Design and Analysis of Fiber Bragg Grating Sensor to Monitor Strain and Temperature for Structural Health Monitoring

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Short Report

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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 nm 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.

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 [1]. These fiber optic sensors are normally made by distinguishing two physical parameters which have different sensitivities to temperature and strain [2], [3]. 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 [2]. For instance, utilizing two superimposed FBGs, two resolvable wavelengths in tilted FBG [4], two FBGs of different diameters [5] or with diverse composition [6] written in fibers and a single FBG of different refractive index [7] between fibers across a splice point or between fibers with various levels of doping components [8]. 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) [9], superstructure FBG [10], an inspected FBG joined with an LPG [11] and an FBG joined with a polarization-keeping up loop mirror [12].

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 [13].

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' [14]. 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 (λ_B) is defined [14] as written below:

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

where, Λ refers to grating periodicity, λ_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 photoelastic effect which causes variation in core index of refraction cannot be ignored. The shift in bragg wavelength is measured by following equation [14]:

$$\Delta\lambda_B = (K_\varepsilon \Delta\varepsilon)\lambda_B + (K_T \Delta T)\lambda_B \qquad (2)$$

where, K_T and K_ε are the wavelength sensitivity coefficients to temperature and strain, respectively for a fiber bragg grating sensor whose values are given by [14]:

$$K_\varepsilon = \left[1 - 0,5n_{eff}\left(p_{12} - v(p_{11} - p_{12})\right)\right]\lambda_B \qquad (3)$$

$$K_T = [1 + \xi]\lambda_B \qquad (4)$$

where, p_{11} and p_{12} are the fiber optic strain tensor components and v is referred as fiber Poisson's ratio, ξ 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 µm and length of 0.05 cm. Secondly, bragg gratings are inscribed inside the fiber core with a radius of 4.6 µm and having grating period of 0.53381599 µm. Next step is to design an outer cylinder i.e. cladding with a length of 0.05 cm and having radius of 62.5 µm. The graphical representation of core, cladding and gratings are shown in Fig. 2.

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)	70000
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

In meshing, tetrahedral technique is used for cladding with maximum element size of 27 µm and minimum element size of 2 µm. 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 provides information in wavelength encoded form, i.e. when strain is applied to the fiber bragg gratings, it causes shift in the bragg wavelength (λ_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:

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 Thermal-optic coefficient	5.5E-007 8.3E-006
4	Temperature	25 °C – 100 °C

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 °C). For this simulation, various amounts of load (150, 200, 250 and 300) are applied

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 ($\Delta\lambda_B$). To check the performance of fiber bragg grating sensor, the strain values of amount of 150, 200, 250 and 300 [pm/µm] are applied.

Table 3
Values of strain at constant temperature

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

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 °C 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.

Table 4
Values of temperature at constant strain

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.

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

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.

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Figures

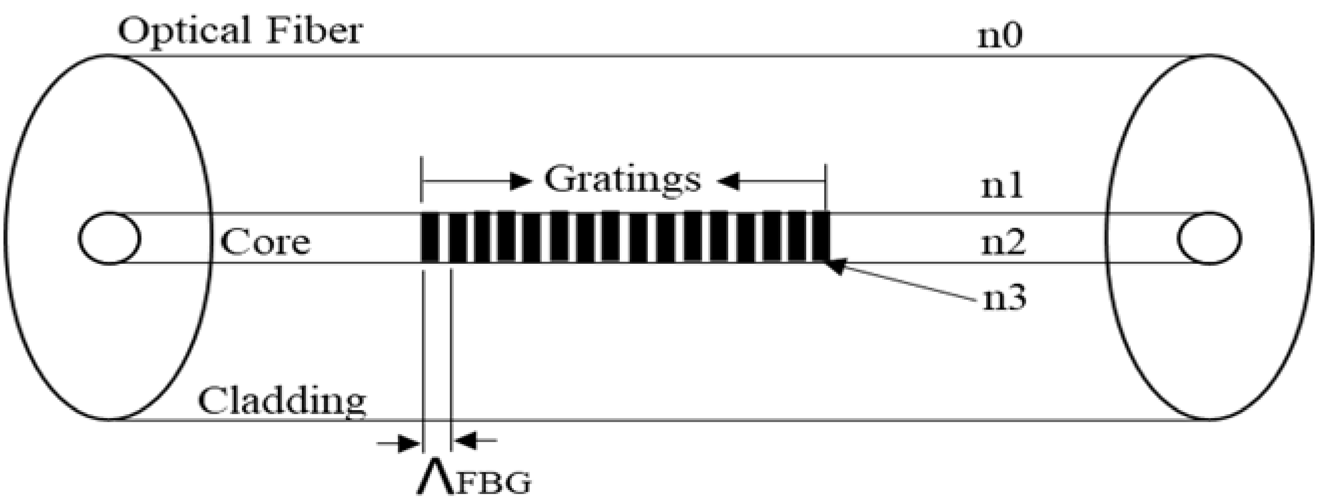

Figure 1

Fiber bragg grating sensor

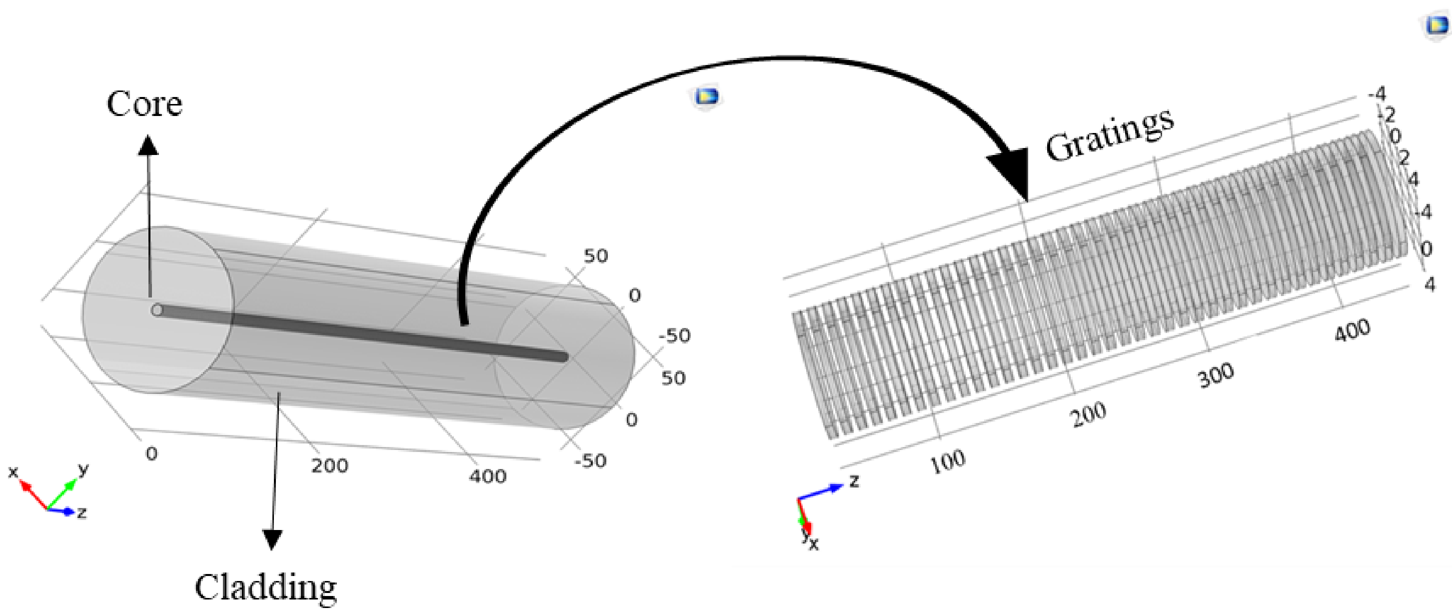

Figure 2

(a) Fiber grating sensor and (b) Bragg gratings of FBG sensor

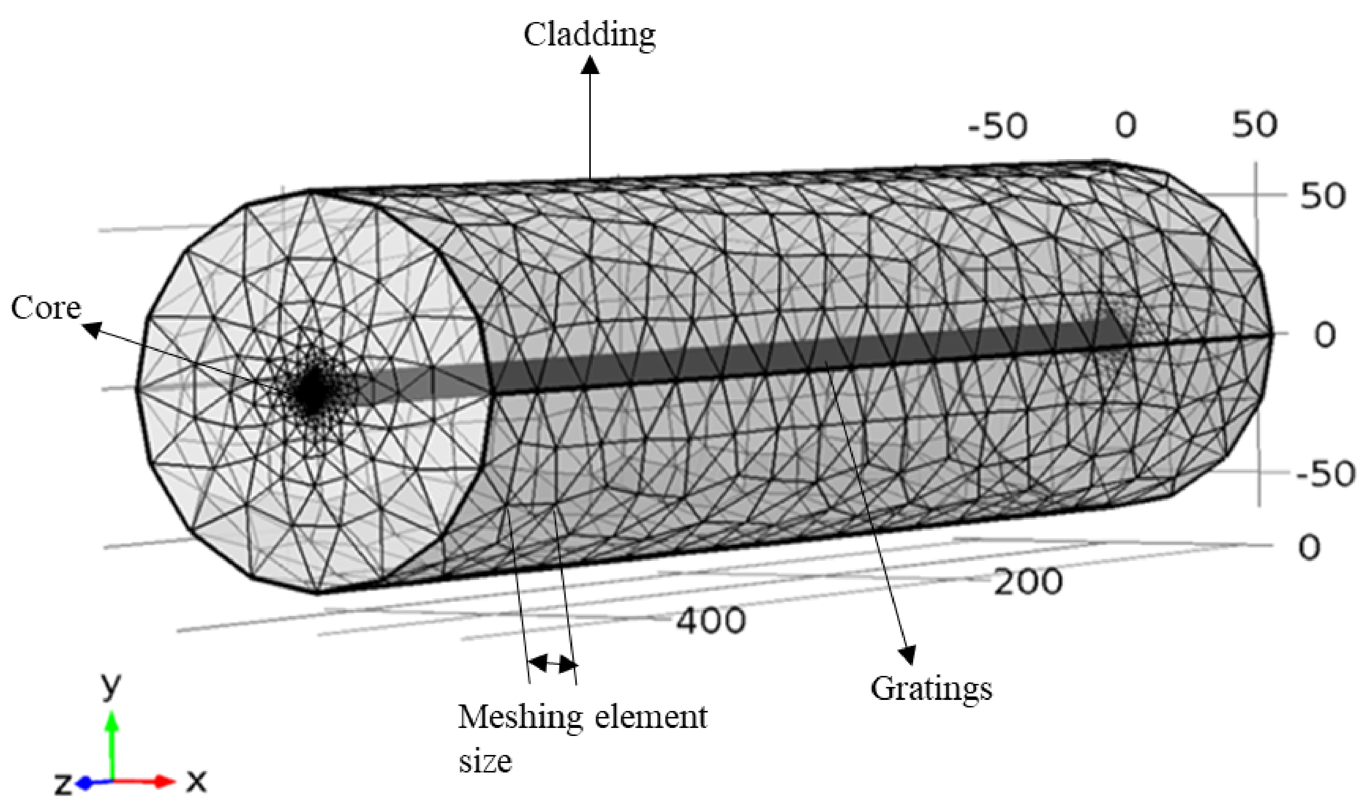

Figure 3

Meshing of fiber bragg grating sensor

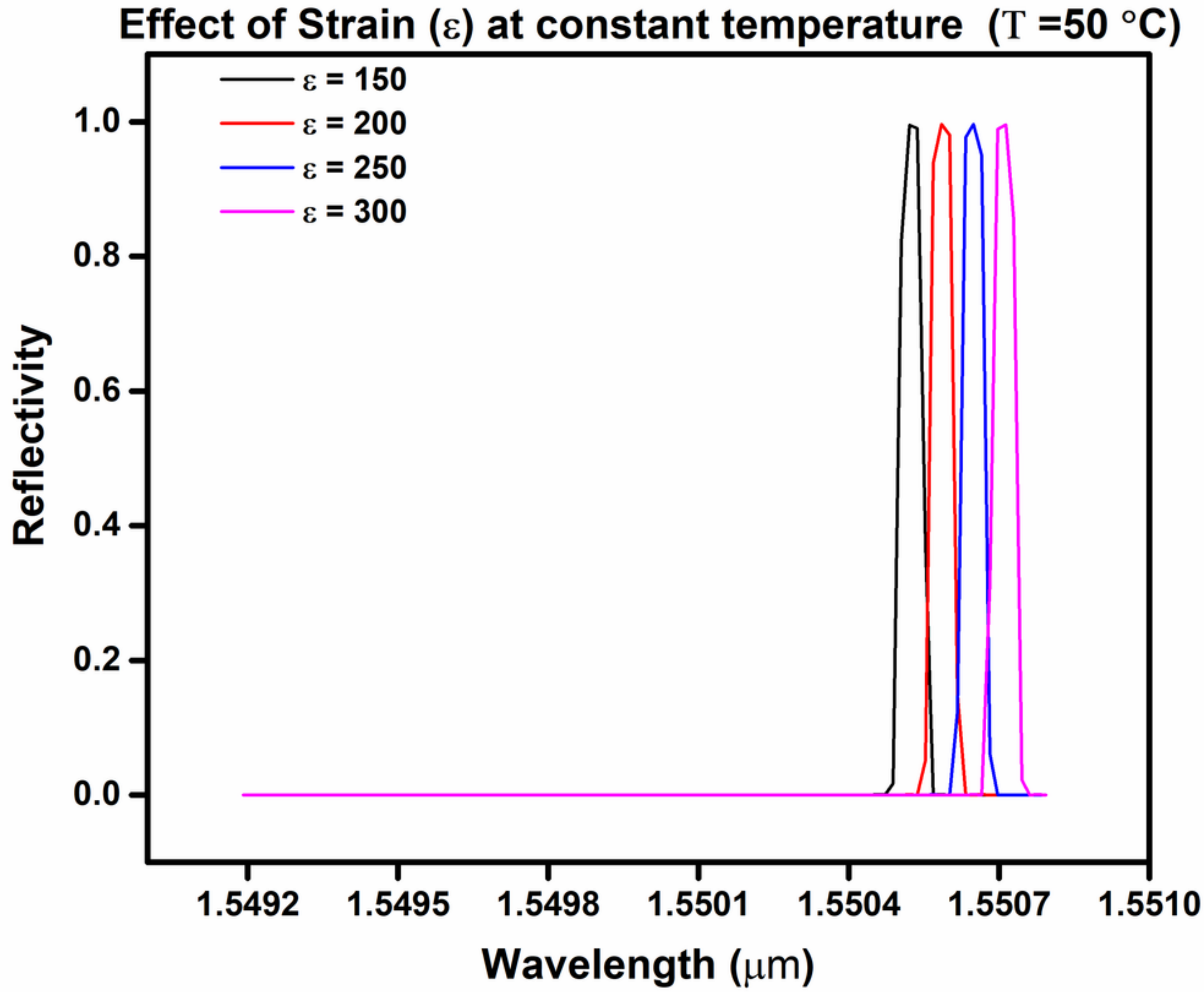

Figure 4

Effect of strain on wavelength

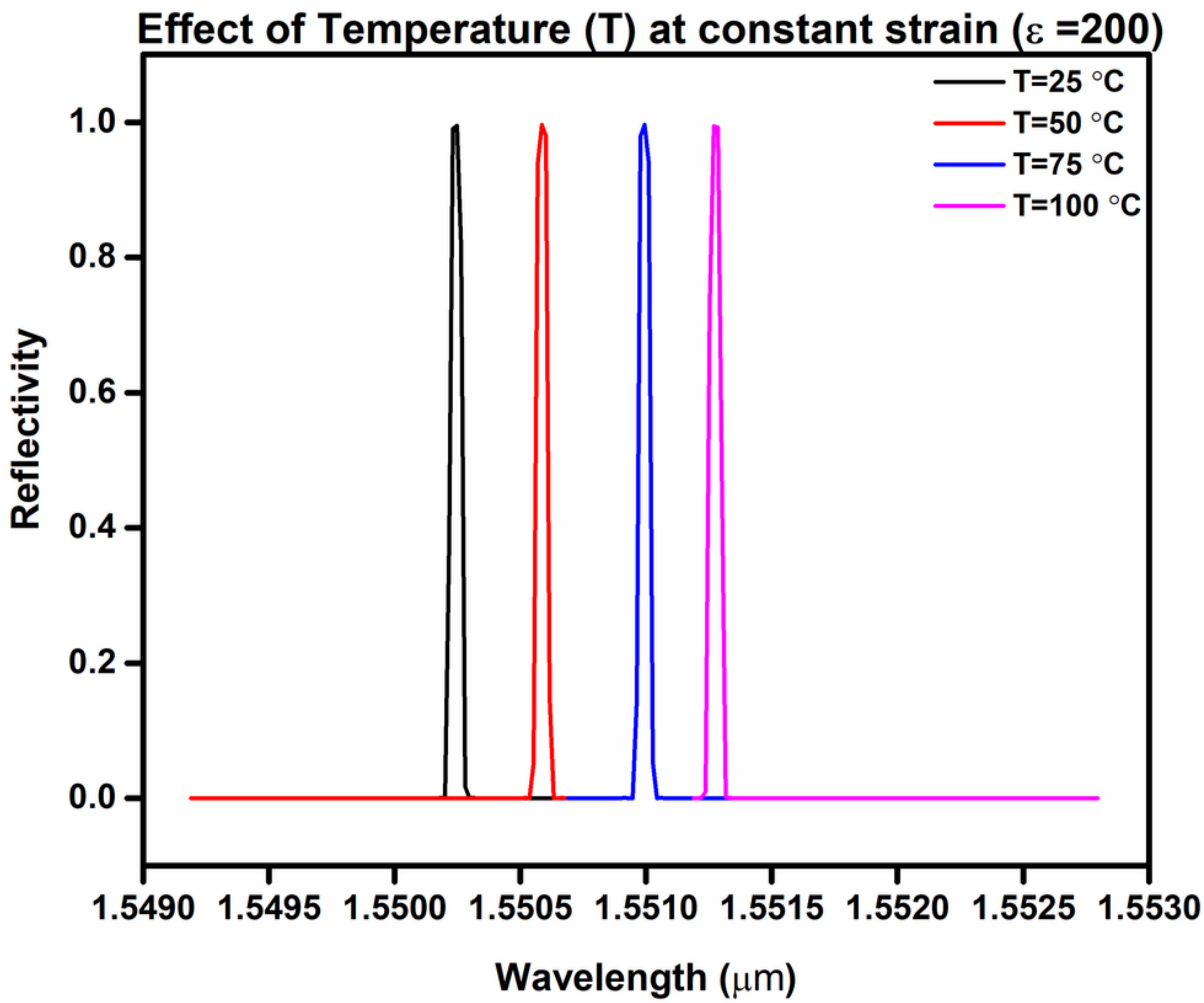

Figure 5

Effect of temperature on wavelength

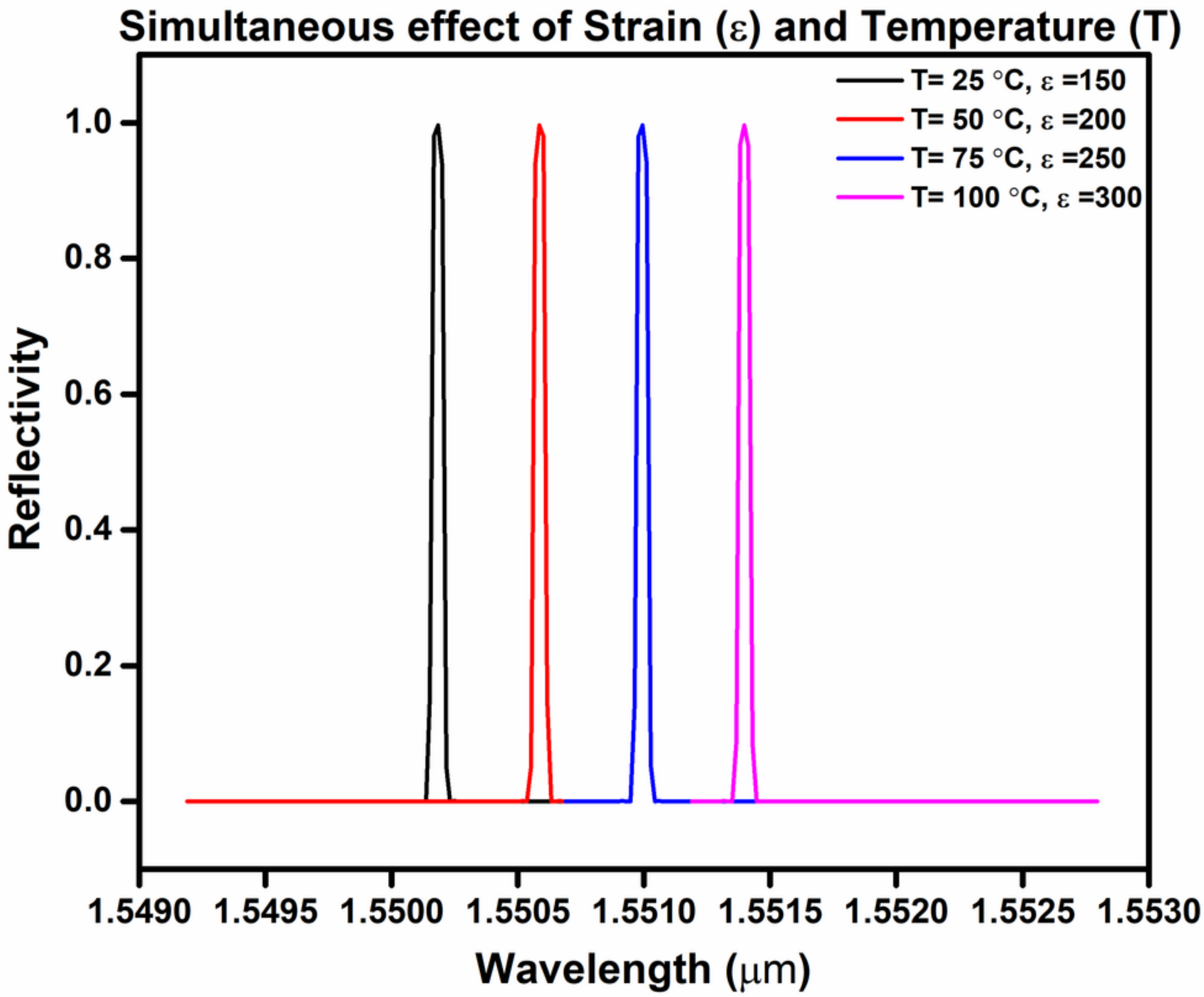

Figure 6

Effect of strain and temperature on wavelength