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A Temperature Insensitive Strain Sensor using Long Period Grating Photonic Crystal Fiber.

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Abstract—We present a study of strain and temperature sensitivities of long period gratings written on photonic crystal fiber. The role of dispersion factor γ into the sensitivities is elaborated. The polarity of the dispersion factor determines the polarity of the sensitivity. The effect of variation in the waveguide properties due to the structure of photonic crystal fibers to the sensitivities is explained. By selecting a proper LPG period and mode order a temperature insensitive strain sensor is realized.

Keywords-*Long period grating, photonic crystal fiber, strain optic cofficient, thermo otic coefficient, strain and temperature sensor.*

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I. Introduction

Photonic crystal fibers are a special class of optical fibers which has a cladding that consists of microstructured array of air holes that run along the fiber axis. They are also called as holey fibers or microstructured optical fibers. Basically the internal structure is made up of air filled capillaries that is arranged in a hexagonal lattice. Light is allowed to pass through the fiber when a defect is realized in its internal structure. This defect can be realized by removing one or more capillaries at the centre. PCF contains several parameters that can be manipulated like lattice pitch, shape and diameter of air holes, lattice shape and refractive index of glass. Using these parameters and combining the properties of optical fibers enables PCF to have impossible properties that cannot be achieved in conventional fibers due to which they have attracted a lot of attention in recent times [1-14]. There are two types of PCFs. One is called as the solid core PCF in which the defect is realized by removing the central capillary. The light is guided through the fiber by modified total internal reflection. This is possible due to the presence of air holes that leak higher order modes and only allows one fundamental mode to pass through. This mode posses the smallest diameter equal to the diameter of the defect [15, 16]. The second type of PCF is called as the hollow core PCF in which the defect is realized by inserting a capillary at the centre that has a diameter bigger than the other capillaries[17]. The guiding mechanism in this case is photonic bandgap wherein it allows only those modes whose frequencies fall in the photonic bandgap.

Long period gratings (LPG) are formed by introducing periodic modulations of the refractive index of the fiber. This perturbation causes the fundamental guided mode to couple with different cladding modes. This coupling produces dips in the transmission spectrum. LPGs have found applications in many devices like band rejection filters [18, 19], mode converters [20], erbium doped fiber amplifier [21] and as physical sensors for strain, temperature, curvature and refractive index [22-25]. LPGs have several advantages like small backward reflection, low insertion loss, low electromagnetic interference, small size and low cost [26, 27]. Properties of LPGs are very much different from fiber bragg gratings (FBG). In FBGs coupling takes place between forward and reverse propagating modes whereas in LPGs the fundamental guided mode couples with different cladding modes. By choosing the appropriate fiber type, period and cladding mode temperature and strain sensitivity can be positive, negative or zero [26, 28-34]. By exploiting these factors one can achieve high strain sensitive and temperature insensitive fiber sensor.

Temperature sensitivity in conventional fibers is very high because it is made up of two materials having different thermal expansion coefficients. So it possess very high thermal expansion coefficient. On the other hand PCF is made of just one material so it posses only one thermal expansion coefficient. Therefore temperature insensitive sensors can be achieved using PCF [35]. LPGs on PCF show different properties as compared to LPGs on conventional fibers. The resonance wavelength reduces as the period increases contrary to LPG [36-38]. LPGs inscribed on PCF using CO_2 laser are stable as the gratings inscribed are everlasting, whereas in case of LPGs inscribed on conventional fibers using UV exposure, the gratings starts aging with time. So the gratings are not stable [39]. Resonance wavelength of LPGs in PCF shows blue shifting under applied strain in contrast to LPGs in conventional fibers [40, 41].

In this paper, an endlessly single mode photonic crystal fiber is considered in which LPG is inscribed and its strain and temperature characteristics are checked. In order to understand its properties dispersion factor is defined. In this case the dispersion factor is always found to be negative and high strain sensitive and temperature insensitive fiber is obtained.

II. LPG theory

In LPG the fundamental guided mode couples with different forward propagating cladding modes when perturbation is introduced. This coupling produces dips in the transmission medium at resonant wavelengths that satisfy the phase matching condition. The phase matching condition is given by [26]

$$\lambda = (n_{co} - n_{cl})\Lambda \quad (1)$$

where λ is the resonant wavelength, n_{co} and n_{cl} are the effective indices of fundamental guided mode and cladding modes respectively and Λ is the period of LPG.

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When strain is applied on LPG the resonant wavelength shifts from its original position due to waveguide effect as period of LPG increases with strain. The radius of the core also reduces as strain is increased thereby affecting the differential effective index. Strain and temperature characteristics of LPG are a strong function of the strain optic coefficients and thermo optic coefficients respectively. So when LPG is under strain or temperature these parameters also changes. From equation (1) the temperature and strain sensitivity is given by [33]

$$\frac{d\lambda}{dT} = \lambda * \gamma * \left(\alpha + \frac{\xi_{co} n_{co} - \xi_{cl} n_{cl}}{n_{co} - n_{cl}}\right) \tag{2}$$

$$\frac{d\lambda}{d\varepsilon} = \lambda * \gamma * \left(1 + \frac{\eta_{co} n_{co} - \eta_{cl} n_{cl}}{n_{co} - n_{cl}}\right) \tag{3}$$

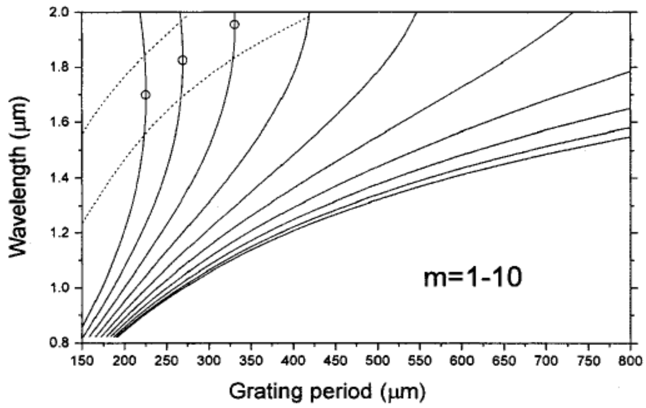
where ε is the applied strain, T is the surrounding temperature, ξ_{co} and ξ_{cl} are the thermo optic coefficients of core and cladding respectively, η_{co} and η_{cl} are the strain optic coefficients of core and cladding respectively, α is the linear expansion coefficient, γ is the dispersion factor or sensitivity factor which gives a clearer understanding into the sensitivity characteristics of LPG in PCF.

A. *Dispersion factor γ*

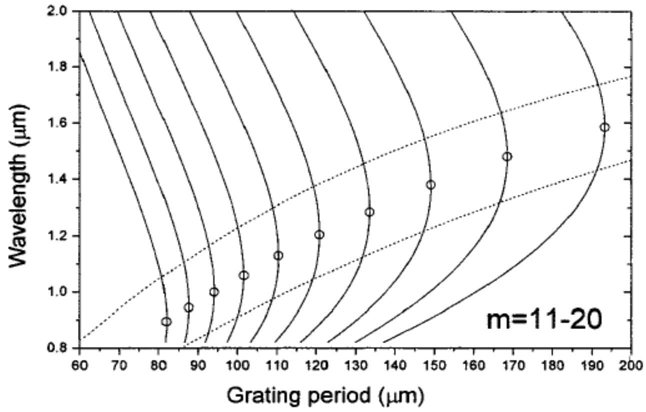
When LPG is subjected to strain and temperature the effective indices of fundamental guided mode and the cladding modes changes due to variations in the waveguide effect. This change in the waveguide effect is understood by a dispersion factor that is expressed as [32,33, 39]

$$\gamma = \frac{\frac{d\lambda}{d\Lambda}}{n_{co} - n_{cl}} = \frac{\Delta n_e}{\Delta n_g} \tag{4}$$

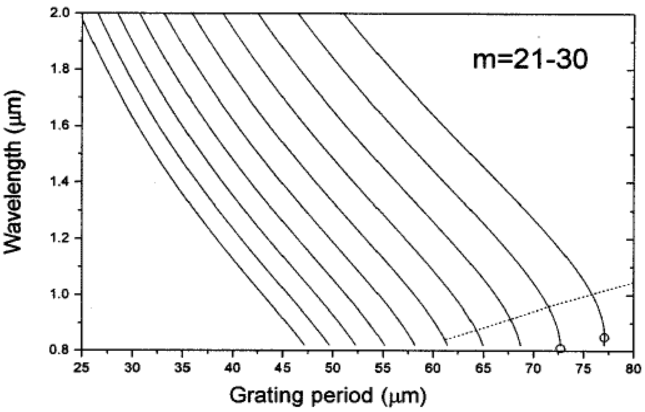
where $\Delta n_e = n_{co} - n_{cl}$ and $\Delta n_g = n_{g,co} - n_{g,cl}$ respectively. The polarity of Δn_e will always be positive, so therefore the polarity of γ will depend on the polarity of Δn_g. The characteristic curves for modes ranging from m = 1 to 30 are shown in Figure (1). The curves for m = 1 to m = 7 show a positive slope throughout the wavelength range and the curves for m = 21 to m = 30 shows a negative slope. In contrast the slope of the characteristic curves for m = 8 to m = 22 change from positive to negative as the wavelength increases and is denoted by circles which are called as turning points in Figure 1[33]. At a particular period two resonant wavelengths exist to couple to the same cladding modes [42]. During fabrication process one resonant wavelength in the normal region shifts towards longer wavelengths and the other resonant wavelength in the anomalous region shifts towards shorter wavelengths and at a certain both the bands will overlap. The point where it overlaps is the turning point. At this turning point the slope of the characteristic curve in infinity so hence, γ is also infinity. Each cladding mode shows turning point provided the wavelength range is large [43]. Basically this turning point indicates maximum sensitivity. So in order to achieve high sensitivity one should choose appropriate period and cladding mode so that the resonant wavelength is very close to the turning point.



(a)



(b)



(c)

Figure 1. Plot of resonance wavelength versus grating period. (a) m = 1 to m = 7 (b) m = 11 to m = 20 (c) m = 21 to m = 30. The circles marked are turning points. The dashed lines are regions of high sensitivity [33].

III. PROPERTIES OF LPG ON PCF

The strain and temperature sensitivities of PCF-LPG is calculated in this section. A solid core endlessly single mode fiber PCF is considered having a triangular lattice. Triangular lattice is the most commonly used lattice structure.

Figure□ □ □ shows the group indices of core and cladding modes as function of wavelength. Group index of core is calculated as $n_{g,co} = n_{co} - \lambda(n_{co}/d\lambda)$ and group index of cladding is calculated using $n_{g,cl} = n_{cl} - \lambda(n_{cl}/d\lambda)$ [33, 39].

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From the graph it is clear that the group index of cladding modes $n_{g,cl}$ is highly dispersive. Therefore group index of cladding is more than the group index of core which is the opposite to that of conventional single mode fiber [39].

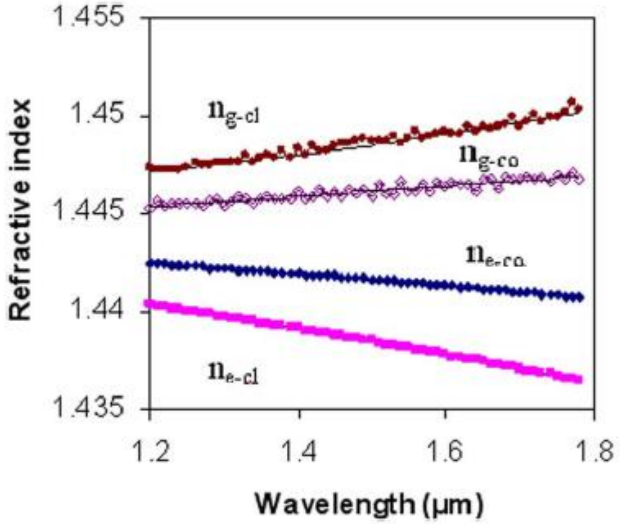

Figure 2. plot of group indices of core and cladding modes w.r.t. to wavelength[39].

Figure 3 shows the characteristic curve of LPG on PCF, i.e. the plot of resonant wavelength versus LPG period [36-38]. From the graph it is evident that LPG period increases as resonant wavelength decreases which is in contrast to conventional fiber. This is because of the highly dispersive characteristics of cladding due to the presence of air holes [39].

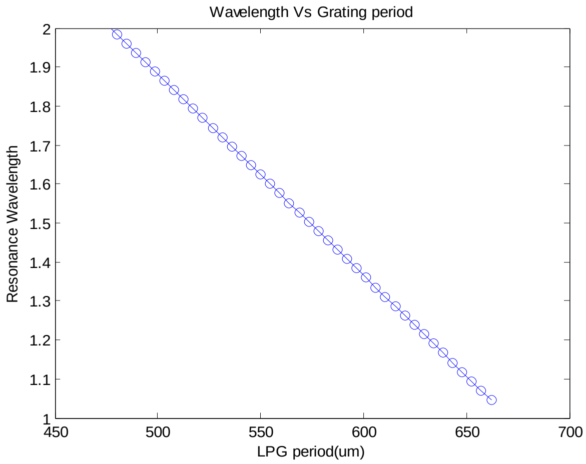

Figure 3. Resonant wavelength versus LPG period curve

The sensitivity factor or waveguide factor γ can positive or negative as mentioned earlier. Δn_e will always be positive. The polarity of γ depends on Δn_g. If $n_{g,co}$ is more than $n_{g,cl}$ then γ is positive. This is the case of conventional fiber where the dispersion properties of both core and cladding are the same. If $n_{g,co}$ is less than $n_{g,cl}$ then γ will be negative. This is for the case of higher order cladding modes [33]. From figure 4 the value of dispersion factor is taken as -1.15~ -1.35 for LPG period from 320 to 470 µm.

The strain sensitivity of LPG on PCF dλ/dε is influenced by four factors: the strain optic coefficients of core and cladding, the LPG period, the dispersion factor and the mode order. Taking into consideration the mode order specified in [32,33], the strain characteristics of LPG on PCF is checked. Figure 5 shows the strain sensitivity of PCF-LPG by varying the values of strain optic coefficient of cladding for a period range from 200 to 700 µm. the value of strain optic coefficient of core is

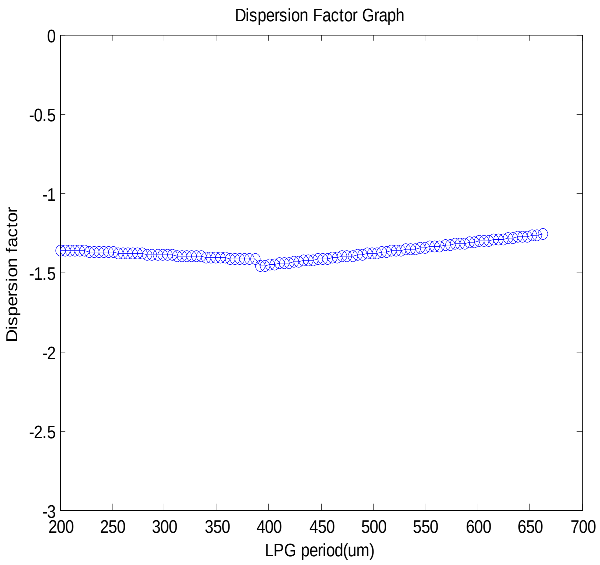

Figure 4. Dispersion factor versus period curve of LPG on PCF

taken to be a constant value of $\eta_{co} = -0.22$ for pure silica core [27,33]. The strain sensitivity can be positive or negative depending upon the values of η_{co} and η_{cl}. When η_{cl} is more than η_{co} then the strain sensitivity of LPG-PCF is negative. When η_{co} is less than η_{cl} then the strain sensitivity is positive.

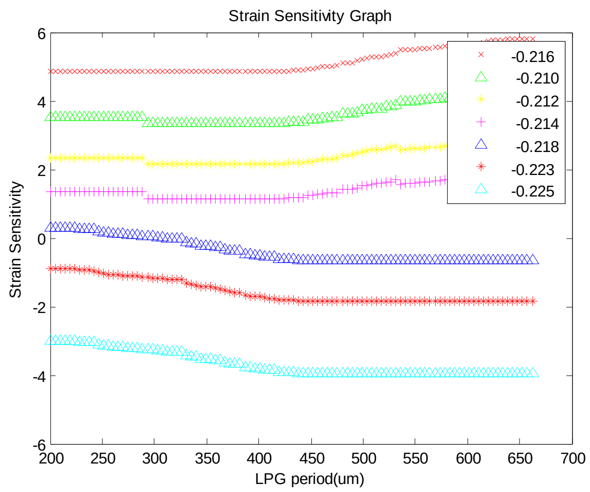

Figure 5. Strain sensitivity versus period curve of LPG-PCF

Similarly temperature sensitivity of LPG-PCF dλ/dT is dependent on four factors: the thermo optic coefficients of core and cladding, the LPG period, dispersion factor and the mode order. Considering the same mode order as in the previous case the temperature sensitivity of PCF-LPG is checked. Figure 6 shows the calculated sensitivity values of LPF-PCF by varying the value of thermo optic coefficient of cladding. Thermo optic coefficient of core is taken to be a constant as $\xi_{co} = 7.8\ X\ 10^{-6}\ /^{0}$C and the value of linear expansion coefficient is

α = 4.1 X $10^{-7}/^0C$ [39]. The sensitivity can be positive or negative depending on the values of thermo optic coefficients of core and cladding. If ξ_{cl} is larger than ξ_{co} then the temperature sensitivity will be positive. When ξ_{cl} is smaller than ξ_{co} then the temperature sensitivity will be negative.

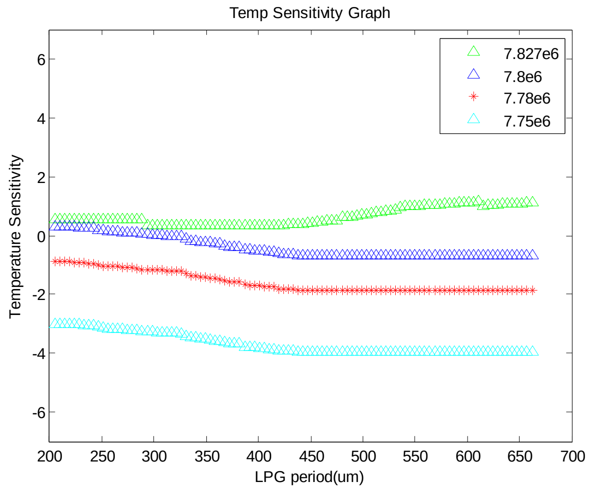

Figure 6. Temperature sensitivity versus period curve of LPF-PCF

The resonance wavelength chosen is 1.406 µm and the period chosen is 580 µm. the calculated strain sensitivities are 5.295µm/1000µm, 3.159µm/1000µm, 2.283µm/1000µm, 1.406µm/1000µm, -1.662µm/1000µm, -4.73µm/1000µm. the calculated temperature sensitivities are 0.1288pm/^{0}C, -0.2164pm/^{0}C, -0.347pm/^{0}C.

IV. CONCLUSION

The strain and temperature sensitivities of LPG on ESM PCF have been studied. It has been observed that one can achieve positive, negative or zero sensitivities by choosing proper LPG period and cladding mode order. This again depends on other factors like the strain and thermo optic coefficients. Dispersion factor γ plays a very significant role in determining the sensitivities of the sensor. The dispersion factor gives a deeper understanding into the magnitude and the polarity of the sensor. Here in this paper when higher order modes and higher period range is chosen then one can achieve high strain sensitivity and almost zero temperature sensitivity. By exploiting the properties and the parameters of PCF combined with the properties of LPG the desired sensitivities can be achieved. This temperature insensitive strain sensor has found a number of industrial applications due to its low cost and simplicity.

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