the photo-alignment technique, which relies on the appearance of photo-induced optical anisotropy and dichroic absorption in thin amorphous films [48]. Such a technique allows not only for planar and splay alignments, but for more complex, such as transverse or transverse tilted alignments (Figs. 3c-d) [49]. Photo-alignment technique has been also successfully applied to obtain periodic patterns of different and stable alignments within a single capillary [50], [51], and thus can be e.g. used to create long period gratings. Such approach has been presented in [52], where light- controllable and erasable long-period fiber grating was obtained in a PCF filled with an LC mixed with 4-methoxyazobenzene (4MAB). Importantly, the photo- alignment technique has been proved to be quite effective in PLCFs, even if nematic LCs were replaced by ferroelectric LCs which are much more difficult to be aligned a [53], [54].

Another interesting subject when dealing with PCFs filled with liquid crystals is selective infiltration. Recently, numerous techniques of selective infiltrations of PCFs with various materials have been reported [55]–[59]. The PCFs selectively infiltrated with LC have been studiedtheoretically [60] and experimentally in the case of selectively filled HB PCFs [61]. Other types of selective infiltration were reported in [62], where two different liquid crystals were used to fill one fiber. There was also some experimental work on selective infiltration of a single microchannel (or group of them) [63], [64, p. 6],[65].

A significant progress in PLCFs technology has been observed over the last decade in terms of liquid crystal materials used for infiltration. A dominant number of works were performed with most popular nematic LCs, but in some works dual-frequency nematics were used, allowing for the transverse of planar reorientation, depending on the frequency of a steering signal [18], [44], [66]. It also worth mentioning some attempts to infiltrate PCFs with blue phase liquid crystals [67]–[69]. To improve the response of the PLCFs the LCs were doped either with dyes (to increase efficiency of optical tuning [19], [70]) or with metallic nanoparticles (i.e. [24], [71], [72] - more about nanoparticle doped PLCFs in section4.6).

B. Mechanisms of lightpropagation

The mechanisms of light guidance in PCFs [34] are much more complex when compared to light propagation in conventional fibers. They are strictly related to specific features of a particular fiber design, including cladding and core geometrical and material parameters. Importantly, some unique characteristics, and thus differences in light guidance, may additionally appear after complete or selective infiltration with a particular material of special characteristics.

Depending on the fiber geometry and refractive indices of the component materials, the light guidance mechanism in a solid core PCF may show some similarities to the total internal refraction (TIR) in a standard optical fiber when the light propagates in the core with a higher refractive index compared to the effective refractive index of the periodic cladding (Fig. 4a). Such a guidance mechanism is referred to as index guiding and by proper design and fabrication process, some extraordinary properties of the fiber can be achieved in such modeofoperationincludinge.g.endlesslysingle-mode and single-polarization guidance, or dispersion profile suitable for a specific application. The second mechanism of the light guidance in PCFs is bandgap guidance (Figs. 4b-c). It is strongly related to the periodicity of the cladding, allowing for photonic bandgap creation. The latter permits light confinement in the core with a lower refractive index than that of the cladding. This condition is typically fulfilled when the airmicrochannels of a solid-core PCF are infiltrated with a high-index material or in a PCF with theair-core.

The combination of both mentioned guiding mechanisms is also possible, leading to so-called hybrid guidance in a PCF,, in which index and bandgap guiding can be observed [73], [74].

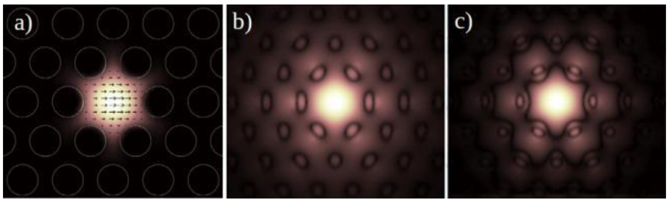

Fig. 4. Examples of the modes guided in PCFs and PLCFs: a) index guided mode - mode field is well localized in the core; bandgap guided mode in the first- (b) and the second-order (c) photonic band gaps (to enhance clarity of the electric field of EM wave penetrating the microstructure, the color scale is logarithmic).

When considering a PCF infiltrated with a liquid crystal, it is worth noting that both ordinary and extraordinary refractive indices of typical LCs are higher than those of silica glass in the whole spectral range including visible and near infrared light. It implies that bandgap guidance is typically achieved in PLCFsDue to optical properties of LCs, bandgap guidance (i.e. spectral locations and widths of the bandgaps) strongly depend on material characteristics, molecular orientation, and light polarization. For such polarization-dependent bandgaps, the guided modes of two orthogonal polarization can be individually guided within their respective bandgaps and exhibit different dispersion curves. However, index-guiding propagation can be also achieved in a PCF infiltrated with customized (low-birefringence) liquid crystals with refractive indices slightly lower than those of the glass in a specific thermal and spectral range [13]. Moreover, by taking an advantage of special designs, it is also possible to obtain PLCFs which combine guiding properties of both above- mentioned mechanisms. Such hybrid guidance in PLCFs, allowing e.g. that two orthogonal polarizations are guided by different physical mechanisms [75], [76], extends the functionalities and potential applications of PLCFs. For instance, hybrid-guiding in PLCFs allows for a wider range of tunability of polarization properties, resulting in practical realization of polarization control components for fiber optic systems.

It is worth noting that when microchannels are infiltrated with a high-index material, or when high-index rods are present in the PCF structure, the fiber can also be considered as a two-dimensional photonic lattice, allowing, in a specific case, for so-called discrete light propagation (Fig. 5) [77].The latter is typical for photonic structures with a periodic spatial distribution of the refractive index takes place when the light is switching between weakly-guiding waveguide channels *via* an evanescing coupling [78]. Discrete light propagation in PLCFs has been studied theoretically and experimentally [8], [79]–[81].

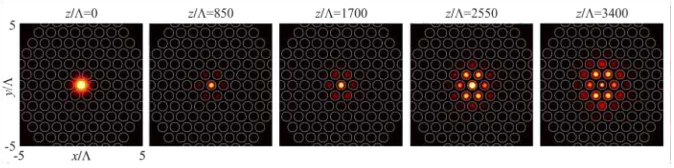

Fig. 5. Numerical results for a low-power Gaussian beam with an initial waist of 0.85·Λ and a wavelength of 0.13·Λ, presenting discrete diffraction of the beam launched into the center of periodic structure of a triangular geometry with an inter-hole distance of Λ and the air-holes diameter of 0.75·Λ. Refractive indices taken for calculations are 1.4537 for silica glass and 1.5109 forNLC.

C. Spectral properties and photonic bandgaps tuning in photonic liquid crystalfibers

As described in previous section, the most common effect of infiltration of solid-core silica PCFs with LCs is bandgap guiding obtained instead of broadband index guiding observed in empty PCFs. The first observation of bandgap guidance in PLCFs has been reported in [2], where a solid-core PCF was filled with a cholesteric LC and the change of temperature allowed for tuning the bandgaps. Similar effects have been reported later by a number of research groups (e.g. [10], [38], [82]). It has been particularly shown that the position of the bandgaps can be quite accurately determined with use of the ARROW model [19], [83], or by a more complex simulation (e.g. [22], [82], [84]). An interesting effect has been reported in [13], where not only thermal tuning of bandgaps was demonstrated, but also a temperature-induced and reversible change of the guiding mechanisms from bandgap- to index- guiding and *vice versa*. The latter was possible thanks to unique characteristics of a low-birefringence LC, which ordinary refractive index for a certain temperature range was lower than the refractive index of silica glass. Similar tuning of photonic bandgaps can be in principle obtained in PCFs filled with almost any liquid (e.g.) [85] however its results are generally more evident in LCs for which the thermo-optic effect is usuallyhigh.

A significant advantage of using liquid crystals is that the position of the bandgaps can be also effectively tuned with an electric field, due to electrically-induced reorientation of LC molecules. The reorientation of molecules causes a change in the effective refractive indices of LCs, and also induces anisotropy that can modify the polarization properties of the PLCF (as widely discussed in section 4.4). In PCFs filled with nematic liquid crystals, the application of an electric field initially causes a drop in optical power (due to increased scattering losses during molecular reorientation) and finally a new set of bandgaps appear (e.g.. [13], [17], [86], [87]). Continuous tuning of bandgaps is possible if a dual-frequency LC is used and its initial orientation is of the splay-type [18],

[88]. An interesting phenomenon was observed in the case of a PCF filled with a blue-phase LC [69], where the bandgap shifts were different for both orthogonal linearpolarizations.

As already mentioned, the positions of the bandgaps are determined by the properties of the cladding, i.e. size of the holes, lattice constant and refractive indices of the LCs. An interesting observation was made in [89], where PLCFs with a various core size were analyzed, showing that even for higher order modes in a fiber with a very large core, the position of photonic bandgaps is similar for that observed in a analogous fibers with smaller cores. Moreover, the attenuation of the PLCF with a large core area was much lower that for fibers with a smaller core, which was explained by the fact that a much lower percentage of optical power is guided through a strongly scattering microchannels filled with an LC.

The formation of photonic bandgaps is always connected with the formation of spectral regions in which not only attenuation is rapidly changing, but also chromatic dispersion [90]. For each bandgap the function describing the wavelength dependence of an effective refractive index has exactly one inflection point. It means that its second derivative, which is directly proportional to dispersion, is equal to zero at some specific wavelength(s). The dispersion of bandgap guiding PLCFs was measured for the first time by Wahle *at el.* in [91], confirming that a zero dispersion wavelength is present in each of the photonic bandgaps. It has been also measured that within a single bandgap the dispersion can change from -2500 ps km $^{-1}$ nm $^{-1}$ to 2500 ps km $^{-1}$ nm^{-1} within a spectral range of only 15 nm. Later, the same group demonstrated an impressive tuning of the zero dispersion wavelengths [66], which was observed in the PCF filled with a dual frequency LC so the positions of the zero dispersion wavelengths could be either blue or red shifted depending on the frequency of the applied voltage.

D. Electrical tuning of polarization properties of photonic liquid crystalfibers

Electrically-induced reorientation of LC molecules inside PCFs allows for dynamic modification of optical properties, including birefringence and polarization dependent losses (PDL). Some examples of PDL tuning were already mentioned in the previous section, i.e. in the case of asymmetric band-gap tuning in a PCF filled with a blue phase LC [69]. In the case of bandgap guiding, the electric tuning of PLCF bandgaps (see section 4.3) is always accompanied by the tuning of birefringence, usually with a significant PDL. In some cases, if LC molecules are reoriented with a high electric field, a new set of bandgaps appears, which in practice can be considered as single-polarization guiding (as e.g. in [14,17,87]). Such fibers can be used as tunable polarizers in which the polarization axis is defined by the direction of the electric field. In the simplest case, the electric field is usually applied by using two flat electrodes, so the direction of the field is perpendicular to the surface of the electrodes. However, it has been demonstrated that by using four- electrode steering it is possible to obtained four different directions of the field, and thus it is feasible to create atunable polarizer in which the polarization axis could be "rotated" by 45 degrees [92]. In [92], four electrodes were created with a V-grooves assembly. However, there are other methods to obtain a similar result, e.g. by using two short flat electrodes and two wires at the side of the fiber [93], [94] or by surrounding the fiber with four [95] or six [96] cylindrical electrodes.

Birefringence tuning, as a natural consequence of molecular reorientation, should be always taken into consideration when a PLCF is tuned with an electric field. The examples of detailed analysis and measurements of birefringence tuning were present e.g. in [14], [18], [88], [97]. The continuous electric tuning of birefringence demonstrated in [18] allowed for a relative change of the phase birefringence equal to $3\cdot10^{-5}$. A slightly larger tuning was reported in [88], where the birefringence tuning was equal to $5\cdot10^{-5}$ in a 20 mm long sample of PLCF, which allowed for a continuous change of phase between both orthogonal modes up to 250 degrees. Similar tunable waveplates were also reported in[98].

All examples of PDL and birefringence tuning presented above were realized in bandgap guiding fibers so that the bandwidth of the potential devices based on such fibers were limited. Keeping in mind that the attenuation of bandgap guiding PLCFs is relatively high, typically in the order of few dB/cm, an alternative solution in form of the high-index host fibers could be used to ensure index guiding for any orientation of the LC molecules. PLCFs based on PBG08 glass were presented in [27], allowing for broadband operation with low losses (in the order of 0.2 dB/cm) and with birefringence tuning up to $2\cdot10^{-4}$. More examples of index-guiding fibers were presented in [99], where electrically tunable broadband waveplates, polarizers and attenuators were reported. It has been also considered that a set of three independently tuned PLCFs could be used to create an all-in- fiber polarization controller[100].

Summarizing this part, it is also worth mentioning that the investigations on electric tuning of PLCFs have been made also in the context of electric field sensing and recently a number of sensing experiments were reported (e.g. [8], [21], [101]–[103]).

E. All-optical modulation in photonic liquid crystalfibers

Apart from thermally or electrically/magnetically induced changes in the optical properties of PLCFs, all-optical modulation, i.e. changes in refractive indices of the LC due to its optical nonlinearity, is possible [28], [31]. Its main mechanisms in nematic liquid crystals include electronic, thermal and reorientational ones. While the electronic contribution to the third-order nonlinear effects in LCs can be neglected (as it is of the same order of magnitude as in ordinary liquids) and the effects caused by thermal nonlinearity are similar to those observed in other materials, the reorientational nonlinearity of LCs is many orders of magnitude greater than the conventional Kerr effect in dielectric media. The optical Kerr constant characteristic for this type of nonlinearity takes the value up to 10^{-3}cm^{2}/W and can be increased by six orders of magnitudesby suitable dopants [104]. As a result, with both positive and negative Kerr-type nonlinearities occurring in NLCs, as related to the reorientational and the thermal nonlinearities, respectively, the refractive index of an LC can linearly increase or decrease with light intensity. Eventually, nonlinear effects, related to both mechanisms of optical nonlinearity, appearing simultaneously or separately in an LC, may result in dramatic changes in propagation characteristics in LC-based photonic devices. When the power of a propagating beam increases, the refractive index of an illuminated liquid crystalline material can be modified by nonlinear effects. It means that the optical parameters of a PLCF structure and its guiding features can be affected by the propagating beam itself. In means that in a nonlinear regime, light induces a defect in the periodic structure, changing its guidingcharacteristics.

Typical practical devices utilizing optically induced changes in the propagational properties of PLCFs are all- optical switchers and modulators in which the bandgap characteristics are induced by light. One of the examples is the all-optical modulation presented in [19], where a pulsed laser has been applied to modulate the spectral position of the bandgaps in a PCF infiltrated with a dye-doped NLC. This particular device utilizes local heating of the NLC and in principle does not introduce a polarization dependent loss as it is typical of electrical tuning of photonic bandgaps[86].

An all-optical switch based on liquid-crystal infiltrated photonic bandgap fiber in transverse configuration has been presented in [105]. The switch is composed of a PLCF transversally oriented between a conventional input and output fiber and can operate over a broader spectral range when compared to the already mentioned PLCF-based optical switch [19]. Moreover, no additional optical components such as couplers or filters are required as the control and signal beams are not guided along the same path as in many other devices. Single polarization devices, similar to the one described in

[106] can be achieved when designed to possess significant scattering losses for only one polarization.

The demonstration of an all-optically controllable dye- doped liquid crystal infiltrated PCF is presented in [70]. The reversible all-optical controllability of the photonic bandgaps is attributed to the state transitions of LC achieved due to UV- and green-light induced trans-cia ans cis-trans isomerizations of the azo-dye, respectively. The variation of the index contrast between the core and the cladding results in the shift of the transmissionspectrum.

An all-optical switch has been also achieved in a dual-core PCF with its core region consisting of soft glass and with a nematic liquid crystal used to infiltrate the channels in the cladding region [107]. Apart from typical sensitivity to external perturbation such as applying a heat source or an electric field, the PCF couplers present in the structure are capable of supporting soliton-like pulses due to the self- focusing nonlinearity of soft glass. In this sense nonlinear properties of the fiber have been used to demonstrate all- optical switching of short-duration pulses with the coupler features tuned, due to LC sensitivity to temperature and electricfield.

Other possibilities of all-optically induced changes in PLCFs are those related to nonlinear discrete light propagation [80]. The main advantage of practical application of a PLCF- based waveguide matrix stems from nonlinear effects which can be easily achieved, leading in turns to extreme changes in propagation characteristics. In particular, beam self- defocusing and its localization in the form of a discrete gap soliton at high optical powers have been demonstrated in a PLCF by employing thermal nonlinearity [79]. On the other hand, a discrete spatial soliton has been obtained in PLCF- based waveguide matrices thanks to self-focusing reorientational nonlinearity [80]. Such a feature allows for all- optical switching, routing, and electromagnetic sensing to be potentially achieved in PLCFs[8].

F. Nanoparticles in photonic liquid crystalfibers

Over the last few years nanoparticles (NPs) have beenfound to improve electro-optics properties of LCs as they caninfluence e.g. LC response times and lower the Fredricsthreshold [71], [108]–[110]. It is worth mentioning that theNPs size matching the LC molecules dimensions can stronglyinfluence the intrinsic properties of the NPs-doped LC [111].However, the application of such dopants provided also newdifficulties. One of the crucial issues is the aggregation ofNPs, especially in mixtures with higher concentrations of NPs.First attempts to infiltrate a PCF with LCs doped withbarium titanate NPs were reported in 2009 [24], providingnew features such as: frequency modulation response ortransmission spectrum with tunable attenuation. Another NPsmaterial used in PLCFs was titanium (Ti). The firstexperimental evidence of the thermo-optic properties of aPLCF with a Ti-doped 5CB nematic LC has been recentlyreported in [72], where a noticeable difference in both:molecules orientation and propagation spectra of the PLCF was observed.

One of possible dopants for LCs are gold nanoparticles. The PCF infiltrated with 6CHBT nematic liquid crystal doped gold nanoparticles was found to improve thermo- and electro- optical properties of the PLCF [112]. The results obtained indicate that, by increasing the NPs doping rate, a significant reduction of rise times occurs under an external electric field , while there is a simultaneous reduction of the nematic - isotropic phase transition temperature. Similar results were also reported for the photonic crystal fibers infiltrated with the same 6CHBT nematic LC doped with spherical silver nanoparticles [113]. da The presence of silver NPs in 6CHBT was found to modify the spectral properties of the infiltrated PCF. A significant improvement of switching times was observed for the NPs-doped LC-infiltrated PCF under the influence of an external electric field as well a decrease of the nematic-isotropic phase transition temperature was also reported. Moreover, by increasing concentration of NPs reduction in both LC refractive indices and in the nematic- isotropic phase transition temperature was observed. Furthermore, in the presence of external electric fieldNP- doped LCs reduced not only switching times but alsothe

Frederics threshold value. The presence of NP in PLCFs by significant improvement of electro-optical parameters broadens up applicability ofPLCFs.

IV. POTENTIAL APPLICATIONS AND FUTUREPERSPECTIVES

PLCF-based photonic devices (that have emerged from initial demonstrators of LCF-based technology), representing a special group in the class of fluid-infiltrated PCFs, offer a wide range of opportunities spanning many topics and novel practical applications. The latter stem mainly from the possibility of dynamic changes in light propagation due to adjustable diffraction and dispersion characteristics. In fact, the optical parameters of PLCF-based devices with highly tunable characteristics can be changed by applying external factors and fields, as well as induced by nonlinear effects related to reorientational and thermal nonlinearities in LCs. PCFs infiltrated with liquid crystals are perfect candidates for all-in-fiber components, allowing for control and manipulation of light propagation in fiber optics networks. In this sense, they are also promising building blocks for realization of multifunctional optical fiber devices. The main idea of introducing LCs into PCFs is to get new levels of adjustment and boost the functionality of these fibers due to their new propagation, spectral, thermo-optic, electro-optic and polarization properties. Tunability ranges achieved in PLCF- based devices depend on many different factors and conditions such as materials, alignment of LC molecules, light guiding mechanism, fiber geometry, and many others. In this sense PLCFs have to be carefully designed to meet the requirements of a final device. A wide selection of liquid crystalline materials and specific phases (of different birefringence, refractive indices, etc.), on the other hand, allows for a PLCF with tailored properties such as single-polarization, high- birefringence, different propagation mechanisms and reversible switching between them, which implies a broad range of potentialapplications.

Several practical components for optical fiber systems have been proposed so far, including tunable bandgap switches [114], polarizers [99], polarization controllers [100] and rotators [115], reversible and tunable long-period gratings [52], [116], electro-tunable notch [117], [118], noise[119],

tunable polarization-maintaining [120] and Sagnac [121] filters, all-in-fiber gain equalization filter with an adjustable slope [24]. PLCFs have been also successfully proposed to be applied as sensing elements for an electric field [24], [101], as well as for temperature and pressure [21] measurements. The idea of a multi-parameter fiber-optic sensor of temperature, electric field and hydrostatic pressure has been also presented [23].

Even if the first experimental studies on PLCFs ended up with demonstration of tunable switchers [2], it has to be noted that the dynamics of switching (obtained via molecular reorientation) is governed by the viscosity of a LC, its elastic constants as well by the thickness of LC confined geometry, and thus switching times are in the millisecond scale as in typical nematics. Anyhow, the tunability of the device can be achieved by changing the amplitude and frequency of an applied external electric field [24]. A selectively infiltrated PLCF has been successfully applied for electric field measurement, with its ability to measure electric fields with an intensity of up to 40kV/cm [124].

In addition, the suitability of PLCF-based photonic devices for filters, polarization elements (waveplates, polarizers) and sensors is highly dependent on tunability of the transmission spectrum while PBG tunability is highly related to liquid crystal parameters [125]. Specifically, the possibility to control birefringence of a PLCF can be the key element of tunable polarization elements and devices. In fact, while light propagation in PLCFs is in principle strongly dependent on light polarization, PLCFs-based polarization components in the form of polarization switches [106], controllers [100] and splitters [126], have been successfully demonstrated in practice. It is worth noting that while the voltage-tunable birefringence in LC-infiltrated glass-core PCFs has been exploited in the first two cases, the polarization splitter has been designed with the use of the same principle but in a dual- corePCF.

In the context of the potential practical application envisioned above, some technical issues should be pointed out. One of the main potential challenges is the effective connection of PLCFs with other types of fibers. One method is classical splicing of PLCFs in which LC was pulled away from the spliced end. Alternatively, the PLCFs can be connected with other types of fibers by photochemical methods, which allows also for connections between polymer and glass fibers [127], [128]. Even if the effective connection between PLCFs and classic fiber were made, there would be still the issue of back-reflection (caused by both LC back-scattering and by reflection and interface between two fibers, especially if they are made of a different material with various refractive indices). Another issue that should be overcome in potential practical applications is thermal stability or compensation of thermal drifts. However, it could be made electronically by proper calibration of the device and drivers. Finally, in the case of PLCFs tuned with an external electric field, there are usually relatively high voltages required, in practice any PLCF section to be tuned should be driven by a separate high-voltage generator that is not cost effective; moreover, potentially compact devices would be accompanied with bulky drivers. All the mentioned technical issues open up new research possibilities, even if for some particular applications, current state-of-the-art PLCFs devices could be sufficient.

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