Index insensitive micro-strain sensor based on hollow core photonic crystal fiber

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In this paper, application of a Hollow Core Photonic Crystal Fiber (HC-PCF) as a micro-strain sensor has been demonstrated. Two different designs of HC-PCF with different core diameters (large core PCF and small core PCF) have been investigated for different strain levels ranging from 0 µε to 2000 µε at the wavelength, 1550 nm. High strain sensitivities of 3.71 pm/µε and 2.3 pm/µε have been achieved for the large core PCF and small core PCF, respectively. Also, due to the special air-hole structure of HC-PCF, the sensitivity of strain measurement remains unaffected of the changes in Surrounding Refractive Index (SRI).

1. Introduction

Optical fiber sensors have emerged as a unique solution in particular cases(e.g., in environments with electrical hazard or potentially explosive). Although, sensors based on conventional optical fibers are well established [1], PCF, despite of its youth in sensing field has gained attention of the researchers. PCF is a recently developed class of optical fiber [2] which are characterized by periodic arrangement of air-filled capillaries running along entire length of the fiber, centered on a solid or a hollow core. The biggest attraction in PCFs is that by varying the size and location of the holes of the cladding and/or the core, the transmission spectrum, mode shape, dispersion, birefringence etc. can be tuned to reach values which are not possible with conventional optical fibers. PCFs turn out to be a promising and enhanced solution for practical applications where monitoring of strain-induced changes is important, such as, in the fields of experimental mechanics, metallurgy, aeronautics, and significantly, in health monitoring of complex structures [3].

Q. Shi *et al.* [4] obtained a strain sensitivity of 1.55 pm/µε and insensitivity to temperature and bend, with the help of Fabry-Perot-type strain sensor based on HC-PCF. B. Dong *et. al* [5] proposed a modal interferometer based micro-displacement sensor constructed with help of SMF-PCF-SMF structure to achieve a strain sensitivity of ~0.0024 dB/µm and a low temperature sensitivity. H. Gong *et. al* [6] presented a modal interferometer based on short length PCF for strain measurement to achieve a strain sensitivity of 1.83 pm/µε.

In spite of the vast research in the field of strain sensing using PCF, it has not lead to commercialization of PCF sensors. So, techniques have to be developed so as to make PCF sensing more cost effective. Also, strain sensitivity needs to be increased in order to measure comparatively lower magnitudes of applied strain. This can be done by manipulating the geometry of the PCF, e.g., by varying the core diameter or by changing the pitch of the fiber in order to obtain a higher sensitivity. Insensitivity to temperature is an issue which has mostly been researched upon in the past. PCF sensors which can also avoid the cross sensitivity to other parameters, e.g., changes in SRI, vibration, bend etc, have to be designed.

In this paper, we present two different structures of Hollow Core Photonic Crystal Fiber which differ in their core diameters (large core and small core) and demonstrate their application as a strain sensor. The Finite-Difference Time-Domain (FDTD) method is used to simulate operation of sensor at different strain levels. Comparison of the strain sensitivities of the two fibers has been done. Insensitivity of this sensor to the changes in SRI has also been verified.

2. Theory and simulation setup

A PCF is made up of two materials which have a high contrast of refractive index. Thus, it can be referred to as a 3D structure having a 2D refractive index distribution such that the light remains confined to the core. When light enters a HC-PCF, the fundamental core mode is spread widely, and higher order modes, including the cladding modes, are excited in the PCF. The total intensity can be calculated as [7]:

$$I(\lambda) = I_{co}(\lambda) + I_{cl}(\lambda) +$$

$$2[I_{co}(\lambda)I_{cl}(\lambda)]^{1/2} cos\left(\frac{2\pi\Delta nL}{\lambda}\right) \qquad (1)$$

where $I_{co}(\lambda)$ *and* $I_{cl}(\lambda)$ are the powers of the interfering core and cladding modes at wavelength λ, and L is the length of the HC-PCF. The transmission spectrum is directly related to the optical path difference φ which depends on the differential effective index Δn of the two modes. Dips in the transmission spectrum can be seen when the phase matching condition is satisfied [8].

$$\varphi = \frac{2\pi \Delta n L}{\lambda} = \frac{2\pi (n_{co} - n_{cl})L}{\lambda} = (2n + 1)\pi \qquad (2)$$

where n is some positive integer and φ is the phase difference between the two interfering modes. n_{co} and n_{cl} denote the effective modal refractive indices of the fundamental core mode and the higher order cladding modes respectively.

Application of axial strain, or here, microstrain, results in the elongation in length of the PCF or, a transverse contraction of the PCF. Since, the phase difference between the two interfering modes depends on the length, L of the PCF as well as the effective index Δn between the modes, there occurs a shift in the resonance wavelength in the spectrum due to change in length of the HC-PCF. The resonance wavelength is given by [8]

$$\lambda = \frac{(n_{co} - n_{cl})L}{2n + 1} \qquad (3)$$

The shift in the resonance wavelength due to the change in the length of the fiber can be calculated by differentiating equation (3) with respect to L. This is given by [7,9]

$$\Delta\lambda = 1 + \frac{L}{\Delta n} \frac{d(\Delta n)}{dL} \lambda\varepsilon \qquad (4)$$

As can be seen from equation (4), the shift in resonance wavelength is a linear function of the strain applied. Thus, this shift can be employed for the measurement of applied strain.

In our work, we have investigated two different geometries of hollow core PCF as strain sensors. We call these as large core PCF (air filling ratio: 0.75, pitch: 2μm) and small core PCF (air filling ratio:0.45, pitch: 7μm). Both of these are hexagonal lattice structures designed with silica as the base material comprising of circular air holes centered on a hollow circular core. As can be seen from equation (4), the shift in resonance wavelength is higher at longer wavelengths [8], thus the operating wavelength is chosen as 1550 nm in order to achieve higher strain sensitivity. Different levels of strain ranging from 0 με to 2000 με are applied on both the structures (assuming uniform deformation of the holes through- out the structure), and the corresponding shift in resonance wavelength is observed. Strain sensitivities of both the sensor structures are calculated and compared. Effect of changes in SRI on the strain sensitivity of the said sensor is also analyzed.

3. Results and discussions

We analyzed the mentioned sensor geometries individually for different strain levels ranging up to 2000 με. Generally, micro level of strain induces minute changes in the length of the sensor as well as in its cross sectional geometry. This affects the position of the dips obtained in the spectrum, as compared to the condition when no strain was applied. By correlating the position of these dips in the spectrum, a calibration curve can be obtained. The transmission spectrum of small core HC-PCF, when it is

subjected to four different levels of axial strain can be seen in Fig. 1. A significant shift in the wavelength of the transmission dips is observed near wavelengths 1540 nm and 1560 nm.
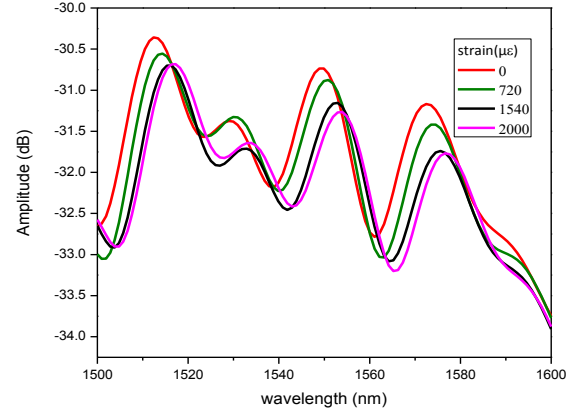

Fig. 1. Transmission spectra of small core HC-PCF with different levels of applied strain

We observe a similar shifting of the transmission spectrum around wavelength 1560 nm for the large core HC-PCF when subjected to varying strain levels as shown in Fig. 2. Thus, the applied strain can be detected and evaluated by measuring the shift in the resonance wavelength. We observe from Fig. 1 and 2 that the transmission dips shift to a longer wavelength without a change in shape. Only a variation in intensity is observed which indicates participation of more than two modes in the process of interference [10].
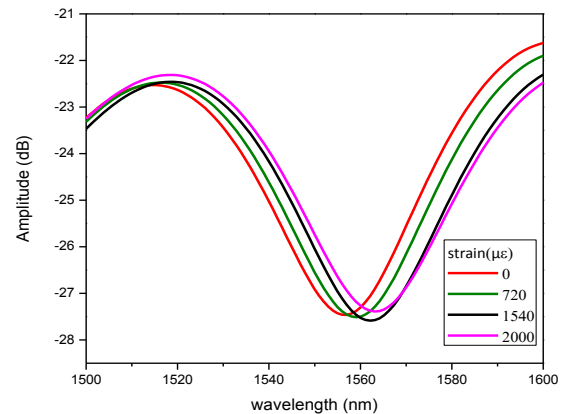

Fig. 2. Transmission spectra of large core HC-PCF with different levels of applied strain

The relationship between the wavelength of the dips and the applied strain for small core PCF and large core PCF geometries of the sensor are shown in Fig. 3 (a) and (b), respectively. A linear behavior can be seen in both these cases. The value of correlation factor R^2=0.99717 and R^2= 0.99849 are obtained from Fig. 3(a) and (b), respectively.

Y=2.3E-3X+1561.02805
R^2=0.99717

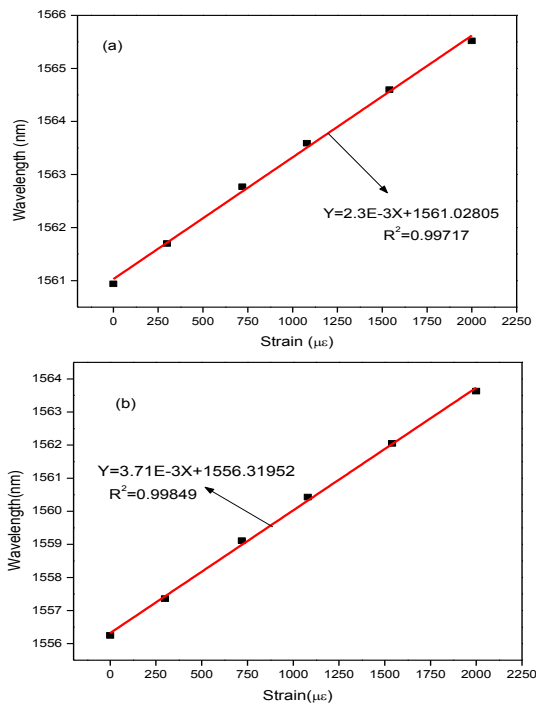Y=3.71E-3X+1556.31952
R^2=0.99849

Fig. 3. Wavelength shift versus strain graph for (a) small core HC-PCF (b) large core HC-PCF

The strain sensitivity of the said sensor can be calculated by measuring the slope of the wavelength shift versus strain curve. We obtained high strain sensitivities of 2.3 pm/µε and 3.71 pm/µε for small core HC-PCF and large core HC-PCF, respectively. We observed that strain sensitivity achieved with large core HC-PCF is comparatively higher than that achieved with small core HC-PCF. This observation shows that lower pitch or, higher air filling fraction in a HC-PCF results in a greater sensitivity for strain. The sensitivity of large core HC-PCF, i.e., 3.71 pm/ µε is also higher as compared to the earlier reported PCF based strain sensors. We also investigated the large core HC-PCF for variations in SRI. The dependence of resonance wavelength shift on changes in the refractive index of the surroundings is shown in Fig. 4.
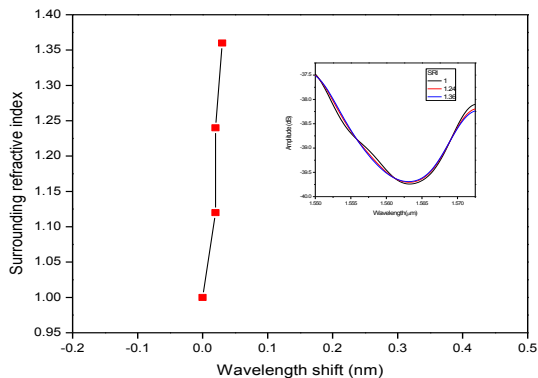

Fig. 4. Resonance wavelength dependence of large core HC-PCF on SRI (Inset: transmission spectra of large core PCF for different SRI as indicated)

We observe that the wavelength shift is negligible for variations in SRI, hence, the strain sensitivity for HC-PCF remains unaffected by refractive index changes in the environment. This property of HC-PCF makes it an attractive solution as a sensor for environments with variable refractive index.

4. Conclusions

Two simple configurations of HC-PCF based strain sensor have been presented. A higher strain sensitivity of 3.71 pm/µε is observed with large core HC-PCF as compared to 2.3 pm/µε with small core PCF signifying the role of higher air filling fraction in sensing. The obtained strain sensitivity of 3.71 pm/µε is comparable to existing configurations of PCF-based sensors. The sensor shows linear response to strain and also, is independent of surrounding refractive index. Hence, the presented sensor structure is an attractive solution for strain sensing in environments with varying refractive index as well as for measuring lower strain levels in health monitoring applications.

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