Nanohybrid optical sensor for simultaneous measurements of strain, temperature, and vibration for civil application

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Published in Micro & Nano Letters; Received on 27th April 2017; Revised on 23rd May 2017; Accepted on 17th July 2017

A design of a nanooptical sensor, i.e. hybrid Bragg gratings over photonic crystal waveguide is proposed to monitor the strain, temperature, and vibration simultaneously. The shift in wavelength, i.e. red shift (towards the right) and blue shift (towards the left), is observed in response to applied strain, vibration, and temperature, respectively. The proposed sensor gives a better performance to measure the strain (with a 9 nm wavelength shift), temperature (with 8 nm wavelength shifting), and the vibration (with 10 nm wavelength shifting).

1. Introduction: The health monitoring of buildings is of prime importance in today's scenario as we face a huge problem of ageing infrastructure within a few years of its construction. The deformation of civil infrastructure is the major hazard that occurs due to the earthquake, landslides, cyclones and so on, leading to certain losses to lives as well as the economy [1]. The developed techniques of health monitoring are still in the nascent stages of application practically and need to be developed into techniques which can be implemented with ease in the field.

The buildings are the major part of any country, but various undesired effects such as earthquake, rainfall, manmade hazards, algal bloom, and climate change on rainfall patterns can harm these structures and further human being [2]. It is required to monitor the structure/buildings for these hazards at early stages so that suitable remedy action can be taken accordingly. In a tropical country like India, where ~80% of the annual rainfall takes place in the two monsoon months, rusting, cracking related problems are more alarming, especially in bridges and so on. India also has a very long coastline where marine weather prevails [3]. Typically, structure requires a major restoration work within 15 years of its construction. Consequently, it has become urgent to have a reliable method for accurately measuring the rate of corrosion, strain, vibrations, temperature in existing as well as new structures in a better way [4, 5]. Currently, fibre-optic sensors are the best alternative to monitoring the health of civil structure along with its high speed, large sensitivity, easy installation, exact measurement and so on. So, it is important to further design and investigate the new optical sensors to monitor the health of civil structures.

In the recent few decades, photonic crystals fibre (PCF) [6, 7] has provided the potential platform for a wide range of applications in numerous domains. 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 and so on can be tuned to reach values which are not possible with conventional optical fibres [8].

Lu *et al.* [9] proposed a highly sensitive silver wire to sense the temperature. Further, Jhang *et al.* [10] analysed a PCF structure with hexagonal silver-coated air holes for pressure sensing applications and achieved a high value of sensitivity as 32.89 nm/N. Peng *et al.* [11] have demonstrated a PCF-based surface plasmon resonance (SPR) temperature sensor to obtain a temperature sensitivity of 720 pm/°C.

All these sensors were proposed to sense the single parameter only. There is need of hybrid optical sensors which can fabricate on single substrate and can sense multiple parameters simultaneously. In this work, a new nanohybrid optical sensor (NHOS) is proposed by constructing three Bragg gratings on single photonic crystal waveguide (PCW). These three gratings are designed to sense strain, temperature, and vibration, respectively. This design also allows us to measure deformation for structure.

2. Nanohybrid sensor design: Bragg grating PCW sensor or NHOS is designed using a square lattice of air hole on a silicon wafer as shown in Fig. 1. The gratings are achieved by crafting a wavelength-specific dielectric mirror upon the fibre core and consists of periodic sections of high and low refractive indices [12–14]. Whenever the grating is exposed with a broad-spectrum light, some of its energy is transmitted and another part is reflected. This periodic grating works like a filter, reflecting only a narrow wavelength range [15, 16], which is identified as the Bragg wavelength λ_B (1). FBG can be used as a wavelength-specific reflector permitting certain wavelengths except one which fulfil the Bragg law [6]:

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad (1)$$

where Λ signifies a period of the grating, λ_B indicates the reflected wavelength and $n_{\text{eff}} = 1.46$ mm characterises actual group refractive index of the fibre cores.

To compute the transmission, reflection, and electric field distribution in PCW the Helmholtz equation is consider [3]

$$\frac{1}{\varepsilon(r)}\nabla \times \{\nabla \times E(r)\} = \frac{\omega^2}{c^2}E(r) \quad (2)$$

where ε is the permittivity of material, $\boldsymbol{r}$ is the coordinate space vector. The $E(r)$ represent the electric field component and it is define as $E(r) = E_{k,n}(r)\cdot e^{jkr}$, where $E_{k,n}$ is the periodic function.

When light enters 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]

$$I(\lambda) = I_{\text{co}}(\lambda) + I_{\text{cl}}(\lambda) + 2\left[I_{\text{co}}(\lambda)I_{\text{cl}}(\lambda)\right]^{1/2}\cos\left(2\pi\Delta nL/\lambda\right) \quad (3)$$

where $I_{\text{co}}(\lambda)$ and $I_{\text{cl}}(\lambda)$ are the powers of the interfering core and cladding modes at wavelength λ, respectively, and L is the length of the PCF. Application of axial strain, micro strain, 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

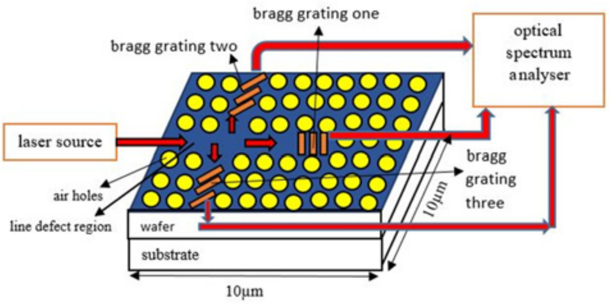

Fig. 1 *Block diagram of proposed NHOS for strain, temperature, and vibration measurements*

wavelength [8]. The shift in the resonance wavelength due to the changing strain, temperature, vibration can be calculated by [4]

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(\frac{1}{n_{\text{eff}}}\frac{\partial_{n_{\text{eff}}}}{\partial T} + \frac{1}{\Lambda}\frac{\partial\Delta}{\partial T}\right)\Delta T \quad (4)$$

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(\frac{1}{n_{\text{eff}}}\frac{\partial_{n_{\text{eff}}}}{\partial \varepsilon} + \frac{1}{\Lambda}\frac{\partial\Delta}{\partial \varepsilon}\right)\Delta \varepsilon \quad (5)$$

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(\frac{1}{n_{\text{eff}}}\frac{\partial_{n_{\text{eff}}}}{\partial V} + \frac{1}{\Lambda}\frac{\partial\Delta}{\partial V}\right)\Delta V \quad (6)$$

As it can be seen from (4) and (6), the shift in resonance wavelength is a linear function of the applied strain, the temperature, and the vibration.

The proposed sensor has a square structure, lattice constant $a = 300$ nm, cylindrical air holes radius $r = 200$ nm, length and width of waveguide = 10 μm, thickness of wafer and substrate is set to 1 μm. The NHOS is a silicon-based sensor in which the line defect is introduced by removing the holes. A light source is connected with sensor as shown in Fig. 1. From the source, light is transmitted through the waveguide to optical spectrum analyser for display the variation of light when the strain, temperature, and vibration is applied.

In proposed sensor, Bragg grating 1 (sensor 1) is used to monitor the strain, Bragg grating 2 (sensor 2) is set to monitor the temperature, and Bragg grating 3 (sensor 3) is used to monitor the vibration. These sensors start detecting the variation in light whenever any changes occur in strain, temperature, and vibration.

3. Results and discussions: Fig. 2 shows light propagation through proposed sensor. From Fig. 2, it can be observed that the transmitted light covers all the given path to further sense the different measurands.

Fig. 3 shows the variation of transmission with respect to wavelength when the proposed sensors are exposed to strain and temperature. From the graph, it can be observed that the reference wavelength shifts to higher and lower wavelengths when strain and temperature are applied to the sensor, respectively.

The graph consists of four curves of different colours. On the right hand side of the reference wavelength, the four curves represent different transmission values for the different strains applied. The green, blue, red, and black curves on the right side of reference wavelength are for 90, 300, 400, and 500 με strain, respectively.

Similarly, at the left part of the reference wavelength, the four curves represent different transmission values for the different applied temperatures applied. The red, black, green, and blue curves on the left side of reference wavelength are for 10, 50, 100, and 150°C temperature, respectively. From Fig. 3, it can be

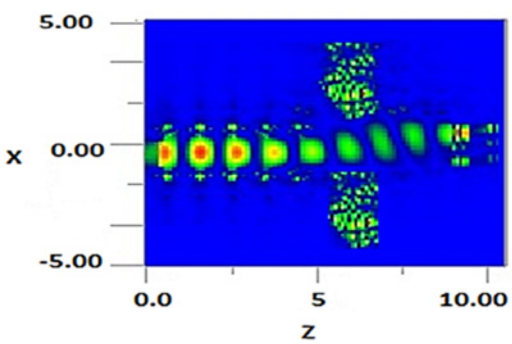

Fig. 2 *Light propagation through proposed waveguide in XZ plain, (X and Z represent the width and length of waveguide, respectively)*

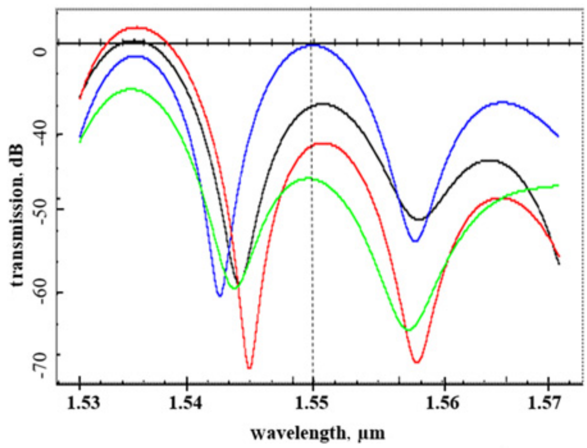

Fig. 3 *Transmission spectra of designed NHOS for different levels of applied strain and temperature*

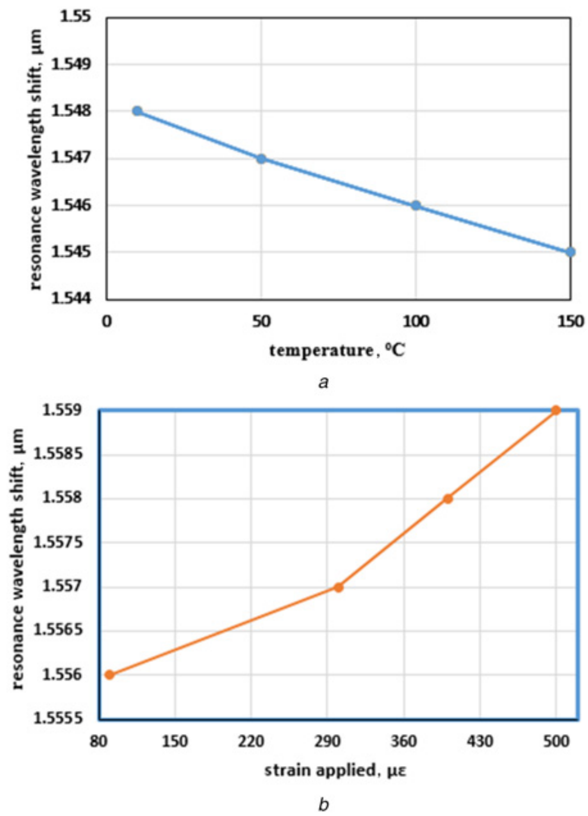

Fig. 4 *Shift in wavelength as a function of*
a Temperature
b Strain

doi: 10.1049/mnl.2017.0216

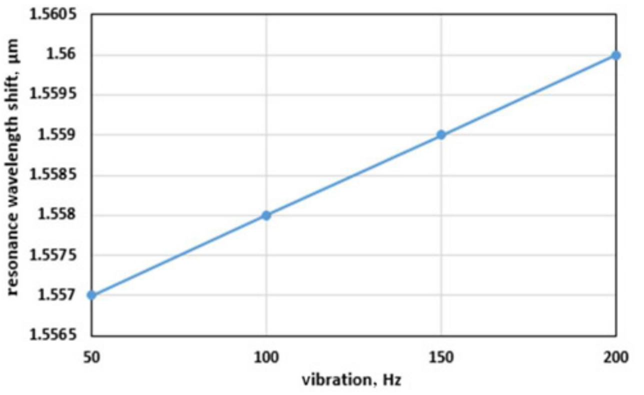

Fig. 5 *Wavelength shift dependence on variation of vibration*

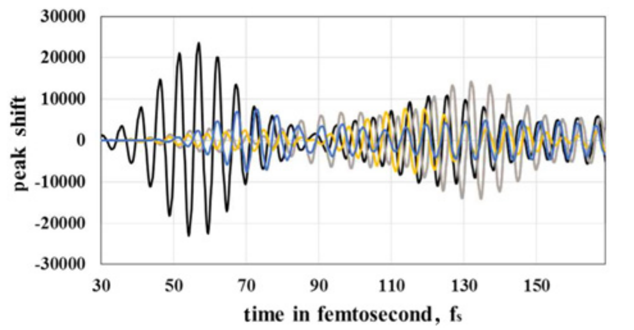

Fig. 6 *Time-domain response when vibration is applied (i.e. black, blue, yellow, and grey curves represent the peaks for, at reference wavelength, at vibration level 50 Hz, at vibration level 100 Hz, and at vibration level 150 Hz)*

seen that the dip in transmission over wavelength domain at the right side of reference wavelength is directly proportional to applied strain and at the left side of reference wavelength it is inversely proportional to applied temperature. For better clarification, the graph has been taken between wavelength shifts a function of applied strain and applied temperature, as shown in Fig. 4.

From Fig. 4*a*, it can be observed that when the values of temperature are applied (i.e. 10, 50, 100, 150°C) on sensor then wavelength shows a shift with 2, 3, 4, and 5 nm from the reference wavelength, respectively.

The shift in the wavelength from reference wavelength of 6, 7, 8 and 9 nm can be observed in Fig. 4*b* with respect to the applied strain of 90, 300, 400, and 500 µε, respectively.

Fig. 5 demonstrates the resonance wavelength shift for different vibration levels. When we increase the level of vibration such as 50, 100, 150, and 200 Hz, the resonance wavelength shows the shift with 7, 8, 9, and 10 nm, respectively. From the results, it can be observed that, vibration sensor is highly sensitive as compared to strain and temperature sensor. From the results, it can also be reported that, temperature sensor is the least sensitive of all. However, the proposed sensor has an ability to monitor these measurands at same time.

From Fig. 6, the effect of vibration on sensor over time can be observed in terms of peak shift. From the result, it is concluded that the peaks are start shifting towards the right side when the level of vibration is increased.

4. Conclusion: Photonic-based NHOS is proposed to sense the strain, temperature, and vibration at the same time. These measurands are measured using different Bragg gratings, which are written on PCW. From the wavelength shift, time-domain response and transmission spectrum, it is observed that the proposed sensor is suitable to sense the strain, temperature, and vibration simultaneously. As a result, it was reported that, sensor 1 sense the strain with maximum wavelength shift 9 nm, sensor 2 sense the temperature with maximum wavelength shift 8 nm and sensor 3 (highly sensitive than other sensors) sense the vibration with maximum wavelength shift 10 nm was achieved. Due to demonstrated sensitivity (maximum wavelength shift), and high coupling efficiency, the proposed sensor is an enhanced solution for applications such as measurement of strain in hazardous environments and health monitoring of civil structures.

5. Acknowledgments: This work was supported by a grant from Rajiv Gandhi national fellowship under University Grants Commission, grant no. F117.1/201415/RGNF2014 15SCPUN61657/ (SAIII/Website).

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