Design and analysis of fiber Bragg grating sensor to monitor strain and temperature for structural health monitoring

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Received: 19 July 2021 / Accepted: 22 September 2021 / Published online: 13 October 2021
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Abstract
In this paper, we have proposed a Bragg grating based sensor to monitor health of civil structures at distinct temperatures. We have considered increased number of gratings with suitable refractive index to enhance sensitivity of fiber Bragg grating sensor. Analysis of Bragg wavelength with respect to load and temperature is successfully studied. The simulation results reveal that when independently strain (50 units per simulation) and temperature (25 °C) are increased uniformly, a linear shift in Bragg wavelength 0.064 and 0.347 nm is observed, respectively. Similarly, when both strain and temperature are increased (ε = 50 & T = 25 °C) concurrently, a directly proportional relation is found in Bragg wavelength (0.403 nm). The results verify the enhanced performance of as-proposed sensor, employing it could be potentially used in civil, bio-medical and military domains.

Keywords FBG · Wavelength shift · Optical sensors · Structural health monitoring

1 Introduction
To monitor health of massive structures/infrastructures, vibrational and environmental parameters, the fiber optic sensors are extensively used. Among all the optic sensors, fiber Bragg grating sensors are the best for this purpose (Kumar 2018). These fiber optic sensors are normally made by distinguishing two physical parameters which have different sensitivities to temperature and strain (Xu et al. 1994; Xu et al. xxxx). Fiber Bragg gratings (FBGs) have been of awesome enthusiasm for optical detecting innovation on the grounds that they are cost-effective, compact and small in size, simple to fabricate, able to withstand with harsh conditions and moreover their optical spectra have great linear responses as for different values of temperature and strain. Numerous methods in view of FBGs have been accounted for concurrent strain and temperature separation (Xu et al. 1994). For instance, utilizing two superimposed FBGs, two resolvable wavelengths in tilted FBG (Chehura
et al. 2007), two FBGs of different diameters (James et al. 1996) or with diverse composition (Cavaleiro et al. 1999) written in fibers and a single FBG of different refractive index (Guan et al. 2002) between fibers across a splice point or between fibers with various levels of doping components (Frazão and Santos 2004). Besides, the estimation from an FBG might be joined with that of an alternate detecting method, for example, utilizing cross hybrid FBG/long period fiber grinding (LPG) (Patrick et al. 1996), superstructure FBG (Guan et al. 2000), an inspected FBG joined with an LPG (Frazão et al. 2002) and an FBG joined with a polarization-keeping up loop mirror (Frazão et al. 2013).

On the other hand, all the fiber Bragg grating sensors based on different refractive index have increasingly aroused research interests in the last decade because of many advantages like they show high sensitivity, high immunity to electromagnetic interference (EMI), high spatial resolution and stability (Hill and Meltz 1997). Furthermore, in retrospect, an experiment was conducted on different types of gratings such as tilted, uniform and chirped grating shapes. After applying dissimilar strain and temperature on FBG sensor on each grating type, the outcomes (~9 nm wavelength shift) from the uniform grating FBG sensor were tremendously good (Kaur and Kaler 2017; Kaur et al. 2017).

2 Theory

In fabrication process of fiber Bragg grating sensor, the core of single-mode fiber (SMF) is exposed to intense ultraviolet light in a periodic stance. The exposure makes a static change in the refractive index of core and creates a chronic index modulation. This stable index modulation is called ‘grating’.

Due to refraction change at each grating reflection of light occurs in a small amount. All the reflected light adds coherently at a specific wavelength and results in one large reflection. It happens when the grating period inscribed in core is approximately half the wavelength of input light signal. This is named as ‘Bragg condition’ and the wavelength that experiences this reflection is known as ‘Bragg wavelength’. The diagram of fiber Bragg grating sensor is shown in Fig. 1.

The signals other than Bragg wavelengths do not have same phase, are basically transparent. The Bragg wavelength ($\lambda_B$) is defined (Torres et al. 2011) as written below:

$$\lambda_B = 2n_{eff}\Lambda$$  \hspace{1cm} (1)

where, $\Lambda$ refers to grating periodicity, $\lambda_B$ indicates Bragg wavelength and $n_{eff}$ is the effective refractive index.

This as-proposed sensor could work efficiently, owing to the unique characteristics of Bragg gratings inscribed in fiber. For instance, when the optical fiber is compressed or stretched, the fiber Bragg grating sensor will measure strain. This happens due to
deformation in optical fiber structure which further leads to change in period of gratings and consequently in Bragg wavelength. Apart from that, the role of photo elastic effect which causes variation in core index of refraction cannot be ignored. The shift in Bragg wavelength is measured by following equation (Torres et al. 2011):

$$\Delta \lambda_B = (K_e \Delta \epsilon) \lambda_B + (K_T \Delta T) \lambda_B$$

(2)

where, $K_T$ and $K_e$ are the wavelength sensitivity coefficients to temperature and strain, respectively for a fiber Bragg grating sensor whose values are given by Kaur and Kaler (2017):

$$K_e = [1 - 0.5n_{eff}(p_{12} - \nu(p_{11} - p_{12}))] \lambda_B$$

(3)

$$K_T = [1 + \xi] \lambda_B$$

(4)

where, $p_{11}$ and $p_{12}$ are the fiber optic strain tensor components and $\nu$ is referred as fiber Poisson’s ratio, $\xi$ is termed as fiber thermos-optic coefficient and $n_{eff}$ is called as refractive index of fiber.

3 Design and simulation

The proposed fiber Bragg grating sensor is a three-dimensional (3D) model. The geometry for fiber Bragg grating sensor consists of two cylinders: core and cladding. Here, the refractive index of first cylinder which is representing core is taken as 1.4457. The gratings having refractive index of 1.4467 are inscribed within the core of fiber. In general, the difference between refractive index of gratings and refractive index of core is in order of $10^{-3}$, known as amplitude of induced refractive index (dn). The refractive index of other cylinder which is representing cladding is taken as 1.4357. The difference between refractive index of core and refractive index of cladding is in order of $10^{-2}$.

Firstly, for designing a fiber Bragg grating sensor, an inner cylinder i.e., core of sensor is designed with a radius of 4.6 $\mu$m and length of 0.05 cm. Secondly, Bragg gratings are inscribed inside the fiber core with a radius of 4.6 $\mu$m and having grating period of 0.53381599 $\mu$m. Next step is to design an outer cylinder i.e., cladding with a length of 0.05 cm and having radius of 62.5 $\mu$m. The graphical representation of core, cladding and gratings are shown in Fig. 2.

A specific set of parameters is used to design Bragg gratings are listed below with values:

The primary focus to design an FBG sensor which can demonstrate greater sensitivity results in terms of change in Bragg wavelength ($\lambda_B$) when independently different strain and temperature apply on it. In order to achieve that, all the parameters with precise length have been chosen, which provide excellent efficacy of designed FBG sensor.

In meshing, tetrahedral technique is used for cladding with maximum element size of 27 $\mu$m and minimum element size of 2 $\mu$m. For core and gratings, the maximum element size is 300 nm. The graphical representation of meshing of fiber Bragg grating sensor is shown in Fig. 3.
4 Results and analysis

The fiber Bragg grating sensors provide information in wavelength encoded form, i.e. when strain is applied to the fiber Bragg gratings, it causes shift in the Bragg wavelength ($\lambda_B$) of the FBG spectral. In order to recover the output data from the encoded wavelength, a system is required which must be able to detect changes in wavelength accurately. For this purpose, an optical spectrum analyzer is used. On the other hand, an interrogation system is required to map the encoded output data into power measurement. To study and analyse the effect of dynamic strain on a particular temperature, simulation has been performed.

The list of sensor parameters used to calculate power spectrum, delay and dispersion are given below:

The simulation operation is performed to observe and analyse the effect of strain and temperature on the transmitted wavelength propagating through optical fiber. The results demonstrated that different load values produce unique shift in peak transmitted/reflected wavelength of FBG spectral response at a particular temperature. The results shown in Fig. 5 shows effect of strain at a constant temperature ($T = 25 \, ^\circ C$). For this simulation, various amounts of load (150, 200, 250 and 300) are applied Tables 1, 2.
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Fig. 4 Effect of strain on wavelength

Table 1 Grating definition

| S.no. | Name             | Value          |
|------|------------------|----------------|
| 1    | Grating shape    | Sine           |
| 2    | Average index    | Uniform        |
| 3    | Period chirp     | No chirp       |
| 4    | Apodization      | Gaussian       |
| 5    | Grating length (L) (µm) | 70,000 |
| 6    | Index modulation (dn/H) | 0.0001 |
| 7    | Shift            | 0              |
| 8    | No. of segments  | 1000           |
| 9    | Period (P) (µm)  | 0.53381599     |
| 10   | Taper’s parameter| 0.5            |
| 11   | Index change     | 0              |

Table 2 Sensor parameters

| S. no. | Name                                | Value                  |
|--------|-------------------------------------|------------------------|
| 1      | Static-optic parameters: Photoelastic coefficient | $p_{11}=0.121$ $p_{12}=0.27$ |
| 2      | Poisson’s ratio                     | 0.17                   |
| 3      | Thermo-optic parameters: Thermal expansion coefficient | 5.5E-007 8.3E-006 |
| 4      | Temperature                         | 25 – 100 °C           |
Figure 4 shows the shift in Bragg wavelength as per introduction of different strain values at a particular temperature (T = 50 °C). The strain applied of 1 [pm/µm], causes 0.002 nm shift in Bragg wavelength (Δλ_B). To check the performance of fiber Bragg grating sensor, the strain values of amount of 150, 200, 250 and 300 [pm/µm] are applied.

As per the plots depicted in Fig. 4, a uniform shift (~ 0.064 nm) has been observed in the peak wavelength of fiber Bragg grating sensor spectrum, when strain applied is changed linearly (50 [pm/µm] per simulation). The Table 3 shows particular wavelength shift for each value of strain applied at temperature (T = 50 °C).

The shift in Bragg wavelength of fiber Bragg grating sensor as per the effect of temperature has been plotted in Fig. 5. The value of temperature is varied independently from 25 to 100 °C through linear steps of 25 °C, whereas the value of strain (ε) is kept constant at 200 pm/µm. The results indicate the linear relationship between temperature applied and wavelength shift. A uniform shift of ~ 0.347 nm is obtained corresponding to every change in temperature.

| Temperature (°C) | Strain (ε) | Wavelength shift (nm) |
|------------------|------------|-----------------------|
| T = 50           | 150        | 0.521                 |
|                  | 200        | 0.585                 |
|                  | 250        | 0.649                 |
|                  | 300        | 0.714                 |

Fig. 5 Effect of temperature on wavelength
The per degree rise in temperature in accordance to wavelength shift is calculated to be 17 pm/°C, indicating the enhanced sensitivity of as-proposed fiber Bragg grating sensor. The Table 4 refers to shift in wavelength with per step increase in temperature.

The concurrent study of temperature (T) and strain (ε) has been observed via increasing these both linearly at the same time. The rise in temperature from 25 to 100 °C through steps of 25 °C and upsurge in strain from 150 to 300 pm/µm through uniform steps of 50 pm/µm are taken under consideration. It is found that Bragg wavelength is directly proportional to change in temperature (T) and strain (ε) taken simultaneously, as shown in Fig. 6. As per the linear change in these values, a uniform shift of ~0.406 nm in Bragg wavelength is achieved. Correspondingly, the Table 5 depicts the wavelength shift for each value of strain and temperature taken for simulation.

![Simultaneous effect of Strain (ε) and Temperature (T)](image)

**Fig. 6** Effect of strain and temperature on wavelength

| Strain (ε) | Temperature (°C) | Wavelength shift (nm) |
|------------|------------------|-----------------------|
| ε = 200    | 25               | 0.238                 |
|            | 50               | 0.585                 |
|            | 75               | 0.930                 |
|            | 100              | 1.277                 |

The per degree rise in temperature in accordance to wavelength shift is calculated to be 17 pm/°C, indicating the enhanced sensitivity of as-proposed fiber Bragg grating sensor. The Table 4 refers to shift in wavelength with per step increase in temperature.

The concurrent study of temperature (T) and strain (ε) has been observed via increasing these both linearly at the same time. The rise in temperature from 25 to 100 °C through steps of 25 °C and upsurge in strain from 150 to 300 pm/µm through uniform steps of 50 pm/µm are taken under consideration. It is found that Bragg wavelength is directly proportional to change in temperature (T) and strain (ε) taken simultaneously, as shown in Fig. 6. As per the linear change in these values, a uniform shift of ~0.406 nm in Bragg wavelength is achieved. Correspondingly, the Table 5 depicts the wavelength shift for each value of strain and temperature taken for simulation.
5 Conclusion

We have proposed a grating-based strain sensor for monitoring the health of massive structures. It is concluded that with increase in number of gratings in fiber Bragg gratings sensor, the shift in peak wavelength of FBG spectrum wavelength has been achieved desirably, with respect to independently applied strain and temperature. The same simulation is performed to efficiently record concurrent effect of strain and temperature. All these cases show linear shift in Bragg wavelength as per uniform change in input parameters. These results reveal enhanced sensitivity of FBG sensor for strain and temperature corresponding to 2 pm/μstrain and 17 pm/°C, respectively. Hence, the simulation results are very useful in the designing of FBG strain sensor which further can be used to measure strain at huge buildings, flyovers, pillars in manufactory and some infrastructures. Moreover, considering the high temperature sensitivity this as-proposed sensor could be well exploited in the bakeries, steel and oil industries as well.

Table 5 Values of strain and temperature

| Temperature (°C) | Strain (ε) | Wavelength shift (nm) |
|------------------|------------|-----------------------|
| 25               | 150        | 0.182                 |
| 50               | 200        | 0.585                 |
| 75               | 250        | 0.994                 |
| 100              | 300        | 1.404                 |

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