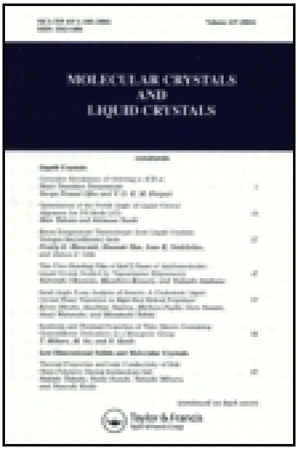

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Multi-Parameter Sensing Based on Photonic Liquid Crystal Fibers

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Multi-Parameter Sensing Based on Photonic Liquid Crystal Fibers

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Experimental results of spectral properties of liquid crystals filled solid-core photonic crystal fibers in view of a new type of multi-parameter fiber-optic sensor of temperature, electric field, and hydrostatic pressure are presented.

Keywords: liquid crystals; microstructured fibers; photonic bandgap; photonic crystal fibers

1. INTRODUCTION

Photonic liquid-crystal fibers (PLCFs) are advanced microstructured fibers composed of photonic crystal fibers (PCFs) in which air holes are filled out with liquid crystals (LCs) [1,2]. In this kind of fiber structures the refractive index of the fiber optic cladding can be easily modified by external factors such as temperature, pressure, electric or magnetic fields [3–6]. This fact leads to a possibility of photonic band gaps (PBGs) tuning or even switching between two different wave-guide mechanisms either based on the modified total internal refraction (mTIR) phenomenon or on the PBG effect. Consequently, PCFs filled with substances with refractive indices that can be easily

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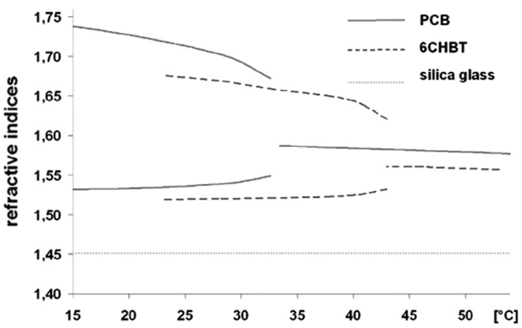
modified by external factors open up a possibility to create tunable optical devices [7] and sensors.

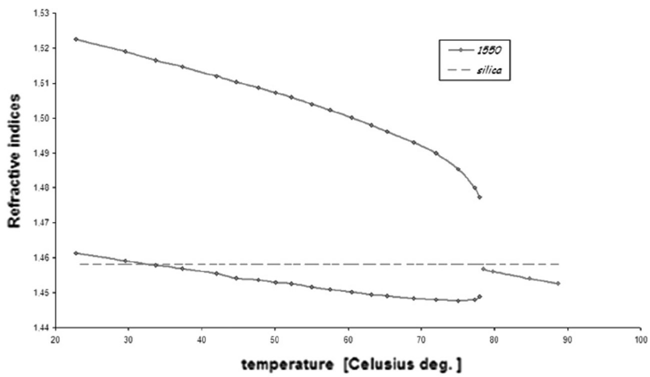
2. MATERIALS AND EXPERIMENTAL SETUPS

To fill PCFs we used three different nematic LCs synthesized at the Military Univ. of Technology (Warsaw, Poland): a low-birefringence 1550 mixture and two medium birefringence nematics: 6CHBT and 5CB. Temperature dependence of the LCs used for PCF falfilment are shown in Figures 1a,b.

As a host we used three PCF structures: 070124 with 3 rings of holes, 070123P1 with 6 rings of holes both manufactured at the Maria Curie Sklodowska University (UMCS, Lublin, Poland) and a



(a)



(b)

FIGURE 1 (a) Refractive indices as a function of temperature for nematic LCs: with medium birefringence 5CB (PCB) and 6CHBT (b) Refractive indices as a function of temperature for 1550 low-birefringence nematic LC mixture.

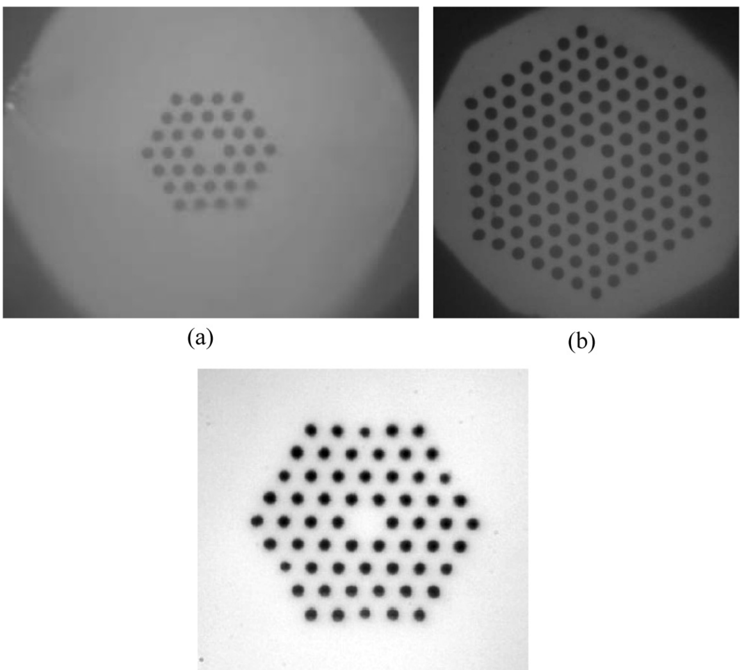
commercially available PCF LMA-PM-5 (prod. by *Crystal Fibre*) (Figs. 2a–c).

If a solid-core PCF is filled with a LC characterized by both refractive indices higher than the refractive index of the silica glass, the effective refractive index of the cladding is higher than the refractive index of the silica fiber core and the only propagation mechanism in the PLCF which is possible is based on the PBG effect.

The manufactured PLCFs were subjected to influences of effects induced by temperature, electric field, or hydrostatic pressure and were investigated in the setups described below.

2.1. Temperature Setup

The first step was to prepare PLCF samples to measure temperature-induced effects. The sample consisted of two prototype solid-core.



(a) (b)

(c)

FIGURE 2 Cross sections of the host PCFs: (a) 070124 UMCS with 3 rings of holes, (b) 070123P1 UMCS with 6 rings of holes, and (c) LMA-PM-5 (prod. by *Crystal Fibre*).

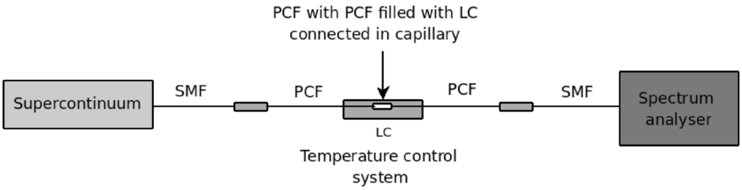


FIGURE 3 Experimental setup to investigate propagation properties of the PLCF under the influence of temperature.

070123P1 PCFs (with 6 rings of holes): one of the PCF was filled (section of 1.5 cm) with the 1550 nematic LC whereas another PCF was not filled (empty). These fibers were connected together in glass capillary. Details of the whole manufacturing process are presented elsewhere [1–4].

Then the whole sample was connected to a white-light source (input) and to a spectrometer (output). Exactly the same procedure was used to prepare two other samples: the 070124 PCF (3 rings of holes) filled either with 6CHBT or with the 1550 low-birefringence nematic LC. The experimental setup shown in Figure 3 consisted of supercontinuum light source, a temperature control system (Peltier's module) on which the samples were placed, an Optical Spectrum Analyser (OSA).

2.2. Electric Field Setup

The experimental setup for measuring influence of electrical field consisted of two electrode plates generating electrical field, an amplifier, an AC generator and a voltmeter. The experimental setup is presented in Figure 4. Two host PCFs with 3 and 6 rings of holes (070124 and 070123P1) filled with liquid crystals: 5CB, 6CHBT and 1550 appropriately were investigated. A short section (up to 4 cm) of the host PCF (~50 cm long) was filled with the LC. Hence, the filled PLCF

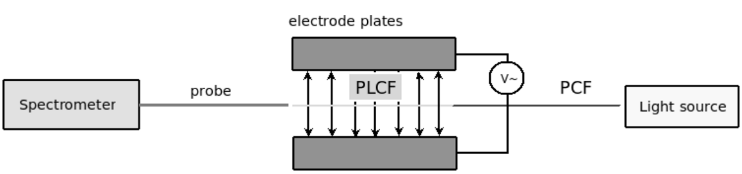


FIGURE 4 Experimental setup to investigate propagation properties of the PLCF under the influence of electric field.

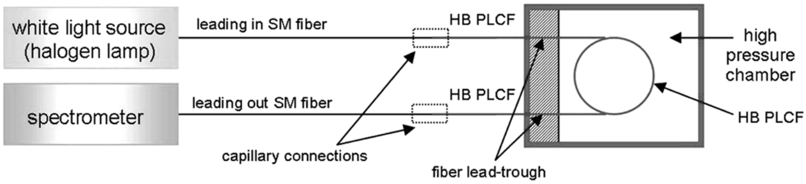


FIGURE 5 Experimental setup to investigate propagation properties of the HB PLCF under the influence of hydrostatic pressure.

under investigation was placed between both electrode plates and voltage was controlled with about few kHz frequency range.

2.3. Hydrostatic Pressure Setup

The experimental setup for measuring influence of hydrostatic pressure is shown in Figure 5. First section (of ~20 mm) of the 35 cm-long PCF LMA-PM-5 was filled with a 6CHBT LC and then the LC was moved to the middle part of the PCF by pressurized air. The PLCF was next inserted into a high-pressure chamber through a specially designed system. The one side of PLCF sample was connected to the white-light source and the second one to a spectrometer both of them were connected through capillary connections with single-mode (SM) leading fibers. Finally, hydrostatic pressure was applied to the chamber, modified and controlled with a dead-weight piston manometer. Another sample UMCS-070124 PCF with 3 rings of holes filled with 5CB was used in this experiment and prepared in the same method as was described above.

3. RESULTS

In next subsections we present the best results obtained in the selected configuration of the PLCF samples in view of multi-parameter sensing of temperature, electric field or hydrostatic pressure.

3.1. Thermal Effects in PLCFs

The PCF used as a host structure was a solid-core fiber ~35 cm long with 3 rings of holes filled with 6CHBT (section of ~1.5 cm). The temperature range varied from 0°C to 70°C and intensity of the output light generally increased with temperature. The experimental results are shown in Figure 6. A potential PLCF-based temperature sensor can operate for selected wavelengths (e.g., 479 nm or 622 nm) and specific temperature ranges (Fig. 7).

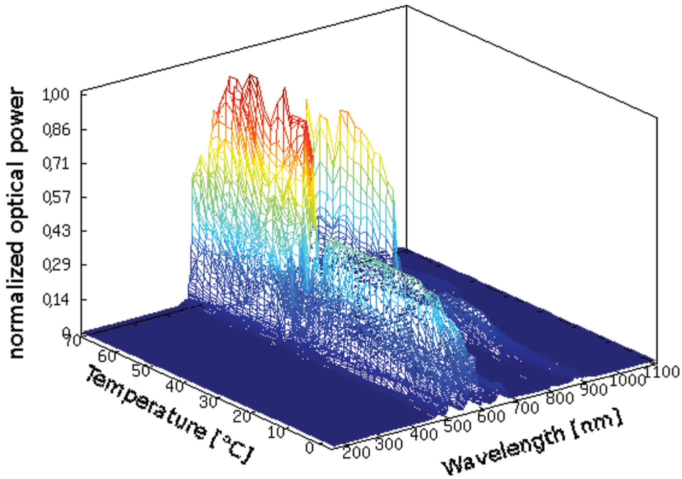


FIGURE 6 PCF with 3 rings of holes filled with 6CHBT under influence of temperature.

It was also possible to tune positions of the photonic band gaps as presented in Figure 8. In this measurement was used a ~34 cm long PCF with 6 rings of holes infiltrated with the 1550 LC (section 1 cm).

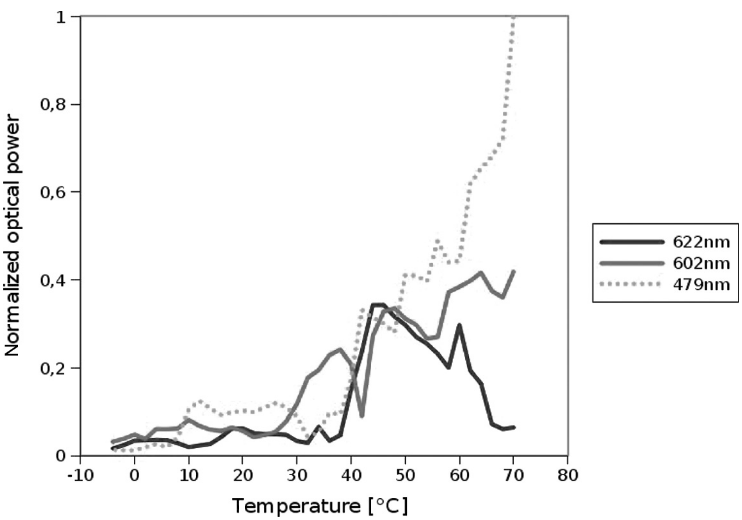


FIGURE 7 Normalized optical power for selected wavelengths vs. temperature (PCF with 3 rings of holes filled with 6CHBT).

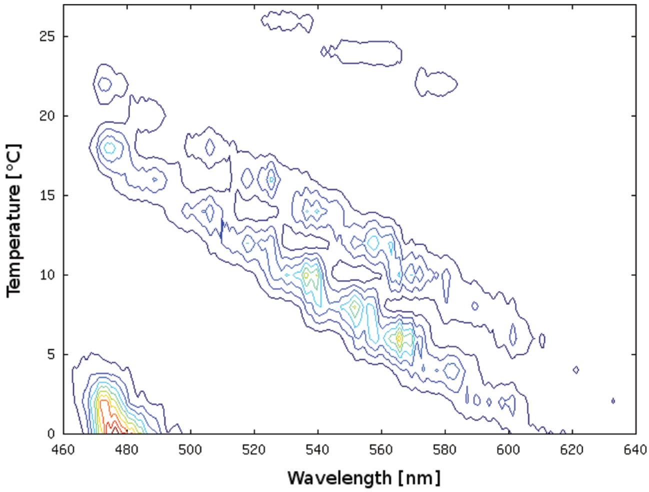


FIGURE 8 Thermal tuning of PBG positions in the PCF with 6 rings of holes infiltrated with nematic LC with numbered 1550 (data described in temperature scale).

This PBG tuning was observed for the temperature range: 0–23°C. As a result, the operating wavelength strongly depends on temperature and this opens up new perspective applications of the PLCF.

For the PCF with 3 rings of holes (~36 cm) infiltrated with the 1550 LC (section 9 mm). Figures 9, 10 it is observed that this sample can operate only for higher temperature.

Based on the results obtained (PCF with either 3 or 6 holes with the 1550 LC) it is evident that any prospective PLCF-based temperature sensor can operate in two ranges of temperatures 0–30°C and above 55°C. The observed decay of propagation in the temperature around 35°C can be attributed to the fact that ordinary refractive index of the 1550 nematic LC (responsible for the light propagation) matches the refractive index of the silica glass and hence the whole PLCF structure becomes uniform and isotropic and the light is radiated out.

3.2. Electric-Field Tuning of PBGs in PLCFs

The PCF with 6 rings of holes was filled with 5CB to observe electrical field-induced effects. A distance between both electrodes was controlled in the range from 0.25 mm to few mm. At room temperature (23°C) several PBGs were observed and after introducing an external

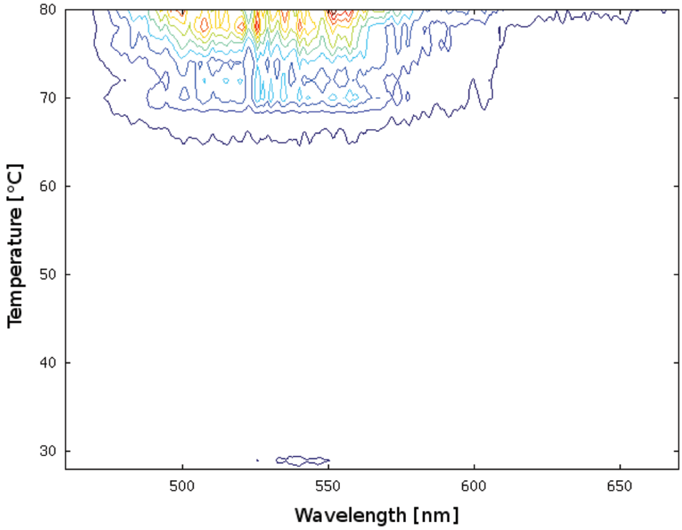


FIGURE 9 Power of light for temperature changes for the PCF with 3 rings of holes infiltrated with the 1550 LC (data described in temperature scale).

electrical field, a decrease at the output power was detected up to 300 V. Results of electrical tuning of PBGs in a PLCF (filled with 5CB) are shown in Figures 11a,b.

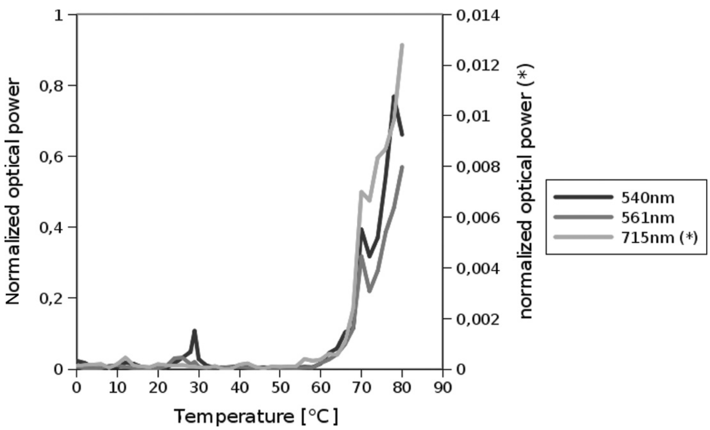


FIGURE 10 Normalized optical power for selected wavelengths in function of temperature for the PCF with 3 rings of holes infiltrated with the 1550 LC.

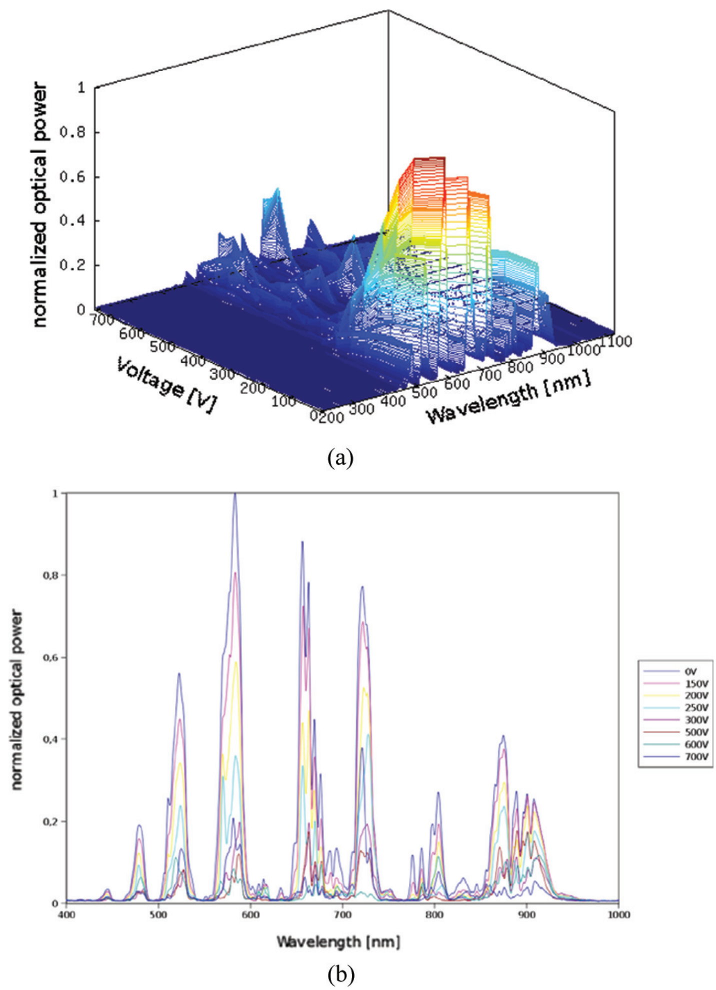
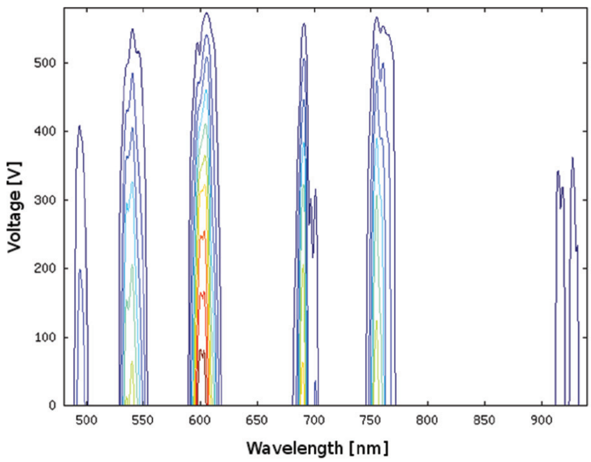


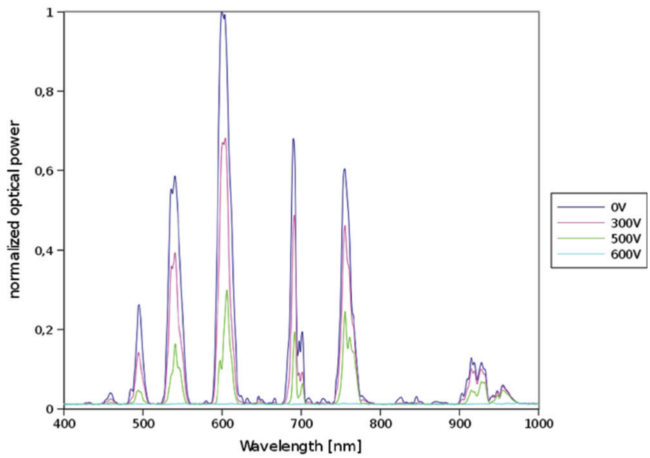
FIGURE 11 (a) Normalized optical power in spectral and voltage domain for PCF with 6 rings of capillaries filled with 5CB, (b) Selective light propagation in PCF with 6 rings of holes filled with 5CB (0.5 mm between covers).

Figures 12a,b presents results of the measurements for the sample consisted of PCF with 3 rings of holes filled with 5CB.

We observed the Frederiks effect (Figs. 14a–c) that occurred for the electric field intensity of the order $\sim 0.5 * 10^{-6}\,\mathrm{V/m}$, the same magnitude was detected for remaining measurements. This change



(a)



(b)

FIGURE 12 (a) Power of light for PCF with 3rings filled and 5CB (1 mm between electrodes) (data described in temperature scale), (b) Selective light propagation in PCF with 3 rings and 5CB (1 mm between electrodes)

in the output optical power due to the Frederiks effect can be easily detectable as shown in Figs. 11–14. By adjusting a value of the electric field intensity corresponding to the Frederiks effect with specific "guest" LCs, a potential PLCF-based threshold electric field sensor can be proposed.

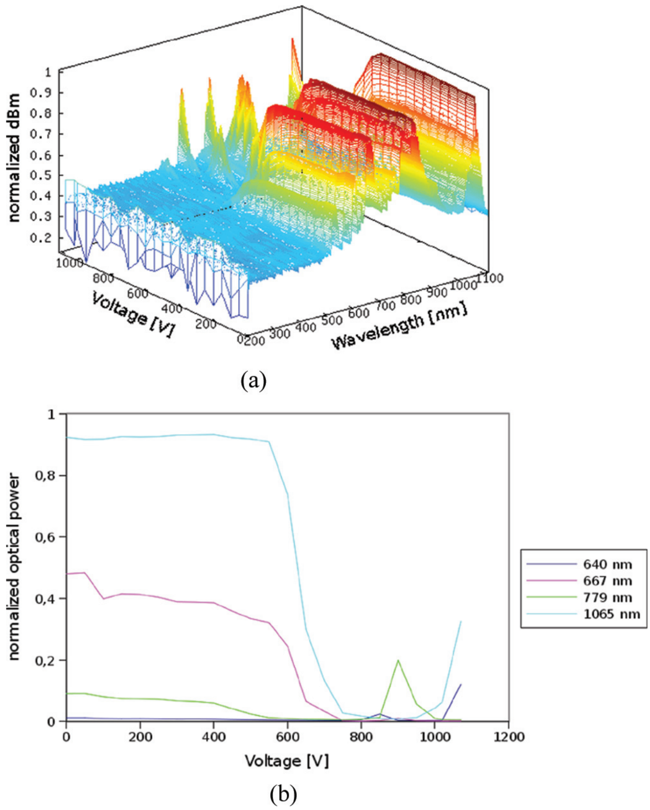


FIGURE 13 (a) Changes of light intensity for PCF with 6 rings of holes filled with 6CHBT (1 mm between electrodes) in log scale, (b) Output power for selected wavelengths – PCF with 6 rings and 6CHBT (1 mm between electrodes)

3.3. Hydrostatic Pressure Effects in PLCFs

Positions of photonic band gaps transmission maxima depend not only on the refractive index of the LC but also on the geometry (diameter) of the cladding capillaries. Hydrostatic pressure acting on the PLCF can change holes diameters and then induce a change in the PBG wavelength. Hydrostatic pressure induces local structural changes decreasing diameter of micro-holes and distance between them. LMA-PM-5 PCF was filled with 6CHBT and without any external perturbation two PBGs in the transmission spectra were observed. However, influence of hydrostatic pressure resulted in narrowing of these

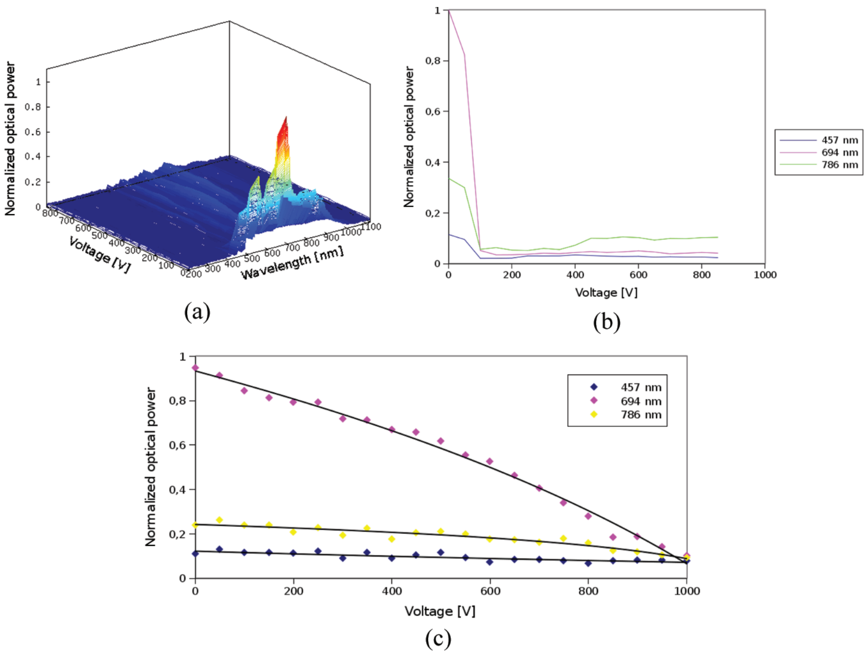


FIGURE 14 (a) Changes of light intensity for PCF with 3 rings and 6CHBT (0.25 mm between electrodes), (b) Output power for selected wavelengths – PCF with 3 rings and 6CHBT (0.25 mm between electrodes), (c) Changes of light intensity for selected wavelengths – PCF with 3 rings of holes filled with 6CHBT (2.5 mm between electrodes)

changes towards longer wavelengths. This effect was especially evident for the range of 600 to 750 nm in which the observed narrowing effect was about 40 nm. Instead, one-side narrowing effect of the PBGs in the transmission spectra was observed and it was repetitive (Fig. 15).

Sensitivity of the PLCF to hydrostatic pressure can create a basis for prospective constructions of fiber-optic pressure sensor. Normalized optical power is linear and the sensor response for hydrostatic pressure must depend on the operating wavelength (Fig. 16). Hence, by injecting only a selected wavelength into the PLCF and observing the output light it is able to scale the sensor head to measure hydrostatic pressure.

Another fiber used in this experiment was UMCS-070124 PCF with 3 rings of holes filled with 5CB. Here was observed several PBGs and increasing hydrostatic pressure was narrowing PBGs towards shorter wavelengths (Fig. 17). Peak light intensities decrease exactly

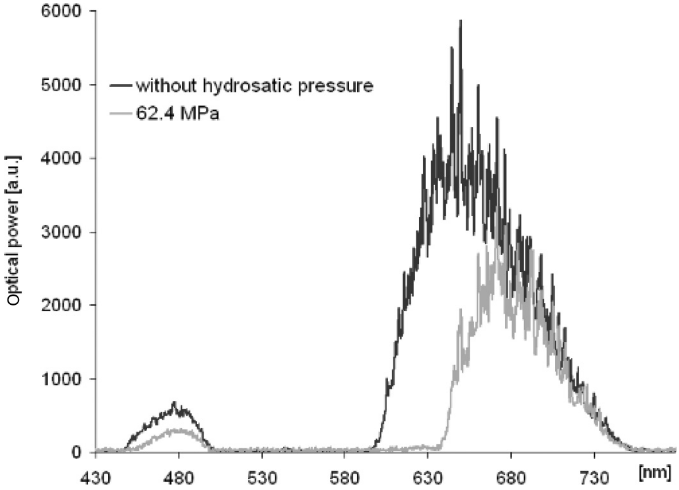


FIGURE 15 Transmission spectra for LMA-PM-5 PCF infiltrated with 6CHBT LC under influence of hydrostatic pressure.

at the same rate with pressure for 538 nm and 600 nm wavelengths whereas for 912 nm the output intensity starts to decay at higher pressure values (Fig. 18).

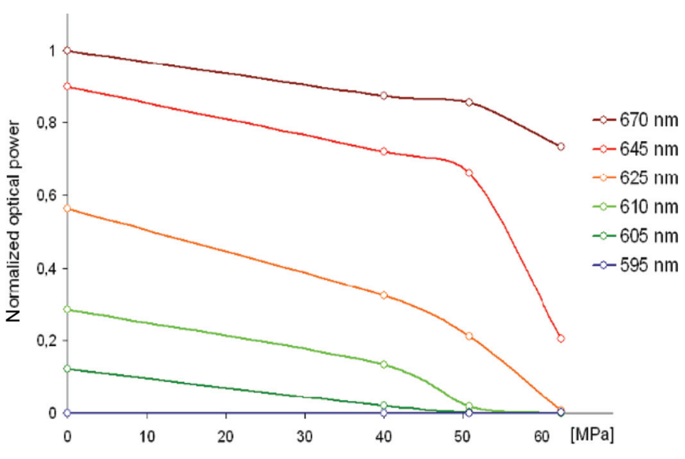


FIGURE 16 Normalized optical power for selected wavelengths in function of hydrostatic pressure for LMA-PM-5 PCF with the nematic 6CHBT.

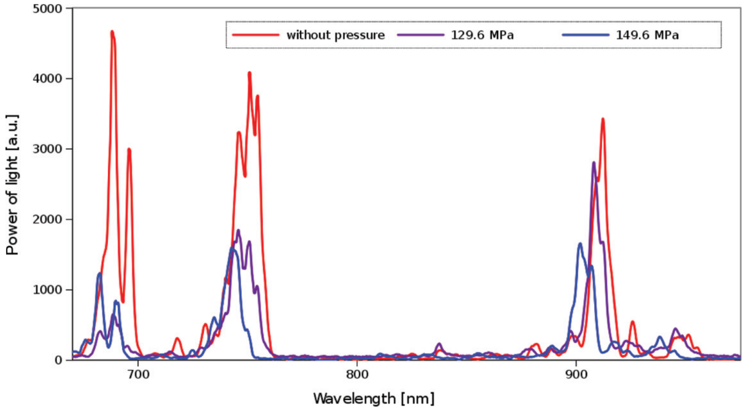


FIGURE 17 Transmission spectra for PCF with 3 rings of holes infiltrated with 5CB under influence of hydrostatic pressure

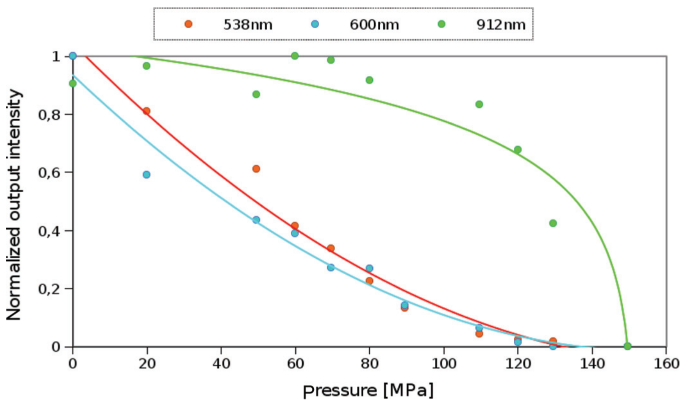


FIGURE 18 Normalized output intensity for selected wavelengths in function of hydrostatic pressure for PCF with 3 rings of holes infiltrated with 5CB.

4. CONCLUSIONS

We have demonstrated propagation effects in the photonic liquid crystal fibers composed of a PCF filled with LCs. Changes in the output optical spectrum induced by temperature, electric field and hydrostatic pressure can be used for measurement of these quantities. The spectral shifts of the PBG wavelengths are repeatable and are typical for PLCFs operating in the photonic band gap regime. A specific photonic band gap under external influence has specific behavior: it can be moved towards either shorter or longer wavelengths and also it can modify its width or intensity. Due to these properties of the PBGs there is a possibility to construct sensors operating at specific ranges of external parameters such as temperature, electric field or hydrostatic pressure. It is evident that by using different combinations of PCFs and LCs we can propose a new method of optical fiber sensing with wide sensitivity and operating regions.

At the current stage it is to early to envisage any practical applications of the PLCFs to real sensing systems, since the PLCFs can respond simultaneously to changes induced by numerous environmental parameters that is obviously a basis of multiparameter sensing. When a single parameter has to be measured there is a great need for either compensation or taking into account at the data processing stage an influence of other environmental parameters. This is a subject of further research and optimization activities that are still in progress.

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