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The Use of Fiber Bragg Grating as a Sensor High Accuracy Temperature

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Abstract- Accurate temperature monitoring is crucial in various sectors, especially in extreme environments where conventional sensors are often unreliable. Fiber Bragg Grating (FBG) is an optical sensor technology that offers significant advantages, such as high temperature sensitivity, immunity to electromagnetic interference, compact size, high flexibility, and the ability to integrate into multiplexed systems. This article presents a comprehensive literature review discussing the working principle of FBG as a temperature sensor, its physical and optical characteristics, and the challenges in its implementation. FBG works based on the principle of temperature-dependent Bragg wavelength changes through changes in the refractive index and lattice period in the optical fiber core. Its sensitivity to temperature ranges from 6–13 pm/°C and can be increased through modifications such as the attachment of bimetal. Other advantages include high measurement accuracy and durability against harsh environmental conditions. However, the use of FBG still faces obstacles such as high equipment costs, fabrication complexity, and the need to separate the effects of strain and temperature in the measurement. Based on the analysis results, FBG has excellent prospects as a high-accuracy temperature sensor for industrial and advanced technology applications, provided that further development is carried out in terms of efficiency, system integration, and calibration methods.

Keywords: *Fiber Bragg Grating, sensor suhu optik, panjang gelombang Bragg, sensitivitas termal, penginderaan serat optik*

1 Introduction

Accurate temperature monitoring is crucial in a wide range of industrial applications, from material processing to structural health monitoring. Conventional temperature sensors often face limitations in sensitivity, size, and resistance to extreme environments. Fiber Bragg Gratings (FBGs) emerge as an innovative solution that overcomes these limitations by offering precise temperature measurement, resistance to electromagnetic interference, and the ability to operate in harsh environmental conditions (Hairi & Meyzia, 2023).

Since the discovery of FBG (Fiber Bragg Grating) is associated with the work of Hill et al at the Research Center Optical communications in Canada in 1978 has made Fiber Bragg Grating (FBG) a very promising technology in high-performance communication systems (Nasir, 2023). According to Casimer DeCusatis (2013), FBG has developed into a key component in various applications. The advantages of FBG make it very potential for use in various other fields. In telecommunication systems, FBG functions as a dispersion compensator in fiber optic transmission, a demultiplexing filter for WDM systems, and as a long-period grating for gain smoothing in erbium-doped fiber amplifiers (Murianti et al., 2018). In addition, FBG also opens up new opportunities for fiber optic applications outside of telecommunications, such as nonlinear frequency conversion, spectroscopy, and remote sensing.

One application of this fiber optic modification is sensors. The simplest sensor application involves varying light intensity, as it only requires a simple source and detector.(Molardi, 2019)An example of this

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sensor application is measuring the temperature inside an aircraft jet engine by using optical fibers to transmit radiation to a radiation pyrometer located outside the engine.(Widasari, ER, Pramono, SH, & Purnomo, 2013). In addition, extrinsic sensors can also be used in a similar way to measure the internal temperature of electrical transformers, where the extreme electromagnetic fields present make other measurement techniques impossible (Ali & Irawan, 2023). Uses of these extrinsic sensors include measuring vibration, rotation, displacement, speed, acceleration, torque, and twisting.(Putri, SE, & Harmadi, 2017). The output from the modification of the Bragg grating on the optical fiber is what attracts scientists to further development.

Previous research conducted by Yuliana et al. (Sari et al., 2015) showed that Fiber Bragg Grating (FBG) can be used to determine wavelengths in the C-Band range through simulation. Meanwhile, Khlaifi et al. (2021) emphasized the importance of boundary detection in the use of FBG to distinguish between temperature, strain, and pressure. Another study by Pang et al. (2020) focused on measuring temperature and refractive index on a fiber Bragg grating to determine the sensitivity and linearity of the FBG. Temperature changes can be used to modify the FBG to suit specific needs. However, the effect of temperature changes on FBG has not been widely studied and applied in industry because the changes are small and insignificant. This study aims to analyze the effect of temperature changes on FBG characteristics through mathematical equations and graphical simulations, thereby improving FBG performance in various fiber optic technology applications.

2 Research methodology

This research uses a descriptive qualitative approach, which aims to deeply understand the processes, experiences, and meanings behind the use of Fiber Bragg Grating (FBG) as a high-accuracy temperature sensor. The researcher acts as a key instrument in data collection and analysis, and focuses on the natural conditions and experiences of the subjects involved in the development and utilization of FBG sensors (Fauza, 2025). To achieve this research objective, the methodological stages will focus exclusively on an in-depth literature study.

2.1 Comprehensive Literature Study

This stage involves extensive research and review of various relevant scientific literature sources. We will systematically collect and analyze leading scientific journals, research reports, conference proceedings, textbooks, and other publications that specifically discuss the working principles of Fiber Bragg Gratings, the advantages of FBG technology in various applications, and in particular, the use of FBGs as temperature sensors. This search will utilize trusted academic databases to ensure the information obtained is valid and reliable.

2.2 Identify Characteristics, Strengths, and Challenges

FBG Characteristics:Describe the physical and optical properties of FBGs that enable them to function as temperature sensors. Advantages of Using FBG:The various advantages of FBGs, such as high accuracy, electromagnetic immunity, compact size, multiplexing capability, and durability, will be discussed. The analysis will include perspectives from various researchers and practitioners. Implementation Challenges:Identifying constraints or issues that may arise in the development and utilization of FBG sensors, such as cost, fabrication complexity, or sensitivity to environmental parameters other than temperature.

3 Results and Discussion

Fiber Bragg grating translated from the English phrase is Fiber Bragg Grating or abbreviated as FBG.Besides being used as optical filters, FBGs are also widely used as sensors. 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. (Suzairi Daud and Jalil Ali, 2018).

According toS. Singh et al (2021), FBG is a periodic structure embedded in the core of an optical fiber, which reflects a specific wavelength of light called the Bragg wavelength. This wavelength depends on the effective refractive index and the grating period, both of which are affected by temperature and strain. When the temperature changes, the refractive index and grating period change, causing the Bragg wavelength to shift. This shift can be measured precisely using an Optical Spectrum Analyzer (OSA), so that temperature changes can be detected accurately.

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

Where:

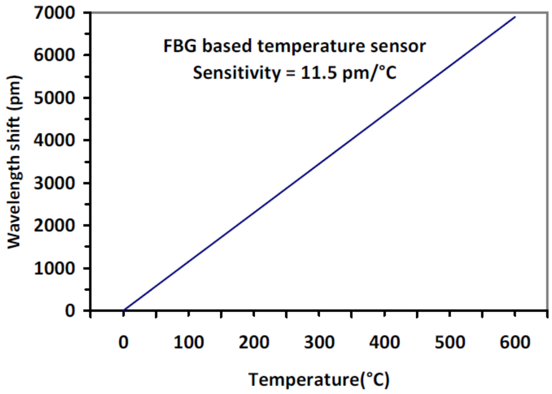
$\Delta\lambda_B =$ pergeseran panjang gelombang Bragg

$\lambda_B =$ panjang gelombang Bragg awal

$\alpha =$ koefisien ekspansi termal

$\varepsilon =$ koefisien perubahan indeks bias terhadap suhu

$\Delta T =$ perubahan suhu



Picture1. Graph of the relationship between temperature and the shift in the peak wavelength of Fiber Bragg Grating (FBG)

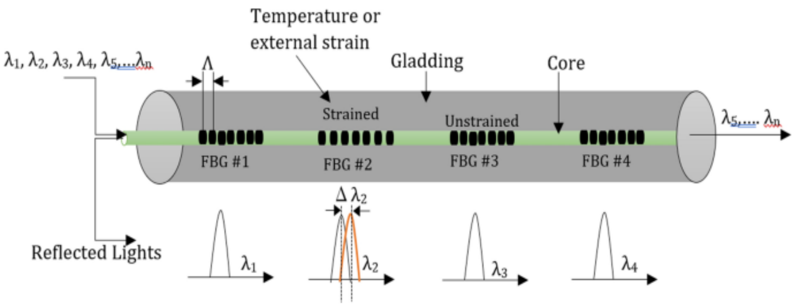
The temperature change graph for a Fiber Bragg Grating (FBG) shows the relationship between temperature changes and the shift in the peak wavelength of the FBG. This shift occurs because the FBG is sensitive to temperature changes, where an increase in temperature will cause a shift in the Bragg wavelength toward a longer wavelength, and vice versa. The temperature sensitivity of the FBG is approximately 11.5 pm/°C.(Tempsens, nd)

3.1 Characteristics of Fiber Bragg Grating (FBG) as a High Accuracy Temperature Sensor

Fiber Bragg Grating (FBG) is a segment of optical fiber that has a periodic grating with a spacing between gratings of approximately half the wavelength of the reflected light.(Zhou, K., Wei, L., & Cheng, 2008)This grating functions to reflect light with a specific wavelength called the Bragg wavelength, while light with other wavelengths is transmitted. The physical and optical properties of the FBG that enable it to function as a highly accurate temperature sensor include:

a. Physical Structure and Working Principle

- FBG consists of a refractive grating printed periodically in the core of the optical fiber.

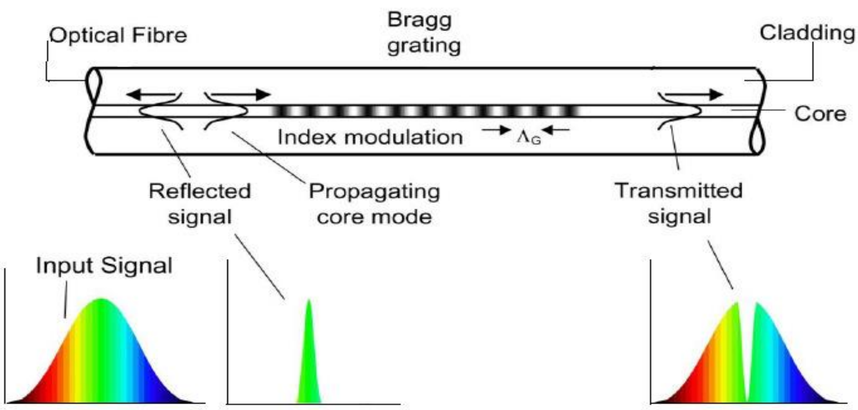


Picture 2. Schematic diagram of the working principle of the Fiber Bragg Grating (FBG) sensor

- The figure shows a schematic diagram of a Fiber Bragg Grating (FBG) sensor and its working principle. When light with different wavelengths (λ1, λ2, λ3, etc.) enters the FBG, only certain wavelengths (called Bragg wavelengths) are reflected, while others are transmitted.(Yassin et al., 2024).
- The Bragg wavelength reflected by the FBG depends on the grating period and the effective refractive index of the fiber according to the equation:$(\lambda_{\mathrm{B}})(\Lambda)(n_{eff})$

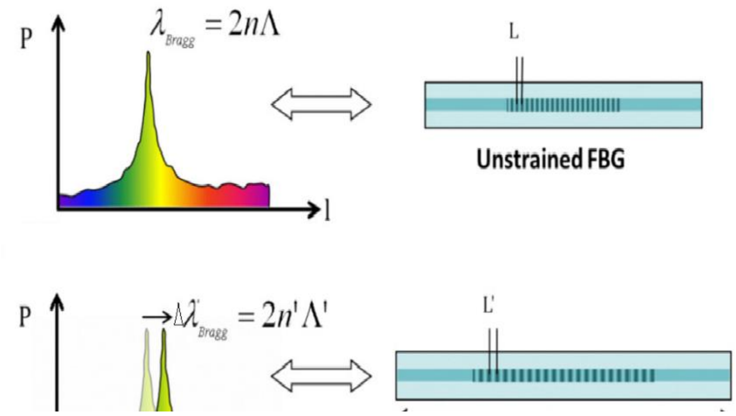
$$\lambda_{\mathrm{B}} = 2n_{eff}\Lambda \tag{2}$$

- A fiber optic Bragg grating can reflect certain wavelengths (also called Bragg wavelengths) and transmit/forward others due to the presence of an optical grating in the fiber's core. The optical grating has a periodic spacing pattern. When light hits the optical grating, scattering occurs, known as the Bragg effect. (Siddiq, 2020).
- When temperature changes, both the refractive index and the lattice period change due to thermal effects and material expansion, causing a measurable shift in the Bragg wavelength.(Andi Rosman N, 2015)(Nuras, 2020)(Indriani, nd).



Picture 3. Illustration of changes in reflected wavelength due to changes in temperature or strain in FBG

When the lattice period expands or contracts due to changes in temperature/strain, the change in reflected wavelength is measured as shown in the figure below.



Picture 4. Fiber Bragg Grating sensitivity diagram to temperature
Source: TEMPSENS

b. Sensitivity to Temperature

- FBGs are very sensitive to temperature changes because temperature changes cause changes in the refractive index and expansion of the lattice.
- The temperature sensitivity of FBGs is typically in the range of about 6–13 pm/°C for pure FBGs, and can be increased by methods such as attaching a bimetallic strip that introduces additional strain.(Andi Rosman N, 2015).
- This wavelength shift is measured with an Optical Spectrum Analyzer (OSA) to determine the temperature change accurately.(Andi Rosman N, 2015).

c. Optical Characteristics

- The peak reflectance of the Bragg wavelength can reach more than 95%, ensuring a strong and clear reflected signal for detection.
- Bragg wavelength changes due to temperature and strain can be separated by appropriate calibration techniques, thus allowing accurate temperature measurements even in the presence of mechanical disturbances.(Andi Rosman N, 2015; Nasrulloh et al., 2021).
- The formula is , where is the effective refractive index of the optical fiber core and is the grating period.$\lambda_B = n_{eff}\Lambda n_{eff}\Lambda$(Saptadi, 2014).
- When the temperature changes, optical fibers experience expansion, or thermal conditions. Although its contribution is smaller than the change in refractive index, thermal expansion is still significant.(Purbowaskito & Handoyo, 2017; Urbach & Wildian, 2019).

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

Fiber Bragg Grating (FBG) has become a very popular sensor technology and is widely used in various temperature measurement applications. The following is a description of the main advantages of FBG based on a literature review and the perspectives of various researchers and practitioners.

- High Accuracy
  FBGs are capable of providing temperature measurements with a very high degree of accuracy. This is due to their sensitivity to very precise wavelength changes, allowing temperature changes to be detected in detail and quickly.Kersey, et al (1997), FBG has high resolution capability in detecting temperature and strain changes, making it very suitable for applications that require precision measurements.

- Immunity to Electromagnetic Interference
  One of the main advantages of FBG is its nature of being unaffected by electromagnetic interference (EMI).(Kustianto et al., 2023)Because FBGs are fiber-optic based, they are free from interference from electromagnetic fields that typically plague conventional electrical sensors. This is particularly important in industrial or laboratory environments with a lot of electronic equipment.Rao (1997), immunity to EMI makes FBGs very reliable for use in harsh environments full of electromagnetic interference.
- Compact and Flexible Size
  FBG has a very small size and is light, so it is easy to install in various locations that are difficult to reach by conventional sensors.(Jasim, AA, & Al-Shehri, 2018). In addition, the optical fiber used is very flexible, allowing installation on curved surfaces or complex structures. According toHill & Meltz (1997), these physical advantages enable the use of FBGs in medical, aerospace, and building structure applications.
- Multiplexing Capability
  FBGs can be configured in multiplexing systems, combining multiple sensors onto a single optical fiber without the need for separate cables for each sensor. This reduces installation costs and increases measurement efficiency.Measures (2001)This multiplexing capability allows temperature monitoring at multiple points simultaneously with a compact and easy-to-integrate system.
- Durability and Environmental Resistance
  FBGs are highly resistant to extreme environmental conditions, such as high temperatures, humidity, and corrosion. The optical fibers used are chemically resistant and durable, ensuring a long lifespan.Majumder et al
  (2008)This durability makes FBG an ideal choice for applications in the oil and gas industry, as well as outdoor environments.

3.3 Challenges of Implementing Fiber Bragg Grating (FBG) Sensors as High-Accuracy Temperature Sensors

- **Production and Equipment Costs**
  FBG sensors require special equipment for fabrication such as a grating writing system on optical fibers and a relatively expensive wavelength measurement tool (Optical Spectrum Analyzer), thus increasing the production and implementation costs of this sensor.(Andi Rosman N, 2015). In addition, the installation and maintenance costs of fiber-optic-based systems are also a challenge, especially for industrial applications that require multiple measurement points.
- **Fabrication and Integration Complexity**
  The precise and consistent manufacturing process for FBGs requires complex fabrication techniques and sophisticated equipment, making them difficult to mass-produce at low cost. Integrating FBGs with other materials, such as bimetals, to increase sensitivity also adds complexity to sensor design and fabrication.(Andi Rosman N, 2015).
- **Sensitivity to Environmental Parameters Other Than Temperature**
  The FBG sensor is sensitive to changes in strain and temperature simultaneously, so it is necessary to separate the measurements between the effects of mechanical strain and temperature so that the temperature measurement results are accurate.(Abang, A., & Abdullah, 2015). Other environmental factors such as vibration, pressure, and mechanical fluctuations can affect the sensor signal and interfere with the accuracy of the temperature measurement.(Fadilla & Saktioto, 2021)Compensating for these external influences requires careful calibration techniques and signal processing algorithms.
- **Limited Temperature Operating Range**
  Some existing FBG sensors are still limited in operation at low temperatures (<100°C), so the

development of sensors for high temperature applications requires increased sensitivity and material stability.(Andi Rosman N, 2015).

- **Measurement Resolution and Accuracy**
  The change in wavelength produced by the FBG sensor is very small (on the order of picometers), so a measuring instrument with high resolution and good stability is required to obtain accurate data.(Fadilla & Saktioto, 2021). Measurement accuracy is also influenced by the quality of the optical fiber and environmental conditions around the sensor.(Fidanboylu, K., & Efendioglu, 2009).

4 Conclusion

Fiber Bragg Grating (FBG) is a very promising temperature sensor technology for various applications, especially in extreme environments that require precise and interference-resistant temperature measurements. The working principle of FBG is based on the shift in the Bragg wavelength due to temperature changes, which affect the refractive index and grating period in optical fibers. This allows for accurate temperature measurements with a sensitivity ranging from 6–13 pm/°C. FBG has several advantages such as high accuracy, small and flexible size, resistance to electromagnetic interference, and multiplexing capabilities that allow temperature monitoring at multiple points simultaneously in a single system. In addition, FBG is also resistant to extreme environmental conditions, making it suitable for industrial, medical, and infrastructure applications. However, the implementation of FBG as a temperature sensor still faces challenges, especially in terms of production costs and supporting equipment such as expensive Optical Spectrum Analyzers, the complexity of the fabrication process, and the difficulty in distinguishing the effects of temperature from mechanical strain. Therefore, further development is needed, both in terms of material technology, compensation systems, and cost efficiency, so that the use of FBG can be more optimal and widespread in the future.

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