

# Sensitivity Analysis of Fiber Bragg Grating Sensors for Temperature and Strain Monitoring in Precision Healthcare and Drug Delivery Applications

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## ABSTRACT

The modern healthcare system requires reliable sensing solutions to integrate with digital trends like artificial intelligence, machine learning and internet of medical things. Traditional sensors have limitations to fulfil requirements of transforming healthcare. The optical fiber is most promising for development of advanced sensors for healthcare measurements due to its small size, light weight, immunity to noise and high sensitivity for precise measurement of healthcare parameters. The variation in refractive index of core of optical fiber forms grating which is desirable for sensing applications and is known as fiber Bragg grating sensor. The grating is sensitive to physical factors such as strain, temperature and pressure which makes it suitable for measurement of healthcare parameters. The Grating reflects the specific wavelength known as Bragg wavelength. The physical factors change the grating properties and introduce the shift in the Bragg wavelength. The shift in the reflected Bragg wavelength is proportional to strain and temperature. In medical sensing applications high reflectivity with low noise is desirable for high detection sensitivity in precise measurement of healthcare parameters. The mathematical model for temperature and strain sensitivity is developed to determine temperature and strain sensitivity. The analytical model is validated by using FBG sensor simulation model. The optimized design is proposed to obtain improved temperature sensitivity. The proposed FBG model gives temperature sensitivity of 16 pm/°C. Also obtained strain sensitivity of 0.8 pm/με is close to typical strain sensitivity of FBG Sensor. Due to high sensitivity, the proposed FBG sensor model is more promising than the conventional electronic sensors for real time accurate and precise monitoring of biomedical parameters. Such accurate real time monitoring can significantly support optimized drug delivery by enabling controlled dosage administration and timely therapeutic interventions.

**Keywords:** Fiber Bragg Grating sensor; Sensitivity; Reflectivity; Side lobe levels, healthcare, drug delivery.

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## I. INTRODUCTION

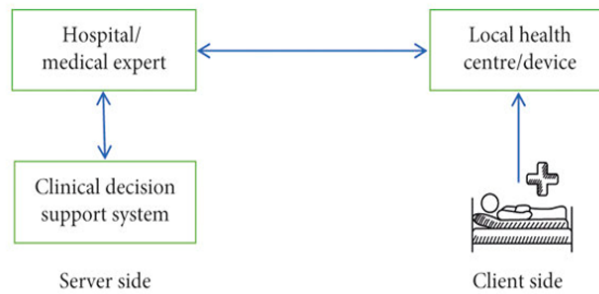
The rapid evolution in technology is transforming healthcare services to provide more patient centric services. The recent technological trends like IoT, Artificial Intelligence, Machine Learning and cloud computing are playing vital roles in healthcare industry to enhance efficiency and give better patient outcomes. The emerging Healthcare 5.0 standard emphasized a more personalized and user focused approach to patient care [1]. The transformation Healthcare 4.0 to healthcare 5.0 is more focused on overall well-being with remote

monitoring, smart hospitals, predictive analytics to address health issues before they emerge [2]. The remote monitoring with IoT is shown in figure 1 which allows medical professionals to gather precise information and take timely decisions for personalized and protective care. This also avoids frequent hospital visits and reduces overall healthcare costs. One of the requirements of modern healthcare systems is to collect precise patient information by using the sensors. Hence the sensor technology along with recent technological trends is playing important role in healthcare transformation. The

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different types of medical sensors are used to collect patient information. The medical sensors which measure vital information such as body temperature, heart rate, respiration rate and blood pressure are known as

physiological sensors. Chemical sensors measure pH value and glucose levels while biosensors are mainly concerned about tissues, protein and DNA measurements.



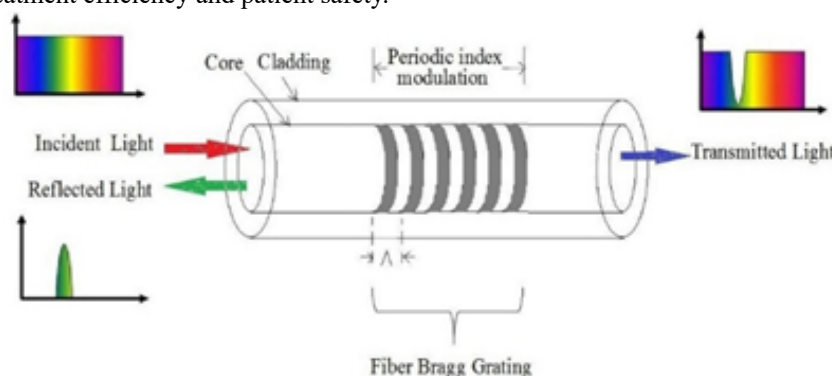
**Figure 1:** IoT based Healthcare system [3]

The advancement in sensor technology such as wearables has opened new opportunities for patients to continuously monitor their own health. Also, sensor technology is migrated from traditional to more advanced sensors in terms of their operating principles. The several factors of medical sensors such as sensitivity, noise immunity, compatibility are equally important while integrating the sensors with healthcare systems. Traditional sensors are based on electronic principles which have certain limitations. The sensors based on optical detection principle offer many advantages over traditional sensors. The optical fiber-based sensors are most promising to support the requirements of advanced healthcare trends. Different types of optical sensors are available to measure physiological, chemical and biological information of the patient. The Fiber Bragg grating sensor (FBG) is one type of optical fiber sensor that is most suitable for healthcare 5.0 standard. The FBG is superior to traditional sensors due to its small size, light weight, biocompatibility, immunity to radio frequency interference or electromagnetic interference and multiplexing capability [4][5]. Also, due to its high sensitivity, it is ideal candidate for cutting edge technologies which rely on precise monitoring physiological, chemical and biological parameters for accurate diagnosis and patient well-being. This capability facilitates intelligent drug delivery systems by providing continuous feedback for dose adjustment, thereby improving treatment efficiency and patient safety.

The design of the FBG is crucial for medical sensing applications. It is necessary to understand the challenges and factors which affect sensing performance. The careful selection of FBG design parameters such as core and cladding dimensions, grating length, grating period, modulation index and apodization profile is essential to obtain high sensitivity and precision in measurement. The optimized design parameters give high reflectivity and low side lobe levels which are essential for high sensitivity in noisy environments. FBG sensors are highly sensitive to external perturbation such as temperature, strain and pressure. FBG sensor exhibits linear sensitivity for temperature and strain. FBG operates on the principle of the wavelength shift which shows linear change with temperature and strain. Hence in the transformed healthcare standard, FBG sensors are more promising than the conventional clinical sensors due to their noise immunity and high sensitivity.

## 2. FBG SENSOR PRINCIPLE

FBG structure consist of single mode fiber whose core is exposed to strong ultraviolet laser to obtain periodic variation in the refractive index (R.I). This periodic variation of R.I. is known as fiber grating [6]. The typical structure of FBG sensor is shown in figure 2.



**Figure 2:** Fiber Bragg Grating Structure [6]

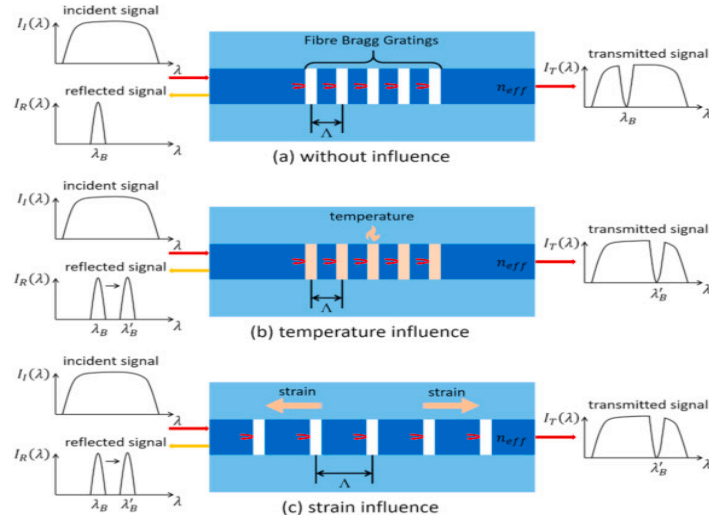
The amplitude of periodic variation is known as modulation index ( $n_{eff}$ ) and the length for which periodic variation is obtained is known as grating length ( $L$ ). The spatial period of R. I. variation is known as grating period ( $\Lambda$ ). All these parameters are crucial to design FBG for sensing applications.

Grating reflects specific wavelength while transmit all

other wavelengths when broadband light is passed through. The reflected wavelength is known as Bragg wavelength given by equation (1).

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where  $n_{eff}$  is known as effective refractive index and  $\Lambda$  is the grating period.



**Figure 3:** FBG working principle: (a) Without influence (b) Influence of temperature (c) Influence of strain [7]

### 3. FBG SENSIVITY TO TEMPERATURE AND STRAIN

In a stable environment the reflected wavelength is given by equation (1). The external perturbation such as temperature or strain can affect this wavelength and shifts it from its value defined by equation (1). This wavelength shift is given as,

$$\Delta\lambda_B = 2 \left[ \Lambda \left( \frac{\partial n_{eff}}{\partial x} \right) + n_{eff} \left( \frac{\partial \Lambda}{\partial x} \right) \right] \Delta x \tag{2}$$

Where  $\frac{\partial n_{eff}}{\partial T}$  represents variation in the refractive index and  $\frac{\partial \Lambda}{\partial l}$  is the change in the grating period.  $x$  represents an external perturbation. The effect of external perturbation on Bragg wavelength shift is shown in figure 3.

The typical FBG sensitivity to temperature and strain is given by equation (2) and (3) respectively.

$$S_T = \lambda_B (\alpha + \xi) \tag{3}$$

$$S_\epsilon = \lambda_B (1 - p_e) \tag{4}$$

where,  $\xi$ = thermo-optic coefficient of silica fiber.

$p_e$ = effective photo-elastic coefficient of silica fiber.

The typical parameters of FBG sensor fabricated from silica are listed in table 1. These parameters are considered to determine temperature and strain sensitivities.

**Table 1:** Parameters for Standard Silica FBG Sensor

Parameter	Symbol	Value
Bragg wavelength	$\lambda_B$	1550 nm
Effective photo-elastic coefficient	$p_e$	0.22
Thermal expansion coefficient	$\alpha$	$0.55 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$
Thermo-optic coefficient	$\xi$	$8.6 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$

The temperature and strain sensitivities are calculated for above FBG specification using equation (3) and (4).

The calculated temperature sensitivity is,

$$S_T = \lambda_B (\alpha + \xi)$$

$$S_T = 1550 \times (0.55 \times 10^{-6} + 8.6 \times 10^{-6})$$

$$S_T = 14.18 \text{ pm}/^\circ\text{C}$$

And the calculated strain sensitivity is,

$$S_\epsilon = \lambda_B (1 - p_e)$$

$$S_\epsilon = 1550 \times (1 - 0.22)$$

$$S_\epsilon \approx 1.21 \text{ pm}/\mu\epsilon$$

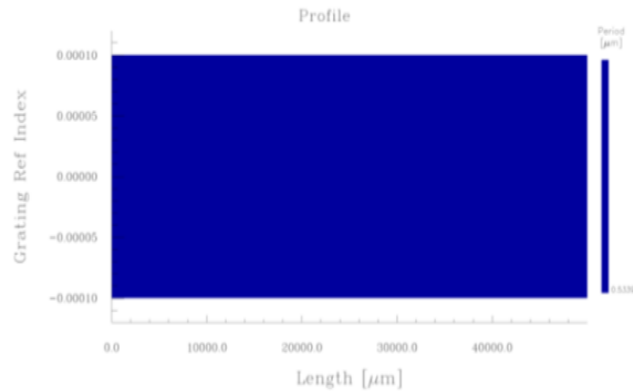
The derived mathematical model is useful to determine the temperature and strain sensitivities of the fiber Bragg Grating sensor operating at Bragg wavelength of 1550 nm wavelength. The calculated temperature and strain sensitivities are different. FBG offers temperature

sensitivity of 14.18 pm/°C and strain sensitivity of  $S_\epsilon \approx 1.21 \text{ pm}/\mu\epsilon$ . These sensitivity values are suitable for precise monitoring of the healthcare parameters. The relatively higher temperature sensitivity enables accurate body temperature monitoring. The strain sensitivity of 1-1.3 pm/  $\mu\epsilon$  is suitable for detection of small mechanical perturbations applicable for measurement of pulse rate, respiration rate and blood pressure. The obtained

sensitivities validate the effectiveness of proposed FBG sensors for healthcare measurements.

**4. FBG SENSOR SIMULATION MODEL**

The OPTIGRATING tool is used to investigate performance uniform FBG sensor for temperature and strain sensitivity. If the modulation is uniform along the entire length of the grating is known as Uniform grating profile, shown in figure 4.



**Figure 4:** Uniform FBG Sensor Profile

The typical optimised structural parameters of uniform and strain sensitivity. These parameters are listed in table 2. The parameters of the grating sensor are considered to determine temperature

**Table 2:** FBG Simulation Parameters

Sr. No.	Parameter	Value
1	Wavelength	1550 nm
2	Core diameter	4.6 µm
3	Cladding diameter	62.5 µm
4	Grating period	0.5338 µm
5	Grating Length	10 mm
6	Modulation Index	0.0003

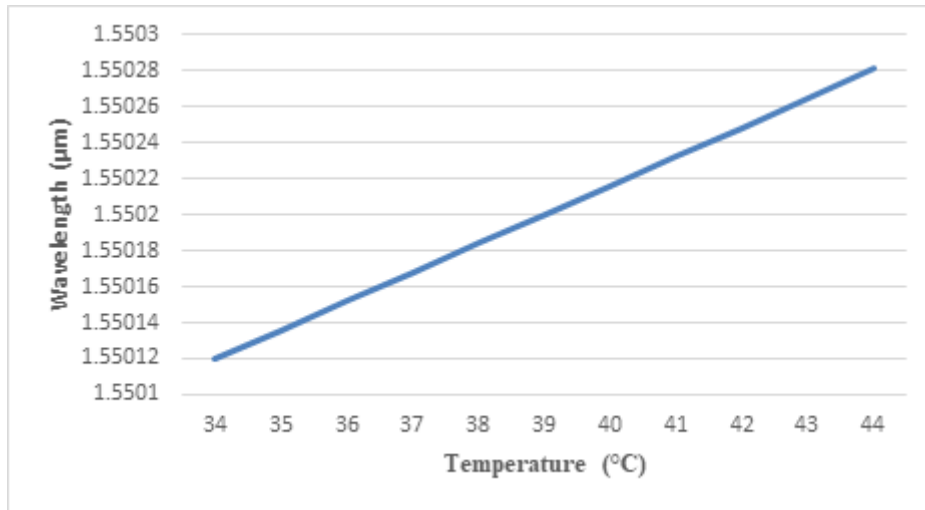
The effect of grating length, grating period and modulation index is observed by using simulation framework and optimized parameters are determined.

**4.1 Temperature Sensitivity Analysis**

The uniform Grating with length of 10 mm, core cladding diameter of 4.6µm and 62.5 µm, modulation index of 0.0003 is used to observe effect of variation of temperature on wavelength shift. The temperature range considered represents normal human body temperature range. The temperature varies with 1 °C and corresponding wavelength shift is observed. The wavelength shift increases with temperature shown in figure 5. It is

observed that FBG shows the linear response to the applied temperature.

The corresponding wavelength shift as a function of temperature is shown in table 3. The wavelength shift with temperature demonstrates a linear relationship over the temperature range of 34 °C to 44 °C. The wavelength increases due to thermal expansion of grating period and thermos-optic change in the effective refractive index. The obtained sensitivity is consistent with standard silica-based FBG characteristics. The temperature sensitivity is determined from the slope of above characteristics.



**Figure 5:** Wavelength Shift with Temperature

$\Delta\lambda = 1.550136 - 1.550120 = 0.000016 \mu\text{m}$  and  $\Delta T = 35 - 34 = 1 \text{ }^\circ\text{C}$ . Using  $S = \frac{\Delta\lambda}{\Delta T}$  gives  $S = 0.000016 \mu\text{m} / 1 \text{ }^\circ\text{C}$

**Table 3:** Effect of temperature on wavelength shift for Uniform FBG Sensor

Sr. No	Temperature (°C)	Wavelength (μm)
1	34	1.550120
2	35	1.550136
3	36	1.550152
4	37	1.550168
5	38	1.550184
6	39	1.550200
7	40	1.550216
8	41	1.550232
9	42	1.550248
10	43	1.550265
11	44	1.550281

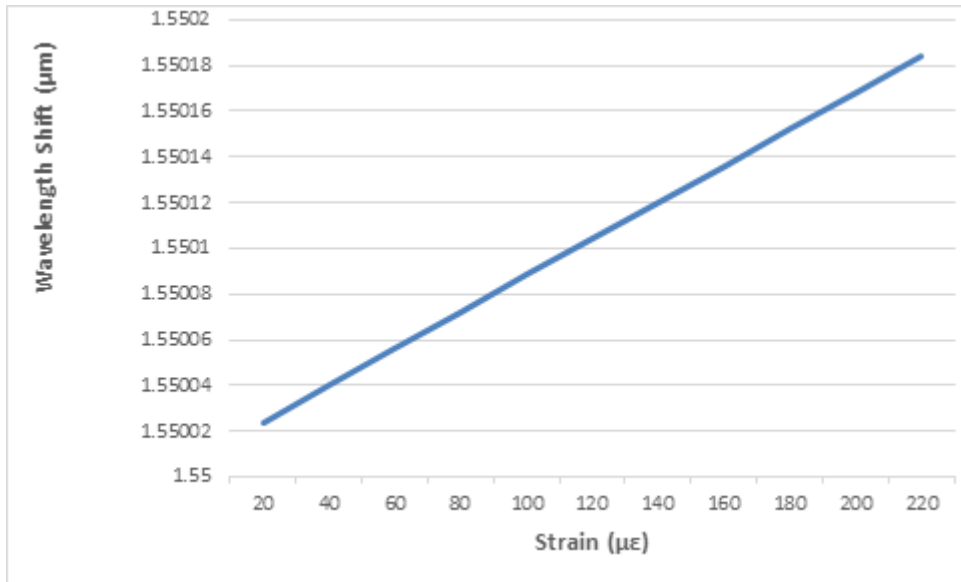
Hence the proposed FBG structure offers high sensitivity of 16 pm/°C. In medical sensing applications it makes FBG suitable for precise measurement of body temperature.

**4.2 Strain Sensitivity Analysis**

The effect of variation of strain on the sensitivity of uniform Grating sensor is shown in figure 6. The corresponding values of wavelength shift as a function of strain are listed in table 4. It is observed that FBG has almost linear response to strain variation. The strain sensitivity of FBG sensor is determined by slope of figure 6.

$\Delta\lambda = 1.5500882 - 1.5500721 = 0.0000161 \mu\text{m}$  and  $\Delta\varepsilon = 100-80= 20 \mu\varepsilon$ . Using  $S = \frac{\Delta\lambda}{\Delta\varepsilon}$  gives  $S=0.8015 \text{ pm}/\mu\varepsilon$ .

The proposed optimized design provides a high temperature sensitivity of 16 pm/°C. Also, the obtained strain sensitivity of 0.8 pm/με is comparable to typical strain sensitivity of FBG sensor. Hence this optimized FBG sensor can provide high sensitivity to measurement of body temperature, hear rate, respiration rate and blood pressure.



**Figure 6:** Wavelength Shift as a function of Strain

**Table 4:** Effect of Strain on Wavelength shift for Uniform Grating

Sr. No.	Strain (µε)	Wavelength Shift (µm)
1	20	1.550024
2	40	1.5500401
3	60	1.5500561
4	80	1.5500721
5	100	1.5500882
6	120	1.5501042
7	140	1.5501202
8	160	1.5501362
9	180	1.5501523
10	200	1.5501683
11	220	1.5501843

If initial cost of FBG based system is reduced, then the proposed sensor is more promising than conventional electronic sensor used in biomedical measurements.

**5. CONCLUSION**

FBG sensor is most suitable to support modern healthcare systems due to its high sensitivity and precision in monitoring healthcare parameters. The mathematical model is developed and simulated which gives sensitivity of 16 pm/°C for temperature measurement and strain sensitivity of 0.8 pm/µε. These high sensitivities make the FBG sensors more attractive for measurement of physiological parameters in medical sensing. Although higher temperature and strain sensitivities are achievable through specialized packaging and coating, the proposed sensor offers structural simplicity and gives sensitivity values which are adequate for reliable and precise monitoring of healthcare parameters. The high sensitivity of FGB sensor to temperature and strain enables their use for precise and accurate monitoring of biomedical parameters. The accurate real time monitoring due to high sensitivity of FBG sensors supports the optimized drug delivery thereby improving the patient’s safety.

**Code Availability**

The simulation results are obtained by using OPTIGRATING simulation tool. Hence no specific code was developed for this research work.

**Data availability**

The datasets generated and analyzed during the current study are derived from simulation models. The related data can be made available from the corresponding author upon reasonable request.

**Supplement**

Additional supporting data are available from the corresponding author upon request.

**Author contributions**

Conceptualization: SJ and AJ. Methodology: SJ and AJ. Formal analysis: SM and JJ. Investigation: SJ and AJ. Resources: SM. Data curation: JJ. Writing (original draft preparation): SJ. Writing (review and editing): AJ and JJ. Supervision: AJ and SM.

**Competing interests**

The corresponding author declares that none of the authors have any competing interests.

### Disclaimer

The authors are solely responsible for the content and conclusions of this study.

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