Radius: Journal of Science and Technology
Vol. 3, Issue 2, (2026) 262006 (7pp)

Numerical Investigation of Fiber Bragg Grating Sensors for Temperature Measurement

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Abstract: The present study deals with the temperature sensing capabilities of single mode silica optical fibers by Fiber Bragg Grating (FBG) approach via theoretical analysis and computer simulation in MATLAB. The underlying principle is that due to temperature variations, the grating period and the effective refractive index change causing a wavelength shift called Bragg wavelength shift. In the process, the connection between temperature change and wavelength shifts due to both thermal expansion and thermo-optical effect is analyzed. The results show the capabilities of FBG sensors to be applied for accurate temperature measurements over wide range of values. Due to their resistance to electromagnetic interference, remote sensing and multipoint measurement capability, the sensors can be used in industries, power transmission systems and structural health monitoring. At the same time, there are several restrictions connected with the high cost of sensors, difficulties in installation and cross-sensitivity to temperature and strain.

Keywords: Temperature measurement, Fiber Bragg Grating Technique, Bragg wavelength shift, Thermo-optic effect, Optical fibre sensor

1. Introduction:

In this technique, a microscopic grating pattern is observed in the core of an optical fibre on the application of high intensity light including UV Lasers and femtosecond Lasers, which is connected to object whose temperature is to be measured. This portion reflects only the specific wavelength of light (Bragg's wavelength) but passes other wavelength light through it; hence acting as an optical filter. These FBGs have a short modulation period less than 1 micrometre). FBG sensors are highly advantageous because they are not affected by radio waves or electromagnetic interference (EMI) **[1]**, they can be installed in explosive environments which is otherwise not safe for human beings, and they are capable of multiplexing which means there can be strings of multiple sensors which can be connected along a single fibre which increases its capacity to measure large temperature profile. Another important requirement was the multi-point temperature measurement **[2, 3]** which many instruments (for example mercury and IR thermometers) were failing as they have to physically move to different points. These problems were successfully met by present day fibre optic temperature measuring techniques including FBG. The light source can also be SLD (Super luminescent light emitting diode) **[4]** which is hardware element which uses ASE (Amplified Spontaneous emission) to produce high intensity light. Centre wavelength of such a source can be between 770 nm to 1680 nm.

For understanding the FBG working procedure at the atomic level, we can say that the optical fibre core is made up of silica glass (SiO_2) with the doping of germanium (Ge), phosphorus (P)

https://doi.org/10.5281/zenodo.23647790
Received: 11 September 2026 | **Revised:** 01 October 2026
Accepted: 08 October 2026 | **Published Online:** 30 October 2026

or Boron (B) in small quantities. Now, when the intense light hits the core, it breaks the chemical bonds like germanium dioxide (GeO_2) exhibiting the principle of photosensitivity. It also results in increase in the core's refractive index. In some cases, the economical cables which are of short range are made up of plastics like Polymethylmethacrylate (PMMA) **[5]**.

In some case or setup; light is first passed through the optical coupler before hitting the optical fibre. The role of coupler is to split the light from the source so that the FBG sensor can be activated **[6]**. It also forms the reverse path of the reflected light before it is fed to the analyser or we can say that the optical coupler routes the light signals in such a way that reflected temperature data gets separated from forward travelling source light. When the laser light falls on optical fibre, it modifies the glass thereby creating alternating bands of low and high refractive index which are microscopic in nature **[7]**.

The spacing between the grating expands when there is rise in temperature and shrinks on vice-versa. Simultaneously, there is change in refractive index of glass core, the same information is carried back by reflected light. With the change in grating width and refractive index, specific wavelength also gets changed or shifts. With the increase in temperature; reflected wavelengths gets shifted towards the longer (or red) wavelengths and similarly, with the decrease in temperature; reflected wavelengths gets shifted towards the shorter (or blue) wavelengths. Interrogator is an optical device which measures the exact peak of this reflected wavelength. As the wavelength shift has a definite relationship with the temperature changes (about 10 pm/°C to 11.5 pm/°C); precise temperature of the object can be measured **[8]**. The Figure 1 depicts the reflecting and transmitting behaviour of incident light into the optical fibre.

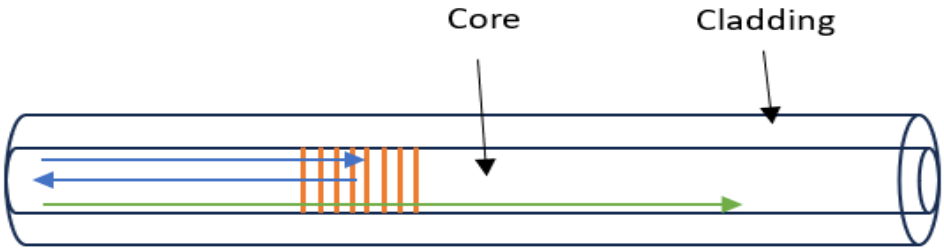

Figure 1: Behaviour of incident light in the form of reflection and transmission.

Bragg's Condition is the specific condition which allows light of a particular wavelength to be reflected by FBG **[9]** and is given by equation 1:

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

where, λ_B is the central Bragg wavelength (generally expressed in nm), n_{eff} is the effective refractive index of the fibre core and Λ_B is the grating period. It is generally measured in nm.

This pattern is observed in periodic spaced zones in the optical fibre and has refractive index slightly more than the core. Since, there are many lines in the grating in the core which are spaced and there may be hundreds of such lines which reflects back the light. All such reflected light waves combine together coherently to create a strong reflect back at the exact Bragg's wavelength. Some of the temperature sensor cable is having cladding coating of acrylate or polyimide, wherein outer sleeve is made up of 900 µm PTFE (Polytetrafluoroethylene) **[10]** and have spectral width less than 0.6nm. This PTFE is having excellent properties of heat, chemical and moisture resistant.

Now the reflected light is fed to the optical spectrum analyser (OSA) which is also called interrogator **[11]**. As the reflected light travels back into the interrogator. Internal optical

components (such as a spectrometer, optical filter, or CCD/photodetector array) capture this returning spectrum. High-speed processing algorithms track the exact center of the reflected peak. By comparing the shifted wavelength ($\Delta\lambda_B$) against a baseline calibration, the system calculates the precise temperature change (ΔT). The property of FBG is that it can reflect only Bragg wavelength (which constitute a very narrow band). Hence, whenever there is any change in temperature on the either side (rise or fall of temperature), the grating expands or shrinks resulting in the shift of reflected wavelength. This OSA can now fetch the change in the spectrum and can detect the wavelength shift. Hence, it works as wavelength tracker. This OSA can be labelled as a high-resolution temperature monitor as its resolution is in the range of picometers (pm), hence even a minor change in temperature cannot go undetected. The standard sensitivity of FBG is around 11.5 pm/°C.

The calibration of an optical fiber Bragg grating (FBG) temperature sensor system is divided into two distinct procedures: internal wavelength calibration of the interrogator instrument itself, and thermal profiling calibration of the silica glass FBG sensor probe. An interrogator's measurement uncertainty in detecting temperature changes using a silica fiber Bragg grating (FBG) is typically around 0.1°C, corresponding to a wavelength resolution or uncertainty of about 1 pm. The relationship between the temperature change ΔT and the shift in the Bragg wavelength $\Delta\lambda_B$ **[12]** is expressed as:

$$\Delta\lambda_B = \lambda_{B_0} (\alpha + \xi) \Delta T \quad (2)$$

Where, λ_{B_0} is the initial Bragg wavelength, α is the thermal expansion coefficient of the fibre material and ξ is the thermo-optic coefficient of the fibre.

Since, this shift in wavelength is a function of temperature changes; exact temperature of the object can be measured. The OSA have the capability to detect multiple FBGs along a single fibre in different zones, hence different temperature profiles at different locations can be identified. Finally, this OSA is connected to separate or inbuilt signal processing unit and display device which can be PC, which senses this coded information of temperature measurement, converts into digital or readable form for convenience.

In FBG (Fiber Bragg Grating) temperature measurement, the FBG sensor must be in direct thermal contact with the object or medium; which can be solid, liquid or gas. This FBG system can be positioned as surface mounted (or clamped where the surface is flat) **[13]** to the object. This is done with the help of high temperature thermal epoxy or thermally conductive tape for fast heat transfer. Else it can be embedded within the object being measured as in the case of concrete or composite materials composite to accurately capture the internal temperature **[1]**. If the object or the medium is molten metal or liquid existing in harsh conditions; FBG is inserted into protective metal or ceramic capillary tube which is direct contact with liquid is used. Temperature measuring range for solids and liquids can be from extreme cryogenic range (-200 °C) to 1000 °C **[14]**. Similarly, in normal cases gas temperature of 250 °C to 300 °C can easily be measured. But for special cases of high temperature gases (exhaust and turbine gases in power plants where temperature extend up to 1000 °C) and similarly in liquids, specially coated optical fibres are used. Hence, we can say the temperature measurement range is the function of the material used in the optical fibres.

ACCR transmission line conductor is one of the High temperature low sag types of conductors which has good ampacity **[15]**. FBG technique is useful in measuring the temperature of such

conductors. FBG also has applications used in telecom sector as it used as add-drop multiplexers and dispersion compensators in optical networks. In Fiber grating, we can have multiple sensing points (say up to 20) on a single fibre and the system consists of multiple fibres. Here, as well multiple channels are used. A typical instrument used for industrial application may have up to four channels with number of FBGs per channel ranging up to 20. Length of gratings may extend from 10 mm to 15 mm, wavelength resolution of 1 pm and sensor cable length of 500 m. Such devices may have communication interface (for display device connection) as USB 2.0, RJ45 or RJ485. Some of the common features of FBG-based optical fibre is listed in Table 1.

Table 1: Features of FBG-based optical fibre

Features	FBG-based optical fibre
Remote sensing	Yes, real time data can be transferred.
Immunity	Yes, immune to EM and radio waves.
Operation ability	No such problem and can measure both temperature and strain
Range of placement	Multi-point sensors on single fibre line, more reliable.
Measurement type	Contact type internal or surface temperature
Fragility	Medium fragile
Safety & Ecofriendly	Set up is considered ecofriendly as it contains silica, glass and does not contain toxic heavy metals or chemicals which are leaked to the environment.

2. Methodology:

As discussed earlier, we can have the relationship between the temperature change ΔT and the shift in the Bragg wavelength $\Delta\lambda_B$ which is modified and is expressed as:

$$\Delta\lambda_B = \lambda_{B_0}(\alpha + \xi)\Delta T = K_T.\Delta T \quad (3)$$

Where, $\Delta\lambda_B$ is the shift of Bragg wavelength, λ_{B_0} is the initial base Bragg wavelength (e.g., 1550 nm), α is Thermal expansion coefficient of silica ($\approx 0.55\times10^{-6}$/°C), ξ is Thermo-optic coefficient of silica ($\approx 8.6\times10^{-6}$/°C) and K_T = Temperature sensitivity coefficient ($\approx$ 0.01 nm/°C)

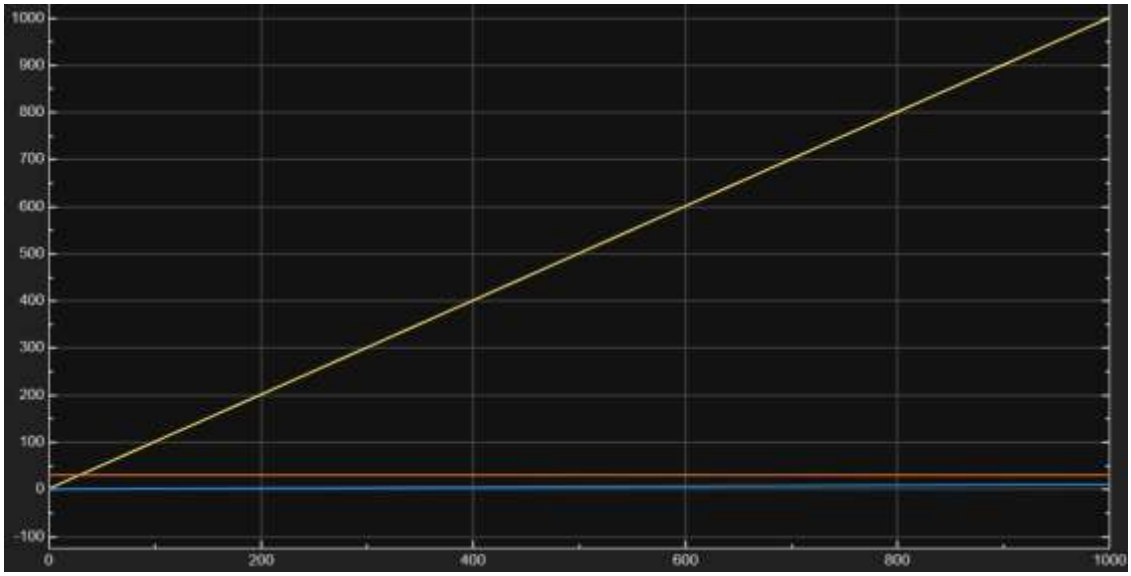

Figure 2: Simulated output of FBG MATLAB Model

Based on equation 3, a FBG MATLAB Simulink model was designed for temperature monitoring for single mode optical fibre made of Silica glass (Germanosilicate glass) and its results were analysed. Ambient temperature of 30 °C was taken as a reference. In Figure 2, yellow line shows the temperature of object under measurement, blue line shows the shift of Bragg's wavelength (Δλ) in nm and orange line shows the ambient temperature of 30 °C.

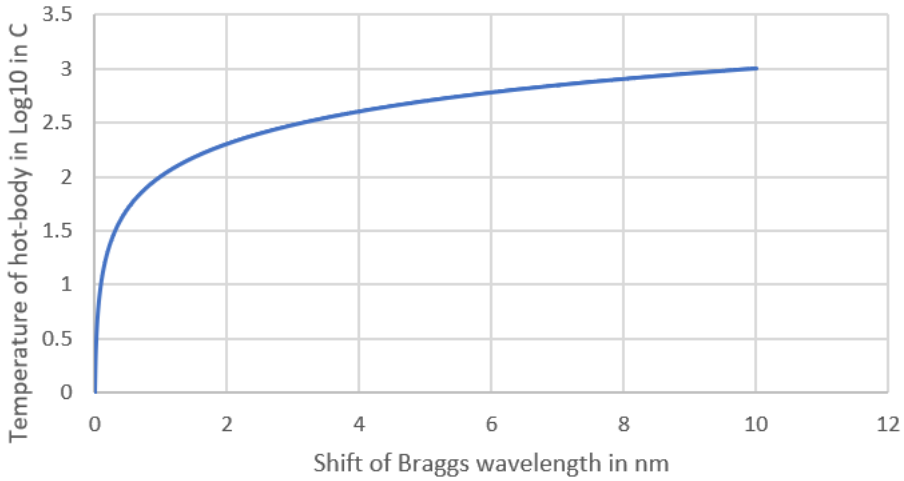

Figure 3: Output of FBG MATLAB Model, in terms of Logarithmic graph, for temperature of object 1 °C onwards.

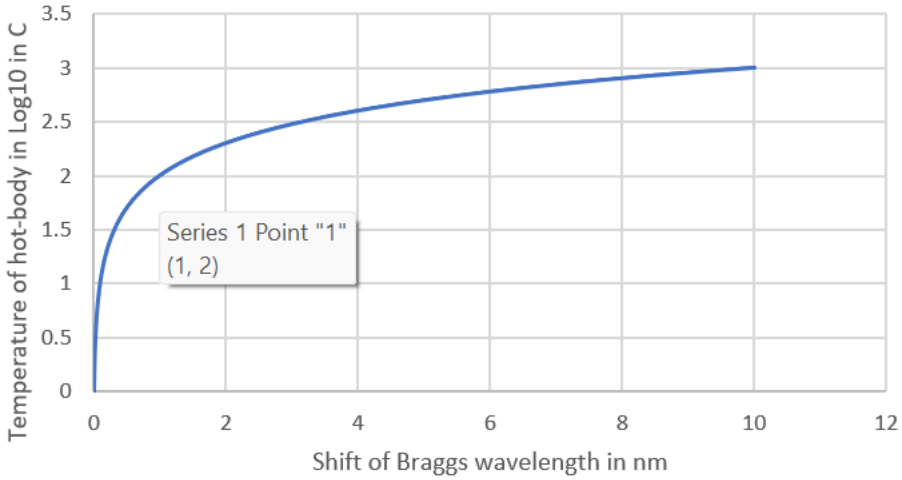

Figure 4: The point (1,2) depicts that the shift of Braggs wavelength is 1 nm when the temperature of the object is 100 °C as $Log_{10}[100] = 2$.

3. Results and Discussion:

We see that as the temperature of the object under measurement is varied from 0 °C to 1000 °C, we get the corresponding change in wavelength of light measured in nm when single-mode silica optical fibre is used.

We have observed from Figure 2 that the variation of shift in Bragg wavelength is very less due to Temperature sensitivity coefficient of Silica (when nano-metre or nm is used as equal parameter); hence we cannot interpret much from the graph. But if the y-axis (Figure 3) is taken as temperature of object under measurement in logarithmic terms and x-axis is taken as shift of Braggs wavelength in nm (ambient temperature being constant and taken as 30 °C), we can say that even the wide range and variation of temperature cannot go un-noticed in terms of shift

in Bragg wavelength. Figure 4 merely is the extension of Figure 3 with one of the points is elaborated as depicted.

Particularly a Silica based single mode fibre of Fibre Bragg Grating can measure the temperature from – 20 °C to 1000 °C, although it depends upon the coating as well. FBG systems are considered "more reliable" than traditional methods (such as thermocouples, RTDs, and thermistors) because they use light instead of electricity to measure temperature **[16]**.

4. Limitation:

Although FBG technique is having excellent temperature sensitivity on either side (cold and hot temperature measurement) and having applications in gas sector, hydro power plant monitoring, power transmission and distribution etc. Its products are not easy to install at every location. Also, these instruments are not easily available at market or online, because of no bulk production, broadly it is made on demand or customised according to the need. Hence, it is costly as well. Because $\Delta\lambda_B$ registers both influences simultaneously, any unmeasured ambient temperature fluctuation introduces a direct error when trying to calculate pure mechanical strain and vice versa **[17]**.

5. Conclusion and Future Scope:

Both theoretical studies and simulations by the use of MATLAB software prove the ability of Fiber Bragg Grating (FBG) based sensors to detect temperature changes due to Bragg wavelength changes caused by temperature change. The study proves that the silica-based optical fiber in its single-mode form is a suitable material for the sensing of temperatures. Future research might include experimental testing of the sensor and comparative study of the use of single mode and multimode optical fiber of different types of materials as well as varying of the grating width and spectral properties.

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