Design and Implementation of Temperature Sensor Using PCF Infiltered by EBBA Liquid Crystal

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Abstract: The use of efficient sensor design gains most interest due to its close relation with the improvements happen in application fields and manufacturing. The photonic crystal fibers are receiving increased attention as a newly tool to establish an active sensors when they are infiltered by a sensitive fluid. In this paper, the photonic crystal fiber is used to design a sensor is sensitive to temperature. This sensor is operating on large mode area of photonic crystal fiber (LMA-10 PCF) infiltered by EBBA liquid crystal. The test shows that EBBA is very sensitive to the temperature variation. The temperature sensor design requires passing through multi sequenced stages till reaching the operating mode. The operating test results show that the proposed temperature sensor is operated along wide range of temperature, and measures an accurate value at little changes may happen in the temperature. The determined sensitivity of the proposed sensor was highly estimated, which ensures the ability of proposed temperature sensor to be applied in the manufacturing field.

Keywords: photonic crystal fiber, power intensity, transmittance, temperature sensitivity.

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1. Introduction

Optical fiber is used in our daily lives in the connecting to the internet, making telephone calls and reading our e-mails. Different applications in optical communication networks were performed using photonic crystal fiber, such as: spectroscopy, astronomy, biomedical imaging, diagnostic, and structural sensing. Photonic fiber crystal is an efficient technology for producing different types of physical sensors used in manufacture; one of the important sensors is the temperature sensor, which is wide used in many manufacturing applications [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]. Therefore, photonic crystal fibers can be categorized in two types depend on its material: it is may be solid-core photonic crystal fiber or hollow-core photonic crystal fibers. 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 [3]. In the solid core PCF, the effective refractive index of the gladding will be lowered when with the refractive index of the core, allowing the guidance mechanism to be total internal reflection, without need to dope the core, allowing the solid core PCFs to be made with a single material. Whereas, the hollow PCF confines the light by the bandgap mechanism, which based on the photonic bandgap effect [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) [5].

2. Related Work and Contribution

There are many papers devoted to PCF based sensor design. They differ in many aspects such as; liquid crystal material, types of PCF, or even the used laser wavelengths. The feasibility of using PCF for temperature sensor design is investigated in the following literatures:

2.1 Related Work

Numerous articles were developed to achieve more efficient technique for serving a wide range of applications related to the field of interest. Jian Ju et al investigated theoretically and experimentally of the temperature sensitivity through two-mode(TM) photonic crystal fiber(PCF) sensor, and was measured the temperature sensitivity and found equal to 0.083 rad/.m at 543 nm and 0.147 rad/.m at 975 nm and 0.136 rad/.m at 1310 nm [6]. O.Frazao et al demonstrated the temperature insensitive and strain sensor by using Hi-Bi photonic crystal fiber loop mirror.the optical sensor was characterizedin temperature and strain with coated Hi-Bi photonic crystal fiber and uncoated Hi-Bi photonic crystal fiber , the optical sensor is insensitive to temperature (0.9 pm/k) [7]. A.Bozolan et al demonstrated the optical fiber temperature sensor based on colloidal quantum dot luminescence. The result show the temperature sensitivity equal to 70 pm/ spectral shift over the range from 5 to 90 [8]. Ashwini.M et al studied the temperature property of gratings in photonic crystal fiber and analyzed the relationship between frequency shift, wavelength shift, effective index and temperature by finite difference time domain method. The result show that the PCF gratings are in proportion to the temperature and thus applicable as temperature sensor [9]. Ran Wang et al demonstrated the sensor probe for temperature measurement by using reflective photonic crystal fiber(LMA-8 PCF).the experimental result show that the reflected power exhibits a linear response with temperature with sensitivity equal to 1db/,and the emperature sensitivity with mixture of liquids is about 0.75 db [10]. J.E.Antoni-Lopez et al demonstrated the temperature sensitivity by using customized multicore fiber (MCF),measured temperature sensitivity with high sensitivity and accuracy and found the sensitivity equal 29pm/ at lower temperatures and increasing temperature up to 1000 and found the temperature sensitivity equal 52 pm [11].

2.2 Contribution

The contribution we address in the present work is the achievement of high performance temperature sensor using PCF is infiltrated with Nematic EBBA liquid crystal. 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). Pervious literatures refer to the common use of liquid crystal of type MBBA in the sensing applications, while the present work uses EBBA, which is a new achievement especially when it uses four test wavelengths (632, 850, 1060, and 1550 *nm*). This promise to make the performance of the proposed temperature sensor is valued in terms of sensitivity, repeatability and low cost.

3. Transmission Fiber Technology

Fiber optic in sensor field have proven to be very important in measuring temperature in original metal and glass productions, in power generation operations, oven and automated welding equipment. Another application were in optical fiber depend on the temperature measurement is efficient in high temperature processing operations in cement and chemical industries. This type of fiber optic sensor is the one of the most required in commercial market through the high number of applications in different fields. Accordingly, the temperature sensor based on photonic crystal fibers were quickly developed in order to produce new sensor with improve properties such as sensibility and stability [12].

3.1 Optical Fiber

An optical fiber is a cylindrical dielectric waveguide that transmits light along its axis, by the process of total internal reflection. The fiber consists of a core surrounded by a cladding layer, both of which are made of dielectric materials. To confine the optical signal in the core, the refractive index of the core must be greater than that of the cladding. Conventional optical fibers are formed from two different type of silica. The middle of the fiber is forming the core of the fiber with higher refractive index, whereas the second part is forming the glad of optical fiber and surrounds the core with refractive index that should be lower than the core as shown in Figure (1) [1].

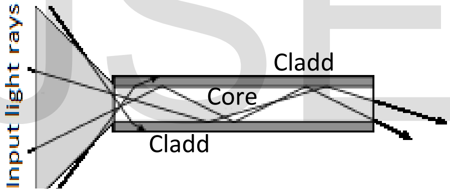


Fig (1) Conventional photonic crystal fibers [1].

The major difference between two kinds of fibers based on the fact that the waveguide properties of photonic crystal fibers are not from spatially varying glass composition, as in conventional optical fiber, but from an arrangement of air holes which go through the whole length of fiber. Photonic crystal fiber (PCF) is also called holey fiber or microstructure optical fiber that was firstly reported by Philip Russell [10]. This new generation of optical fiber was appeared in mid 1990s to investigate the idea of making PCF from single material. 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. 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 [13].

3.2 Photonic Liquid Crystal

A photonic liquid crystal is a periodic optical nanostructure that affects the motion of photons in much the same way that ionic lattices affect electrons in solids. Photonic crystals occur in nature in the form of structural coloration, which promise to be useful in a range of applications. The distinguishing characteristic of the liquid crystalline state is the tendency of mesogens to point along a common axis called the director (n) which is a unit vector and is called the liquid crystal director. In the solid state, molecules are highly ordered and have little translational freedom. The characteristic orientation order of the liquid crystal state is between the solid and liquid phases [14]. The alignment of the molecules for each phase is shown in the Figure (2). The physical properties of such liquid crystal are distinguished into scalar and non-scalar properties.

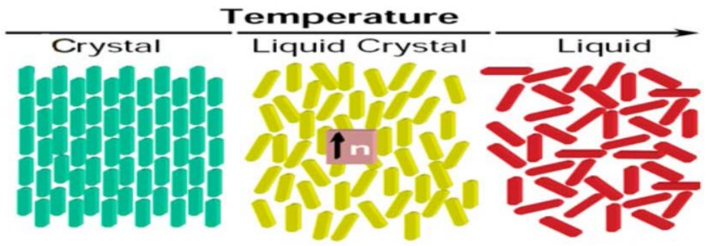


Fig (2) Alignment of molecules for solid, liquid crystal and liquid phases [50].

4. Proposed Temperature Sensor Design

The generic structure of the proposed design is shown in Figure (3). 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. The last stage is testing the sensitivity of the proposed sensor in terms of varying the temperature. More details about each stage are given in the following sections:

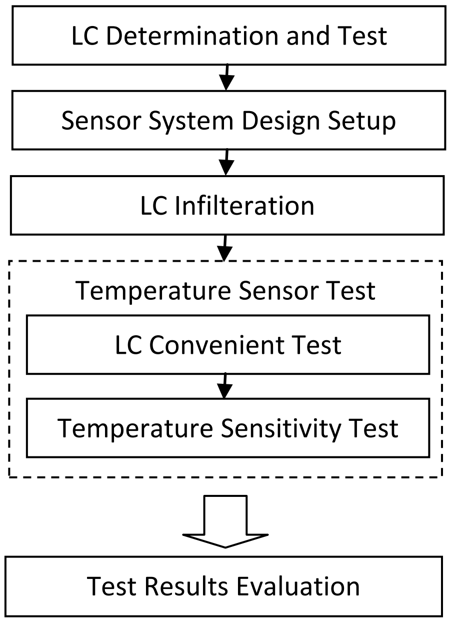


Fig (3) Work flow of the proposed PCF sensor design.

4.1 LC Determination and Testing

The considered physical characterization is the transmittance of the adopted liquid crystal, the behavior of the transmittance is considered as a function to the different wavelengths. Also, Abbe refractometer can be used to measure the refractive indices of EBBA liquid crystal material with different temperature. The acceptable values of such indices are 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^{o}C). 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 (4) refer to the relationship between the refractive indices of EBBA and temperature through the heating process.

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

Temperature(^{o}C)	**$n_{heating}$ ±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

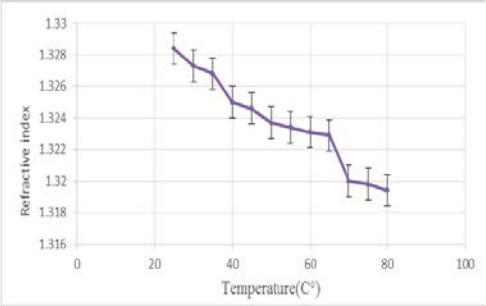


Fig (4) Shows the variation of refractive index of EBBA with temperature in the heating process.

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 [15], and 4-Methoxy-Benzylidene-4-Butyl-n-Aniline (MBBA) liquid crystal given in [16]. 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. 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 (5) 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.

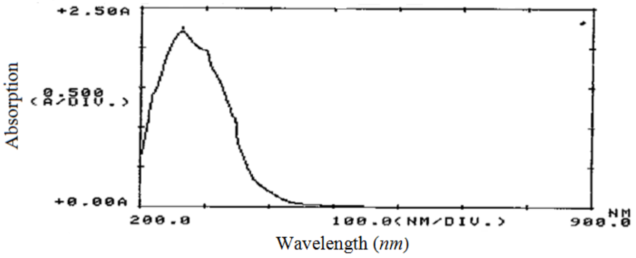


Fig (5) Absorption behavior of EBBA.

4.2 Sensor Design Setup

The proposed sensor design is based on using small amount of EBBA infiltrated inside the PCF to be used with solid core LMA-10 PCF at different temperature and different wavelengths (1550, 1060, 850 *nm*) and laser helium-neon with 632.8 *nm*. Such that, photonic crystal fiber will become sensitive to temperature, and this will have effects the output light power through the filled photonic crystal fiber. The experimental setup of the temperature sensor is shown in Figure (6).

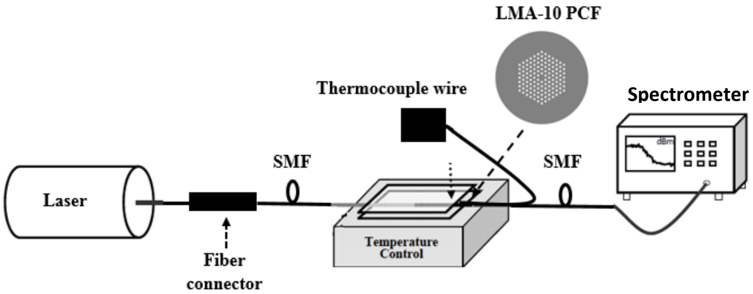


Fig (6) Setup of the temperature sensor photonic crystal fiber.

The laser source shown in Figure (6) is used to provide laser beams of different wavelengths 1550, 1060, 850 *nm*, the power of such laser almost 1*mw*. Also, the helium-neon laser is used to provide a laser beam of wavelength 632.8 *nm*. The fiber of type LMA-10 PCF is used as a sensor head, such type consist of a six rings of air holes surrounded the solid core as mentioned in appendix. The optical spectrum analyzer OSA(YOKOKKAWA, Ando AQ6370) with resolution 0.02 *nm* was used to monitor the interference spectra of the sensor. Also a hot plate (Thermostiertific type

1900) is used in addition to thermo couple wire of type K. Full collapsing technique was used to connect photonic crystal fiber to single mode fiber. Before splicing PCF with SMF, they are cleaved by high precision cleaver (CT-30), then they are spliced by fusion splicing machine (FSM-60). A free space connector with less loss is used to connect them from other side to give an access for liquid infiltration.

4.3 Liquid Crystal Inflteration

The PCF temperature 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 SMF, 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.

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 [61], 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 (7) show the splicing of photonic crystal fiber with single mode fiber.

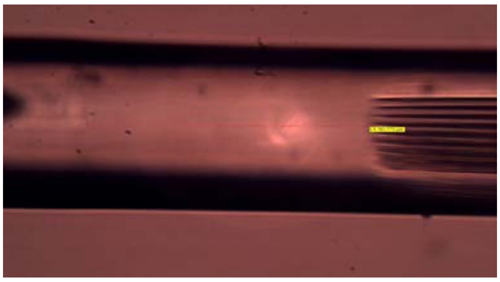


Fig (7) PCF-SMF splicing.

C. LC Infilteration

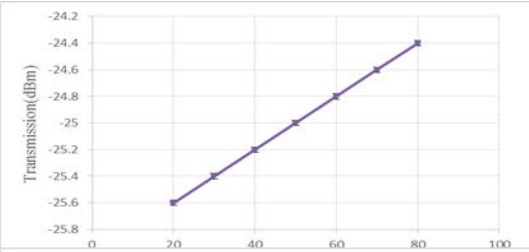
The inflteration of LC in the PCF in the present work is carried out by using capillary tube method, this method used because the techniques of inflteration are unavailable. By this method can LC a rise in PCF approach *1cm*. This type of sensor based on use a small amount of EBBA that sensitive to temperature. Where, EBBA is infiltrated through the photonic crystal fiber by means of capillary effect, time article to be taken to rise almost an hour. This fluid is used with solid core LMA-10 PCF at different temperature and different wavelengths (1550, 1060, 850 *nm*) and laser helium-neon with 632.8 *nm*. Such that, photonic crystal fiber will become sensitive to temperature, and this will have effects the output light power through the filled photonic crystal fiber.

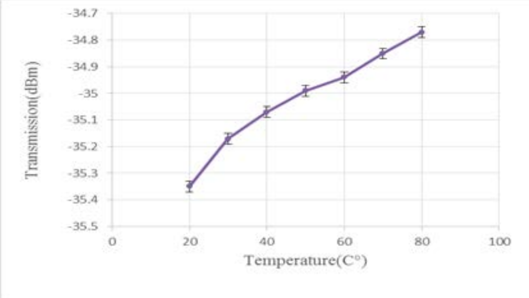
6. Temperature Sensitivity Result

The used PCF in the temperature sensor is composed to two pieces; the first is a solid core LMA-10 PCF that spliced to the second piece of type SMF-28. The photonic crystal fiber of type LMA-10 was used to carry experiment applying with different wavelengths (1550, 1060, 850, and 632.8 *nm*). The values of the power change directly to the value of transmission intensity, such that, the power intensity (*P*) is the employed as a measure for the temperature sensitivity at different transmission (*T*) conditions, the measurements of power intensity is estimated at different wavelengths. Table (2) listed the measured transmission with the variation of temperature at wavelength (1550, 1060, 850, and 632.8*nm*). This refers to the relation between the refractive index distribution over air holes and temperature change of the spectrum with increasing temperature. Figures (8-11) show the behavior of the transmission with the variation of temperature. The results have been shown that the transmission is increased with the increase of temperature; this is due to influence refractive index on the propagation mode that becomes less confined in the fiber. The slope of power intensity behaviors can be employed to determine the sensitivity of the temperature sensor as given in Table (3) and shown in Figure (12).

Table (2) Power intensity versus transmission condition at different wavelengths.

t(℃)	**λ= 1500 (nm)**		**λ= 1060 nm**		**λ=850 nm**		**λ=632.8 nm**	
	P (mW)	*T* (dBm) ±0.02	*P* (mW)	*T* (dBm) ± 0.02	*P* (mW)	*T* (dBm) ± 0.02	*P* (mW)	*T*(dBm) ± 0.02
20	0.0027542	-25.6	0.0002911	-35.35	0.00930	-20.31	0.00640	-21.93
30	0.002884	-25.4	0.000304	-35.171	0.00934	-20.29	0.00643	-21.91
40	0.00302	-25.2	0.0003111	-35.07	0.00942	-20.25	0.00647	-21.89
50	0.0031622	-25.0	0.0003165	-34.99	0.00952	-20.21	0.00651	-21.86
60	0.0033113	-24.8	0.0003205	-34.94	0.00960	-20.17	0.00654	-21.84
70	0.0034673	-24.6	0.0003269	-34.85	0.00975	-20.10	0.00659	-21.81
80	0.0036307	-24.4	0.0003332	-34.77	0.00990	-20.04	0.00664	-21.77





1550 *nm*.

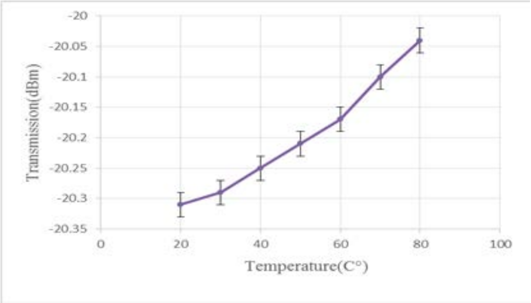


Fig (10) Transmission versus temperature at 850 *nm*.

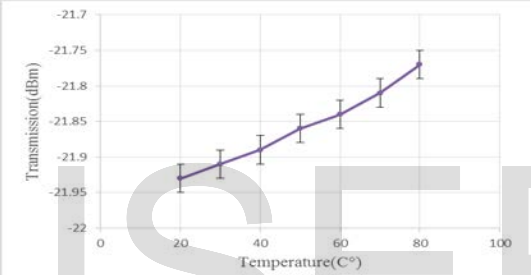


Fig (11) Transmission versus temperature at 632.8 *nm*.

Table (3) Sensitivity variation with temperature and wavelength**.**

Wavelength (nm)	**Sensitivity ($dBm/^oC$)**
1550	0.020000
1060	0.008971
850	0.004536
632.8	0.002607

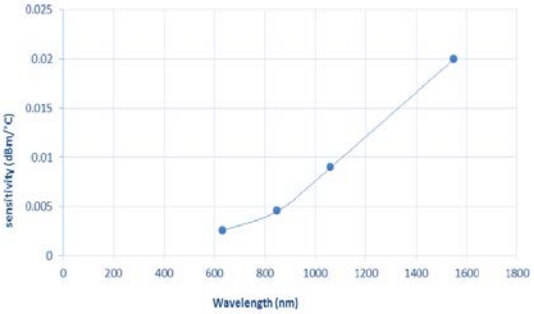


Fig (12) Sensitivity of temperature at different wavelength.

7. Results Analysis

It is shown that the increasing in temperature affect on the molecules of liquid crystal and photons emerging from liquid crystal through the fiber. This increase in temperature leads to increased the vibrating energy of the liquid crystal, because of the strong bonds between the liquid crystal molecules, the effect does not appear that not much vibrating liquid crystal molecules only a very slight vibration of possible neglecting. In addition, the increased in temperature also leads to increased kinetic energy of the photons, and this makes the largest number of photons is implemented through the liquid crystal down to spectrometer. This means an increase in the power of light emerging from the fiber and thus lead to increase transmission with different wavelengths , but at wavelength equal to 1550 nm found that the temperature sensitivity as high as possible because at this wavelength be less loss and attenuation as possible.

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