Tanzania Journal of Engineering and Technology 2025, **44**(**1**):18-32
OPEN ACCESS articles distributed under Creative Commons Attribution Licence [CC BY-ND]
Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v44i1.1062

Regular Research Manuscript

Design and Performance Analysis of Fiber Bragg Grating Temperature Sensor for Industrial Processes Sensing Applications

Paul Stone Brown Macheso

Department of Physics and Electronics, School of Natural and Applied Sciences, University of Malawi, P.O. Box 280, Zomba, Malawi

Corresponding author: pmacheso@unima.ac.mw, ORCID:0000-0001-5060-306X

ABSTRACT

The Fiber Bragg Grating (FBG) sensor has become a widespread sensing device because of its small size, passive design, immunity to electromagnetic interference, and direct ability to measure physical properties like temperature and strain. Recently, femtosecond infrared laser processing and regeneration techniques have resulted in the development of stable high-temperature gratings, which are a powerful tool in smart factories, an aspect of the fourth Industrial Revolution (4IR), and show promise for application in harsh environments like high pressure, high temperature, or ionizing radiation. The development of stable high-temperature gratings that can withstand harsh environmental factors like high temperatures, pressures, and ionizing radiation exposure is especially important in light of the Fourth Industrial Revolution (4IR), where smart factories require reliable, distributed, and real-time sensing systems. FBG sensors are essential instruments for developing Industrial process applications because of their capacity to function dependably under challenging conditions and their versatility for incorporation into industrial processes. The results of the FBG sensor show a high sensitivity of 0.01429 nm°C^{-1}, a Figure of Merit (FOM) of 1.632 x 10^{-12}°C^{-1}, and a Full Width Half Maxima (FWHM) of 8.7525 nm. The sensor's determined Quality factor (Q) was 177.8.

ARTICLE INFO

Submitted: Sep. 26, 2024

Revised: Jan. 7, 2025

Accepted: Feb. 16, 2025

Published: Apr. 2025

Keywords: *Fiber Bragg Grating, Temperature, Sensitivity, Full Width Half Maximum, Q-Factor, Finite Difference Time Domain.*

INTRODUCTION

At the Communication Research Centre in Canada, Ken Hill originally presented the Fiber Bragg Grating (FBG) in 1978 (Hill *et al*., 1978) . FBG structures have attracted a lot of interest in the field of optical sensing since their inception, mainly because of their unique benefits, which include affordability, small size, high precision, real-time responsiveness, high sensitivity, and immunity to electromagnetic interference (Hill & Meltz, 1997) (Tosi, 2018). FBGs are a dependable and adaptable option for a variety of sensing applications because of these qualities. The versatility of FBG sensors is demonstrated by their capacity to measure a wide range of physical and environmental factors, such as temperature, pressure, tension, and refractive index (Othonos, 1997). Fundamentally, FBGs depend on the refractive index within the optical fiber core being periodically modulated longitudinally (Yucel *et al*., 2016). This periodic arrangement allows certain light wavelengths to transmit while reflecting others, introducing special optical features (Kashyap, 2009). These features enable accurate and effective simultaneous measurement of numerous parameters, which supports the usefulness of FBGs in optical sensing applications (Othonos & Kalli, 1999).

Additionally, Fiber Bragg Grating (FBG) sensors have become an essential technology in the context of Industry 4.0 for measuring temperature, strain, and pressure, among other crucial factors (J. L. Santos, 2021). These sensors use the idea of light reflection in optical fibers, and the periodic change in the refractive index along the fiber core is what gives them their sensitivity (Roblek *et al.*, 2016). Their sensing mechanism is based on the selective reflection of light wavelengths caused by this periodicity (Udd & Spillman, 2015). As passive optical components, FBG sensors only permit the transmission and reflection of particular light wavelengths. Other wavelengths of the light pass through, while the reflected part is represented by the Bragg wavelength, which is based on the refractive index and the periodic structure of the grating (Cusano *et al.*, 2011). The Bragg wavelength shifts in response to changes in temperature or strain, for example, making it possible to quantify these factors precisely. The sensitivity and efficacy of these sensors are further increased by light scattering caused by the refractive index difference within the fiber (Hisham, 2019). Because of these special qualities, FBG sensors are essential for Industry 4.0 applications, especially in smart factories and systems that need high-precision, real-time monitoring in a variety of environmental conditions.

LITERATURE SURVEY

In (Dhingra *et al.*, 2021), a suggestion of a sensor based on Fiber Bragg Grating (FBG) for tracking the state of civil constructions in a range of temperatures was presented. The sensitivity of the suggested sensor is improved by including more gratings with optimal refractive indices. Performance is assessed by doing thorough investigations of the Bragg wavelength shifts in relation to applied load and temperature variations (Dhingra *et al.*, 2021). The Bragg wavelength shift and the applied parameters had a linear relationship, according to the simulation results. There is a 0.064 nm shift in the Bragg wavelength for strain increments of 50 units per simulation. Similarly, the wavelength change is 0.347 nm for a uniform temperature increase of 25 °C. The combined effect of increasing temperature (T = 25 °C) and strain (ε = 50) results in a cumulative and directly proportional Bragg wavelength shift of 0.403 nm (Dhingra *et al.*, 2021). These results confirmed that the suggested FBG sensor configuration had improved sensitivity and accuracy. The sensor's enhanced performance demonstrates its potential for a variety of uses, such as military operations, biomedical diagnostics, and civil infrastructure health monitoring (Dhingra et al., 2021). Its adaptability and usefulness in advanced sensing technologies were highlighted by its capacity to accurately identify and measure strain and temperature changes under a variety of circumstances but its drawback was not employed in Industrial 4.0 processes.

Optical waveguides are written directly onto the two sides of a three-core fiber from a single-mode fiber using a femtosecond laser micromachining technology were discussed in (M. Chen *et al.*, 2024). With an optical waveguide length of 1420μm and an angle of 1.15°, the intermediate fiber core was welded and aligned. This technique achieved a fiber Bragg grating (FBG) signal-to-noise ratio (SNR) of 20dB while implementing parallel writing technology for multi-core fibers (M. Chen *et al.*, 2024). The sensor's strain and temperature properties were examined. Experimental work revealed that the strain sensitivity is 1.69pm/με and the average temperature sensitivity is 11.3pm/°C (M. Chen *et al.*, 2024). The stability and temperature and strain response properties of the sensor were good. This technique established a basis for further research including curvature and torsion and offers a novel way to parallel writing in multi-core fibers but an implementation in Industrial 4.0 processes was lacking.

In (Khan *et al*., 2023) two different sensing probes, one U-shaped and the other capillary-shaped, were used in the design and development of an affordable Fiber Bragg Grating (FBG) temperature sensor package that used sophisticated demodulation techniques. An optical spectrum analyzer and two in-house intensity demodulation techniques were used to examine these probes. Within a range of 1 °C to 3 °C, all configurations showed little hysteresis and repeatability, demonstrating the accuracy and dependability of the sensor (Khan et al., 2023). Through the incorporation of a CFBG-FBG intensity demodulation scheme, performance testing employing twin-FBG intensity demodulation techniques demonstrated an expanded operational temperature range of up to 181.50 °C with a resolution of 0.120 °C (Khan *et al*., 2023). These findings supported the sensor package's increased sensitivity and resilience. The excellent sensitivity and resolution of the probe designs, along with their versatility, made them viable options for a range of temperature monitoring applications in the environmental, biomedical, domains while neglecting the smart industrial applications.

In (Liu *et al*., 2024) a presentation of a new all-fiber dual-parameter sensor that uses a reflecting Lyot filter (RLF) and Fiber Bragg Grating (FBG) structure to measure strain and temperature simultaneously. The FBG was fused in front of the RLF to function as the reflecting sensing head, and the sensor design included an in-line polarizer and a polarization-maintaining (PM) reflector to create the RLF (Liu et al., 2024). This setup allowed dual-parameter detection using a matrix-based method by taking use of the different wavelength responses of the RLF and FBG to changes in temperature and strain. The sensor's response was exceptionally linear, as evidenced by the regression coefficients for the linear fitting above 0.992 (Liu *et al*., 2024). Additionally, the suggested sensor provided a wide temperature and strain detection range in addition to a simple and affordable construction method (Liu *et al*., 2024). These features highlighted its potential for wide-ranging uses in domains that demand accurate and dependable dual-parameter sensing.

Additionally it has been determined that thorough and accurate temperature monitoring is essential to the safe operation of lithium-ion batteries. (J. Wang *et al*., 2024) described, a large-capacity temperature monitoring approach based on an ultra-weak fiber Bragg grating (UWFBG) array was developed to solve the problems of inadequate temperature monitoring and the lack of guidance on suitable monitoring locations in energy storage power stations (J. Wang et al., 2024). Monitoring the temperature over six surfaces and two electrodes of each cell in a battery pack made up of six cells connected in series allowed researchers to show how effective was the system. A significant disadvantage, though, was that this approach had not been incorporated into Industry 4.0 frameworks, which limited its ability to provide automated, large-scale, real-time monitoring in sophisticated industrial settings. Its application in dynamic, high-throughput situations, where increased efficiency and automation are crucial, was limited by its inability to integrate seamlessly with industrial IoT platforms, predictive maintenance systems, and smart energy management protocols.

Three temperature sensor networks made up of Fiber Bragg Gratings (FBGs) with various Bragg wavelengths were examined in a study by (Spolitis *et al*., 2017). They looked at the -20°C to 40°C temperature range. They used an Optical Spectrum Analyzer (OSA) as the interrogator and an amplified stimulated emission Broadband Source (BBS) as the light source in their studies. Finding the smallest spacing intervals necessary for the FBG sensors to operate precisely within the designated temperature range was the main goal of the study. To assess the capabilities and constraints of the FBG sensor networks, they carried out tests in a range of network conditions (Spolitis *et al.*, 2017). Notwithstanding the insightful information acquired, their strategy failed to incorporate Industry 4.0 technologies, which are essential for enabling effective and intelligent monitoring systems in contemporary industrial settings. These technologies include real-time data analytics, automated decision-making systems, and IoT-enabled sensor networks.

FBG Temperature Sensors' Significance for Industrial 4.0. Integration

A key element of Industry 4.0's successful transition to intelligent production is an intelligent, integrated network. The gathering and real-time analysis of data by sophisticated sensors in such a network facilitates efficient decision-making (L. M. A. L. Dos Santos *et al.*, 2021). Key operations like condition monitoring, predictive maintenance, and system optimization are made possible by these sensors, which provide a smooth information flow that may be leveraged to increase production efficiency (J. L. Santos, 2021) (S. Wang *et al.*, 2016). In order to make the overall manufacturing process more flexible and effective, self-optimization skills are also crucial for allowing production lines to automatically adapt to variations in demand, process variations, or system failures *(Hassoun et al.*, 2023).

High levels of factory automation made possible by the use of sensor-based technologies optimize assembly lines, lower human error, and enable large-scale product solution customization (Miller & Mendez, 2014). This in turn promotes increased production flexibility, which is essential for satisfying future expectations for mass-customized or individualized goods. With technologies like real-time location tracking, predictive maintenance, and intelligent resource allocation anticipated to become standard in industrial operations soon, Industry 4.0 also offers better asset management (J. L. Santos, 2021).

Though the Industry 4.0 vision offers promising opportunities, several sensor technologies such as Fiber Bragg Grating (FBG) sensors have not yet been completely optimized for smooth integration into the network of intelligent production system (Nayak *et al.*, 2024). This optimization gap poses a number of difficulties. For example, although being highly respected for their capacity to monitor physical parameters like temperature, strain, and pressure, FBG sensors must overcome a number of operational and technical challenges in order to be integrated into more complicated industrial systems (Yucel *et al.*, 2016). To overcome these obstacles, sensor designs must be standardized, data-processing algorithms must be optimized for quicker, more precise real-time feedback, and more affordable manufacturing methods must be developed to enable widespread industrial deployment of these sensors (J. L. Santos, 2021) . Furthermore, because it is difficult to integrate FBG sensors into current industrial control and monitoring systems, their use in high-demand contexts, including harsh environments or high-volume manufacturing lines, is still restricted despite its benefits. This restriction prevents these sensors from being widely used in Industry 4.0 environments, where system-wide integration and real-time data processing are essential (Munín-Doce *et al.*, 2020). Additional developments in sensor technology, system integration, and cost reduction are required to fully exploit the potential of FBG sensors in the Fourth Industrial Revolution. The full potential of

FBG sensors in intelligent manufacturing and production systems won't be realized until these issues are resolved (Ustundag et al., 2018).

Numerous advantages arise from the use of FBG sensing technology into Industry 4.0 applications. One of the main benefits is its high sensitivity and precision, which allow for accurate real-time temperature readings, which are essential for industrial process monitoring and optimization (Ustundag *et al*., 2018). FBG sensors also provide remote sensing capabilities, which are especially useful for keeping an eye on dangerous or difficult-to-reach areas. This lowers the need for manual intervention and improves worker safety (Hassoun et al., 2023). Continuous monitoring in challenging industrial conditions is made possible by the long-term stability of FBG sensors, which guarantees dependable operation over lengthy periods of time.

Additionally, FBG sensors have a high degree of resistance to electromagnetic interference, which is important in industrial settings where electrical noise can impair conventional sensors' performance (Udd, 2018). Because of their ability to withstand interference, FBG sensors can function well in settings where other kinds of sensors might not, guaranteeing that reliable data is continuously gathered (Udd, 1992). FBG sensors are a crucial technology in the continuous development of Industry 4.0 because of these benefits. The complete integration and optimization of FBG sensors into extensive industrial systems has not yet been accomplished, despite their potential (Santos, 2021). For FBG temperature sensors to be widely adopted and used in the industry 4.0 framework, issues such sensor calibration, data integration with IoT platforms, and cost-effectiveness in high-volume production scenarios must be resolved (French *et al*., 2017).

Additionally, the capacity of FBG sensors to multiplex along a single optical fiber allows for the simultaneous monitoring of several parameters, including pressure, strain, and temperature. Industry 4.0's complex data-collecting requirements are well-suited to these multiplexing capabilities (Lazaro, 2024). Moreover, real-time data streaming and analysis are made possible by the integration of FBG sensors into the 4IR ecosystem (L. M. A. L. Dos Santos *et al*., 2021). These sensors produce data that may be processed using big data analytics to forecast maintenance requirements, optimize workflows, and yield insightful information. Furthermore, real-time data streaming and analysis are made easier by the incorporation of FBG sensors into the industry 4.0 ecosystem (B. Chen *et al*., 2017). In contemporary industrial applications, where real-time feedback and ongoing monitoring are necessary for efficient process control, this skill is essential. To guarantee that stakeholders have access to the most recent information, data produced by the FBG sensors can be instantly sent to cloud-based platforms or centralized control systems (Kalsoom *et al*., 2020). The gathered data can be processed and examined using machine learning algorithms and advanced data analytics to forecast maintenance requirements, streamline production processes, and offer insightful information for increasing productivity and decreasing downtime (Wang *et al*., 2016).

Preemptive maintenance measures could be initiated before any serious problems occur, for instance, by using real-time temperature and strain data to predict equipment wear or failure. Furthermore, integrating FBG sensor data with supply chain or asset management systems, among other industrial systems, may lead to improved decision-making and more precise forecasts throughout the production process. FBG sensors are a vital component in the shift to smarter, more effective industrial systems since they have the fundamental capacity to forecast, optimize, and improve operations based on real-time data.

Theory of Fiber Bragg Grating Temperature Sensor

FBG is made up of a single-mode optical fiber's core's periodic modification of its index of refraction (Kashyap, 2009). Uniform fiber Bragg gratings are typically thought of as the basic components of the majority of Bragg grating structures. In these gratings, the grating planes have a constant period and the phase fronts are perpendicular to the longitudinal axis of the fiber (Hisham, 2019). Additionally, light at the specified Bragg wavelength can be reflected since the phase fronts of the light waves are perpendicular to the fiber's longitudinal axis. The precise wavelength that is reflected is determined by the periodicity of the grating structure, and variations in temperature, strain, or other environmental conditions can result in shifts in the Bragg wavelength, making FBGs useful sensors for a variety of applications (Daud & Ali, 2018). According to Bragg's equation, the Bragg wavelength (λ_B) with the highest reflectivity is denoted as (Rajan, 2017).

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

Where (n_{eff}) is the effective refractive index of the fiber, (λ_B) is the Bragg wavelength, which corresponds to the wavelength of light reflected by the FBG, and (Λ) is the periodicity of the grating. The refractive index distribution along the fiber n(z) of a Bragg grating provides a comprehensive description of the FBG sensing device (Daud & Ali, 2018).

$$\boldsymbol{n(z) - n_0 = \Delta n_{dc}(z) + \Delta n_{ac}(z).\cos\left(\frac{2\pi}{\Lambda}\, z + \theta(z)\right)} \tag{2}$$

Where (z) is the position (n_0) is the refractive index before the grating inscription (Δn_{ac} (z)) is the refractive index modulation amplitude (Λ) is the grating period (θ(z)) is the period chirp slowly varying with (z) and (Δn_{dc}(z)) is the average change in refractive index.

A popular method for modelling the optical properties of fiber bragg gratings is Erdogan's Coupled Mode Theory (Kashyap, 2009). It is, which was first developed for uniform gratings, has been widely used to accurately simulate the optical characteristics of different fiber gratings. It offers a thorough examination of how light waves interact with the grating structure as they pass through the fiber, enabling accurate predictions of the reflection spectra, the impact of outside variables like temperature or strain on the Bragg wavelength, and other pertinent optical characteristics of the FBG (Hisham, 2019). This theory is now a basic tool for designing and analysing FBGs, especially for use in communication and sensing systems. The expression for the reflectance of a uniform grating that is obtained from coupled mode theory is expressed as (Daud & Ali, 2018):

$$R == \frac{k^2 \sinh^2 \gamma L}{\gamma^2 \cosh^2 \gamma L + \frac{\Gamma^2}{4} \sinh^2 \gamma L} \tag{3}$$

where $\gamma^2 = k^2 + \frac{\Gamma^2}{4}$ with k representing the coupling coefficient denoted as:

$$k = 2\frac{\Delta n}{2n_{eff}}\frac{1}{\Lambda} = \frac{2\Delta n}{\lambda_B} \tag{4}$$

While Γ is the phase mismatch denoted using the periodic modulation wave vector K.

$$\Gamma = 2\beta - K \tag{5}$$

For $\Gamma = 0$ (phase matching), the maximum reflectivity can be expressed as

$$\boldsymbol{R_{max} = \tanh^2 kL} \tag{6}$$

The applied strain on the FBG and the surrounding ambient temperature has a significant impact on the Bragg wavelength of the FBG sensor (Daud & Ali, 2018). The Bragg wavelength shift caused by temperature and applied strain on the FBG's (n_{eff}) and grating pitch (Λ) is found in (7).

$$\boldsymbol{\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial \Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial \Lambda}{\partial T}\right)\Delta T} \tag{7}$$

where (T) is the temperature (*l*) being the grating length ($\Delta\lambda_B$) is the change in Bragg wavelength. The first and second terms represent the change in strain and temperature of the FBG respectively. Since they are temperature-sensitive, FBGs are widely used, especially in challenging conditions in this case the industrial processes settings of smart factories (J. L. Santos, 2021). The effective refractive index of the guided mode and the grating period both change and these two factors together account for the majority of the thermally driven variations in Bragg wavelength. When under constant strain, Equation 8 can be used to express this fractional wavelength shift for a temperature change (ΔT) (Daud & Ali, 2018).

$$\Delta\lambda_B = \lambda_B\,(\xi + \alpha)\,\Delta T \tag{8}$$

Where $\alpha = \left(1/\Lambda\right)\left(\frac{\partial\Lambda}{\partial T}\right)$ is the thermal expansion coefficient of the fiber and $\xi = (1/n_{eff})\ (\partial n_{eff}/\partial T)$ is the thermo-optic coefficient. The germanium doped silica core's thermo-optic co-efficient (ξ) is quantified at **8.6 x10^{-6} °C^{-1}** using Eq. 8, whereas the thermo-expansion co-efficient (α) is **0.55 x 10^{-6} °C^{-1}** (Hisham, 2019).

Simulation of FBG Temperature Sensor for Industrial Process Sensing Applications

FDTD Numerical Approach

In computational photonics, the Finite Difference Time Domain (FDTD) approach is a popular and effective numerical methodology for solving Maxwell's differential equations in the time domain (Franek *et al*., 2006). It makes it possible to precisely calculate transmission spectra and magnetic field distributions at every location in space by modeling the propagation of electromagnetic fields. This method is very useful for examining the behavior of electromagnetic waves in a variety of media, such as photonic integrated devices (Yee & Chen, 1997). FDTD, one of the most sophisticated numerical analysis techniques known, allows for thorough modeling of field distributions by directly resolving Maxwell's equations in their differential form (Lesina et al., 2015). The two-dimensional Maxwell equations offer a particular framework for studying field dynamics for transverse electric (TE) modes. The FDTD method's accuracy and adaptability make it essential for developing and refining photonic systems in fields like integrated optics, sensing, and telecommunications (Maksymov *et al*., 2011). The derived Maxwell's equations are understood to be in terms of finite differences. It is thought that the medium's equations ignore dispersion, absorption, and light generation where (E) is the Electric and (H) is the magnetic field respectively

$$\nabla \times E = -\mu\,\frac{\partial H}{\partial t} \tag{9}$$

$$\nabla \times H = \varepsilon\,\frac{\partial E}{\partial t} \tag{10}$$

The equations are expressed independently by their vector components once the curl operators have been evaluated. The Eq 11-13. is the form of the two-dimensional Maxwell equations for the transverse electric (TE) mode:

$$\frac{\partial E_z}{\partial y} = -\mu\,\frac{\partial H_x}{\partial t} - \sigma_m H_x \tag{11}$$

$$\frac{\partial E_z}{\partial y} = \mu\,\frac{\partial H_y}{\partial t} - \sigma_m H_y \tag{12}$$

$$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = \varepsilon\,\frac{\partial E_z}{\partial t} - \sigma E_z \tag{13}$$

In which (μ) is the permeability, (ε) is the permittivity, and (σ) is the conductivity.

Proposed FBG Temperature Sensor Parameters

The Fiber Bragg Grating (FBG) temperature sensor was thoroughly investigated numerically utilizing sophisticated mathematical modelling approaches, such as 3D Finite Difference Time Domain (FDTD) simulations and MODE profile analysis (Yee & Chen, 1997). These techniques provide extremely precise quantitative insights, enabling a more thorough comprehension of the transmission and reflection properties of the sensor under various circumstances. An auto-non-uniform mesh resolution of 1.5–1.6 µm was used in the simulation process to provide exact computational accuracy for the wavelength spectrum under analysis. A Perfectly Matched Layer (PML) boundary condition was used to increase the simulations' dependability. In order to preserve the accuracy of the optical analysis, this efficiently absorbed outgoing waves and stopped back reflections into the active region. By using these methods, the study showed how computational approaches may be used to optimize FBG sensor designs and open the door for their wider use in applications that demand accurate temperature monitoring (Railton & Schneider, 1999). The importance of simulation-driven approaches in furthering the creation of reliable, high-performing optical sensors suited for Industry 4.0 and beyond is highlighted by this study.

Table 1: FBG Sensor Design and Simulation Parameters

Design Simulation Parameter	FBG Temperature Sensor Values
Core Refractive Index (RIU)	1.451
Radius of Core	4.15 µm
Cladding Refractive Index (RIU)	1.441
Cladding Length	120 µm
Outer Radius of Cladding	62.5 µm
Inner Radius of Cladding	4.15 µm
Grating Length	100 µm
Inner Radius of Grating	0
Grating Refractive Index (RIU)	1.445
Grating Period (Λ)	0.531 µm
Average Index	Uniform
Number of Gratings	185
Operating Wavelength	1.5 -1.6 µm
Simulation Platform Used	MODE Solver FDTD

RESULTS AND PERFORMANCE ANALYSIS DISCUSSIONS

The performance of the suggested Fiber Bragg Grating (FBG) temperature sensor is assessed and the optical sensing findings are shown in this part. Figure 1 shows the transmission spectrum of the proposed FBG sensor. With incremental increments of 5°C, the Finite Difference Time Domain (FDTD) simulation approach was used to examine the device's output transmission over a temperature range of 25°C to 40°C. The findings demonstrate the sensor's response to temperature changes and its capacity to provide accurate and dependable readings within the designated range.

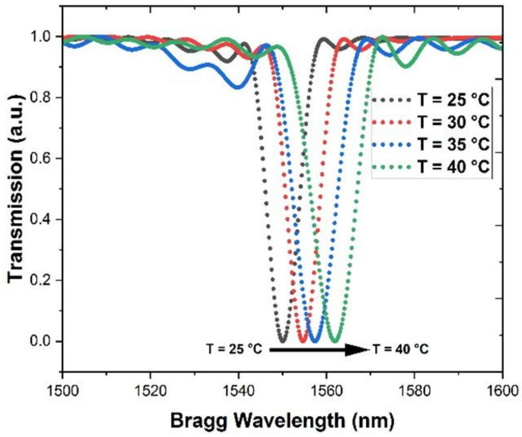

Figure 1: Transmission Spectrum Versus Bragg Wavelength.

Temperature affects the Bragg wavelength shift. Temperature changes are correlated with the normalized wavelength change. Furthermore, it can be mathematically demonstrated that temperature affects the Bragg wavelength shift using Eq. (9), and constant values for thermo-optic co-efficient (ξ) is quantified at **8.6 x10^{-6}°C^{-1}** using Eq. 10, whereas the thermo-expansion co-efficient (α) is **0.55 x 10^{-6}°C^{-1}**(Daud & Ali, 2018). The Bragg wavelength shift of Fiber Bragg Grating (FBG) sensors is directly impacted by temperature variations (Kashyap, 2009). The Bragg wavelength shift shows a significant correlation with the simulated results and increases with temperature. The fiber's thermal expansion and temperature-induced variations in refractive index are the causes of this phenomena. On the other hand, the Bragg wavelength shift decreases as the temperature drops (Udd, 2018) (Sahota *et al*., 2020). Because temperature and Bragg wavelength shift are directly correlated, FBG sensors are very useful for accurate thermal monitoring. FBG sensors can be easily included into smart factory applications, which are a crucial part of Industry 4.0 and allow for real-time temperature monitoring and maximized operational efficiency in automated and networked industrial settings, by utilizing these features (Cusano *et al*., 2011).

The Bragg wavelength shift ($\Delta\lambda_B$) and the Bragg wavelength (λ_B) against the temperature graph for the theoretical calculation are displayed in Figure 2. The graph indicates that the response of the Bragg wavelength to temperature variations was nearly linear. This indicates a proportionality between the Bragg wavelength shift and the temperature variation. A comparison figure was created using the data from the theoretical results.

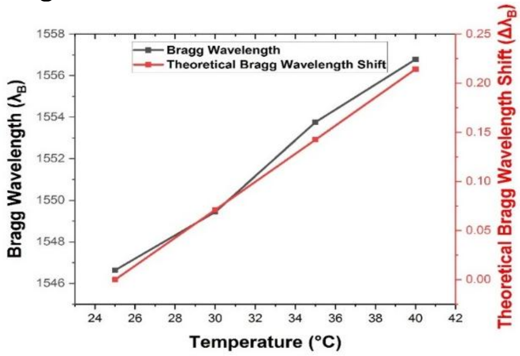

Figure 2: Bragg Wavelength and Theoretical Bragg Wavelength Shift against Temperature.

An FBG's Full Width at Half Maximum (FWHM) can be measured to find its bandwidth in the simplest way possible. There are two main elements that affect the FWHM: the depth of index modulation and the number of grating planes (Hisham, 2019). The transmission spectrum in this investigation was linearly fitted to determine the FWHM. The results of the simulation showed that the FWHM values continuously fell between 7.5-10 nm, suggesting that the FWHM is almost constant and unaffected by stresses or temperature changes. The FBG design is a good fit for high-precision applications where steady bandwidth performance is essential because of this stability, which highlights its dependability and resilience of temperature and refractive index.

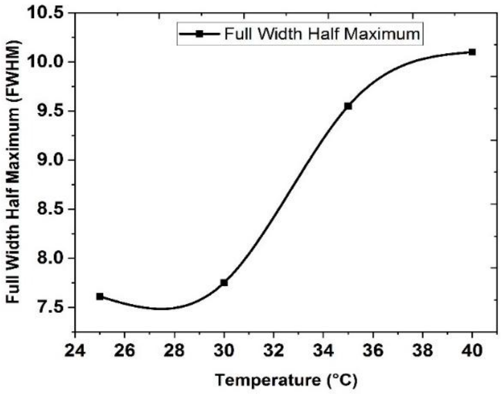

Figure 3: Full Width Half Maximum (Bandwidth) Against Temperature.

When TE modes are present, the electric field is perpendicular to the direction of propagation, or the z-direction, and the magnetic field shows a negligible z-component. With this arrangement, the magnetic field has a little z-component and is primarily perpendicular to the z-direction. The range of the TE modes of light propagation across the FBG temperature sensor is 1.35 to 0.438, as shown in Figure 4. As seen by the red colouring in the picture, this behaviour is related to the phenomena of total internal reflection, in which the electric field inside the core is stronger than in the cladding. One essential characteristic of FBGs that enables accurate light confinement within the core is the presence of entire internal reflection.

A Summary of how temperature, in 5°C increments between 25°C-40°C, influences the FBG's transmission parameters is shown in Table 2. The suggested FBG temperature sensor may detect temperature changes in industrial process sensing environments, as evidenced by a shift in the resonant wavelength. The observed wavelength shift, which theoretically rises from 0 to 4.16, amply illustrates the FBG temperature sensor's dependable performance in a range of scenarios. This behavior indicates that the sensor is extremely useful for industrial process sensing applications since it can efficiently monitor temperature variations in dynamic industrial settings. As demonstrated by the minimal change in bandwidth, the results suggest that the sensor retains exceptional stability and is mainly immune to variations in the FBG's temperature and refractive index. For real-time monitoring and control in industrial settings, this consistency guarantees that the sensor can deliver accurate data free from external influences. The FBG temperature sensor is a perfect fit for integration into sophisticated industrial process sensing applications where smooth automation, data gathering, and predictive maintenance are essential due to its resilience and capacity to function in a variety of challenging environments.

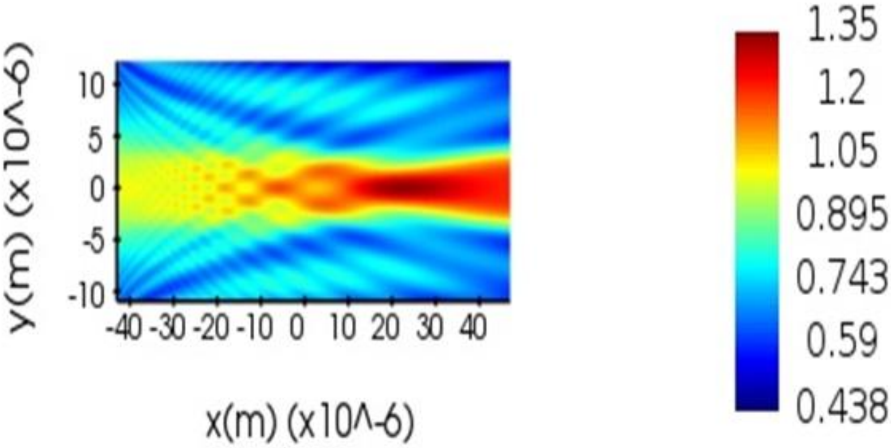

Figure 4: TE Mode in the Fiber Bragg Grating Temperature Sensor.

Table 2 Summary of FBG Temperature Sensor Measurements

Temperature (°C)	Change in Temperature (Δ°C)	Bragg Wavelength (nm)	Theoretical Bragg Wavelength Shift ($\Delta\lambda_B$)	Bandwidth (Full Wave at Half Maximum) (nm)
25	0	1549.74	0	7.61
30	5	1554.46	4.72	7.75
35	10	1557.49	3.03	9.55
40	15	1561.65	4.16	10.1

The Bragg wavelength shift is visible as the temperature increases, as Fig. 2 illustrates. Utilizing the Bragg condition, the FBG temperature sensor may be made for industrial process applications, allowing it to respond to temperature changes by modifying the resonant bragg wavelength in 5°C increments. The ability of the FBG temperature sensor to identify notable changes in the ambient temperature under particular circumstances is what defines its sensitivity. Here, the sensor exhibits its responsiveness in industrial process conditions, demonstrating the system's high sensitivity to environmental physical changes. This feature makes it possible to monitor and control in real time, which is crucial for automation and process optimization in contemporary industrial operations. The wavelength shift per unit change in temperature, or sensitivity $S = \partial\lambda_B/\partial T$, is found using the following equation: where ($\partial\lambda_B$) denotes the wavelength change and (∂T) denotes the temperature change (Daud & Ali, 2018).

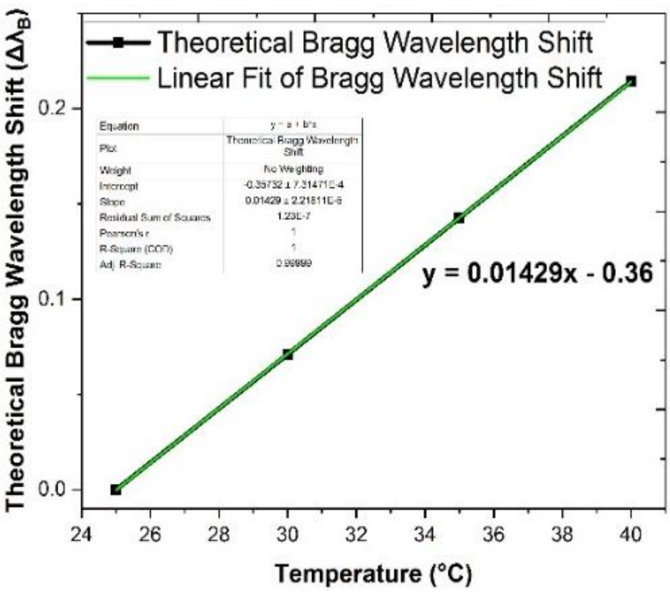

Figure 5. Theoretical Bragg Wavelength against Temperature.

The response of the FBG sensor to temperature changes was determined by examining temperature sensitivity. Theoretically, greater susceptibility to environmental changes is associated with a lower sensitivity. For the FBG temperature sensing system in industrial process monitoring applications, Figure 6 shows the theoretical link between temperature and Bragg wavelength shift. The gradient of the graph indicates the smallest wavelength shift that may be detected, giving information on the sensitivity of the sensor. In industrial settings, precise monitoring and control depend on the sensor's ability to detect even minute temperature changes, which is shown by a steeper gradient. It will be easier to comprehend the FBG sensor's potential for accurate temperature measurement and its suitability for use in real-time industrial monitoring systems if this sensitivity is assessed. The graph of Figure 5 was used to calculate the sensitivity of FBG, which was found to be S = 0.01429 nm°C^{-1} and intercepted at 0.36 nm wavelength. This sensitivity is essentially in line with the results reported in (Daud & Ali, 2018) (Hirayama & Sano, 2000)(Zhang & Yang, 2016), making it a better candidate for Industrial sensing processes because it is ideal for sensing applications, particularly in industrial settings.

A performance parameter known as a sensor's figure of merit (FOM) is used to quantify the temperature efficacy and efficiency of the FBG. As in the case of the FBG temperature sensor, for example, it is generally computed by dividing the sensitivity by the Full Width at Half Maximum of the sensor's spectrum (Bachar et al., 2022), which in this case was FWHM = 8.7525 nm. The FBG temperature sensor's Figure of Merit (FOM), which is expressed as a ratio of sensitivity and FWHM, was calculated to be FOM= 1.632 x 10^{-12}°C^{-1}. The Q-factor, which is the ratio of the resonant peak wavelength, was calculated to be Q =177.8 because it was 1555.83nm respectively. This FBG temperature sensor is a perfect option for deployment in industrial processes because of its high Q-factor, which suggests that it be employed for sensing applications in smart factories. In industrial settings where accuracy and dependability are critical, the sensor's high Q-factor suggests that it can provide extremely sensitive measurements with little signal loss. Because of its sensitivity and strong performance, it is ideally suited for industrial processes where real-time data gathering and ongoing monitoring are essential for production optimization, equipment health maintenance, and overall efficiency enhancement.

Table 3 displays a comparison the temperature sensitivity of our proposed FBG sensor to that of other FBG temperature sensors with an emphasis of recent covered research.

Table 3: Comparison of Temperature obtained in this study with values obtained in other studies

Year	Reference	Sensitivity (nm°C^{-1})
2016	(Kumar *et. al.*, 2016)	0.0132
2019	(Du *et. al.*, 2019)	0.011
2021	(Hsu *et. al.*, 2021)	0.01071
2021	(R. A. G. dos Santos *et. al.*, 2021)	0.00875
2025	Proposed Contribution	0.01429

This work's future scope will be diverse and go beyond the FBG temperature sensor's existing conceptual framework. The FBG temperature sensor itself will be fabricated as the initial phase, guaranteeing the incorporation of high-precision parts that satisfy industrial application specifications. In addition to the fabrication, work will be done to determine the resolution and accuracy of the sensor to make sure it can accurately measure temperature changes in industrial settings, even under challenging circumstances. Concurrently, it will be essential to build interrogation methods. Open-source embedded system microcontrollers will be used in the design, allowing for customization and adaptability to a range of industrial use cases. In order to enable real-time data transmission and analysis, these microcontrollers will be specifically designed to process the optical signals produced by the FBG temperature sensors. The objective is to develop an effective and economical method for tracking and managing temperature, a crucial factor in several industrial operations. The FBG temperature sensors' scalability and adaptability would be greatly improved by this method. FBG sensors' energy efficiency and low maintenance needs are significant advantages, especially in large-scale operations, as they don't need power for the measuring process itself. This feature, together with their adaptability to a variety of temperatures and conditions, makes them ideal for monitoring industrial processes.

This work's ultimate goal is to revolutionize industrial process management. FBG sensors' high sensitivity, resilience, and energy efficiency may enable more precise data collecting and enhance system optimization in general. With the potential to significantly lower operating expenses and downtime, this sensor technology revolution could have long-term sustainability advantages. Furthermore, this project could democratize the usage of sophisticated industrial monitoring solutions by utilizing open-source technologies and embedded systems, making them more accessible to a range of companies looking to streamline their operations. One innovative way to help the continuous automation and digitization of industries is the incorporation of FBG sensors into industrial processes.

CONCLUSION

This study simulates and assesses an FBG temperature sensor design for use in sensing applications in Industrial 4.0 Applications more especially smart factories. The detectable shift in wavelength that is recorded demonstrates the sensor's sensitivity to even the smallest alterations in input temperature. The three most important parameters considered while assessing the performance of the proposed sensor design are normalized transmission spectrum, temperature sensitivity, and quality factor. The results show a high Figure of Merit (FOM)=1.76 x 10 $^{-3}$/°C and a Full Width Half Maxima (FWHM) of 8.7525 nm, indicating a high sensitivity of S=0.01429 nm°C^{-1} and Q =177.8 was the sensor's determined Quality factor. The results collected point to the potential benefits of using the FBG sensor in industrial operations, confirming its enhanced performance. Because of the sensor's high sensitivity, dependability, and accuracy, it is a perfect fit for integration into a variety of industrial settings where precise temperature and other parameter monitoring is crucial for productivity and efficiency.

REFERENCES

Bachar, L., Klein, R., Tur, M., & Bortman, J. (2022). Castro-Caicedo, A. J., Torres, P., Nieto-Callejas, M. J., Lain-Huerta, R., & Suarez-Burgoa, L. O. (2019). Manufacturing and reliability of a fiber Bragg grating strain sensor designed for uniaxial compression test of rocks. Dyna, **86**(208), 234-242. *Mechanical Systems and Signal Processing*. doi.:10.1016/j.ymssp.2021.108629

Chen, B., Wan, J., Shu, L., Li, P., Mukherjee, M., & Yin, B. (2017). Smart factory of industry 4.0: Key technologies, application case, and challenges. *IEEE Access*, **6**, 6505–6519. doi:10.1109/ACCESS.2017.2783682.

Chen, M., Zhou, Z., Li, H., Liu, S., & Zhao, Y. (2024). Research on temperature and strain sensing of novel femtosecond laser-based three-core optical fiber parallel Bragg grating. *IEEE Transactions on Instrumentation and Measurement*. doi: 10.1109/TIM.2024.3522679

Cusano, A., Cutolo, A., & Albert, J. (2011). *Fiber Bragg grating sensors: recent advancements, industrial applications and market exploitation*. Bentham Science Publishers. doi:10.2174/97816080508401110101

Daud, S., & Ali, J. (2018). *Fibre Bragg grating and no-core fibre sensors*. Springer. doi:10.1007/978-3-319-90463-4

Dhingra, I., Kaur, G., & Kaler, R. S. (2021). Design and analysis of fiber Bragg grating sensor to monitor strain and temperature for structural health monitoring. *Optical and Quantum Electronics*, **53**, 1–9. doi 10.1007/s11082-021-03270-7

Dos Santos, L. M. A. L., da Costa, M. B., Kothe, J. V., Benitez, G. B., Schaefer, J. L., Baierle, I. C., & Nara, E. O. B. (2021). Industry 4.0 collaborative networks for industrial performance. *Journal of Manufacturing Technology Management*. doi.:10.1108/JMTM-04-2020-0156

dos Santos, R. A. G., Leal-Junior, A. G., Ribeiro, M. R. N., Benincá, E. A., Marques, C. A. F., Pereira, L., Antunes, P., Corrêa, J. H. G. M., Pontes, M. J., & Neto, A. F. (2021). Datacenter thermal monitoring without blind spots: FBG-based quasi-distributed sensing. *IEEE Sensors Journal*, **21**(8), 9869–9876. doi: 10.1109/JSEN.2021.3058513

Du, Y., Han, Q., Hu, H., Sang, M., Zhao, X., Song, X., Wang, H., & Liu, T. (2019). High-sensitivity refractive index and temperature sensor based on cascading FBGs and droplet-like fiber interferometer. *Sensors and Actuators A: Physical*, **299**, 111631. doi: 10.1016/j.sna.2019.111631

Franek, O., Pedersen, G. F., & Andersen, J. B. (2006). Numerical modeling of a spherical array of monopoles using FDTD method. *IEEE Transactions on Antennas and Propagation*, **54**(7), 1952–1963.doi: 10.1109/TAP.2006.877202

French, R., Benakis, M., & Marin-Reyes, H. (2017). Intelligent sensing for robotic re-manufacturing in aerospace An industry 4.0 design based prototype. *2017 IEEE International Symposium on Robotics and Intelligent Sensors (IRIS)*, 272–277. doi:10.1109/IRIS.2017.8250134

Hassoun, A., Aït-Kaddour, A., Abu-Mahfouz, A. M., Rathod, N. B., Bader, F., Barba, F. J., Biancolillo, A., Cropotova, J., Galanakis, C. M., & Jambrak, A. R. (2023). The fourth industrial revolution in the food industry-Part I: Industry 4.0 technologies. *Critical Reviews in Food*

Science and Nutrition, **63**(23), 6547–6563.doi.:10.1080/10408398.2022.2034735

Hill, K. O., Fujii, Y., Johnson, D. C., & Kawasaki, B. S. (1978). Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication. *Applied Physics Letters*, **32**(10), 647–649. Doi.: doi:10.1063/1.89881

Hill, K. O., & Meltz, G. (1997). Fiber Bragg grating technology fundamentals and overview. *Journal of Lightwave Technology*, **15**(8), 1263–1276. doi: 10.1109/50.618320

Hirayama, N., & Sano, Y. (2000). Fiber Bragg grating temperature sensor for practical use. *ISA Transactions*, **39**(2), 169–173. doi:10.1016/S0019-0578(00)00012-4

Hisham, H. (2019). *Fiber bragg grating sensors: development and applications*. CRC Press. doi:10.1201/9780429275135.

Hsu, C.-Y., Chiang, C.-C., Hsieh, T.-S., Hsu, H.-C., Tsai, L., & Hou, C.-H. (2021). Study of fiber Bragg gratings with TiN-coated for cryogenic temperature measurement. *Optics & Laser Technology*, **136**, 106768. doi:10.1016/j.optlastec.2020.106768.

Kalsoom, T., Ramzan, N., Ahmed, S., & Ur-Rehman, M. (2020). Advances in sensor technologies in the era of smart factory and industry 4.0. *Sensors*, **20**(23), 6783. Doi.: 10.3390/s20236783

Kashyap, R. (2009). *Fiber bragg gratings*. Academic press. doi:doi.org/10.1016/C2009-0-16830-7

Khan, R. Y. M., Ullah, R., & Faisal, M. (2023). Design and development of cost-effective fiber Bragg grating temperature sensor package. *Measurement Science and Technology*, **34**(8), 85122. Doi.: 10.1088/1361-6501/acd01c

Kumar, J., Prakash, O., Agrawal, S. K., Mahakud, R., Mokhariwale, A., Dixit, S. K., & Nakhe, S. V. (2016). Distributed fiber Bragg grating sensor for multipoint temperature monitoring up to 500 C in high-electromagnetic interference environment. *Optical Engineering*, **55**(9), 90502. DOI: 10.1117/1.OE.55.9.090502

Lazaro, R. C. (2024). *FBG-Based Sensors for Oil and Gas Industry: Assessment of Heat Transfer, Structural Health, Liquid Level, Thermal Conductivity and Salinity.http://repositorio.ufes.br/handle/10/17934*

Lesina, A. C., Vaccari, A., Berini, P., & Ramunno, L. (2015). On the convergence and accuracy of the FDTD method for nanoplasmonics. *Optics Express*, **23**(8), 10481–10497. doi:10.1364/OE.23.010481

Liu, Z., Zhang, H., Liu, Y., Xue, L., & Chen, Z. (2024). All-fiber temperature and strain simultaneous measurement sensor based on reflective Lyot filter cascaded with fiber Bragg grating. *AOPC 2024: Optical Sensing, Imaging Technology, and Applications*, **13496**, 108–114. doi:10.1117/12.3046161

Maksymov, I. S., Sukhorukov, A. A., Lavrinenko, A. V, & Kivshar, Y. S. (2011). Comparative study of FDTD-adopted numerical algorithms for Kerr nonlinearities. *IEEE Antennas and Wireless Propagation Letters*, **10**, 143–146. doi:10.1109/LAWP.2011.2114319

Miller, J. W., & Mendez, A. (2014). Fiber Bragg grating sensors: Market overview and new perspectives. *Fiber Bragg Grating Sensors: Recent Advancements, Industrial Applications and Market Exploitation*, **8,** 313–320. doi: 10.2174/978160805084011101010313

Munín-Doce, A., Díaz-Casás, V., Trueba, P., Ferreno-González, S., & Vilar-Montesinos, M. (2020). Industrial Internet of Things in the production environment of a Shipyard 4.0. *International Journal of Advanced Manufacturing Technology*. doi.:10.1007/s00170-020-05229-6

Nayak, D. R., Sharma, P., Mohapatra, A. G., Nayak, N., Keswani, B., & Khanna, A. (2024). IoT-Driven Predictive Maintenance Approach in Industry 4.0: A Fiber Bragg Grating (FBG) Sensor Application. *Fog Computing for Intelligent Cloud IoT Systems*, 203–227. https://www.oreilly.com/library/view/fog-computing

Othonos, A. (1997). Fiber bragg gratings. *Review of Scientific Instruments*, **68**(12), 4309–4341. doi:10.1063/1.1148392

Othonos, A., & Kalli, K. (1999). *Fiber Bragg gratings: fundamentals and applications* *in telecommunications and sensing* (Vol. 3, Issue 2). Artech house Boston.

Railton, C. J., & Schneider, J. B. (1999). An analytical and numerical analysis of several locally conformal FDTD schemes. *IEEE Transactions on Microwave Theory and Techniques*, **47**(1), 56–66. Doi.:10.1109/22.740077

Rajan, G. (2017). *Optical fiber sensors: advanced techniques and applications*. CRC press. doi:doi.org/10.1201/b18074

Roblek, V., Meško, M., & Krapež, A. (2016). A Complex View of Industry 4.0. *SAGE Open*. doi:10.1177/2158244016653987

Sahota, J. K., Gupta, N., & Dhawan, D. (2020). Fiber Bragg grating sensors for monitoring of physical parameters: a comprehensive review. *Optical Engineering*. doi:10.1117/1.oe.59.6.060901

Santos, J. L. (2021). Optical Sensors for Industry 4.0. *IEEE Journal of Selected Topics in Quantum Electronics*. doi:10.1109/JSTQE.2021.3078126

Spolitis, S., Lyashuk, I., & Bobrovs, V. (2017). Design and performance evaluation of FBG-based temperature sensors network. *2017 Progress in Electromagnetics Research Symposium-Fall* (*PIERS-FALL*), 2673–2678. doi: 10.1109/PIERS-FALL.2017.8293590

Tosi, D. (2018). Review of chirped fiber bragg grating (CFBG) fiber-optic sensors and their applications. In *Sensors (Switzerland)*. doi:10.3390/s18072147

Udd, E. (1992). Optical fiber sensors. *Fiber and Integrated Optics*. doi:10.1080/01468039208204198

Udd, E. (2018). Overview of Fiber Optic Sensors. *Fiber Optic Sensors*. doi:10.1201/9781420053661-1

Udd, E., & Spillman, W. B. (2015). Field Guide to Fiber Optic Sensors. In *Field Guide to Fiber Optic Sensors*. doi:10.1117/3.1002803

Ustundag, A., Cevikcan, E., Bayram, B., & İnce, G. (2018). Advances in Robotics in the Era of Industry 4.0. *Industry 4.0: Managing The Digital Transformation*, 187–200. doi: 10.1007/978-3-319-57870-5_11

Wang, J., Yang, Z., Wang, S., Gao, L., & Song, J. (2024). Large-capacity temperature points monitoring of lithium-ion battery pack via ultra-weak fiber Bragg grating array. *Measurement*, 116580. doi:10.1016/j.measurement.2024.116580

Wang, S., Wan, J., Li, D., & Zhang, C. (2016). Implementing smart factory of industrie 4.0: an outlook. *International Journal of Distributed Sensor Networks*, **12**(1), 3159805. doi: 10.1155/2016/3159805

Yee, K. S., & Chen, J. S. (1997). The finite-difference time-domain (FDTD) and the finite-volume time-domain (FVTD) methods in solving Maxwell's equations. *IEEE Transactions on Antennas and Propagation*, **45**(3), 354–363. doi: 10.1109/8.558651

Yucel, M., Ozturk, N. F., & Gemci, C. (2016). Design of a Fiber Bragg Grating multiple temperature sensor. *2016 Sixth International Conference on Digital Information and Communication Technology and Its Applications (DICTAP)*, 6–11. doi: 10.1109/DICTAP.2016.7543992

Zhang, Y., & Yang, W. (2016). Simultaneous precision measurement of high temperature and large strain based on twisted FBG considering nonlinearity and uncertainty. *Sensors and Actuators A: Physical*, **239**, 185–195. doi: 10.1016/j.sna.2016.01.012