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Sensitivity Enhancement of Electric Field Sensor Using HC-1550 PCF Infiltaring by EBBA Liquid Crystal

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Abstract: ***The implementation of the electric field sensor was carried out by using short length of hollow core (HC-1550) PCF. A diode laser was used with wavelength equal to 650nm has been used as a light source guide the light to the one side of the fiber, the other side infiltration with EBBA liquid crystal by capillary effect, where record the transmission spectra by using the fiber optic spectrometer. The proposed sensors are used in the next testing stage. For electric field sensing, the EBBA liquid crystal infiltrate the air holes for the hollow core (HC-1550) PCF. The infiltrated section of photonic crystal fiber was equal to ~1 cm. The results show that the power of transmission spectrum will be remains unchanged until reach the electric field intensity to 97.2 Vrms/mm. The region of the electric field sensor operating is between (97.2 Vrms/mm to 146.8 Vrms/mm). The sensitivity can be finding by the slope of transmission and electric field intensity. It has been obtained that reached 0.00123 dBm.mm/Vrms at 650 nm. These sensitivity amounts are acceptable in comparison with that mentioned in literatures, which indicate the correct path of the work flow and ensure the results validation***

Keywords: photonic crystal fiber, power intensity, transmittance, electric field sensitivity

1. Introduction

Communications, fiber lasers, nonlinear devices, high-power transmission, highly sensitive gas sensors, and other areas [1]. Photonic crystal fiber are made from a single material such as silica glass with periodic arrangement of air holes lies along the length of the fiber, with the scale of micro structuring being comparable to the wavelength of the electromagnetic radiation guided by the fibers. The light is confined in solid core by exploiting the modified total internal reflection, so the photonic crystal fibers of non-filling holes are more similar to conventional optical fibers, where the difference of refractive index between the core region and the gladding region is positive, because the refractive index of air-holes is lower than the refractive index of the core [2]. There are two types of photonic crystal fibers: solid core PCFs and hollow core PCF. The solid core with cross-section presents a periodic array of air holes surrounding a solid core, which are extended invariantly along the fiber length. The second one is the hollow core photonic crystal fibers, which means an air-silica gladding surrounding a hollow core [3]. Therefore, different geometry and different materials will present different structural design used to enable different guidance mechanisms in photonic crystal fibers. These guidance mechanisms are: modified total internal reflection and photonic bandgap guidance [4]. Also, the PCFs can be divided into two groups depending on the geometry of arranging holes along the cross section of the photonic crystal fiber: the first is called index guiding photonic crystal fiber (IG PCFs) while the second group is called and photonic band gap fibers (PBGFs), as in Figure (1) shows [5].

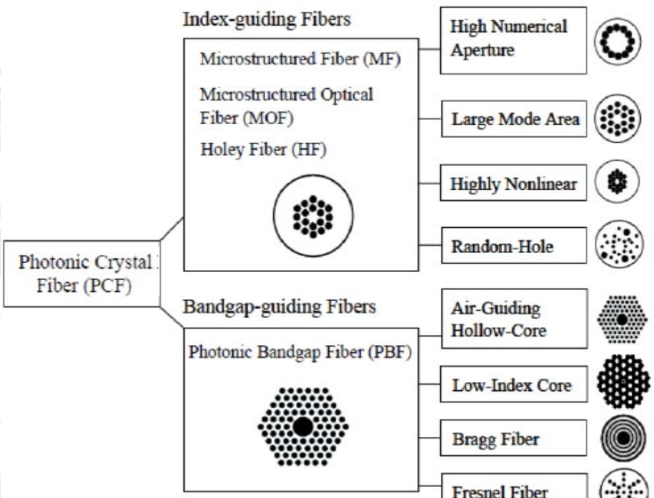

Figure 1: Categorization of photonic crystal fibers [5].

2. Related Work and Contribution

Numerous related works devoted to the sensor design using PCF. They differ in many aspects such as; material of liquid crystal, types of PCF, or even the used laser wavelengths. The feasibility of using PCF for electric field sensor design is investigated in the following literatures:

2.1 Related Work

Many papers were developed to achieve more efficient technique for serving a wide range of applications related to the field of interest: T.R Wolinsk et al in 2006 demonstrated the electric field and temperature effect on the propagation of the photonic liquid crystal fiber composed of solid-core PCF filled with a prototype NLC or with typical nematic pentylocyano-biphenyl (PCB) [6]. T.R Wolinsk et al in 2008 presented experimental results showing the influence of temperature and external electric field and hydrostatic pressure on the propagation properties of the photonic crystal fibers infiltrated with liquid crystal with low and medium material anisotropies. Give information about the value of temperature, voltage, and pressure by measured induced shifts of the photonic bandgap wavelengths [7]. S.Mathews et al in 2011 demonstrated and evaluated the directional sensitivity of maintaining photonic crystal fiber(PM PCF) in an electric field for sensing of electric field and showing that the sensor probe has higher sensitivity to the electric field component aligned along the Hi-Bi PCF axis [8]. S.Mathews in 2011 studied the intensity measurement based electric field sensor by infiltrating an LMA PLC with an liquid crystal(MDA-2782) infiltrated section <1cm , and demonstrated the sensitivity in transmission is 10.1db per kvrms /mm and in reflection is 4.55 db per kVrms /mm [9]. M.M.Tefelska et al in 2014 described four different types of micro-electrodes systems for electric field sensing with photonic crystal fibers infiltrated with liquid crystals. Also analyzed the capillary system theoretically, a capillary system with four micro electrodes (T~36ms) appeared to be the most convenient to operate with photonic liquid crystal fibers [10]. M.Ock Ko et al in 2015 proposed the electric field sensor by using cholesteric liquid crystal (CLC) Fabry-Perot etalon and broad band optical source. The transmitted or reflected wavelength from CLC Fabry-Perot etalon depends on the applied electric field. The valley wavelengths of the transmitted light from CLC device are linearly increased from 1303 nm to 1317 nm as the applied electric field to the CLC device is increased from 0.8 v/m to 1.9 v/m [11].

2.2 Contribution

The present work aims to design a photonic crystal fiber sensor is sensitive to electric field to be operated on a large mode area of photonic crystal fiber (HC-1550 PCF) and EBBA liquid crystal. Pervious literatures refer to the common use of liquid crystal of type MBBA in the sensing applications. The contribution we address is the use of nematic EBBA liquid crystal that infiltrated inside PCF for establish an electric field sensor. Nematics have fluidity similar to that of ordinary (isotropic) liquids but they can be easily aligned by an external magnetic or electric field. Aligned nematics have the optical properties of uniaxial crystals and this makes them extremely useful in different applications such as liquid crystal displays (LCD). The use of EBBA in the present work promise to make the performance of the proposed electric field sensor valued in terms of sensitivity, repeatability and low cost.

3. PCF Sensors

Photonic crystal fiber offers a high degree of freedom in design flexibility, facilitating the development of new sensing application by varying in the size and location of the cladding holes and/or the core of the fiber transmission spectrum, dispersion, mode shape, air filling fraction, nonlinearity and birefringence that can be tuned to reach values are not achievable with conventional optical fibers. Moreover, the existence of air holes gives the possibility of the light propagation in air, and provides the ability to infiltration the liquids or gases into the air holes. This enables a well-controlled interaction between light and sample leading to new sensing application. The applications of the photonic crystal fiber in sensing field can be divided into main categories: biosensors, chemical sensor and physical sensor, depending on the parameter that is measured. The electric field sensor is an important physical sensor due to its relation to the field of high precision industry [12]. More details about electric field sensor are given in the following subsections.

3.1 Electric field sensor

The important applications such as: antennas, metal connection, or conductive electrodes do not use the conventional sensors, they commonly use optic sensors because the fiber optic depend on sensing techniques minimally disarrange the electric field, and part from the sensor head, the connecting fibers are inherently immune to electromagnetic interference. Unattainable fiber based field sensor should present some properties such as simple design, small size and all fiber configuration with high measurement accuracy [12]. The electric field intensity at a point is defined as the force experienced per unit positive charge at a point placed in the electric field, which the electrostatic force per unit charge constituting a field exerting at an arbitrary point, which can be expressed as follows:

$$E = \frac{V}{D} \tag{1}$$

Where, E is the electric field, V is the voltage, and D is the distance between two electrodes plates. For alternating power, the root mean square of the voltage (*Vrms*) is computed by means the maximum value of the voltage (*Vpeak*) as given in eq. (2), whereas the intensity of the electric field is computed by using *Vrms* and *d* as follows [8]:

$$V_{rms} = \left(\frac{3}{8}\right)^{1/2} V_{peak} \tag{2}$$

$$E_{field\,intensity} = \frac{V_{rms}}{d} \tag{3}$$

3.2 Transmission Intensity

Transmittance of the surface of a material is its effectiveness in transmitting radiant energy. It is the fraction of incident electromagnetic power that is transmitted through a sample, in contrast to the transmission coefficient, which is the ratio of the transmitted to incident electric field. The decibel-milliwatts (dBm, or dBmW) is referring to the power ratio in decibels (dB) of the measured power referenced to one milliwatt (*mW*). It is used in radio, microwave and fiber optic networks as a convenient measure of absolute power because of its capability to express both very large and very small values in a short form. Compare dBW, which is referenced to one watt (1000 *mW*). Since it is referenced to the Watt, it is an absolute unit, used when measuring absolute power. A power level of 0 dBm corresponds to a power of 1 *mW*. And 3*dB* increase in level is approximately equivalent to doubling the power, implies, a level of 3*dBm* corresponds roughly to a power of 2*mW*. For each 3*dB* decrease in level, the power is reduced by about one half, making −3*dBm* correspond to a power of about 0.5*mW*. To express an arbitrary power *P* in milliwatt as *x* in dBm, or vice versa, the following equivalent expressions may be used [13]:

$$x = 10\log_{10}\frac{P}{1mW} \quad (4)$$

idem with *P* in watts

$$x = 30 + 10\log\frac{P}{1W} \quad (5)$$

$$P = 1mW.10^{\frac{x}{10}} \quad (6)$$

$$P = 1W.10^{\frac{x-30}{10}} \quad (7)$$

Where *P* is the power measured in *Watt* and x is the power level measured in *decibel-milliwatts*.

4. Proposed Electric Field Sensor Design

The generic structure of the proposed design is shown in Figure (2). It is shown that the proposed method is designed to be consisted of the following multi stages: LC determination and testing, which is necessary to credit the correct behavior of LC physical characteristics. Second stage is the sensor system design setup, which is responsible on construct the sensor components to be used in the next stages. Then, the stage of LC inflteration inside the PCF is carried out. The last stage is testing the sensitivity of the proposed sensor in terms of varying the electric field. More details about each stage are given in the following sections:

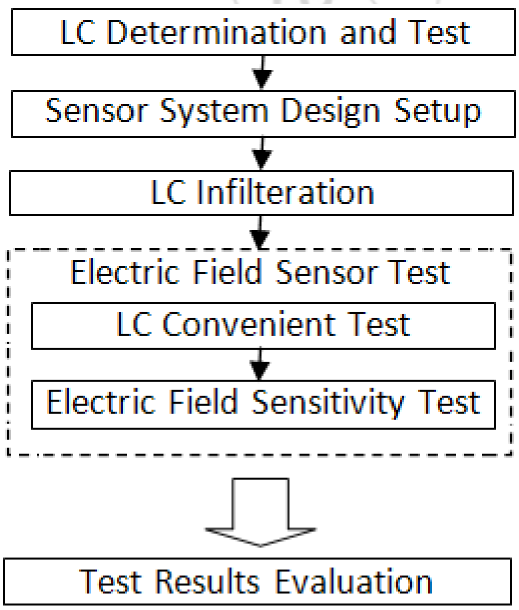

Figure 2: Work flow of the proposed PCF sensor design

4.1 LC Determination and Testing

The suitability of choosing the LC material is depending on the transmission physical property. The transmittance of EBBA is tested, the test is carried out on the refractive index due to its direct relation to the transmittance. The index of refraction is varying with temperature. Therefore, Abbe refractometer is used to measure the refractive indices of EBBA liquid crystal material at different temperature. The acceptable values of such indices indicate light paths inside the PFC. Abbe refractometer is used to measure the refractive index of EBBA many times with varying the temperature of EBBA, measurements were recorded using sodium D line of wavelength λ=589.3*nm* and temperatures range (25-80^oC). The result shows that the increase of temperature leads to decrease the index of refraction values of EBBA (1.3284–1.3198) as given in Table (1). Throughout the refractive index measurements, the temperature is using a HAKKE-D1-G thermometer water bath and a Hewlett-Packard model 201Aquartz thermometer that work in the visible light region, in which the refractometer was connected to the water bath. Figures (3) refer to the relationship between the refractive indices of EBBA and temperature through the heating process. It is shown that the refractive index of EBBA shows very small variation with temperature, this variation is normal compared with other liquids such as water given in [14], and 4-Methoxy-Benzylidene-4-Butyl-n-Aniline (MBBA) liquid crystal given in [15]. This indicates that EBBA that sensitive to temperature variations. Also, it is noticeable that the values of the refractive index are gradually decreasing with increasing the temperature. This is due to the density of EBBA that directly proportional to the refractive index, when the temperature rises lead to a decrease in the density of liquid crystal where due to high temperature the objects is stretch and loss the strength of attraction between molecules and thus get bigger distances between particles and increases the internal molecular movement.

Table 1: The values of refractive index of EBBA with changing temperature

Temperature(^oC)	$n_{heating}$ ±0.001
25	1.3284
30	1.3273
35	1.3268
40	1.3250
45	1.3246
50	1.3237
55	1.3234
60	1.3231
65	1.3229
70	1.3200
75	1.3198
80	1.3194

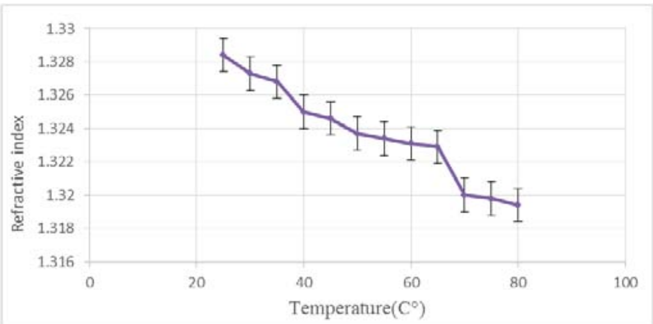

Figure 3: Shows the variation of refractive index of EBBA with temperature in the heating process.

Stretch objects leads to the decrease in the density of matter and thus decrease the refractive index. Furthermore, the UV-Visible spectrophotometer is used to get the absorption spectra of the LC at the region of interest in the wavelength range. The behavior of absorption spectra indicates the useful region of the wavelength that showed maximum amount of absorption. This region can be employed to credit higher efficiency for sensor performance. Figure (4) shows the absorption behavior of the EBBA along the wavelength range (200-900 *nm*). It is shown that the maximum absorption value of the LC at the wavelength (λ_{max}=246 *nm*). The behavior of absorption spectra indicates the useful region of the wavelength that showed maximum amount of absorption. This region can be employed to credit higher efficiency for sensor performance for this reason used wavelength large than 246 nm to avoid the absorption of material to light so, can be obtained high output power.

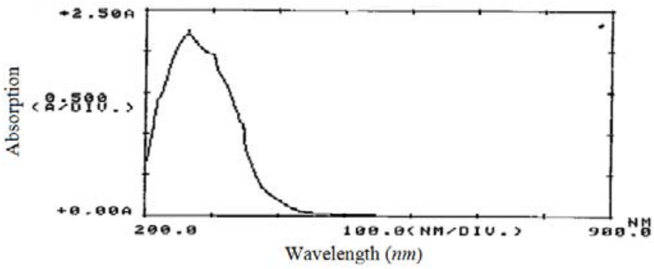

Figure 4: Absorption behavior of EBBA

4.2 Sensor Design Setup

Figure (5) shows the fabrication of the electric field sensor setup. The diode laser (produced by ASTRO company) is used with wavelength equal to 650 *nm*, the power of this laser200 *mw*. The type of the used fiber as a sensor head is HC-1550 PCF. This fiber set between two electrodes plates of spacing distance is equal to 0.25 *cm*. The spectrometer (of type; Ava Spec_2048 XL, produced by AVANTES company) was used to record the transmission spectra with increasing the voltage by using high voltage power supply (100-1000 *v*) and voltmeter (of type; 3PK-600T, produced by Proskit company). Also there is an objective lens is used to focus the light of the laser on the head of fiber as shown in Figure (6).

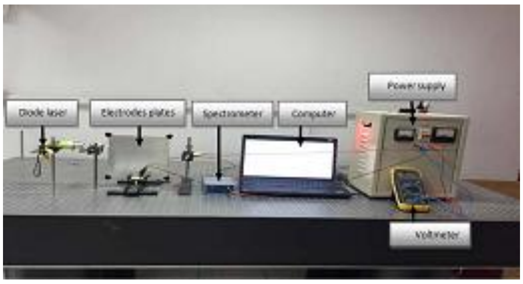

Figure 5: Photographs of electric field sensor setup.

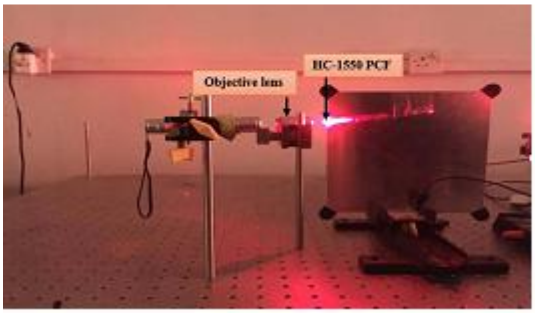

Figure 6: Photographs of electric field sensor setup with objective lens.

4.3 Liquid Crystal Inflteration

This type of sensors based on use a small piece of hollow core photonic crystal fiber infiltrated with liquid. Where, the open end of the photonic crystal fiber was infiltrated with EBBA liquid crystal at room temperature by dipping the cleaved and into the liquid crystal material. The liquid crystal material was drawn into the holes of photonic crystal fiber by capillary action and an infiltration length ~1 *cm* was obtained. The electric field is applied to the infiltrated photonic crystal fiber by means of two electrodes positioned on opposite sides at the infiltrated end of the photonic crystal fiber. The distance between two electrodes is equal to the 0.25 *cm* .The values of voltage in our experiment from zero volt to Vpeak , the used maximum value of Vpeak is 700 *V*. the transmission spectra of the infiltrated photonic crystal fiber sample was record by using spectrometer. Figure (7-a) shows the photograph of empty hollow core PCF, whereas Figure (7-b) infiltrated PCF with prepared liquid crystal (EBBA).

Figure 7: Photographs of photonic crystal fiber.

The PCF electric field sensor has been designed by using solid core photonic crystal fiber (LMA-10). Full collapsing technique was used to connect photonic crystal fiber to single mode fiber. Before splicing PCF with FSM, they are cleaved by high precision cleaver (CT-30), and then they are spliced by fusion splicing machine (FSM-60). Then, EBBA is infiltrated through the photonic crystal fiber by means of capillary effect. More details about such processes are mentioned in the following:

A. PCF Cleaving

Cleaving process aims to remove the coating of the fiber by stripping tools such as the CFs-1 or Fitel S-210. If removal of coating debris was needed, one can use a folded sheet of lint free lens tissue to avoid leakage of liquid into holes. It should be note that the use of any solvent for cleaving the fiber after cleaving process is not allowed since it may cause a failure of connecting and sensing.

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B. PCF Splicing

Photonic crystal fiber spices are different from standard fiber splices because the core cannot be seen through the side of the fiber and the power will be reduced, typical splicer power is about 25% less than that used for comparable solid fibers [16], to collapse of the holes. The most challenging problem in splicing PCF, is a voiding the collapse of the microstructures holes, because high temperatures from splice also giving a chance to glass to flow. There are many splicing techniques used to splice photonic crystal fiber with different fibers, one techniques has been used namely fusion splicers. FSM-60 splicer that produced by Fujikura Company has been used to splice different types of fiber, LMA-10 PCF spliced with a single mode fiber (SMF-28) from one end. The other end of PCF LMA-10 was connected by a free space connector to give an access for liquid infiltration. The present setup comprises of a piece of LMA-10 photonic crystal fiber spliced from one end with single mode fiber SMF-28. The other end of the LMA-10 photonic crystal fiber was connected to give an access for liquid infiltration by free space connector. Figure (8) show the splicing of photonic crystal fiber with single mode fiber.

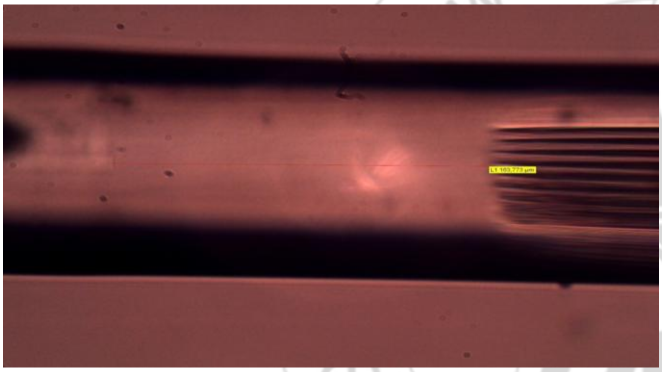

Figure 8: PCF-SMF splicing.

C. LC Infiltration

The infiltration of LC in the PCF in the present work is carried out by using capillary tube method, this method used because the techniques of infiltration are unavailable. By this method can LC a rise in PCF approach *1cm.* This type of sensor based on use a small amount of EBBA that sensitive to temperature. Where, EBBA is infiltrated through the photonic crystal fiber by means of capillary effect, time article to be taken to rise almost an hour.

5. Electric Field Sensitivity Result

One type of photonic crystal fiber which is HC-1550 was used to carry experimentally applying with wavelength equal to 650 nm. The values of the voltage can be change to the electric field intensity by using equation (3). It is found that there is a relation between the electric field intensity and transmission as show in table (3).

The transmission response of the device with increasing electric field intensity is shown in figure (9).between a field intensity of zero and 97.92 V_{rms}/mm, the transmission remains unchanged. Above this threshold field intensity, the nematic liquid crystal molecules begin to reorientation which results in a gradual decrease in transmission through the infiltrated photonic crystal fiber with EBBA liquid crystal with the increasing electric field intensity until an of ~(146.8 V_{rms}/mm) is reached. The transmission response in the electric field intensities from 97.92 V_{rms}/mm to 146.8 V_{rms}/mm is close to linear. The linear part of the transmission response for the infiltrated photonic crystal fiber in the electric field intensity show that the sensitivity to the electric field equal to 0.00123 dBm/(V_{rms}/mm).

In order to measure the sensor sensitivity, it should be take in a count just the region that the sensor operate through this refers to the interval 97.2-146.8 *Vrms/mm* of electric field intensity, but the last literature mention that the best description of the sensor sensitivity is linearly when the behavior of the sensor is decay with increasing transmission intensity, which is the region between 97.2-146.8 *Vrms/mm*.

Table 2: The values of voltage and power

Power (mW)	*Voltage (V)*
0.60496	0
0.60509	100
0.60592	200
0.60586	300
0.60318	400
0.60475	500
0.60949	600
0.60630	700
0.60650	800
0.60660	900

Table 3: The values of electric field intensity and transmission

Transmission (dBm)	*Electric field intensity (V_{rms}/mm)*
-2.18	0
-2.18	24.48
-2.18	48.96
-2.18	73.44
-2.19	97.92
-2.18	122.4
-2.15	146.8
-2.17	171.3
-2.17	195.9
-2.17	220.4

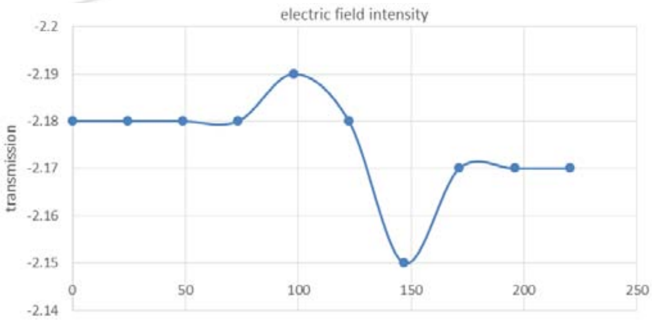

Figure 9: shows the relation between transmission and electric field intensity after infiltration with EBBA liquid crystal at 650 nm.

6. Results Analysis

It is shown that the increasing in temperature affects molecules of liquid crystal and photons emerging from liquid crystal through the fiber. Temperature increasing leads to increase the vibrating energy of the liquid crystal, because of the strong bonds between molecules of the liquid crystal, the effect does not appear that not much vibrating liquid crystal molecules only a very slight vibration of possible neglecting. In addition, the increase of applied voltage leads to increase the electric field, and rise the kinetic energy of photons transmitted to spectrometer. Implies, there is a greater number of photons is implemented through the liquid crystal down to spectrometer. This means an increase in gained power of light emerging from the fiber and this lead to increase the transmittance at a determined range of electric field intensity. This range is regarded as the range of the operating mode of the sensor. The sensor is operated well only at this range of electric field intensity.

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