Liquid Crystal Photonic Crystal Fibers and their applications

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ABSTRACT

Liquid Crystal Photonic Crystal Fibers (LC-PCFs) known also as Photonic Liquid Crystal Fibers (PLCFs) are advanced specialty fibers that benefit from a combination of “passive” photonic crystal fiber host microstructures infiltrated with “active” liquid crystal guest materials and are responsible for a diversity of new and uncommon spectral, propagation, and polarization properties. This combination has simultaneously reinvigorated research in both fields of Liquid Crystals Photonics and Fiber Optics by demonstrating that optical fibers can be more “special” than previously thought. Simultaneously, photonic liquid crystal fibers create a new class of optical waveguides that utilizes unique guiding properties of the micro-structured photonic crystal fibers and attractive tunable properties of liquid crystals. Comparing to the conventional photonic crystal fibers, the photonic liquid crystal fibers can demonstrate greatly improved control over their optical properties.

The paper describes basic physics including guiding mechanisms, spectral properties, polarization phenomena, thermal, electrical and optical controlling effects as well as innovative emerging technology behind these developments. Some examples of novel LC-PCFs highly tunable photonic devices as: attenuators, broadband filters, polarizers, waveplates, and phase shifters recently demonstrated at the Warsaw University of Technology are also presented. Current research progress in the field indicates that a new class of emerging liquid crystals tunable photonics devices could be expected.

Keywords: photonic crystal fibers, liquid crystals, birefringence, tunable fiber optics devices

1. PROGRESS IN THE LIQUID CRYSTAL PHOTONIC CRYSTAL FIBERS

Transmission properties of the photonic crystal fibers (PCFs) can be tailored in a wide range by changing geometry of their microstructured cladding [1]. Generally, in the PCFs light can be guided by two different mechanisms: index-guiding (similar to the classical waveguide effect based on TIR-total internal reflection) and the photonic band-gap (PBG) effect. The PBG propagation occurs when the effective refractive index of the microstructured cladding is higher than the refractive index of the core, and in this case only selected wavelengths can be guided [1]. Transmission properties of PCFs can be also arbitrarily changed by filling their micro-holes with various substances [2] and liquid crystals (LCs) belong to the most interesting materials for these applications due to the high sensitivities to external physical fields. First paper on liquid crystal photonic crystal fibers (LC-PCFs, also as photonic liquid crystal fibers - PLCFs) has been published in 2003 [3], and since that time there has been continuous increase of the number of research group working in the field. Due to the limited capacity of this paper we will focus mainly on the results obtained at the Warsaw University of Technology (WUT).

First research activities in this area have been initiated at WUT since 2003, and they were originally focused on propagation effects in microstructured fibers filled with low-birefringence liquid crystals [4]. Preliminary results were so interesting, that much more effort was devoted to this subject, resulting in detailed investigations of guiding properties of the PCFs filled with various types of nematic LCs. Due to the fact that both refractive indices of majority of liquid crystals are higher than refractive index of the silica glass, a change of the guiding mechanism was observed from index guiding in an empty PCF to the PBG propagation in the LC-filled PCF [5].

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Emerging Liquid Crystal Technologies VI, edited by Liang-Chy Chien, Hiroshi Yokoyama,
Proc. of SPIE Vol. 7955, 795502 · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.885527

Next goal in our research progress was quite natural – to investigate tuning possibilities of the LC-PCFs. Two main tuning mechanisms have been indentified, demonstrated, and investigated: thermal and electric tuning [6]. Thermal tuning allowed us to obtain dynamic change of the guiding mechanism in the LC-PCF in which ordinary refractive index of a specially designed low-birefringence LC mixture was higher, equal or lower than refractive index of the host fiber, depending on the operating temperature [6]. The same LC mixture was used to obtain dynamic switch between single- and dual-core propagation in the selectively filled highly birefringent PCF [7]. Additional research has proved that electrically tunable LC PCFs allows for effective tuning of the polarization properties, which include tunable birefringence and switchable single polarization operation [8].

It is worth to emphasize that efficiency of the electrical steering can be greatly increased if the LC-PCF would be based on the fibers with integrated electrodes [9]. Efficiency of the tuning can be also extended by using an all-optical tuning - an alternative method of influence - that has been also recently applied to the LC-PCFs [10]. Another way to obtain efficient tuning is using of special liquid crystal mixtures. Recently dual-frequency LCs [11], nanoparticle-doped LCs [12], ferroelectric 13], and cholesteric [14] LC mixtures have be applied in LC-PCF research. However, it should be pointed out that the use of more complex substances requires even more sophisticated methods of the controlled LC infiltration to ensure stable and repeatable orientation of the LC molecules. In our group we are presently focusing on the control of the LC orientation by using the photoalignment technique, in which a thin film of photopolymer is created inside the micro-holes, and the linearly polarized UV light is used to determine the direction of the LC alignment [15]. Results observed so far are very promising, and it could be expected that the photoalignment technology would find applications if in prospective photonic devices based on LC-PCFs.

To summarize, a progress in research activities has been only possible due to the fact that most of the experimental investigations had been initially theoretically analyzed with advanced numerical tools. Accurate numerical simulations of the guiding properties of the LC-PCFs require complex methods, in which all important physical properties of the liquid crystal are taken into account (optical anisotropy, molecular orientation and relatively high losses – i.e. [16]). Our theoretical investigations have showed that not only playing with the filling material can be interesting, but also a possibility to modify the host PCF properties can open up a broad range of new possibilities. A very promising result was obtained in microstructured long period fiber gratings (LPFG) combined with a LC [17]. Other interesting effects observed in the LC-PCFs were based on a PCF made of multi-component glasses, with increased value of the refractive index, so that index-guiding propagation was possible even after infiltration with LCs. In particular, low-loss propagation and continuously tunable birefringence was experimentally demonstrated [18]. Our recent theoretical investigations indicate that very interesting effects are also possible in the microstructured fibers with some specially designed geometry – experimental works are in progress and its results will be reported soon.

2. EXAMPLES OF THE APPLICATIONS

Although the technology of LC-PCF manufacturing is still not perfect and does not allow for a full control of the manufacturing process (the main issue is a stable and highly repeatable alignment of the LC molecules), selected practical applications expected and envisaged. In this section we will briefly enumerate some examples of potential applications.

a) b)

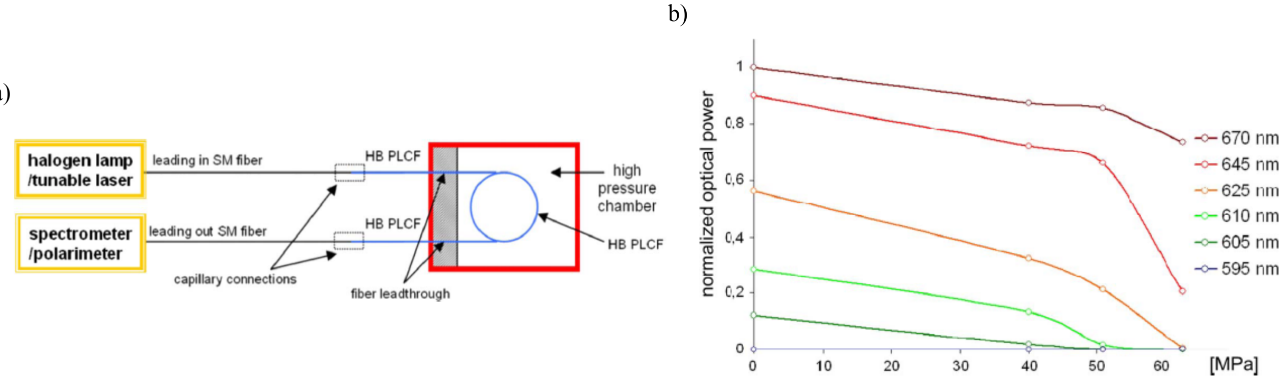

Figure 1. Example of the pressure sensor based on the LC-PCF: experimental setup and performance for selected wavelengths [19]

The first area in which they can be used is optical sensing, where LC-PCFs can be applied as a sensing element or used just for a control of the light delivered/received from the sensor. Due to its relatively high sensitivity to external physical fields, LC-PCFs can detect and sense various physical effect. So far we have demonstrated LC-PCFs as photonic devices for temperature, electric field and pressure sensing [19]. The high sensitivity of these fibers can be sometimes considered as a drawback, due to their relatively high cross-sensitivity, however is seems possible to minimize this negative phenomenon with specially designed setups (in particular thermal drift can be relatively easy compensated electronically). Example of the pressure sensor based on the LC-PCF is shown in Fig.1.

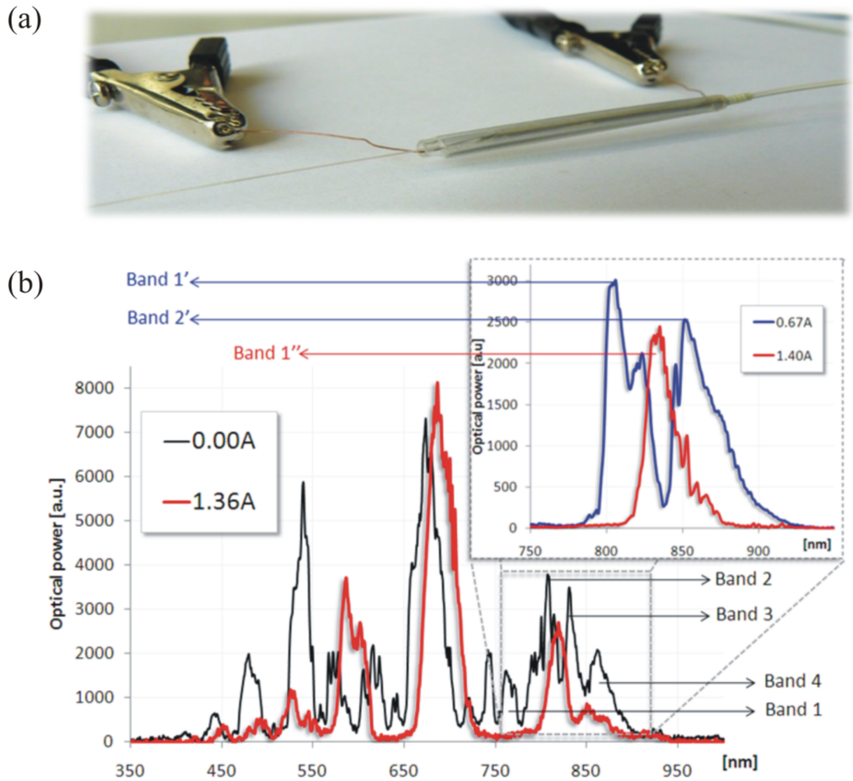

Figure 2. The example of the device based on the LC-PCF with PBG propagation: thermally controlled filter.
a) close-up to the LC-PCF placed inside a compact resistive heater with electrical connectors
b) transmission spectra of the device versus the current flowing through the resistive heater.

Another area of potential application (and probably most promising) is building cost-effective all-in-fiber tunable photonic devices. Silica glass based LC-PCFs, in which PBG propagation is predominant and typical, can be used mainly for spectral filtering of the optical signals. Due to the fact that position of the PBGs can be tuned, it is possible to build tunable filters; those performances can be further increased if a cascade configuration of few different LC-PCFs would be used. Band-gap guiding LC-PCFs can be also used for building other devices (i.e. polarizers, attenuators or phase modulators), however their performance will be limited to the wavelengths corresponding to the PBGs. Selected laboratory demonstrators of the photonic devices have been recently constructed at the WUT [i.e. 20, 21]. Examples of such devices are presented in Fig. 2-4.

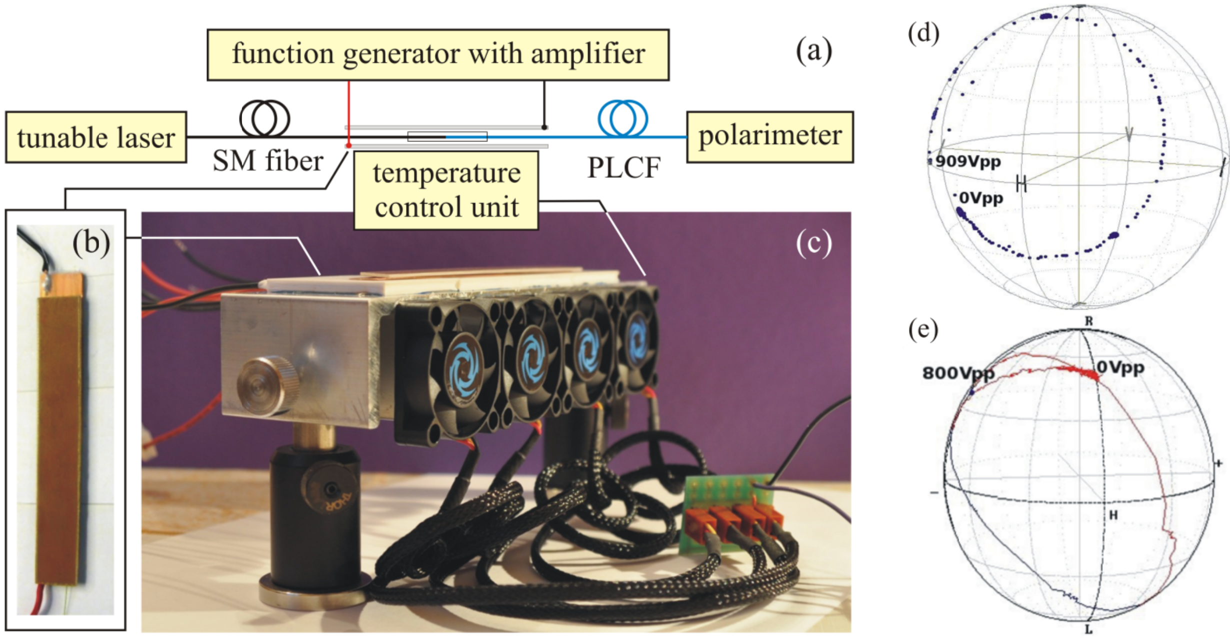

Figure 3. Example of the tunable LC-PCF device: a) experimental setup; b) system of electrodes;
c) temperature control unit including the Peltier modules, radiators and fans;
d), e) - experimentally observed changes in the state of polarization under the influence of electric field.

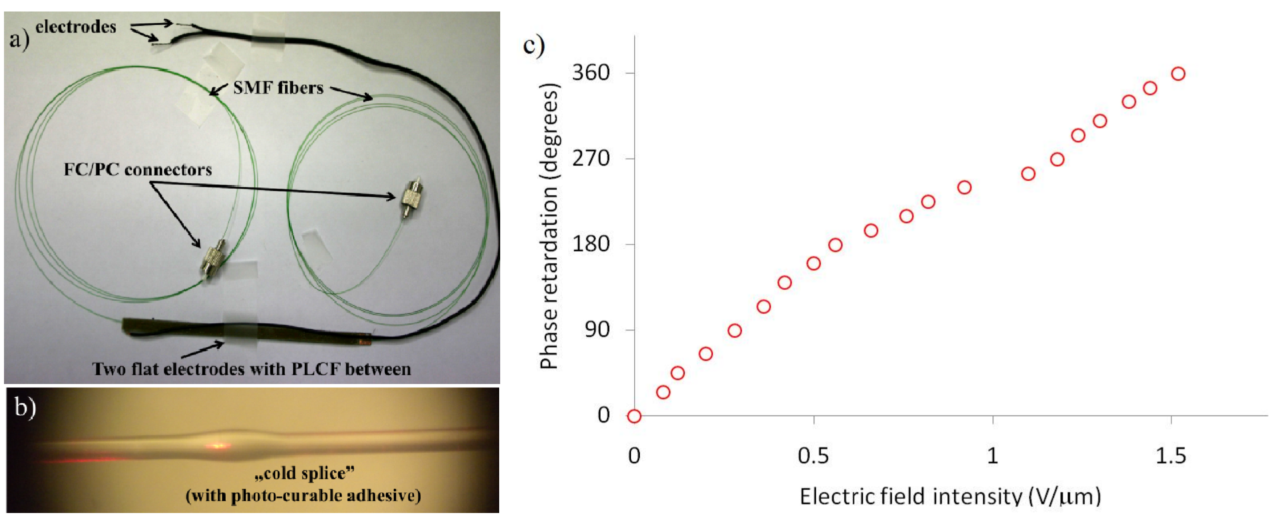

Figure 4. Electrically tunable retarder based on the high index PCF filled with LC;
a) general overview of device; b) close up to the "cold splice" made with photo-curable adhesive;
c) phase retardation in the function of intensity of the steering electric field.

Broadband devices can be build basing on the index-guiding LC PCFs (index-guiding occurs when effective index of the cladding is lower the refractive index of the core). This could be obtained in two ways: by using special liquid crystal mixtures with lowered value of the ordinary refractive index (however a choice of these mixtures is very limited), or by using host PCFs made of glass with increased refractive index (i.e. made of multi-component glasses, however in such case there is an issue of connecting, because thermal splicing cannot be used, due to the different thermal and chemical properties – [18]). Index guiding tunable LC-PCFs can be effectively used for control of polarization of the light, due to the fact that reorientation of molecules in such fibers does not change transmission spectra, but only birefringence and polarization dependent losses (PDL) are tuned. Recently, we have completed demonstrators of all-in-fiber tunable components based on index-guiding LC PCFs, which includes tunable waveplates (based on small tuning of the phase birefringence), tunable polarizers (based on the tunable PDL) and tunable phase shifters (large tuning of the birefringence).

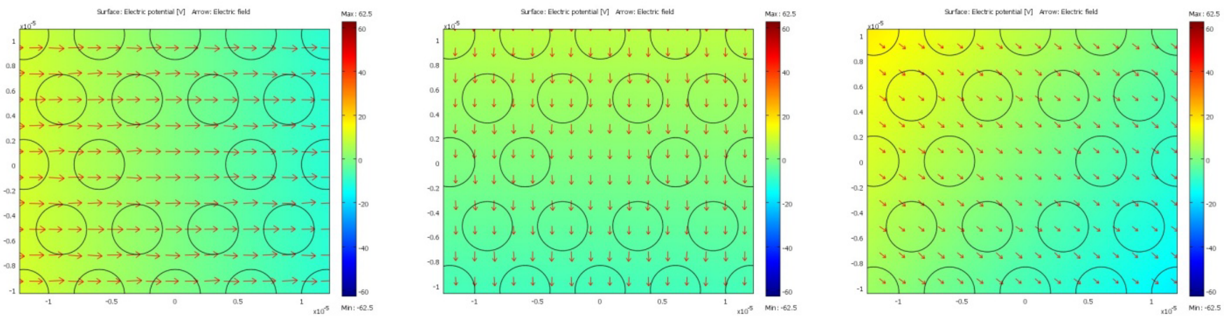

Figure 5. Change of the electric field direction in LC-PCF placed in the four electrodes setup [23]

The functionality of the LC PCFs devices could be even more extended by using four-electrode steering [23], that will allow for a dynamic change of the direction of the field. Consequently it will be possible to make fibers not only with continuously tunable birefringence (or PDL) by also with arbitrarily switchable birefringence axes. Such components can be further utilized for assembling more sophisticated devices such as all-in-fiber polarization controllers and polarization mode dispersion compensators.

3. CONCLUSIONS

Liquid Crystal Photonic Crystal Fibers have become over the last seven years an emerging, but still not matured technology, simultaneously identifying new sensing and photonic devices applications. However, a number of novel photonic devices based on the LC PCFs have been demonstrated and developed at the Warsaw University of Technology in collaboration with other research groups in Poland and worldwide. A special selection of quest liquid crystalline materials and host photonic crystal fibers, as well as possibility of simple adjustment and control of their parameters significantly can broaden up a list of their potential applications. Current works involve basic and applied research leading to new applications of the LC PCF-based devices.

ACKNOWLEDGMENT

The authors acknowledge the Foundation for Polish Science Foundation Mistrz Programme and also a fruitful collaboration with Mr. D. Pysz (ITME, Poland), Dr. R. Buczyński (Warsaw Univ., Poland), Prof. W. Bock (UQO, Canada), Prof. J. Oton (Madrid, Spain), Prof. K. Neyts (Ghent, Belgium), Prof. P. Shum, and Dr. Juan Juan D. Hu (NTU, Singapore) in the field liquid crystal photonic crystal fibers. This work was also partially supported by the Polish Ministry of Science and Education under the grant N517 554139.

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