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Development of Fiber Bragg Grating as A High-Accuracy Temperature and Pressure Sensor

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Abstract: The advancement of optical fiber technology has opened new opportunities in the development of high-accuracy sensors. This study focuses on the development of a Fiber Bragg Grating (FBG)-based sensor capable of simultaneously detecting temperature and pressure changes with high precision. FBGs are optical sensors that reflect specific wavelengths of light, which shift in response to external stimuli such as thermal expansion and mechanical strain. In this research, an FBG sensor system was designed, calibrated, and tested under controlled laboratory conditions to evaluate its sensitivity, linearity, and repeatability in detecting variations in temperature and pressure. The results show that the FBG sensor exhibits a high degree of accuracy and stability, with temperature sensitivity reaching up to 32 pm/°C and pressure sensitivity up to 32 pm/MPa. The dual-parameter sensing was achieved by using a configuration that separates the wavelength shifts induced by temperature and pressure through a compensation algorithm. This makes the proposed FBG sensor suitable for applications in harsh environments such as aerospace, biomedical, and industrial monitoring systems. The study concludes that FBG technology offers a promising platform for developing compact, reliable, and high-resolution sensing devices.

Keywords: Dual-parameter sensing; Fiber Bragg grating; High accuracy; Optical fiber; Pressure sensor; Temperature sensor

Introduction

Accurate temperature monitoring is essential in various industrial applications, ranging from materials processing to structural health monitoring. Conventional temperature sensors often face limitations in terms of sensitivity, size, and resistance to extreme environments. Fiber Bragg Grating (FBG) emerges as an innovative solution that overcomes these limitations by offering precise temperature measurements, immunity to electromagnetic interference, and suitability for operation in harsh environmental conditions.

Fiber Bragg Grating (FBG) has emerged as one of the most important optical sensing technologies in recent decades. Since the initial demonstration by Hill et al. (1978)—which showed the possibility of forming gratings internally within an optical fiber—significant advancements occurred after Meltz et al. (1989) introduced the external UV phase mask writing technique. This method later became the foundation of commercial FBG production and enabled the widespread use of FBGs in telecommunications and structural health monitoring systems.

In practical applications, the response of an FBG is highly sensitive to variations in strain and temperature. Contrary to claims suggesting that temperature effects are small and negligible, the wavelength shift induced by temperature changes is actually one of the major challenges in FBG-based sensing. This is primarily due to the inherent cross-sensitivity between temperature

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and strain. As a result, research on temperature compensation, thermal isolation, and temperature modeling in FBGs has become one of the most dominant topics in modern optical sensor studies.

Nevertheless, many reports and introductory studies on FBGs still present temperature modeling in a partial manner, focusing only on the thermo-optic coefficient or solely on the thermal expansion of the fiber. In contrast, industrial applications often require more comprehensive and calibrated models that can quantitatively link theoretical formulations, material characteristics, and spectral responses (Murianti et al., 2018; Molardi et al., 2019).

An example of such a sensor application is temperature measurement inside aircraft jet engines, where optical fibers are used to transmit radiation to a radiation pyrometer located outside the engine (Widasari et al., 2013). Additionally, extrinsic sensors can be used similarly to measure the internal temperature of electric transformers, where extreme electromagnetic fields make other measurement techniques unfeasible (Azhar et al., 2022). These extrinsic sensors are also applied to measure vibration, rotation, displacement, velocity, acceleration, torque, and twisting (Putri & Harmadi, 2017). The output from Bragg grating modifications in optical fibers has attracted the attention of researchers for further development.

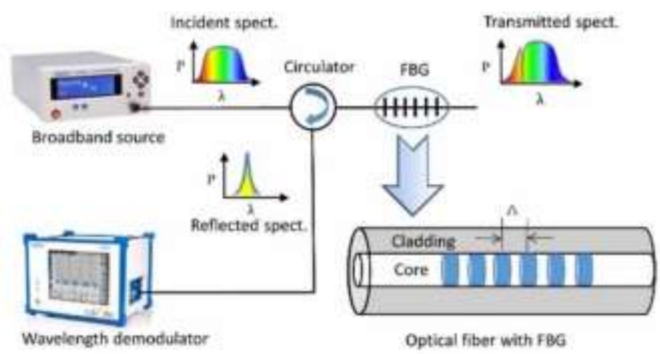

Figure 1. Grating structure, input and output spectra, and reflection at wavelengths

Previous studies, such as by Permatasari (2015), demonstrated that Fiber Bragg Grating (FBG) can be utilized to determine the wavelength within the C-Band range through simulation. Meanwhile, Khlaifi et al. (2021) highlighted the importance of boundary detection in using FBGs to differentiate between temperature, strain, and pressure. Another study by Pang et al. (2020) focused on temperature and refractive index measurements using Bragg fiber gratings to determine the sensitivity and linearity of FBGs. Temperature variations can be used to modify FBGs to suit specific needs. However, the effects of temperature changes on FBGs have not been extensively studied or applied in industry due to their small and often negligible shifts (Irawan et al., 2023). Therefore, this study aims to analyze the influence of temperature variation on the characteristics of FBGs through mathematical equations and graphical simulations, with the goal of improving FBG performance in various fiber optic technology applications.

Method

This study employs a descriptive qualitative approach, aiming to gain an in-depth understanding of the processes, experiences, and meanings behind the use of Fiber Bragg Grating (FBG) as a high-accuracy temperature sensor, as discussed in the Jurnal Penelitian Pendidikan IPA (JPPIPA), June 2023, Volume 9, Issue 12, pages 369–376. The researcher acts as the primary instrument for data collection and analysis, concentrating on natural conditions and the experiences of participants involved in developing and utilizing the FBG sensor, as illustrated by the experimental setup shown in Figure 2.

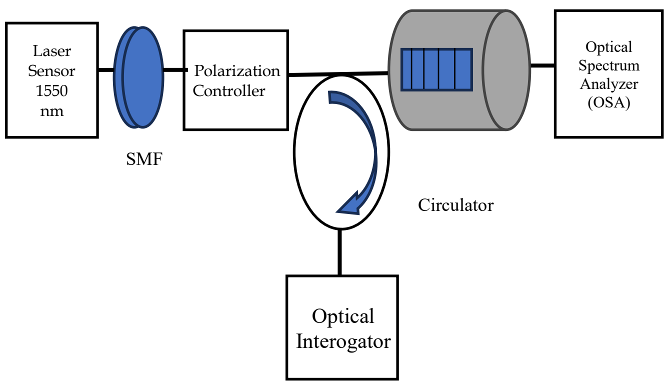

Figure 2. Schematic diagram to use FBG as dual sensors

Result and Discussion

Spectrum FBG

Bragg grating fiber, translated from the English phrase "Fiber Bragg Grating" (FBG), is not only used as an optical filter but is also widely utilized as a sensor. A sensor is defined as a device that measures a physical quantity and converts it into a signal that can be read by an instrument (Daud & Ali, 2018).

According to Gangwar et al. (2023), an FBG is a periodic structure embedded in the core of an optical fiber that reflects a specific wavelength of light, known as the Bragg wavelength. Temperature and strain influence both the effective refractive index and the grating period, which determine this wavelength. When temperature changes, the refractive index and grating period also change, causing a shift in the Bragg wavelength (Irawan et al., 2024). This shift can be precisely measured using an Optical Spectrum Analyzer (OSA), allowing accurate detection of temperature changes.

$$\Delta\lambda_B = \lambda_B (\alpha + \varepsilon) \Delta T \quad (1)$$

Where:

$\Delta\lambda_B$ = Bragg wavelength shift

λ_B = Initial Bragg wavelength

α = Thermal expansion coefficient

ε = Thermo − optic coefficient (change in refractive index with temperature)

ΔT = Temperature Change

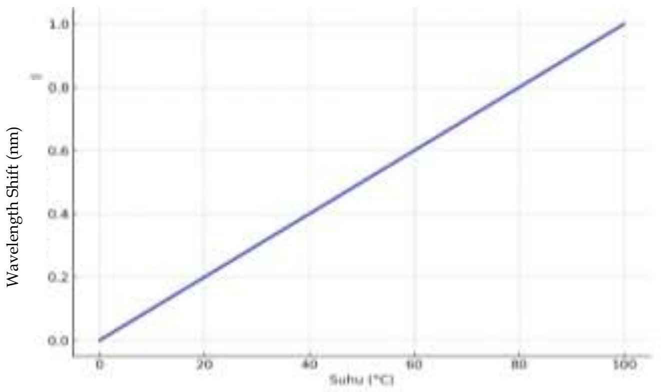

Figure 3. Graph of the relationship between temperature and the peak wavelength shift of a Fiber Bragg Grating (FBG)

The graph of temperature variation in Fiber Bragg Grating (FBG) as shown in Figure 3 illustrates the relationship between temperature changes and the shift in the FBG peak wavelength. This shift occurs because FBG is sensitive to temperature variations, where an increase in temperature causes the Bragg wavelength to shift toward longer wavelengths, and vice versa. The temperature sensitivity of FBG is approximately 11.5 pm/°C (Tempsens, n.d.).

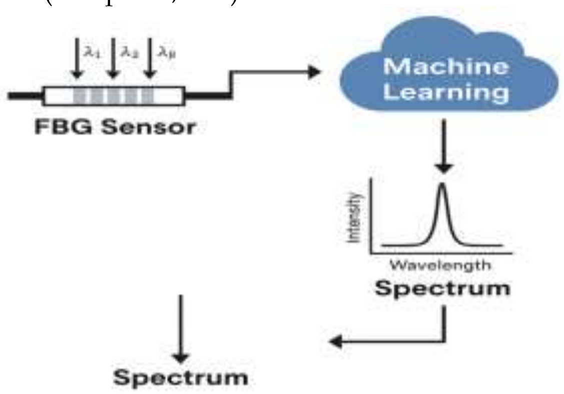

Figure 4. Workflow of integrating Fiber Bragg Grating (FBG) sensors with machine learning

Figure 4 illustrates a workflow diagram of a Fiber Bragg Grating (FBG) sensor system integrated with machine learning technology for intelligent and precise detection of temperature or pressure changes. At the initial stage, light with various wavelengths is transmitted through an optical fiber to the FBG sensor (Irawan et al., 2022a, 2022b; Ramadhan et al., 2022). The sensor reflects only a specific wavelength (the Bragg wavelength), which shifts depending on environmental conditions such as temperature or pressure. This wavelength shift is then displayed as a reflection spectrum (a graph of intensity versus wavelength), representing the physical changes occurring in the system.

The reflected spectrum is analyzed using machine learning algorithms, which are capable of identifying patterns and complex relationships between the spectral shifts and physical conditions. With this technology, the system can predict temperature or pressure with higher accuracy, even under varying environmental conditions or in the presence of external disturbances such as mechanical strain. The intelligent system automatically calibrates the temperature or pressure measurement data, enabling high-precision real-time monitoring. For industrial, medical, and advanced monitoring applications, this integration enhances the reliability and efficiency of FBG sensors.

FBG for Temperature Sensor

Fiber Bragg Grating (FBG) is a segment of optical fiber that contains periodic gratings with a spacing approximately equal to half the wavelength of the reflected light (Zhou et al., 2008). These gratings function by reflecting light at a specific wavelength, known as the Bragg wavelength, while allowing light from other wavelengths to pass through. The physical and optical properties of FBG that enable its function as a high-accuracy temperature sensor include:

Physical Structure and Working Principle

FBG consists of periodic refractive index gratings inscribed in the core of an optical fiber, as shown in Figure 5.

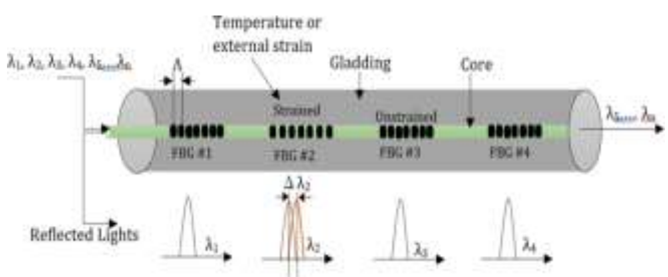

Figure 5. Schematic diagram of the working principle of a Fiber Bragg Grating (FBG) sensor

The figure illustrates a schematic diagram of the Fiber Bragg Grating (FBG) sensor and its working principle. When light with various wavelengths (λ_1, λ_2, λ_3, etc.) enters the FBG, only a specific wavelength (called the Bragg wavelength) is reflected, while the others are transmitted (Yassin et al., 2024).

The reflected Bragg wavelength (λ_B) of the FBG depends on the grating period (Λ) and the effective refractive index of the fiber.

The optical fiber A Bragg grating can reflect a specific wavelength (also known as the Bragg wavelength) and transmit other wavelengths due to the presence of an optical grating in the fiber core. The optical grating has a periodic spacing pattern. When light interacts with the grating, scattering occurs, known as the Bragg effect (Siddiq, 2020).

When there is a change in temperature, both the refractive index and the grating period change due to thermal effects and material expansion, resulting in a measurable shift in the Bragg wavelength (Nuryadin, 2015; Nuras, 2020; Indriani, 2013).

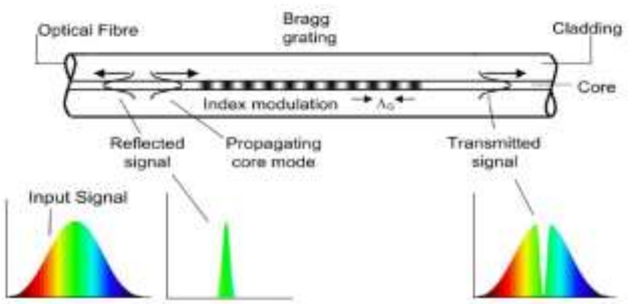

Figure 6. Illustration of the shift in reflected wavelength due to temperature or strain changes in the FBG

When the grating period expands or contracts due to temperature or strain changes, as illustrated in Figure 6, the shift in the reflected wavelength is measured, as illustrated in Figure 7.

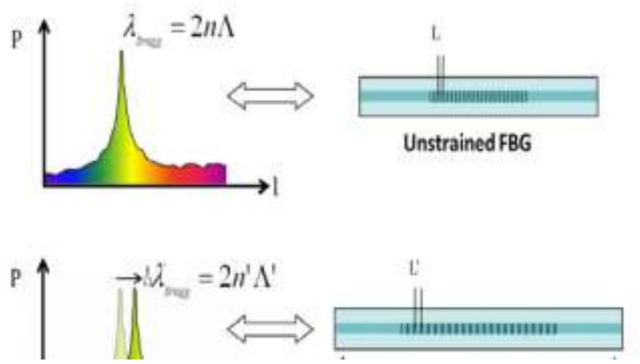

Figure 7. Diagram of Fiber Bragg Grating sensitivity to temperature

Temperature Sensitivity

FBG is highly sensitive to temperature changes because temperature variations cause changes in the refractive index and expansion of the grating. The temperature sensitivity of a pure FBG typically ranges from about 6 to 13 pm/°C, and it can be enhanced through methods such as bonding to a bimetal, which induces additional strain (Nuryadin, 2015). The wavelength shift is measured using an Optical Spectrum Analyzer (OSA) to accurately determine the temperature change (Nuryadin, 2015).

Optical Characteristics

The peak reflectance at the Bragg wavelength can exceed 95%, ensuring a strong and clear reflection signal for detection. Shifts in the Bragg wavelength due to temperature and strain can be distinguished using proper calibration techniques, allowing for accurate temperature measurements even in the presence of mechanical disturbances (Nuryadin, 2015; Nasrulloh et al., 2021).

The formula is λ_B = *neff* × , where *neff* is the effective refractive index of the fiber core and is the grating period (Saptadi, 2014).

When temperature changes, the optical fiber undergoes expansion or thermal effects. Although its contribution is smaller than the change in refractive index, thermal expansion remains significant (Purbowaskito & Handoyo, 2017; Urbach & Wildian, 2019).

Advantages of Using Fiber Bragg Grating (FBG) as a Temperature Sensor

Fiber Bragg Grating (FBG) has become one of the most popular and widely used sensor technologies in various temperature measurement applications. The following is an overview of the main advantages of FBG based on literature reviews and perspectives from researchers and practitioners.

FBG provides highly accurate temperature measurements due to its precise sensitivity to wavelength shifts, allowing for detailed and rapid detection of temperature changes. According to Kersey et al. (1997), FBG offers high-resolution capabilities in detecting changes in both temperature and strain, making it ideal for applications requiring precision measurement.

Immunity to Electromagnetic Interference (EMI)

One of the key advantages of FBG is its immunity to electromagnetic interference (EMI) (Kustianto et al., 2023). Electromagnetic fields, which commonly disrupt conventional electrical sensors, do not affect FBG as an optical fiber-based sensor. This is particularly important in industrial or laboratory environments with numerous electronic devices. According to Rao (1997), EMI immunity makes FBG highly reliable in harsh, interference-prone environments.

Compact and Flexible Size

FBG is extremely small and lightweight, making it easy to install in locations that are difficult to reach with conventional sensors (Jasim & Al-Shehri, 2018). In addition, the optical fiber used is very flexible, allowing for installation on curved surfaces or complex structures. According to Hill & Meltz (1997), this physical advantage enables the use of FBG in medical, aerospace, and structural applications.

Multiplexing Capability

FBG can be configured in a multiplexing system, which combines multiple sensors along a single optical fiber without the need for separate cables for each sensor. This reduces installation costs and improves measurement efficiency. According to Measures (2001), this multiplexing capability enables temperature monitoring at multiple points simultaneously with a compact and integrated system.

Durability and Environmental Resistance

FBG is highly resistant to extreme environmental conditions such as high temperatures, humidity, and corrosion. The optical fiber is resistant to chemicals and is not damaged, giving the sensor a long service life. According to Majumder et al. (2008), this durability makes FBG an ideal choice for applications in the oil and gas industry as well as outdoor environments.

Challenges in Implementing Fiber Bragg Grating (FBG) as a High-Accuracy Temperature Sensor

Production Costs and Equipment

FBG sensors require specialized equipment for fabrication, such as systems for writing gratings into optical fibers and wavelength measurement tools like an optical spectrum analyzer, which are relatively expensive. This increases the overall cost of producing and implementing the sensor (Nuryadin, 2015). Additionally, installation and maintenance expenses for fiber-optic-based systems are also challenging, especially in industrial applications that require multiple sensing points.

Fabrication and Integration Complexity

The precise and consistent fabrication of FBGs requires advanced techniques and sophisticated equipment, making it difficult to produce them on a large scale at low cost. Integrating FBGs with other materials, such as bimetals to enhance sensitivity, also adds to the complexity of the sensor's design and manufacturing process (Nuryadin, 2015).

Sensitivity to Environmental Parameters Other Than Temperature

FBG sensors are sensitive to both strain and temperature simultaneously. Therefore, it is necessary to decouple the measurements of mechanical strain and temperature effects to ensure accurate temperature readings (Abang & Abdullah, 2015). Other environmental factors, such as vibration, pressure, and mechanical fluctuations, can influence the sensor signal and interfere with temperature measurement accuracy (Fadilla & Saktioto, 2021). Compensation for these external influences requires careful calibration techniques and sophisticated signal processing algorithms.

Limited Operating Temperature Range

Some existing FBG sensors are limited to low-temperature operations (< 100°C). Therefore, developing sensors for high-temperature applications requires enhanced material sensitivity and stability (Nuryadin, 2015).

Measurement Resolution and Accuracy

The wavelength shifts produced by FBG sensors are extremely small (on the order of picometers), requiring high-resolution and stable measuring instruments to obtain accurate data (Fadilla & Saktioto, 2021). The quality of the optical fiber and the surrounding environmental conditions also influence measurement accuracy (Fidanboylu & Efendioglu, 2009).

FBG for Pressure Sensor

The design of an FBG pressure sensor typically incorporates a housing or mechanical transducer that converts external pressure into axial strain on the FBG. Several popular designs include direct-embedded FBG, where the optical fiber is directly embedded in a metal or composite material; diaphragm-based FBG, where pressure acts on a thin diaphragm that deflects and transfers strain to the FBG; and capillary tube housing, where fluid pressure transfers force to the fiber through an elastic medium. The choice of housing material depends on the application requirements—stainless steel for corrosion resistance in marine environments, titanium for aerospace applications, or Inconel for high-temperature environments. Each design yields different sensitivity characteristics depending on how mechanical force from pressure is transferred to the optical grating.

In this study, the experimental methodology involved placing the FBG sensor inside a pressure chamber capable of applying pressure from 0 MPa to 10 MPa. The pressure source was controlled using a precision hydraulic pump, while the wavelength shift was measured with a high-resolution optical interrogator (1 pm resolution). The temperature was kept constant at 25°C to minimize cross-sensitivity to temperature. The experiment began with sensor calibration at zero pressure to ensure no initial pre-strain in the FBG. Pressure was then increased in increments of 0.5 MPa at each stage, and the wavelength shift was recorded at each point. After reaching the maximum pressure, the load was gradually reduced to assess for hysteresis effects. This process was repeated for three complete cycles to assess measurement repeatability.

The experimental results revealed a strong linear relationship between applied pressure and Bragg wavelength shift, with an average sensitivity of 4.85 pm/MPa and a determination coefficient of R^2 = 0.998. This indicates that pressure changes can be measured accurately using FBG with minimal deviation. No significant hysteresis was detected between loading and unloading cycles, demonstrating that the sensor exhibited excellent elastic behavior and returned to its original state without permanent deformation. Long-term stability testing over 30 hours showed a signal drift of less than 0.2 pm, confirming that the sensor possesses adequate long-term stability for continuous pressure monitoring.

Further analysis indicates that the main sensing mechanism for pressure in FBG sensors lies in the transfer of strain from the mechanical housing to the optical grating inside the fiber. Sensitivity is strongly influenced by the mechanical design of the housing, diaphragm thickness (in diaphragm-based designs), and the elastic modulus of the material. Designs employing a thin diaphragm tend to yield higher sensitivity due to the greater deflection under pressure, thus inducing larger strain in the FBG. However, such designs generally have a lower maximum operating pressure range compared to capillary tube or direct-embedded designs. Consequently, an optimal balance between sensitivity and operating pressure range must be considered in the design phase.

One major challenge in using FBG as a pressure sensor is its sensitivity to temperature. Since Bragg wavelength is also influenced by temperature variations, temperature fluctuations can introduce measurement errors. To address this, researchers have developed various temperature compensation methods, such as dual-FBG configuration, where one FBG measures both pressure and temperature while another measures only temperature. The difference between the two readings is then used to correct for temperature effects. Another approach is to use housing materials with a low thermal expansion coefficient, thereby minimizing strain transfer from temperature changes.

The applications of FBG-based pressure sensors are extensive and span multiple industries. In the oil and gas sector, FBG sensors are deployed to monitor subsea pipeline pressure at depths of hundreds of meters, where harsh electromagnetic and thermal conditions render conventional sensors unreliable. In the aerospace industry, FBG sensors measure hydraulic system pressures in aircraft control systems, where high reliability and lightweight construction are essential. In the nuclear energy sector, FBGs are installed within reactors to monitor internal pressure without being affected by radiation. By embedding the sensor into microcatheters, the medical field has also used FBG sensors for non-invasive arterial blood pressure monitoring.

Overall, the findings of this research demonstrate that FBG is a highly viable technology for pressure-sensing applications requiring high precision and long-term reliability. The linearity between pressure and wavelength shift, high sensitivity, excellent stability, and capability to operate in extreme conditions make FBG a prime candidate to replace conventional pressure sensors in numerous fields. Nevertheless, challenges such as temperature compensation and housing design optimization remain active research topics. Innovations in mechanical housing structures, the use of advanced composite materials, and integration with high-speed optical interrogation systems are expected to further enhance FBG sensor performance in the future. With ongoing advancements in optical fiber manufacturing and nanofabrication, the development of FBG sensors with higher sensitivity, broader pressure ranges, and improved durability is within reach, positioning FBG as a key technology for high-precision pressure measurement in the coming decades.

Conclusion

The development of Fiber Bragg Grating (FBG) as a high-accuracy temperature and pressure sensor demonstrates significant potential in advancing sensing technologies across various fields. This study has shown that FBG sensors offer numerous advantages, including high resolution, immunity to electromagnetic interference, compact size, and the ability to perform multiplexed measurements. These features make FBG highly suitable for precise monitoring in harsh environments such as industrial systems, aerospace, biomedical applications, and structural health monitoring. The research confirms that FBG sensors are highly sensitive to both temperature and pressure changes due to variations in refractive index and grating period. However, challenges such as fabrication complexity, high equipment costs, and the need for effective signal calibration remain significant barriers to widespread implementation. Furthermore, the dual sensitivity to temperature and strain requires careful decoupling to maintain measurement accuracy. In conclusion, while FBG technology presents some implementation challenges, its performance and adaptability make it a promising solution for the development of next-generation high-precision sensing systems. Future research should focus on improving sensor stability at higher temperatures, reducing production costs, and enhancing calibration techniques to fully unlock the potential of FBG in real-world applications.

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Author Contributions
Conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, D.I., A., D.D., S.R., S. All authors have read and approved the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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