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Comprehensive Review of Fiber Bragg Grating Sensors: Principles, Technologies, and Diverse Applications Across Industries

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***Abstract*:** Fiber Bragg Grating (FBG) sensors have emerged as versatile tools for various sensing applications due to their unique properties such as small size, immunity to electromagnetic interference, and high sensitivity. This study provides a comprehensive review of FBG sensor technology and its diverse applications in different fields. The fundamental principles of FBG sensors, including fabrication techniques and operation mechanisms, are discussed. Various applications of FBG sensors are explored, including structural health monitoring (SHM) of civil infrastructure, aerospace components, and renewable energy systems. FBG sensors have shown significant potential in monitoring parameters such as strain, temperature, pressure, vibration, and corrosion in harsh environments. Furthermore, FBG sensors have been successfully deployed in industries such as oil and gas, healthcare, and transportation for real-time monitoring and early fault detection. Challenges such as sensor integration, long-term performance, and cost-effectiveness are identified, indicating areas for future research and development. Recent advancements in FBG sensor technology, such as advanced fabrication techniques and novel applications in smart grids and environmental monitoring, are also highlighted. Overall, this study underscores the importance of FBG sensors as reliable and efficient tools for a wide range of sensing applications and provides insights into their future prospects for enhancing safety, efficiency, and sustainability across various industries. The ongoing advancements in FBG sensor technology promise to further expand their applicability and effectiveness, making them a cornerstone of modern sensing solutions.

***Keywords*:** Fiber Bragg Grating (FBG), Structural health monitoring (SHM), Strain measurement, Temperature sensing, Aircraft propulsion unit

1. Introduction

Fiber Bragg Grating (FBG) sensors have emerged as a prominent technology in the field of optical sensing, offering unique advantages such as high sensitivity, immunity to electromagnetic interference, and compatibility with harsh environments [1]. Over the years, FBG sensors have gained widespread attention and found applications across diverse sectors ranging from civil engineering to healthcare and beyond .The fundamental principle of FBG sensors lies in the periodic modulation of refractive index within an optical fiber, resulting in wavelength-selective reflection [2-4]. This characteristic enables FBG sensors to detect changes in various physical parameters including strain, temperature, pressure, vibration, and more [5]. In this study, we delve into the technology behind FBG sensors, elucidating their fabrication techniques, operational principles, and inherent advantages. Furthermore, we explore the extensive array of applications where FBG sensors have demonstrated efficacy, including structural health monitoring (SHM), aerospace, renewable energy, oil and gas, biomedical, transportation, and environmental monitoring [6-9]. Despite the remarkable progress made in FBG sensor technology, several challenges persist, such as integration with existing systems, long-term reliability, and cost-effectiveness. By addressing these challenges, FBG sensors hold immense potential for revolutionizing sensing capabilities and advancing safety, efficiency, and sustainability across various industries. This review paper is structured as follows: An introduction is given in the first section, and then in the second section is a review of the literature on FBG sensors. The principles, types, and fabrication methods of FBG sensors are covered in detail in the third section. The fourth and fifth sections delve into the extensive uses of FBG sensors and their expanded applicability, emphasising machine health monitoring, aircraft propulsion units, monuments, vibration, temperature, strain, and gas and petrol detection. The difficulties and potential developments in the field of FBG sensors are discussed in the sixth session. In the seventh session, the experimental setup and configuration were explained. The review's conclusion is finally briefly explained.

2. Literature Review

Sl.No.	Authors	Year	Key Findings	Gaps Identified
1	Hill and Meltz	1997	Detailed the fundamental principles of Fiber Bragg Gratings (FBGs) and their fabrication techniques. Established the basic operation of FBG sensors and their potential applications.	Limited focus on specific applications such as health monitoring and environmental sensing.
2	Y. J. Rao	2006	The advancements in fiber-optic extrinsic Fabry-Perot interferometric sensors, detailing improvements in sensitivity, accuracy, and application versatility.	The study notes the need for enhanced long-term stability and cost-effective production methods to broaden the practical deployment of these sensors.
3	Majumder et al.	2008	Provided a comprehensive reviews the current status and applications of Fiber Bragg Gratings (FBGs) in structural health monitoring, emphasizing their effectiveness in real-time strain and temperature measurement.	Identifies the need for further research into the long-term reliability of FBGs under varying environmental conditions and the integration of these sensors into diverse structural materials.
4	Bao and Chen	2012	Explored the use of FBG sensors in structural health monitoring (SHM) of civil infrastructure, including bridges and buildings. Showed significant potential for improving safety and maintenance efficiency.	The study needs for more extensive field trials and cost analysis for large-scale deployment.
5	Sampath et al.	2015	Highlighted improved accuracy in identifying curing stages. The application of Fibre Bragg Grating (FBG) sensors and Fresnel reflection measurement for in-situ cure monitoring of wind turbine blades was the main focus of this study.	Need for improving the robustness of FBG sensors in harsh environments and optimizing the integration process for large-scale industrial applications.
6	Javdani et al.	2015	Demonstrates the application of a Fibre Bragg Grating (FBG) based sensor system for real-time vibration monitoring by conducting an underwater free-vibration analysis of full-scale marine propellers.	The study identifies the need for enhancing the durability and waterproofing of FBG sensors to ensure reliable long-term performance in harsh underwater environments.
7	Jiang et al.	2017	In order to detect strain and temperature variations for early fault detection, the study examines the use of Fibre Bragg Grating (FBG) sensors in pipeline safety monitoring.	Highlights the need for further research into enhancing the durability and reliability of FBG sensors in harsh pipeline environments to ensure consistent performance over time.
8	Campanella et al	2018	Review gives a thorough introduction to the technology of Fibre Bragg Grating (FBG) strain sensors, emphasising their high sensitivity, adaptability, and variety of uses in the monitoring of structural health.	The review identifies the need for advancements in FBG sensor packaging and installation techniques to enhance their durability and performance in diverse and challenging environments.
9	Wang et al.	2018	Study presents a Fiber Bragg Grating (FBG) based sensor for detecting	Need for improving the robustness and reliability of

			torsional vibrations in rotating machinery, demonstrating high sensitivity and accuracy in measuring rotational dynamics.	FBG sensors under high-speed rotational conditions to ensure consistent performance in industrial applications.
10	Presti et al.	2020	Discusses the application of Fiber Bragg Gratings (FBGs) in medical settings, emphasizing their benefits in precision diagnostics and monitoring physiological parameters.	The review highlights the need for advancements in biocompatibility, miniaturization, and integration of FBG sensors into medical devices to enhance their usability and effectiveness in clinical environments.
11	Lo Presti et al.	2021	Explored introduces a soft wearable system utilizing fiber optic technology for multi-point heart rate monitoring, demonstrating high accuracy and comfort for continuous health monitoring.	Challenges in developing flexible, durable, and comfortable wearable devices incorporating FBG sensors.
12	Mohapatra et al.	2021	Using Fibre Bragg Grating (FBG) sensing technology, the study presents an Internet of Things (IoT)-enabled distributed cardiac monitoring system, demonstrating its potential for highly precise remote and real-time health monitoring.	Need for further research into optimizing the integration of FBG sensors with IoT platforms to ensure seamless communication and data transmission for efficient remote monitoring applications.
13	López-Castro et al.	2022	Emphasises the importance of Structural Health Monitoring (SHM) systems in guaranteeing structural safety and resilience in the wake of seismic events. This evaluation aims to improve post-earthquake assessment procedures.	The review underscores the need for further research into integrating advanced sensor technologies and data analytics to develop more robust and efficient post-earthquake assessment protocols.
14	Mishra et al.	2022	Shows how Fibre Bragg Grating (FBG) sensors are used in real-time to monitor flat wheel detection in railroads. This increases railway safety by demonstrating the sensors' effectiveness in early fault detection and prevention.	Need for further research into integrating FBG sensors into railway infrastructure to enable continuous and widespread monitoring for improved maintenance and safety measures.
15	Brown et al.	2023	Analyzed FBG sensors for earthquake monitoring, showing potential in providing early warnings and assessing structural health post-event.	Extensive field trials and deployment in diverse seismic zones required for validation.
16	Zhang et al.	2023	The review evaluates wearable optical fibre sensors for use in medical monitoring applications, emphasising their potential for highly accurate, comfortable, non-invasive, and continuous health monitoring.	To enhance the integration of optical fiber sensors into wearable devices, addressing issues related to biocompatibility, durability, and data transmission for widespread clinical adoption.

3. Fiber Bragg Grating Sensors and its working principle

An FBG is a kind of distributed Bragg reflector made of a brief optical fibre segment that transmits all other wavelengths of light while reflecting certain ones. Periodic changes in the refractive index of the fibre core, usually brought about by subjecting the fibre to a strong ultraviolet light interference pattern, are the cause of the reflection. The Bragg gratings in an FBG sensor act as a wavelength-selective mirror when a broadband light source passes through it.Certain wavelengths of light are reflected back based on the strain or temperature change, which is shown in figure 1.

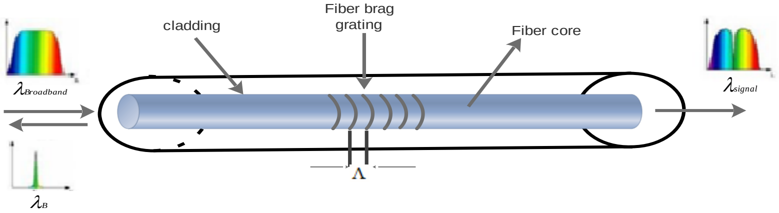


Figure 1. Schematic diagram of FBG Sensor

The maximum reflected light signal has a specific wavelength known as the Bragg wavelength (λ_B,) expressible by the following equations:

$$\lambda_B = 2\eta_e \Lambda \tag{1}$$

where Λ is the periodicity of the grating and η_e is the effective refractive index of the fiber core. By applying strain and changing the temperature, the grating's periodicity is altered. The refractive index can alter the Bragg wavelength as well. Both the thermo-optic effect and the photo-elastic effect have the ability to alter these parameters. In order to identify the change in wavelength of the light reflected, FBG are used as sensors.

$$\frac{\Delta\lambda_B}{\lambda_B} = K_{\varepsilon_z}\varepsilon_z + K_T \Delta T \tag{2}$$

where K_{ε_z} and K_T are two proportionality constants. For the purpose of the thesis the effect of the temperature has been neglected. As the experiment is conducted under room temperature.When light propagates through the fiber, it encounters the grating region where the periodic changes in the refractive index cause a reflection of a specific wavelength (the Bragg wavelength). Any changes in temperature or strain alter the effective refractive index and the grating period, leading to a shift in the Bragg wavelength. By monitoring this shift, it is possible to measure the changes in the physical conditions that affect the fiber [6-7].

3.1. Types of FBGs

Fiber Bragg Grating (FBG) sensors come in various types, each tailored to specific applications and operational requirements. The key types of FBG sensors include uniform FBGs, chirped FBGs, and phase-shifted FBGs.

- Uniform FBGs: With a consistent periodic modulation of refractive index throughout the fibre, these are the most prevalent kind of FBG sensors. When a single parameter, like strain or temperature, needs to be measured precisely, uniform FBGs can be used. This is because they reflect a particular wavelength of light that is determined by the grating period. They find extensive application in the structural health monitoring (SHM) of industrial machinery, aerospace components, and civil infrastructure [10–11].
- Chirped FBGs: Unlike uniform FBGs, chirped FBGs exhibit a varying period of modulation along the length of the fiber. This chirped structure results in a broadband reflection spectrum rather than a single wavelength. Chirped FBGs are utilized in applications requiring distributed sensing over a wide frequency range, such as sensing strain or temperature gradients along a structure. They find applications in dynamic strain sensing, distributed temperature sensing, and multiplexed sensor networks.
- Phase-Shifted FBGs: Phase-shifted FBGs incorporate a deliberate phase shift within the grating structure, introducing a localized perturbation in the reflection spectrum. This phase shift enables enhanced sensing capabilities, such as improved sensitivity and resolution. Phase-shifted FBGs are employed in applications demanding high-performance sensing, including ultra-sensitive strain measurements, acoustic sensing, and high-resolution interrogation techniques.

Each type of FBG sensor offers distinct advantages and capabilities, allowing for tailored solutions to specific sensing challenges. By leveraging the unique properties of these FBG variants, engineers and researchers can design sensor systems optimized for a wide range of applications, from structural monitoring and industrial automation to medical diagnostics, marine system, and environmental sensing [12-16].

3.2. Fabrication Techniques

Fabrication techniques for Fiber Bragg Grating (FBG) sensors are critical in determining their performance, sensitivity, and applicability to various sensing applications [12-19]. Several methods exist for producing FBG sensors, each offering unique advantages and limitations.

- UV Exposure Method: This is the method that is most frequently used to create FBG sensors. A phase mask is used to expose a photosensitive optical fibre to a pattern of UV light. The grating structure is formed by a periodic modulation of the refractive index caused by the UV light along the length of the fibre. This method allows for precise control over the grating period and is suitable for mass production of FBG sensors with uniform characteristics.

- Point-by-Point Inscription: In this technique, an intense laser beam is focused onto the core of the optical fiber to locally modify its refractive index. By translating the fiber relative to the laser beam, a periodic grating structure is inscribed point-by-point along the fiber length. This method offers flexibility in designing complex grating profiles and is particularly suitable for fabricating chirped FBGs and phase-shifted FBGs.
- Interferometric Method: The interferometric method utilizes the interference pattern created by two or more laser beams to induce a periodic modulation of refractive index in the optical fiber. This technique enables precise control over the grating characteristics and can produce FBG sensors with high uniformity and reproducibility.
- Electron Beam Lithography: Electron beam lithography involves using a focused electron beam to pattern a photosensitive material coated on the surface of the optical fiber. This method allows for submicron-scale grating structures to be fabricated with high precision, making it suitable for producing FBG sensors for advanced sensing applications requiring ultra-high resolution.
- Phase Mask Techniques: Phase masks are precision-engineered optical elements that generate the desired grating pattern when illuminated with UV light. By controlling the phase mask parameters and the UV exposure conditions, FBG sensors with tailored characteristics can be fabricated. Phase mask techniques offer high throughput and repeatability, making them suitable for industrial-scale production of FBG sensors.
- Femtosecond Laser Writing: Femtosecond laser writing is a more recent technique that uses ultra short laser pulses to create FBGs. This method allows for the fabrication of gratings with very high precision and can be used to write gratings in various types of optical fibers, including those with non-photosensitive cores.

Each fabrication technique offers distinct advantages in terms of precision, flexibility, scalability, and cost-effectiveness, enabling the production of FBG sensors tailored to specific sensing requirements across various industries.

4. Applications of FBG Sensors

4.1. Health Monitoring of Machines

FBG sensors are extensively used in the health monitoring of machines. They can be embedded in critical components to continuously monitor strain, temperature, and vibration. This real-time monitoring capability helps in early detection of potential failures, thereby reducing downtime and maintenance costs. In rotating machinery, FBG sensors can be used to measure parameters such as shaft vibration, bearing temperature, and load. These measurements provide valuable data for predictive maintenance and enhance the reliability and performance of the machinery [20-22].

4.2. Aircraft Propulsion Units

The aerospace industry has greatly benefited from the adoption of FBG sensors for monitoring aircraft propulsion units. FBG sensors are employed to measure temperature, strain, and pressure in various parts of the propulsion system, including turbines, compressors, and exhaust nozzles [14-15], [19]. The harsh operating conditions of aircraft engines, such as high temperatures and vibrations, demand sensors that can withstand these extremes while providing accurate measurements. FBG sensors meet these requirements and offer the additional advantage of being lightweight and immune to electromagnetic interference. The FBG sensor can be mounted on top/bottom surface of the aircraft wings to measure wind pressure which is shown in figure 2.

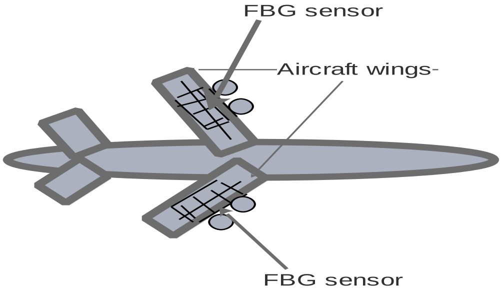


Figure 2. FBG sensors used on top/bottom surface of the aircraft wings

4.3. Structural Health Monitoring of Monuments

The preservation of historical monuments and structures is a significant application area for FBG sensors. These sensors can be embedded in the structural elements of monuments to monitor stress, strain, and environmental conditions over time. By providing continuous data on the structural integrity of monuments, FBG sensors help in assessing the impact of environmental factors, aging, and other stressors. This information is crucial for the timely implementation of conservation measures, ensuring the longevity and safety of these cultural heritage sites [16].

4.4. Vibration Monitoring

Vibration monitoring is another critical application of FBG sensors. They are used in various industries to monitor vibrations in structures, machinery, and vehicles [7], [22]. The high sensitivity and fast response time of FBG sensors make them ideal for detecting even minor vibrations. In civil engineering, FBG sensors are used to monitor vibrations in bridges, buildings, and dams. This helps in identifying structural issues and preventing potential failures. In the automotive industry, FBG sensors are used to monitor vibrations in engines and chassis, contributing to improved vehicle performance and safety. Figure 3 shows the application of FBG sensor used for vibration measurement of machine.

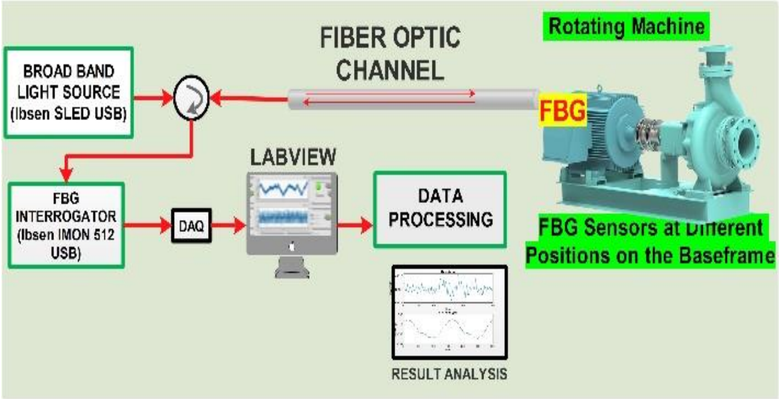


Figure 3. FBG sensor used for vibration measurement of machine

4.5. Temperature Sensing

FBG sensors are highly effective for temperature sensing due to their sensitivity to temperature changes. The Bragg wavelength shift in response to temperature variations allows for precise temperature measurements [27]. These sensors are used in a wide range of applications, from industrial processes to environmental monitoring. In power plants, FBG sensors monitor temperature changes in critical components, ensuring efficient operation and preventing overheating. Figure 4 explains the FBG temperature setup for temperature measurement, which is shown below. In environmental monitoring, they provide data on temperature variations in natural habitats, contributing to climate studies and conservation efforts [20].

Figure .4. FBG temperature sensor set up.

4.6. Strain Measurement

Strain measurement is one of the primary applications of FBG sensors. They are used to monitor structural deformations in various fields, including civil engineering, aerospace, underwater vehicles, and manufacturing industries. In civil engineering, FBG sensors are embedded in concrete structures, bridges, and tunnels to measure strain and detect any structural anomalies. In aerospace, they monitor the strain on aircraft wings and fuselage, providing data that enhances flight safety and performance [23]. In manufacturing, FBG sensors are used to measure strain during the production process, ensuring product quality and consistency.

4.7. Gas and Petrol Detection

FBG sensors have also found applications in gas and petrol detection. They can be functionalized with materials that respond to specific gases, leading to a measurable shift in the Bragg wavelength when the target gas is present. These sensors are used in various industries for leak detection and environmental monitoring. In the oil and gas industry, FBG sensors detect leaks in pipelines and storage tanks, preventing hazardous incidents and environmental contamination [8], [18]. In environmental monitoring, they are used to detect harmful gases in the atmosphere, contributing to air quality management and pollution control.

5. Extended Applications of FBG Sensors

a) Energy Production and Distribution

FBG sensors play a significant role in the energy sector, where they are used to enhance the safety, efficiency, and reliability of energy production and distribution systems.

- Wind Turbines: FBG sensors are used to monitor blade strain, temperature, and vibration in wind turbines, ensuring optimal performance and early detection of potential faults [19].
- Power Grids: In power transmission and distribution systems, FBG sensors monitor the temperature and strain of overhead power lines, transformers, and other critical components, helping to prevent failures and optimize maintenance schedules.
- Nuclear Plants: FBG sensors are employed to monitor temperature, pressure, and radiation levels within nuclear reactors and associated infrastructure, ensuring safe and efficient operation.

b) Geotechnical Engineering

Geotechnical engineering applications benefit greatly from the use of FBG sensors, particularly in monitoring soil-structure interactions and assessing the stability of geological formations.

- Landslide Monitoring: FBG sensors are used to detect minute changes in soil strain and displacement, providing early warning of potential landslides.
- Tunnel and Dam Monitoring: These sensors are embedded in tunnels and dams to measure strain, temperature, and pressure, ensuring structural integrity and safety.
- Foundation Monitoring: In construction projects, FBG sensors monitor the strain and deformation of foundations, helping to detect any issues that could compromise the stability of the structure.

c) Underwater and Marine Applications

The marine environment poses unique challenges for monitoring systems, and FBG sensors are well-suited to meet these demands due to their robustness and resistance to corrosion .

- Submarine Cables: FBG sensors are used to monitor the strain and temperature of submarine communication and power cables, ensuring their reliability and performance.
- Offshore Structures: In offshore oil and gas platforms, FBG sensors monitor the structural health of the platforms, detecting any signs of fatigue or damage due to harsh marine conditions.
- Marine Vessel Monitoring: These sensors are integrated into the hulls of ships and submarines to measure strain, temperature, and vibration, contributing to the safety and efficiency of marine operations [23].

d) Smart Infrastructure

FBG sensors are increasingly being used in the development of smart infrastructure, where they provide real-time data for the management and maintenance of various structural and environmental systems [16], [24-25].

- Smart Buildings: FBG sensors are embedded in building materials to monitor structural health, energy usage, and environmental conditions, contributing to the development of smart buildings that are safer, more efficient, and more responsive to occupants' needs.
- Smart Roads and Bridges: In smart transportation infrastructure, FBG sensors monitor the strain, temperature, and vibration of roads and bridges, enabling proactive maintenance and improving traffic safety.

- Water Supply Systems: FBG sensors are used to monitor the integrity of water pipelines, detecting leaks and pressure changes to ensure a reliable water supply.

e) Industrial Process Monitoring

FBG sensors are widely used in industrial applications to monitor and control various processes, ensuring efficiency, safety, and quality.

- Manufacturing: In manufacturing processes, FBG sensors monitor strain, temperature, and pressure in machinery and production lines, helping to maintain product quality and prevent equipment failures.
- Chemical Processing: These sensors are used to measure temperature, pressure, and chemical concentrations in reactors and pipelines, ensuring safe and efficient chemical processing.
- Oil and Gas: In the oil and gas industry, FBG sensors are employed to monitor the integrity of pipelines, storage tanks, and drilling equipment, preventing leaks and enhancing operational safety [15].

f) Aerospace and Defence

The aerospace and Defence sectors benefit from the advanced capabilities of FBG sensors for monitoring critical systems and ensuring operational safety.

- Aircraft Structural Health: FBG sensors are embedded in aircraft structures to monitor strain, temperature, and vibration, providing real-time data that enhances safety and performance.
- Spacecraft Monitoring: These sensors are used in spacecraft to measure temperature, pressure, and structural integrity, ensuring the safety and success of space missions.
- Defense Systems: In Defense applications, FBG sensors are integrated into various systems to monitor conditions and ensure the reliability and effectiveness of military equipment.

g) Renewable Energy

FBG sensors contribute to the advancement of renewable energy technologies by providing precise monitoring of various parameters in solar, wind, and hydroelectric power systems.

- Solar Panels: FBG sensors are used to monitor the temperature and structural health of solar panels, optimizing their efficiency and lifespan.
- Hydroelectric Plants: In hydroelectric power plants, these sensors monitor the strain and temperature of turbines and other components, ensuring efficient energy production and preventing failures.
- Geothermal Energy: FBG sensors are employed to monitor temperature and pressure in geothermal wells, aiding in the efficient extraction of geothermal energy.

h) Medical Devices and Health Monitoring

FBG sensors are increasingly being integrated into medical devices for patient monitoring and diagnostic purposes. Their biocompatibility, high sensitivity, and immunity to electromagnetic interference make them ideal for use in medical environments [10],[14],[21],[26-27].

- Cardiovascular Monitoring: FBG sensors can be embedded in catheters and stents to monitor blood flow, pressure, and strain within the cardiovascular system, providing real-time data for diagnostic and therapeutic purposes [17].
- Respiratory Monitoring: These sensors can be used in respiratory equipment to measure airflow and respiratory rate, aiding in the management of respiratory conditions such as asthma and COPD.
- Orthopedic Applications: FBG sensors can be implanted in orthopedic devices to monitor the healing process of bones and the performance of prosthetic implants, providing valuable feedback for post-surgical care.

i) Environmental Monitoring

FBG sensors are used extensively in environmental monitoring, where they provide precise and reliable data on various environmental parameters.

- Climate Studies: FBG sensors are deployed in remote and harsh environments to measure temperature, humidity, and other climatic variables, contributing to climate research and monitoring.
- Pollution Detection: These sensors are used to detect pollutants in water and air, providing real-time data for environmental protection and regulatory compliance.
- Agricultural Monitoring: In precision agriculture, FBG sensors monitor soil conditions, crop health, and environmental factors, helping to optimize irrigation, fertilization, and other agricultural practices.

j) Mining Industry

The mining industry utilizes FBG sensors to enhance safety and operational efficiency by monitoring various conditions in mines and mining equipment.

- Mine Shaft Monitoring: FBG sensors measure the strain and deformation of mine shafts, ensuring their structural integrity and safety.
- Equipment Monitoring: These sensors are used to monitor the condition of mining equipment, detecting wear and tear to prevent breakdowns and ensure efficient operation.
- Environmental Monitoring: FBG sensors detect gas concentrations and other environmental factors within mines, preventing hazardous conditions and ensuring the safety of miners.

6. Challenges and Future Prospects

a) Challenges

Despite their numerous advantages, FBG sensors face several challenges that need to be addressed to fully realize their potential. These challenges include:

- Cost: The fabrication and installation of FBG sensors can be costly, limiting their widespread adoption in some applications.
- Durability: Ensuring the long-term durability of FBG sensors, especially in harsh environments, remains a challenge.
- Multiplexing Limitations: While FBG sensors offer multiplexing capabilities, managing a large number of sensors on a single fiber can be complex and may affect performance.

b) Future Prospects

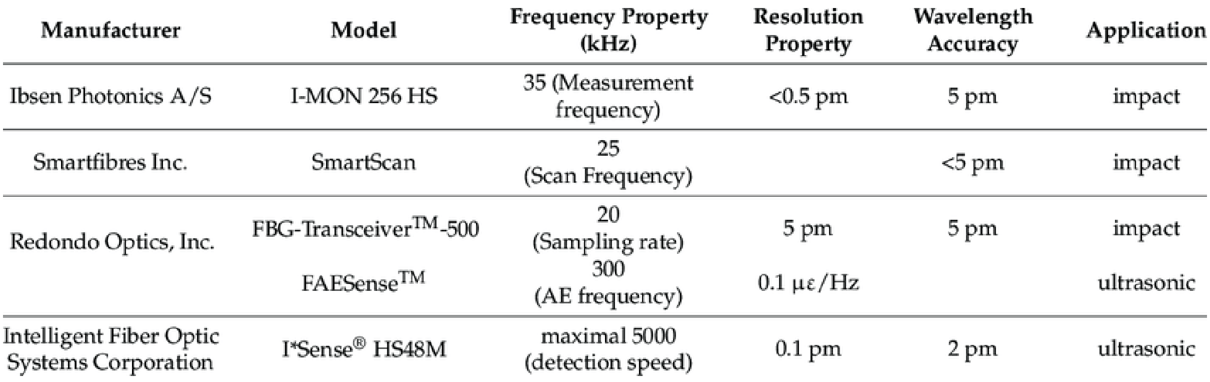
The future of FBG sensors looks promising, with ongoing research and development aimed at overcoming current challenges and expanding their applications. Some of the future directions for FBG sensor technology include:

- Advanced Fabrication Techniques: Developing more cost-effective and efficient fabrication techniques to reduce the overall cost of FBG sensors.
- Durability Enhancements: Improving the durability of FBG sensors through advanced materials and protective coatings, enabling their use in more demanding environments.
- Enhanced Multiplexing: Innovating new methods for better multiplexing of FBG sensors, allowing for the deployment of larger sensor networks without compromising performance.
- Smart Sensing Systems: Integrating FBG sensors with advanced data processing and communication technologies to create smart sensing systems for real-time monitoring and analysis.

Fibre Bragg grating (FBG) sensors are used in distributed cardiac monitoring, which enables continuous and remote patient health tracking, as well as structural health monitoring for real-time infrastructure assessment and maintenance. These sensors are integrated with IoT and big data. In addition to improving vehicle safety through improved automotive component diagnostics, real-time FBG sensor monitoring is essential for earthquake monitoring systems as it enables the provision of early warnings and the post-event assessment of structural integrity[28-29].

7. Laboratory Grade Experimental Setup and System Configuration

Commercial FBG sensors:-



Manufacturer	Model	Frequency Property (kHz)	Resolution Property	Wavelength Accuracy	Application
Ibsen Photonics A/S	I-MON 256 HS	35 (Measurement frequency)	<0.5 pm	5 pm	impact
Smartfibres Inc.	SmartScan	25 (Scan Frequency)		<5 pm	impact
Redondo Optics, Inc.	FBG-Transceiver™-500	20 (Sampling rate)	5 pm	5 pm	impact
	FAESense™	300 (AE frequency)	0.1 $\mu\varepsilon$/Hz		ultrasonic
Intelligent Fiber Optic Systems Corporation	I*Sense® HS48M	maximal 5000 (detection speed)	0.1 pm	2 pm	ultrasonic

Figure. 5. Laboratory Grade Experimental Setup and configuration

8. Conclusion

Fibre Bragg Grating (FBG) sensors have shown to be dependable and adaptable instruments for a broad range of uses in numerous industries. They are perfect for monitoring physical parameters like strain, temperature, pressure, and vibration because of their high sensitivity, immunity to electromagnetic interference, and multiplexing capabilities.From health monitoring of machines and aircraft propulsion units to structural health monitoring of monuments and environmental sensing, FBG sensors provide real-time data that enhances safety, efficiency, and performance. As advancements in fabrication techniques and sensor technology continue to evolve, the potential applications of FBG sensors will expand even further, offering innovative solutions for emerging challenges in diverse fields.

8.1. Future Directions

The ongoing research and development in FBG technology are expected to address current challenges such as cost, durability, and multiplexing limitations. Future innovations may include advanced materials for improved sensor performance, enhanced data processing techniques for better analysis, and the integration of FBG sensors into smart sensing systems. These advancements will pave the way for new applications and further solidify the role of FBG sensors as a critical component in modern sensing technology. By leveraging the unique capabilities of FBG sensors, industries can achieve greater efficiency, safety, and sustainability, ultimately contributing to technological progress and societal well-being.

References

[1] K. O. Hill and G. Meltz, "Fiber Bragg Grating Technology Fundamentals and Overview," Journal of Lightwave Technology, vol. 15, no. 8, pp. 1263-1276, Aug. 1997.

[2] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele, "Fiber Grating Sensors," Journal of Lightwave Technology, vol. 15, no. 8, pp. 1442-1463, Aug. 1997.

[3] Y. J. Rao, "Recent progress in fiber-optic extrinsic Fabry-Perot interferometric sensors," *Opt. Fiber Technol.*, vol. 12, pp. 227–237, 2006.

[4] B. Culshaw and A. Kersey, "Fiber Optic Sensing: A Historical Perspective," Journal of Lightwave Technology, vol. 26, no. 9, pp. 1064-1078, Sep. 2008.

---

[5] X. Bao and L. Chen, "Recent Progress in Distributed Fiber Optic Sensors," Sensors, vol. 12, no. 7, pp. 8601-8639, Jul. 2012.

[6] S. K. Majumder, T. K. Gangopadhyay, A. K. Chakraborty, K. Dasgupta, and D. K. Bhattacharya, "Fiber Bragg Gratings in Structural Health Monitoring—Present Status and Applications," Sensors and Actuators A: Physical, vol. 147, no. 1, pp. 150-164, Sep. 2008.

[7] J. Wang, L. Wei, R. Li, Q. Liu, and L. Yu, "A Fiber Bragg Grating Based Torsional Vibration Sensor for Rotating Machinery," *Sensors*, vol. 18, no. 8, p. 2669, 2018.

[8] X. Qiao, Z. Shao, W. Bao, and Q. Rong, "Fiber Bragg Grating Sensors for the Oil Industry," *Sensors*, vol. 17, no. 3, p. 429, 2017.

[9] P. Moyo, J. M. W. Brownjohn, R. Suresh, and S. C. Tjin, "Development of fiber Bragg grating sensors for monitoring civil infrastructure," Engineering Structures, vol. 27, no. 12, pp. 1828-1834, 2005.

[10] J. Leng and A. Asundi, "Structural health monitoring of smart composite materials by using EFPI and FBG sensors," *Sensors and Actuators A: Physical*, vol. 103, no. 3, pp. 330-340, 2003.

[11] C. E. Campanella, A. Cuccovillo, C. Campanella, A. Yurt, and V. M. N. Passaro, "Fibre Bragg Grating Based Strain Sensors: Review of Technology and Applications," *Sensors*, vol. 18, pp. 3115, 2018.

[12] S. Chen, J. Wang, C. Zhang, M. Li, N. Li, H. Wu, Y. Liu, W. Peng, and Y. Song, "Marine Structural Health Monitoring with Optical Fiber Sensors: A Review," *Sensors*, vol. 23, no. 4, p. 1877, 2023.

[13] B. Van Esbeen, C. Finet, R. Vandebrouck, D. Kinet, K. Boelen, C. Guyot, G. Kouroussis, and C. Caucheteur, "Smart Railway Traffic Monitoring Using Fiber Bragg Grating Strain Gauges," Sensors, vol. 22, no. 9, p. 3429, 2022.

[14] X. Zhang, C. Wang, T. Zheng, H. Wu, Q. Wu, and Y. Wang, "Wearable Optical Fiber Sensors in Medical Monitoring Applications: A Review," *Sensors*, vol. 23, no. 15, p. 6671, 2023.

[15] T. Jiang, L. Ren, Z. Jia, D. Li, and H. Li, "Application of FBG Based Sensor in Pipeline Safety Monitoring," *Applied Sciences*, vol. 7, no. 6, p. 540, 2017.

[16] T. Wu, G. Liu, S. Fu, and F. Xing, "Recent Progress of Fiber-Optic Sensors for the Structural Health Monitoring of Civil Infrastructure," *Sensors*, vol. 20, no. 16, p. 4517, 2020.

[17] D. Lo Presti, F. Santucci, C. Massaroni, D. Formica, R. Setola, and E. Schena, "A multi-point heart rate monitoring using a soft wearable system based on fiber optic technology," *Sci. Rep.*, vol. 11, p. 21162, 2021.

[18] P. Rajeev, J. Kodikara, W. K. Chiu, and T. Kuen, "Distributed Optical Fibre Sensors and Their Applications in Pipeline Monitoring," *Key Engineering Materials*, vol. 558, pp. 424-434, 2013.

[19] U. Sampath, H. Kim, D. G. Kim, Y. C. Kim, and M. Song, "In-Situ Cure Monitoring of Wind Turbine Blades by Using Fiber Bragg Grating Sensors and Fresnel Reflection Measurement," *Sensors*, vol. 15, no. 8, pp. 18229-18238, 2015.

[20] N. Nayak, B. Keswani, D. R. Nayak, P. Sharma, A. G. Mohapatra, and A. Khanna, "Fiber Bragg grating temperature sensor and calibration scheme in high magnetic field environment: An application for aluminium electrolysis cell in potline," in Proc. Int. Conf. Comput., Commun., Intell. Syst. (ICCCIS), pp. 86–90, 2022.

[21] D. L. Presti, C. Massaroni, C. S. J. Leitao, M. D. F. Domingues, M. Sypabekova, D. Barrera, I. Floris, L. Massari, C. M. Oddo, S. Sales, et al., "Fiber Bragg Gratings for Medical Applications and Future Challenges: A Review," *IEEE Access*, vol. 8, pp. 156863–156888, 2020.

[22] A. Theodosiou, "Recent Advances in Fiber Bragg Grating Sensing," *Sensors*, vol. 24, no. 2, p. 532, 2024.

[23] S. Javdani, M. Fabian, J. Carlton, T. Sun, and K. Grattan, "Underwater Free-Vibration Analysis of Full-Scale Marine Propeller Using a Fiber Bragg Grating-Based Sensor System," *IEEE Sensors Journal*, vol. 16, pp. 1-1, 2015.

[24] M. A. Butt, G. S. Voronkov, E. P. Grakhova, R. V. Kutluyarov, N. L. Kazanskiy, and S. N. Khonina, "Environmental Monitoring: A Comprehensive Review on Optical Waveguide and Fiber-Based Sensors," *Biosensors (Basel)*, vol. 12, no. 11, pp. 1038, Nov. 17, 2022.

[25] A. G. Mohapatra, J. Talukdar, T. C. Mishra, S. Anand, A. Jaiswal, A. Khanna, and D. Gupta, "Fiber Bragg grating sensors driven structural health monitoring by using multimedia-enabled IoT and big data technology," *Multimedia Tools and Applications*, vol. 81, pp. 34573–34593, 2022.

[26] A. G. Mohapatra, P. K. Tripathy, M. Mohanty, and A. Khanna, "IoT enabled distributed cardiac monitoring using Fiber Bragg Grating (FBG) sensing technology," in *Proceedings of 2nd Doctoral Symposium on Computational Intelligence (DoSCI-2021)*, Lucknow, SSRN Elsevier, 2021, pp. 1-6.

[27] S. Mishra, P. Sharan, and K. Saara, "Real time implementation of fiber Bragg grating sensor in monitoring flat wheel detection for railways," *Engineering Failure Analysis*, vol. 138, p. 106376, 2022.

[28] J. Brown, A. Davis, and L. Smith, "FBG Sensors for Earthquake Monitoring: Early Warning Systems and Structural Health Assessment," Journal of Seismology, vol. 27, no. 2, pp. 415-429, Apr. 2023.

[29] B. López-Castro, A. G. Haro-Baez, D. Arcos-Aviles, M. Barreno-Riera, and B. Landázuri-Avilés, "A Systematic Review of Structural Health Monitoring Systems to Strengthen Post-Earthquake Assessment Procedures," Sensors, vol. 22, no. 23, pp. 9206, 2022.