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Research Article

FIBER OPTIC TEMPERATURE-INSENSITIVE, STRAIN SENSORS FOR NUCLEAR APPLICATIONS

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ABSTRACT

A long period fiber grating (LPG) sensor in photonic crystal fiber with a strain sensitivity of -2.0 pm/ $\mu\varepsilon$ for axial strain range from 50-1300 micro-strain has been demonstrated. Such a strain sensors are remarkably less sensitive to temperature variation. They have been shown to be resistant to nuclear radiation (at least up-to 75 kGy) and are thus useful for sensor applications in secondary loops of nuclear reactors and in particle accelerators. Such LPG based strain sensors have not been studied in nuclear environment anywhere as per our knowledge.

Key Words: *Photonic Crystal Fiber, Long Period Grating, Gamma-dose, nuclear radiation*

INTRODUCTION

Photonic Crystal Fibers (PCFs) also known as Holey fiber are a new class of optical fibers that have attracted intense scientific research during past few years. Typically, these fibers incorporate a number of air holes that run along the length of the fiber, and the size, shape and distribution of the holes can be designed to achieve various novel wave-guiding properties that may not be possible in conventional fibers. Various PCFs have been demonstrated so far that exhibit remarkable properties such as endlessly single mode fiber, large mode area and highly non-linear performance. Temperature-insensitive Long Period Gratings(LPGs) have attracted much attention because of their potential applications in achieving stable optical filters, gain flatteners as well as in realizing temperature–insensitive sensors for Industrial and nuclear applications. Conventional fibers contain at least two different glasses, each with a different thermal expansion coefficient, thereby giving rise to high temperature sensitivity. PCFs are virtually insensitive to temperature because they are made of only one material (and air hole). LPGs in PCF fibers have not yet been reported in India. Besides, the effect of high nuclear radiation on such PCF based grating sensors has not been reported by any group to the best of our knowledge (Rego,2005), (Berghmansa,1998).

THEORY

A long period grating (LPG) is formed by introducing periodic modulation of the refractive index along a single mode fiber. Such a grating induces light coupling from the fundamental guided mode to co-propagating cladding modes at discreet resonant wavelengths (Chaube,2007). LPGs in conventional fibers have been extensively used as band rejection filters, gain flattening filters, tunable couplers and sensors. In general, as fiber devices and sensing elements, LPGs offer low back reflection, insensitivity to electromagnetic interference and low insertion loss and cost effectiveness. For a long period grating with periodicity Λ, the wavelength $\lambda^{(m)}$ at which mode coupling occurs is given by

$$\lambda^{(m)} = (n_{eff} - n_{cl}^{m})\Lambda \qquad (1)$$

Where, n_{eff} is the effective refractive index of the propagating core mode at wavelength λ and n_{cl}^{m} is the effective refractive index of the m^{th} cladding mode. The variation in the grating period and modal effective indices due to strain and temperature causes the coupling wavelength to shift. This spectral shift is distinct for each loss band and is a function of the order of corresponding cladding mode.

The axial strain sensitivity of LPGs may be examined by expanding equation (1) to yield:

$$\frac{d\lambda}{d\varepsilon} = \frac{d\lambda}{d(\delta n_{eff})}\left(\frac{dn_{eff}}{d\varepsilon} - \frac{dn_{cl}}{d\varepsilon}\right) + \Lambda\frac{d\lambda}{d\Lambda} \tag{2}$$

Where $\delta\ n_{eff} = (n_{eff} - n_{cl})$ is the differential effective index, ordinal m has been dropped for the sake of simplicity. The two terms on the right side can be divided into material (first term) and waveguide (second term) contributions. The temperature sensitivity of LPG grating is given by

$$\frac{d\lambda}{dT} = \frac{d\lambda}{d(\delta n_{eff})}\left(\frac{dn_{eff}}{dT} - \frac{dn_{cl}}{dT}\right) + \Lambda\frac{d\lambda}{d\Lambda}\frac{1}{L}\frac{dL}{dT} \tag{3}$$

Where, λ is the central wavelength of the attenuation band, T is the temperature, L is the length of the LPG and Λ is the period of the LPG. For standard long period gratings with periodicity of hundreds of micrometers, the material effect dominates the waveguide contribution. Hence only first term in equations (2) and (3) are considered for evaluation of sensitivity. For photonic crystal fibers which are single material fibers, the first term in equation (3) becomes negligible, resulting in low temperature sensitivity. This opens-up the field for temperature- insensitive sensors. Since the endlessly single mode fibers in present work are made using pure silica, they are expected to be to be highly resistant to nuclear radiation. We have demonstrated that the transmission spectra of LPG is not affected up-to a gamma dose of 75 kGy. Therefore, they are suitable for sensor applications in particle accelerators and near earth space missions.

EXPERIMENT

Inscription of LPGs have been demonstrated using various techniques such as UV treatment, heat treatment with a CO_2 laser or by applying mechanical pressure. Formation of LPG in pure-silica core PCF fibers is not straight forward because there is no photosensitivity provided by Ge-O_2 vacancy defect centers. The LPGs in PCF are primarily formed due to modification of glass structure. However, any geometrical deformation results in flaws or cracks that result in fracture of the fiber and therefore LPGs in PCF require high precision systems. Our fully automated CO_2 laser based grating writing system can set the grating period (200µm- 800µm) with a precision of one micron while laser intensity can be stabilized within ±5 %. Fig. 1 shows the schematic diagram of our grating writing system. The fiber is exposed to CO_2 laser for predetermined period and the beam is scanned repeatedly over the fiber until grating of sufficient strength is formed. This operation is performed through an AutoCAD file in which period and length of the grating is set. This method is more accurate and free from human errors. The spectral response is recorded using an Optical Spectrum Analyzer (OSA) which is connected to LPG through patch-cords as shown in the fig.1.

During application of LPG based strain sensors, one of the main difficulties is the cross sensitivity between strain and the temperature. The common methods for cross sensitivity reduction are using temperature compensation and simultaneous strain and temperature measurement. Conventional fibers contain at least two different glasses, each with a different thermal expansion coefficient, thereby giving rise to high temperature sensitivity. By use of CO_2 laser method, a LPG sensor with strain sensitivity -0.45 pm/µε and a temperature sensitivity of 59.0 pm/ $^{\circ}$C was written in corning SMF-28 fiber (Rao, 2003). In this paper, we present a LPG-PCF sensor fabricated in ESM-PCF with a high strain sensitivity (-2.0 pm/ µε) and negligible temperature sensitivity.

Fig. 2 shows the cross section of ESM-PCF. The PCF used in our experiment is an ESM-12-02 (Endlessly single-mode 12µm) fiber made by Crystal Fiber, Denmark. This fiber exhibits low loss across mode field diameter. The fiber is endlessly single-mode (i.e. it has no higher order mode cut-off) and,

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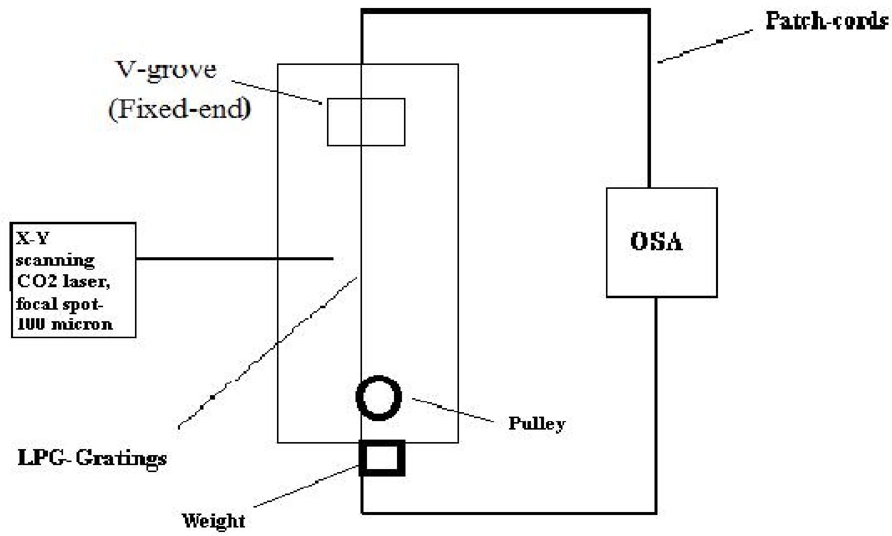

Figure 1: Experimental set up for the writing Long period gratings (LPGs)

therefore, delivers pristine mode quality at all wavelengths. The ESM-12 has a standard 125µm outer diameter and is compatible with all common fiber tools.

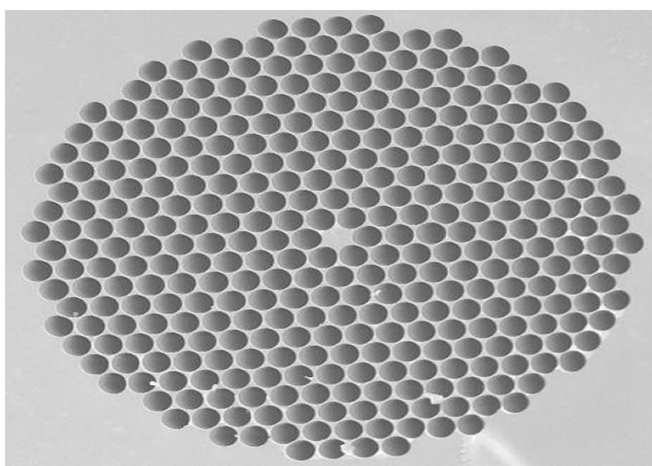

Figure 2: SEM micrographs of an ESM- PCF.

For the preparation of LPFG in an endless-single-mode photonic crystal fiber (ESM-PCF) both ends of the PCF are fusion spliced to SMFs. The loss for each splice is about 0.74 dB. An X-Y scanning CO2 laser is used for the fabrication of LPGs in the ESM-PCF. The CO2 laser operates at a frequency of 2 kHz and has a maximum power of 10 W. The laser power is controlled by the mark-speed of the laser pulses. The typical grating length and period in our experiment is 23.4mm and 450µm respectively. Fig. 3 shows the transmission characteristics of a LPG fabricated on an ESM-PCF. Attenuation bands in the range of 1300 nm-1700 nm have been investigated by an Optical spectrum analyzer.

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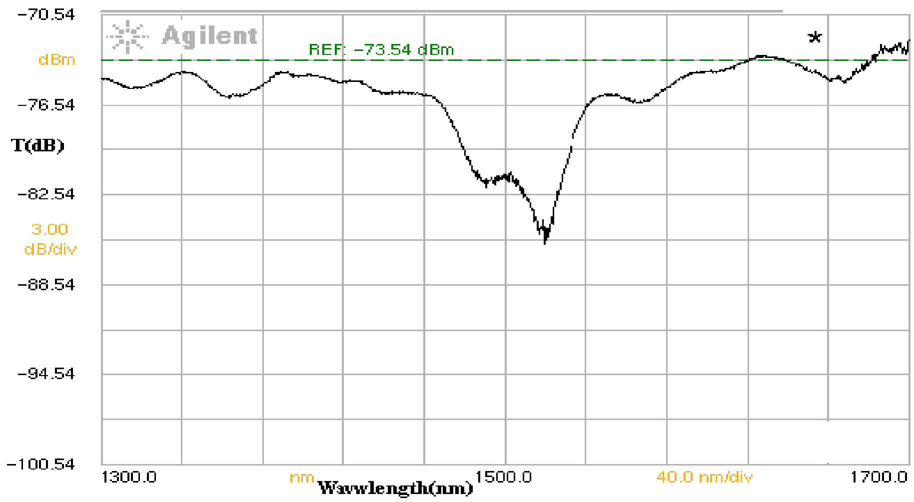

Figure 3: Transmission characteristics of a LPG fabricated on an ESM-PCF with a period of 450µm.

RESULTS AND DISCUSSION

The strain and temperature characteristics were measured by giving a known axial strain. The thermal properties are reordered by keeping the sensor in a heated oven**.** Fig.4 shows the strain response of LPG. It shows that the resonance wavelength varies due to applied strain. There is also slight change in resonance strength. Fig. 5 shows the sensitivity curve for LPG. A linear fit to the experimental observations provide the strain sensitivity of -2.0 pm/ µε.

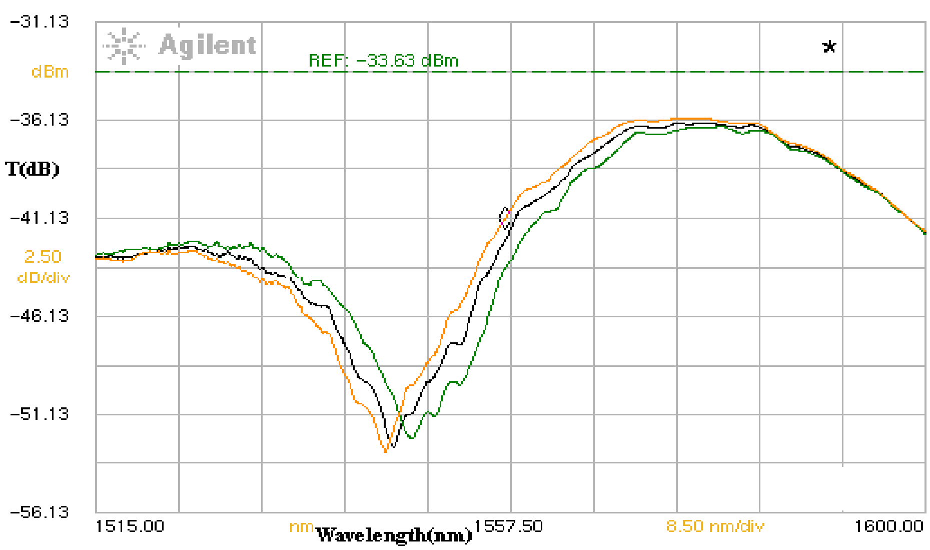

Figure 4: Strain response of a LPG fabricated on an ESM-PCF; Green=0µε, Black=650µε and Orange=1300µε.

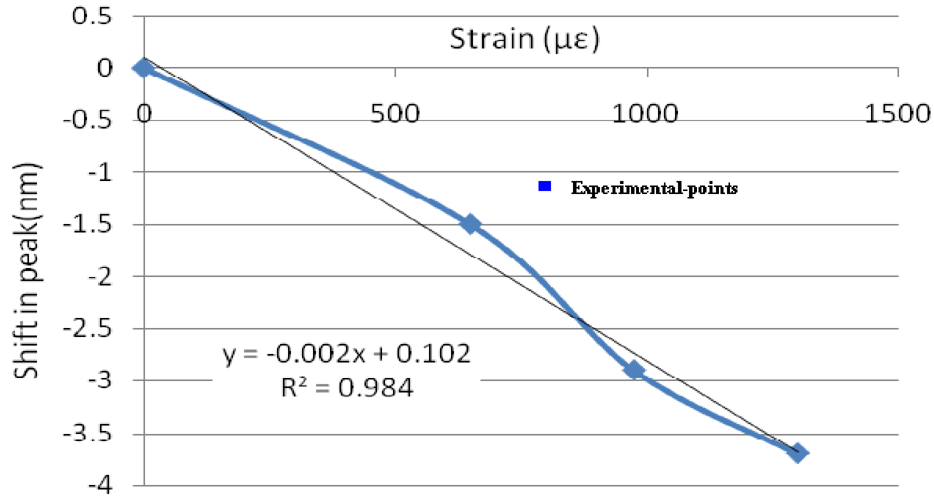

Figure 5: Strain dependent wavelength shift of LPG.

Fig. 6 shows the thermal response of LPG fabricated in an ESM-PCF. It clearly shows that there is negligible variation in the spectral response of LPG even when the sensor is heated up to 100ºC. The estimated thermal sensitivity is 0.004nm/ ºC. This is one order lower compared to LPG based strain sensors in standard single mode fibers.

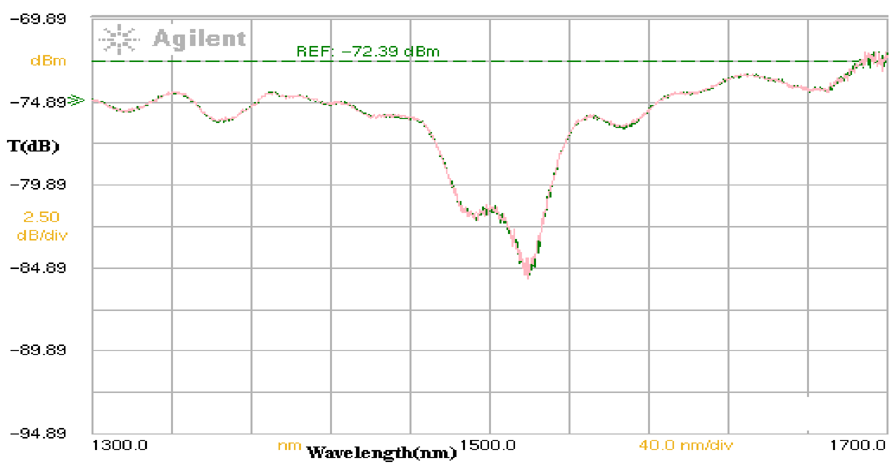

Figure 6: Thermal response of a LPG fabricated in an ESM-PCF; Green=24.5ºC and Pink=100ºC.

To test the sensor performance in nuclear environment, the device was kept in gamma chamber for total dose of 75KGy. After the dose the device was taken out from gamma- chamber and was remounted on test set-up. The spectral response and strain response was measured again. Fig.7 shows the spectral response characteristics. By comparing fig.3 and fig.7, it can be seen that there is no spectral change (resonance dip, dip-strength) in the transmission characteristics of LPG due to irradiation of intense gamma- dose.

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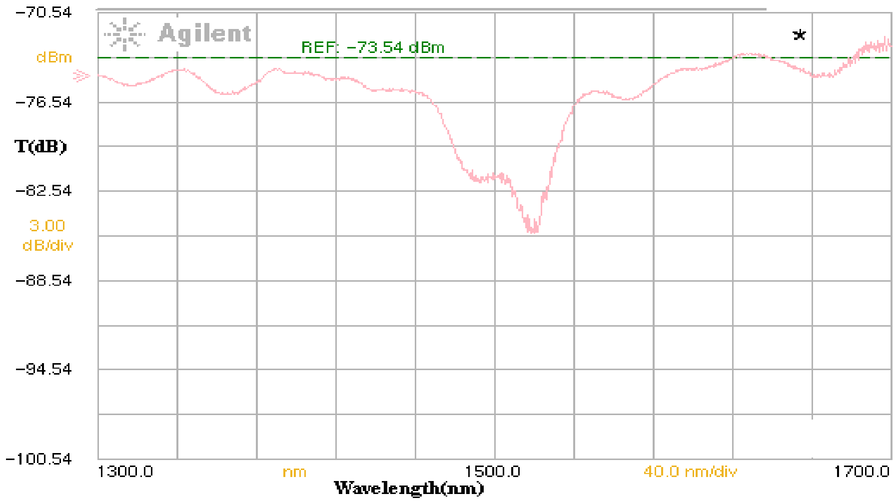

Figure 7: Transmission characteristics of a LPG fabricated in an ESM-PCF after nuclear radiation dose of 75 KGy.

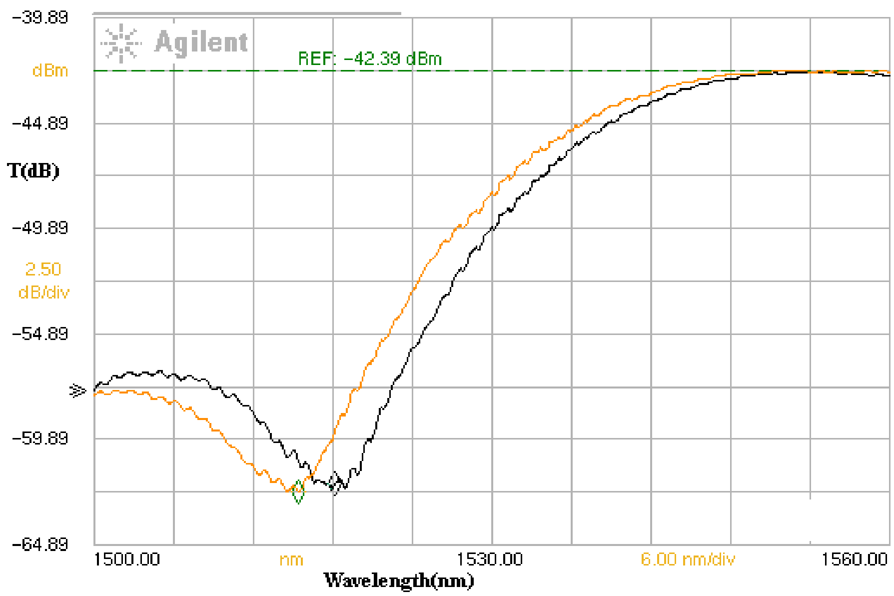

Figure 8: Strain response of a LPG fabricated on an ESM-PCF after nuclear dose of 75KGy; Black=0με and Orange=1300με.

Fig. 8 shows the strain characteristics of irradiated LPG. By comparing fig.4 and fig.8, it is clear that there is no effect on strain sensitivity of LPG device due to gamma-dose. The sensitivity is found to be -2.12 pm/με which is almost equal to the sensitivity observed without irradiation.

Conclusion

We have shown that long period gratings in ESM-PCF offer high strain sensitivity. Such sensors can effectively reduce cross sensitivity between temperature and strain and temperature-induced strain error is only 2.5 με/ °C without using temperature compensation. They can work reliably in 50 με -1300 με range with a resolution of 25με even in thermally unstable environment of ± 10 °C. Moreover, the sensors are resistant to nuclear radiation at least up-to 75 KGy and thus have potential for applications in secondary loop of nuclear reactor and waste treatment facilities.

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