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Characterization of Bragg spectrum shifts in cascaded FBG arrays for thermal sensing

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This paper investigates the temperature-sensing performance of a series-configured Fiber Bragg Grating (FBG) sensing network integrated within an optical communication system. Two homogeneous FBG sensors were modelled using OptiSystem 22.0 and monitored using a Wavelength Division Multiplexing (WDM) interrogator. Linear regression analysis yielded a temperature sensitivity of 1.67 pm/°C (R^2=0.999), demonstrating an excellent linear relationship between temperature and Bragg wavelength shift. The results demonstrate a positive relationship between temperature and wavelength shift, indicating the capability of cascaded FBG sensors for multipoint thermal monitoring applications. The findings highlight the potential of series-connected FBG arrays for integration into future optical sensing and communication networks.

Keywords: fiber Bragg grating, temperature sensing, cascaded FBG, multipoint thermal monitoring

1 Introduction

Environmental monitoring is essential across multiple sectors, including industrial uses, climate research, and infrastructure maintenance [1, 2]. With escalating worries over climate change, pollution, and sustainability [3], there is a growing demand for sophisticated sensing systems capable of delivering real-time, dependable, and precise data on environmental parameters.

Fiber Bragg Grating (FBG) sensors have emerged as a viable alternative for environmental monitoring owing to their exceptional sensitivity, compact design, and immunity to electromagnetic interference [4, 5]. A Fiber Bragg Grating (FBG) is an optical sensor that uses light reflection and diffraction principles to quantify physical characteristics, including temperature, strain, and pressure [6]. Embedding FBGs in structures or environmental monitoring systems enables constant and exact measurements, rendering them essential for applications such as structural health monitoring [7], climate research, and pollution management.

Despite the considerable benefits of FBG technology, its full potential for environmental sensing remains undiscovered, particularly in terms of optimizing sensor combinations for varied environmental conditions. While FBG sensors have been successfully used in a variety of environmental sensing applications, their performance can be affected by the configuration in which they are put. Sensor density, multiplexing methods, fiber coating materials, and array configurations all have an impact on data accuracy, dependability, and sensitivity. However, there is a lack of information about the best design for diverse environmental circumstances and the issues that arise when monitoring multiple environmental parameters at the same time.

Unlike conventional studies that primarily focus on the temperature sensitivity of individual FBG sensors, this work investigates the spectral dynamics of cascaded homogeneous FBG sensors arranged in a series optical network [8, 9]. The study emphasizes the wavelength-shift behavior of the reflected spectrum under multipoint sensing conditions and evaluates the feasibility of integrating temperature sensing functionality into a simplified optical communication architecture. This approach provides insight into the spectral response of series-connected FBG arrays and their suitability for scalable thermal monitoring applications.

2 FBG integration in optical network

2.1 Bragg wavelength

The relationship between Bragg shifting and Fiber Bragg Grating (FBG) sensing is fundamental to how FBG sensors work. FBG is a segment of the optical fiber that has been treated to create a periodic modulation of the refractive index along the length of the fiber. This periodic structure reflects a specific wavelength of light,

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called the Bragg wavelength, while allowing other wavelengths to pass through [10]. The Bragg wavelength, denoted as λ_B, is given by the formula:

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

where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the fiber core, and Λ is the grating period.

The two primary factors that cause Bragg wavelength shifting are temperature and strains. When the temperature changes, it affects the refractive index of the fiber and the length of the grating. An increase in temperature generally leads to an increase in the Bragg wavelength because the fiber expands, increasing the grating period [11]. The change in Bragg wavelength due to temperature is given by:

$$\Delta\lambda_B = \lambda_B(\alpha_T \Delta T + \beta_T \Delta T) \quad (2)$$

where $\Delta\lambda_B$ denotes the change in the Bragg wavelength, λ_B is the Bragg wavelength, α_T represents the thermal expansion coefficient of the fiber, β_T represents the thermo-optic coefficient of the fiber material, and ΔT is the applied temperature change.

Equation (1) governs the reflected wavelength of the FBG, whereas Eqn. (2) describes the theoretical wavelength shift induced by temperature changes through thermal expansion and thermo-optic effects.

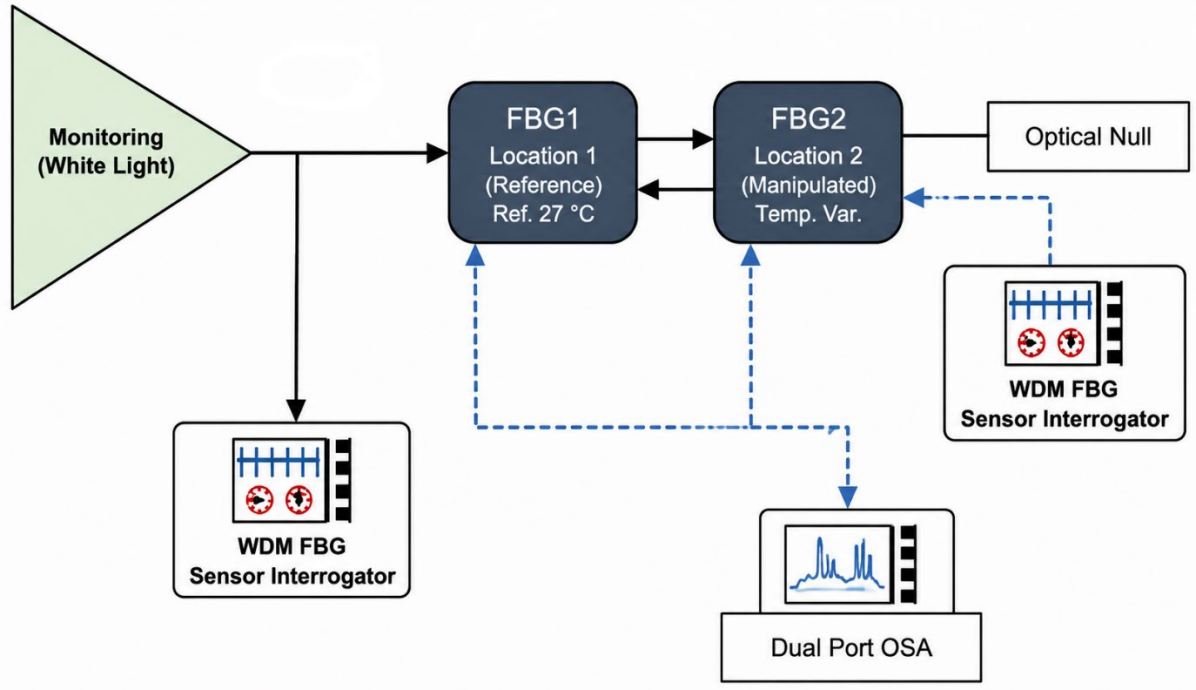


Fig. 1. The simulation layout for FBG sensing

2.2 Configurations and FBG parameters setting

The sensing network (Fig. 1) consists of white light injected into the network as a source, as well as two FBGs named FBG1 and FBG2. These FBGs are connected in series with the same nominal Bragg wavelength (1555.1 nm). FBG1 is configured as the reference FBG, which measures the room temperature at 27 °C, and FBG2 is the one that measures any temperature changes. The temperature value is transferred as a data file into the individual FBG1 and FBG2, as shown in Fig. 2.

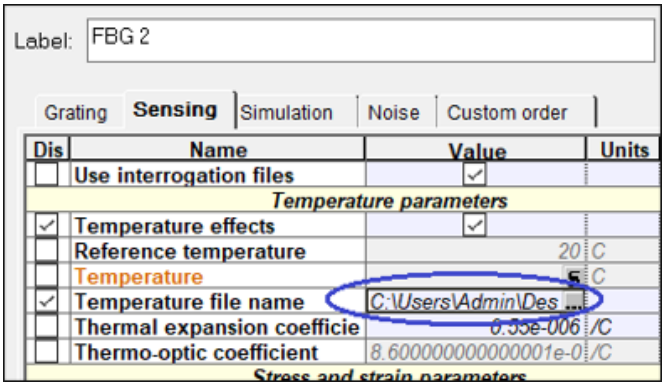


Fig. 2. Setting the FBG temperature simulation data

The dual port optical spectrum analyzer (OSA) monitors the wavelength shift and displays the results in Fig. 3. Figure 4 depicts the reflected spectrum from a WDM FBG sensor interrogator. The FBG simulation temperature values are entered into the Optisystem FBG parameter settings, as shown in Fig. 2.

2.3 Integration into optical network and simulation

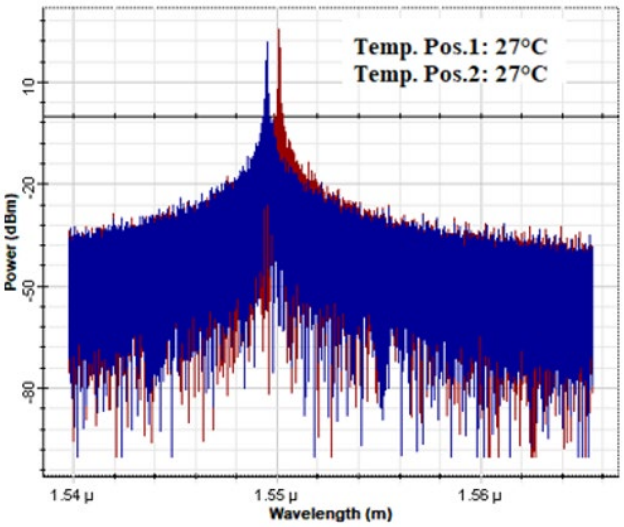
The monitoring signal was generated using a broadband white light source operating at a center wavelength of 1555.1 nm, corresponding to a center frequency of 192.748 THz. The optical source was selected to provide sufficient spectral coverage across the reflection bandwidth of the Fiber Bragg Grating (FBG) sensors, enabling accurate detection of Bragg wavelength variations. The launched optical power was set to −13 dBm, while the reflected optical power measured by the simulated Optical Spectrum Analyzer (OSA) varied between approximately −19.0 dBm and −19.3 dBm due to reflection, transmission, and component losses within the simulated optical sensing network.

A series configuration consisting of two homogeneous FBG sensors, denoted as FBG1 and FBG2, was implemented in the simulation environment. Both gratings were designed with a nominal Bragg wavelength of 1555.1 nm and positioned at different locations along the optical fiber with an equivalent separation distance of 10 km to emulate a practical remote sensing scenario. An optical delay component was incorporated into the simulation to represent the one-way propagation delay associated with this separation. Although the two FBGs share identical Bragg wavelengths, their reflected optical signals arrive at the interrogation system at different times due to the propagation delay, enabling the interrogation unit to distinguish the sensing location of each sensor while preserving identical sensing characteristics.

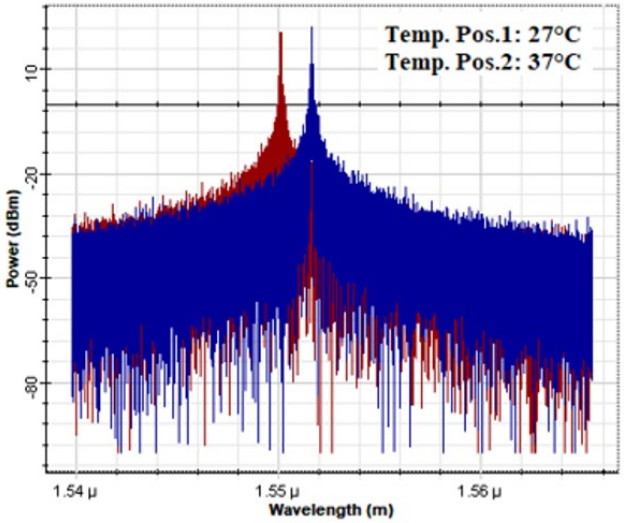
$$t = \frac{n\,L}{c} \tag{3}$$

where t denotes the one-way propagation delay of the optical signal, n is the effective refractive index of the optical fiber, L is the transmission fiber length, and c is the speed of light in a vacuum (3×10^8 m/s).

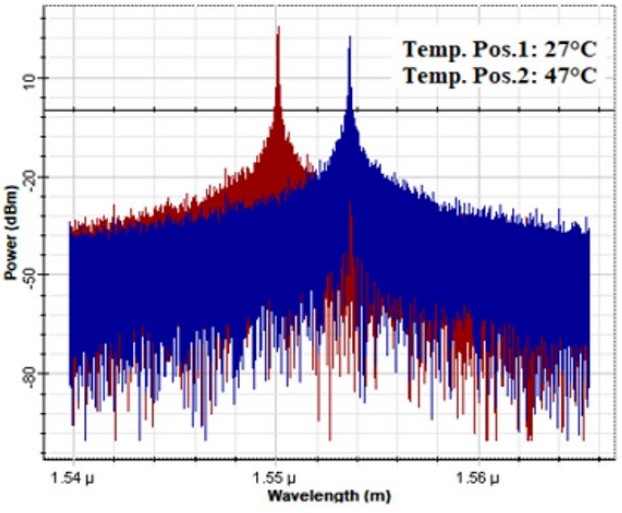
For a 10 km optical fiber with an effective refractive index of approximately 1.468, the one-way propagation delay is approximately 49 µs, calculated using Eqn. (3). This one-way delay was implemented in the optical delay component to represent the physical separation between FBG1 and FBG2. The delay models the transmission time of the optical signal from the source to the sensing location and provides a realistic representation of sensors deployed at different positions along the same optical fiber.



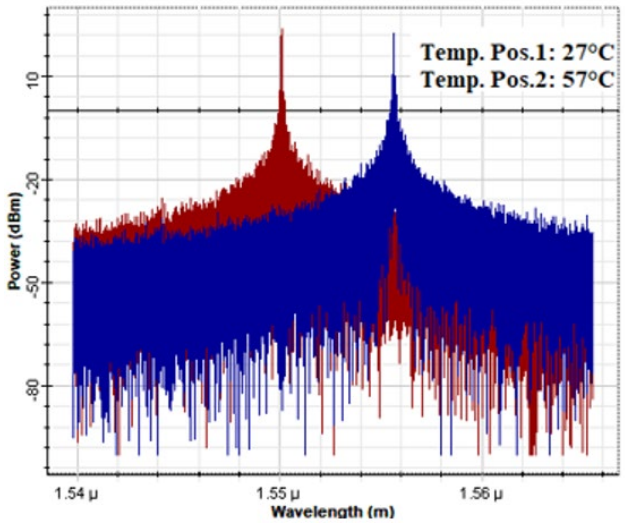
(a)



(b)



(c)



(d)

Fig. 3. Simulated OSA spectra at different temperatures: (a) 27 °C, (b) 37 °C, (c) 47 °C, and (d) 57 °C

Temperature variation was applied to FBG2, while FBG1 was maintained at a constant reference temperature. The temperature-induced response of the sensing grating was analyzed through its reflected spectrum using a Wavelength Division Multiplexing (WDM) sensor interrogator. As the temperature changes, thermal expansion of the fiber material and thermo-optic effects modify both the grating period and the effective refractive index of the fiber core, resulting in a shift of the reflected Bragg wavelength. The interrogation unit continuously monitored the reflected spectra from both gratings, allowing the wavelength displacement of FBG2 relative to the reference FBG1 to be quantified. The simulation architecture was developed to represent a multipoint sensing scenario in which multiple FBG sensors can be deployed along a single optical link. By examining the reflected spectral response under varying thermal conditions, the performance of the proposed series FBG sensing network can be evaluated in terms of wavelength stability, temperature sensitivity, and suitability for multipoint temperature monitoring applications.

The simulation parameters used in the development of the proposed FBG sensing network are summarized in Tab. 1.

Table 1. Simulation parameters

Parameter	Value
Simulation software	OptiSystem 22.0
Optical source	Broadband white light
Centre frequency	192.748 THz
Launch power	–13 dBm
Number of FBGs	2
FBG type	Homogeneous
Nominal Bragg wavelength	1555.1 nm
Reference temperature (FBG1)	27°C
Sensing temperature (FBG2)	27-127 °C
Temperature increment	10 °C
Fibre length	10 km
Optical delay	49 µs (one way)
Interrogator	WDM FBG Sensor Interrogator
Monitoring device	Dual-Port OSA

These parameters define the optical source, FBG sensor configuration, transmission link, and interrogation system employed in the OptiSystem simulation. Providing these settings enhances the reproducibility of the proposed model and enables future studies to replicate the simulation under identical operating conditions.

3 Results and discussion

The peak wavelength corresponding to the reference FBG, maintained at a constant temperature of 27 °C, is labelled as A, whereas the reflected peak wavelength of the second FBG sensor subjected to elevated temperatures is identified as B, as illustrated in Fig. 4(a)-(d). The difference between these two peak wavelengths, represented by (B−A), is calculated and recorded in Tab. 2 as the wavelength shift. This parameter serves as the primary indicator of the sensor's temperature response and provides insight into the thermal sensitivity of the cascaded FBG sensing arrangement

$$S_T = \frac{\Delta \lambda_B}{\Delta T} \tag{4}$$

where S_T is the temperature sensitivity of the Fiber Bragg Grating (FBG) sensor (pm/°C or nm/°C), $\Delta\lambda_B$ is the Bragg wavelength shift (pm or nm), and ΔT is the applied temperature change (°C). Equation (4) was used to determine the temperature sensitivity of the proposed FBG sensing configuration based on the simulated Bragg wavelength shift over the applied temperature range.

Table 2. Results of simulation

Temperature (°C)	Wavelength (nm)	Power (dBm)	Incremental wavelength shift per 10 °C (nm)	Cumulative shift from 27 °C (nm)
27	1555.10	–19.0	-	0
37	1555.12	–19.0	0.015	0.015
47	1555.13	–19.1	0.015	0.030
57	1555.15	–19.1	0.016	0.050
67	1555.16	–19.1	0.015	0.061
77	1555.18	–19.2	0.017	0.078
87	1555.20	–19.2	0.017	0.095
97	1555.21	–19.2	0.018	0.113
107	1555.23	–19.3	0.018	0.131
117	1555.25	–19.3	0.018	0.149
127	1555.27	–19.3	0.018	0.168

The simulation results reveal a progressive increase in wavelength shift as the temperature applied to FBG2 rises. This behavior demonstrates that the reflected wavelength of the FBG sensor is highly dependent on thermal variations within the sensing region.

The observed trend can be explained by the fundamental operating principle of Fiber Bragg Gratings. An increase in temperature causes thermal expansion of the fiber material and simultaneously modifies the effective refractive index of the fiber core through the thermo-optic effect. Both mechanisms contribute to a change in the Bragg condition, resulting in a dis-placement of the reflected wavelength toward longer wavelengths. As temperature continues to increase, the cumulative influence of these effects becomes more significant, producing larger wavelength shifts that can be detected and quantified by the interrogation system. Linear regression analysis of the wavelength-temperature relationship yielded a temperature sensitivity of 1.67 pm/°C with coefficient of determination R^2=0.999, indicating excellent linearity throughout the investigated temperature range. This sensitivity indicates the capability of the cascaded FBG network to detect temperature-induced spectral variations within the investigated operating range. The calculated sensitivity provides a quantitative measure of the sensor response and enables comparison with other FBG-based temperature sensing systems reported in the literature. The observed temperature-dependent wavelength response demonstrates the suitability of the proposed architecture for multipoint thermal monitoring applications. The monotonic increase in wavelength shift indicates stable sensing behavior and supports reliable temperature estimation using wavelength-based inter-rogation techniques. Furthermore, the cascaded FBG architecture employed in this study demonstrates the capability of distinguishing temperature-induced spectral variations at multiple sensing points within a single optical fiber link. Such a configuration offers advantages in multipoint sensing applications by reducing system complexity while maintaining the ability to monitor environmental conditions across different locations. The capability to track wavelength changes from multiple gratings simultaneously makes the system suitable for integration into modern optical communication and monitoring infrastructures. The simulation results demonstrate that temperature variations produce simulated wavelength shifts within the cascaded FBG sensing network, indicating the suitability of the proposed architecture for multipoint temperature monitoring applications.

The simulated wavelength shifts correspond to a temperature sensitivity of 1.67 pm/°C, obtained from linear regression analysis (R^2=0.999), demonstrating an excellent linear response of the proposed sensing configuration. The reflected optical power remained relatively stable throughout the investigated temperature range, varying only from approximately −19.0 dBm to −19.3 dBm. This indicates that temperature variation primarily affects the reflected wavelength, while the reflected optical power exhibits only minor fluctuations.

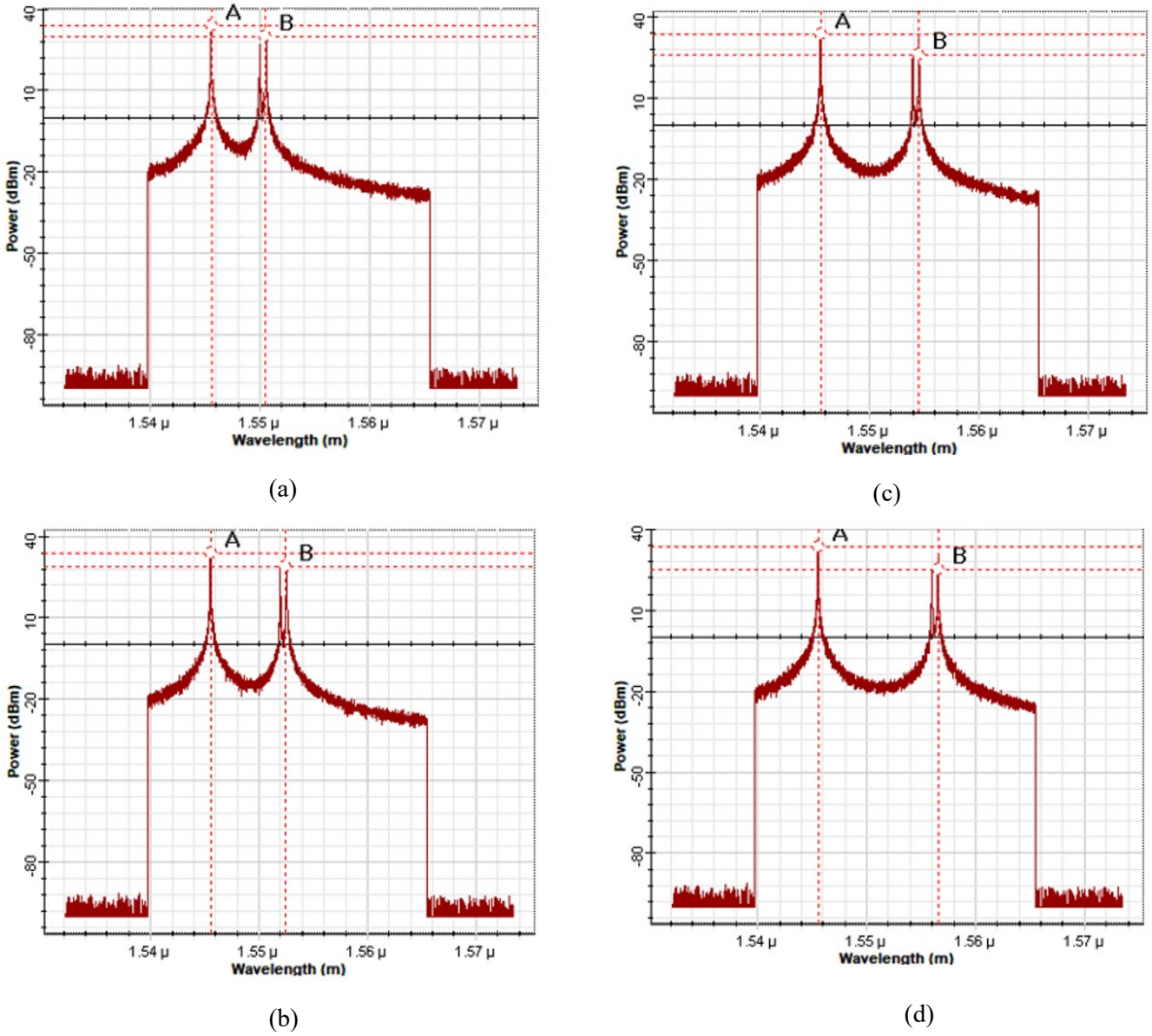


Fig. 4. Simulated reflected wavelength shifts at different temperatures: (a) 27 °C, (b) 37 °C, (c) 47 °C, and (d) 57 °C

The reflected spectrum at the reference condition is centred at approximately 1555.10 nm, corresponding to the nominal Bragg wavelength assigned to both FBG sensors in the simulation. Subsequent temperature variations applied to FBG2 produce observable wavelength shifts in the simulation relative to this reference wavelength.

4 Conclusions

This study demonstrated the feasibility of employing a series-configured Fiber Bragg Grating sensing network for temperature monitoring within optical communication environment. The proposed architecture achieved a temperature sensitivity of 1.67 pm/°C with coefficient of determination R^2=0.999, demonstrating excellent linearity throughout the investigated temperature range.

The reflected optical power exhibited only minor variations throughout the investigated temperature range, remaining between −19.0 dBm and −19.3 dBm. This indicates that temperature changes predominantly influence the Bragg wavelength rather than the reflected signal intensity. Consequently, wavelength shift remains the primary sensing parameter for temperature measurement in the proposed FBG sensing configuration.

The proposed multipoint FBG sensing architecture exhibits a stable wavelength response and provides a practical foundation for future experimental implementation and scalability studies. Future work will focus

on improving sensitivity, increasing sensing capacity, and extending the sensing functionality to additional physical parameters.

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