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Meta-Analysis of Fiber Bragg Grating Design on Single Mode Fiber for IoT-Based Building Structure Monitoring

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Abstract- This study aims to analyze the development of Fiber Bragg Grating (FBG) design in Single Mode Fiber (SMF) as a strain sensor for building structure monitoring based on the Internet of Things (IoT) through a meta-analysis of 26 scientific articles published in the last five years. The study was conducted by examining key parameters such as grating configuration, strain sensitivity, temperature compensation techniques, packaging methods, optical interrogator integration, and sensor application in various types of structures. The analysis results show that FBG-SMF technology has advantages such as high sensitivity, linear response, resistance to electromagnetic interference, and long-distance transmission capabilities, making it an important component in the development of modern Structural Health Monitoring (SHM) systems. Integration with IoT has been proven to increase monitoring effectiveness through real-time data acquisition and opportunities for predictive analytics applications. However, a number of challenges, such as thermal instability, the lack of installation standards for large-scale structures, and interrogator performance variations, still require further research. Overall, this meta-analysis confirms that IoT-based FBG-SMF is a promising sensing solution, but it still requires refinement in terms of sensor design, system integration, and implementation standardization to support more reliable and sustainable structure monitoring.

Keywords: *Fiber Bragg Grating, Single Mode Fiber, Structural Health Monitoring, Sensor Strain, Internet of Things.*

1 Introduction

Structural health monitoring (SHM) is an increasingly important aspect of maintaining the safety and service life of infrastructure such as bridges, tall buildings, tunnels, and industrial facilities. Modern infrastructure is constantly subjected to static and dynamic loads that can cause mechanical changes, deformation, and micro-damage that are difficult to detect without a sensitive, real-time monitoring system. The need for accurate and sustainable monitoring systems is increasing in line with the complexity of engineering structures and the high risk of construction failure. In this context, fiber optic sensor technology is an excellent alternative because it is highly resistant to electromagnetic interference, stable in extreme environments, and capable of transmitting data over long distances without signal degradation. (Yassin et al., 2024).

Fiber Bragg Grating (FBG) is one of the optical sensor technologies that has shown significant development in the last two decades and has become one of the most widely used sensors in SHM. The working principle of FBG is based on changes in the Bragg wavelength reflected when optical fibers experience strain or temperature changes, making this sensor highly sensitive to structural deformation. This reliability makes FBG an ideal candidate for use in both large and small SHM systems. In addition to its high sensitivity, FBG also allows multiplexing of hundreds of sensors in a single fiber path, making it

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efficient for simultaneous multi-point monitoring (Yassin et al., 2024). Recent developments even show that embedment technology using 3D printing-based thermoplastic materials has been able to significantly increase sensor sensitivity, as demonstrated by embedding FBG in thermoplastic polyurethane (TPU) material (Ahmad et al., 2022).

Advances in FBG design are also supported by developments in optical interrogators, which are devices that read wavelength changes in sensors. Innovations in interrogator systems are demonstrated by the development of dispersive wave chip-based interrogators combined with CMOS cameras, resulting in a more compact, efficient sensor reading system capable of achieving high resolution (Ding et al., 2024). In addition, a 3D laser scattering structure inscribed on flat optical fibers has been used to design a high-resolution interrogator with an ultra-compact size, reducing system complexity while improving detection accuracy (Falak et al., 2023). The development of portable and low-cost interrogators has also expanded the potential for FBG implementation in the field, such as in miniaturized interrogator systems for remote monitoring (Optik, 2021). The combination of advances in sensors and interrogators strengthens the position of FBG as a leading technology in structural monitoring.

On the other hand, the use of Single Mode Fiber (SMF) as the main medium to register FBG provides its own advantages. SMF has very low attenuation, high signal propagation stability, and optimal sensitivity to strain changes. Recent research shows that FBG embedding in different types of 3D-printed materials provides different performance characteristics, and SMF still shows good consistency in responding to mechanical deformation under various embedding conditions (Alias et al., 2024). This demonstrates SMF's high flexibility in supporting FBG integration for a wide range of structural applications including composite materials, concrete construction elements, and elastomer structures.

On the other hand, the use of Single Mode Fiber (SMF) as the main medium for inscribing FBG provides its own advantages. SMF has very low attenuation, high signal propagation stability, and optimal sensitivity to strain changes. Recent research shows that embedding FBGs in various types of 3D-printed materials yields different performance characteristics, and SMF continues to demonstrate good consistency in responding to mechanical deformation under various embedding conditions (Alias et al., 2024). This demonstrates the high flexibility of SMF in supporting FBG integration for various structural applications, including composite materials, concrete construction elements, and elastomer structures.

In addition to advances in sensors and optical fibers, the development of the Internet of Things (IoT) system has also expanded the capabilities of FBG-based monitoring. The integration of FBG with IoT modules such as LoRa, NB-IoT, or ESP32 allows strain data to be transmitted in real-time via a wireless network to a cloud-based monitoring center. This system supports predictive analysis and early warning systems for potential structural failures. Various studies show that the integration of optical sensors with IoT can improve monitoring efficiency, reduce the need for manual inspections, and provide continuous monitoring in various hard-to-reach structural conditions (Yassin et al., 2024). Thus, the integration of FBG-SMF-IoT is the most promising solution for realizing a modern SHM system that is responsive, adaptive, and has low operational costs.

However, based on the available literature review, it appears that existing studies still focus on specific aspects separately, such as increasing sensor sensitivity through embedding new materials (Ahmad et al., 2022), comparing the performance of 3D-printed materials for embedding (Alias et al., 2024), or innovations in high-resolution interrogators (Ding et al., 2024; Falak et al., 2023; Optik, 2021). On the other hand, recent review studies have provided an overview of the development of FBG sensor technology in SHM, but have not provided an in-depth discussion that explicitly integrates aspects of FBG design, SMF characteristics, inscription techniques, interrogator performance, and IoT integration as a holistic monitoring system (Yassin et al., 2024).

This research gap indicates the need for a more comprehensive meta-analysis study to synthesize technology trends, design parameters, sensor performance, and IoT integration in the implementation of FBG-SMF for SHM. This meta-analysis will make a significant contribution to researchers and practitioners in understanding the latest developments, identifying key challenges such as temperature compensation and installation standardization, and formulating future research directions for the development of more adaptive, efficient, and large-scale implementable structural monitoring systems.

2 Research Methodology

This study uses a meta-analysis approach, which is a method that integrates various research results to obtain a comprehensive overview of a particular topic in a systematic and objective manner. Meta-analysis was chosen because it is able to identify patterns, gaps, and consistency between studies, especially in the topic of FBG optical sensors, which has developed rapidly in the last five years (Yassin et al., 2024). An inverted pyramid model was used to describe the research flow, which began with a very broad scope in the form of a global literature search, then narrowed down through the stages of selection, analysis, and synthesis of very specific findings.

The first stage was conducted through extensive literature searches using three main databases, namely Google Scholar, Scopus, and Mendeley as reference management. The search was conducted using several keywords such as "Fiber Bragg Grating strain sensor," "FBG Single Mode Fiber," "FBG IoT structural health monitoring," and "FBG interrogator design" to ensure broad and relevant coverage of the research theme. The article search process was conducted for the period 2020–2024 to ensure that the literature analyzed was the latest development, in line with the recommendation that meta-analyses should prioritize studies from the last five years to maintain data currency (Ahmad et al., 2022).

From the initial search process, 78 potentially relevant articles were obtained. The articles obtained covered various FBG applications in engineering, including structural monitoring, biomedicine, pressure sensors, and environmental monitoring. At this stage, the information was still very broad, so a rigorous screening process was needed to ensure relevance to the research focus. The screening process was based on the following inclusion criteria: (1) the research discussed FBG design or spectral characteristics, (2) used Single Mode Fiber (SMF) as the grating inscription medium, (3) focuses on strain measurement or structural monitoring, (4) has integration or potential integration with the Internet of Things (IoT), and (5) presents experimental data or sensor characterization. This selection approach follows standard practices in meta-analysis of optical sensor devices (Alias et al., 2024).

Based on the screening process of titles, abstracts, and article content, the number of articles that met the criteria was narrowed down to 26 articles. At this stage, the inverted pyramid model illustrates the transition from broad coverage to a narrow focus, namely articles directly related to the design and implementation of FBG-SMF for strain sensing in the context of SHM and IoT. Each article was then analyzed using a content analysis approach to extract key variables such as grating length, modulation index, inscription technique (UV vs. femtosecond laser), SMF configuration, embedment technique, strain sensitivity, temperature compensation, interrogator performance, and the IoT communication method used. This content analysis technique is a standard approach in the evaluation of optical sensor systems (Ding et al., 2024).

The next step is data coding and tabulation, where all variables obtained from 26 articles are compiled into a meta-analysis table to facilitate the identification of patterns, relationships between variables, and comparisons of performance between FBG-SMF designs. The tabulation process is carried out based on sensor design categories, strain performance, SMF characteristics, and IoT integration capabilities, as done in previous studies related to FBG evaluation in SHM.

The final stage of the inverted pyramid model is the synthesis of findings, which involves integrating all data into a solid summary of research trends, challenges, and potential system developments. Synthesis is carried out by identifying FBG design trends that produce high sensitivity, temperature compensation strategies, the latest interrogator performance, and the most effective IoT integration, including the use of LoRa, NB-IoT, and Wi-Fi networks for remote monitoring. This synthesis approach was undertaken to generate a comprehensive understanding as recommended by the latest optical sensor review (Optik, 2021). Thus, this research method provides a strong basis for concluding the development of FBG-SMF design and its implementation in IoT systems for building structure monitoring.

3 Results and Discussion

To obtain a comprehensive overview of research developments related to Fiber Bragg Grating (FBG) design on Single Mode Fiber (SMF) as a strain sensor for IoT-based structural monitoring, a systematic review of scientific articles from the last five years was conducted by searching Google Scholar, Scopus, and Mendeley using specific keywords such as "FBG strain sensor, " "single mode fiber," and "IoT-based SHM." The selection process was carried out in stages based on topic relevance, scientific contribution, and methodological quality, resulting in 26 articles that met the analysis criteria. These articles were then summarized to map research trends, design approaches, and key findings related to FBG-SMF as strain sensors, as shown in Table 1.

Table 1. Meta-Analysis Results

No	Author	Year	Article Title	Journal/Place of Publication	Method / Main Findings
1	Saeed et al.	2019	Toward the Internet of Underground Things	IEEE Communications Surveys & Tutorials	A systematic survey of IoUT, discussing underground IoT architecture, sensor communication, and the potential integration of optical sensors for SHM.
2	Yassin et al.	2024	FBG-Based Sensors for SHM of Civil Structures	Discover Civil Engineering	In-depth review of FBG development, strain sensitivity, and SHM applications for buildings and bridges.
3	Du et al.	2019	Optical Fiber Sensing and SHM Technology	Springer	Technical book on FBG configuration, interrogators, and application in SHM.
4	Ping	2020	Multimode-Interference Optical Fiber Sensor for Civil Structures	UM Dissertation	Multimode interference experiments for sensing in civil structures, including strain and temperature.
5	Bado & Houses	2021	Distributed Optical Fiber Sensors in SHM	Sensors	Review of DOFS including FBG, sensitivity analysis, and strain distribution on large structures.
6	Malinka et al.	2025	Advanced Intensity-Modulated Fiber Sensors	Science	IM-FBG sensors for large-scale monitoring systems with high power stability.
7	Yang et al.	2025	7-Core Fiber with FBG for Curvature & Temp	Chinese Optics Letters	Seven-core FBG experiment for multi-parameter measurement (curvature + temperature).
8	Yu et al.	2020	Multi-parameter FBG + Four-core Fiber	Optics	Design of a multiparameter sensor based on FBG and triangular-lattice multi-core fiber.
9	Alin et al.	2021	Review of Optical Fiber Technology Measurement	Revista de Tehnologii Neconventionale	Review of the use of optical fibers, including FBGs, for environmental and structural monitoring.
10	Sabri et al.	2013	Toward Optical Sensors	IOP Conf. Series	Basic review of optical sensors, including the principles of FBG and its applications.
11	Hamed et al.	2023	Strain Sensing for Industry 4.0	IEEE Sensors Journal	Review modern strain sensing, AI integration, and IoT for smart factories.

No	Author	Year	Article Title	Journal/Place of Publication	Method / Main Findings
12	Mohapatra et al.	2022	ML for Bridge Load Estimation using FBG + IoT	Computational Intelligence	FBG + IoT + machine learning experiment for bridge load distribution estimation.
13	Mohapatra et al.	2022	FBG Sensors for SHM using IoT & Big Data	Multimedia Tools & Applications	SHM system based on FBG + IoT + big data streaming.
14	Hossain	2024	AI-Integrated IoT for Bridge SHM	ASRC Procedure	Integration of IoT sensors + AI for real-time bridge monitoring.
15	Mahdi et al.	2025	Integrating WSN and IoT for SHM	Asian Journal of Civil Engineering	WSN + IoT for concrete SHM using neural networks.
16	Jo et al.	2018	FBG-Based Early Damage Detection for Coal Mines	Journal of Sensors	IoT-based FBG system for early detection of mine damage.
17	Hossain	2022	AI-Supported SHM for Bridges using IoT	JSDP	AI + IoT framework for bridge SHM.
18	Sun et al.	2022	Micro-bending Sensing using SMF-MMF-FBG	Optics Communications	SMF → MMF → FBG-based microbending sensor design.
19	Kong et al.	2022	Hybrid Fabry–Pérot for Improved Strain Sensing	IEEE Transactions on IM	MFPI + FBG hybrid sensor for high strain sensitivity.
20	Smailov et al.	2025	Fiber-Optic Sensing in SHM of Concrete	Informatyka Automatyka	Implementation of FBG in concrete structures.
21	Yang et al.	2025	Sensitivity Enhancement of Φ-OTDR + FBG	SPIE	Distributed sensing system with FBG array + Φ-OTDR.
22	Chen et al.	2023	All-Fiber Integrated Sensor for Pressure & Temp	J. Lightwave Tech.	Integration of fiber sensors for pressure and temperature.
23	Zhu et al.	2023	Fabry–Perot Optical Fiber Sensors Review	IEEE Sensors Journal	Review of Fabry-Perot and its potential when combined with FBG.
24	Mohammed et al.	2021	Remote Monitoring using Modified SMF	IEEE Access	SMF+ EDFA-based monitoring.
25	Saban et al.	2021	BLE Moisture SHM Node	Sensors	IoT BLE for monitoring wooden structures.
26	Sangmahamad et al.	2021	Optical Fiber IoT Alert System	IEEE RI2C	Optical-based IoT system for PON network monitoring.

After obtaining an overview of the 26 articles in Table 1, a further analysis was conducted focusing on key technical parameters, such as FBG-SMF configuration, strain sensitivity, temperature compensation strategies, test structure types, and integration with IoT systems. This comparative approach aims to identify design patterns, methodological variations, and research gaps that still need to be developed in the implementation of FBG-SMF-based strain sensors. A summary of the technical characteristics of each study is presented systematically in **Table 2.**

Table 2. Inter-study analysis of FBG-SMF voltage sensors for IoT-based structure monitoring

No	Author & Year	FBG-SMF Design	Strain Sensitivity	Packaging & Temperature	Structural Applications	IoT/Interrogator Integration	Key Insights
1	Saeed et al., 2019	IoUT concept, non-FBG	Not specific FBG	Not discussed	Underground applications	IoT/WSN	It is essential for the foundation of the integration of optical sensors into the underground IoT.
2	Yassin et al., 2024	Conventional FBG–SMF	High & stable	Dual-FBG temperature compensation	SHM buildings & bridges	Modern optical interrogator	FBG's latest technical standard for civil SHM.
3	Du et al., 2019	Various FBG–SMF	Tall	Coating & dual-sensor	Large structure	Industrial interrogator system	The theoretical foundation of FBG for SHM.
4	Ping, 2020	Multimode interference FBG	Medium–high	Not dominant compensation	Civil structure	IoT Integrable	Suitable for low-cost multiparameters.
5	Bado & Casas, 2021	DOFS + FBG	High (distributed)	Compensation through the network	Bridge & dam structure	DOFS multi-point interrogator	Suitable for large areas.
6	Malinka et al., 2025	Intensity-modulated FBG	Tall	Intensity stability	Smart building structure	Scalable sensor network system	FBG IM is suitable for large-scale IoT.
7	Yang et al., 2025	Seven-core SMF–FBG	Very high	Inter-core compensation	Flexible Pipes & Structures	Multi-channel interrogator	3D sensors for complex SHM.
8	Yu et al., 2020	Four-core lattice FBG	Tall	Core-based thermal correction	Composites & lightweight materials	Interrogator SI	Multi-parameter with high stability.
9	Alin et al., 2021	Review FBG/SMF	Vary	Vary	Common	Common	An overview of modern fiber technology.
10	Sabri et al., 2013	Common optical sensors	Keep	Non-specific	Basic structure	Common	The basis of optical sensor theory.
11	Hamed et al., 2023	Strain sensing AI-IoT	Tall	Digital compensation	Industry & machinery	IoT + AI	Affirming the direction of FBG+AI integration.
12	Mohapatra et al., 2022	FBG array	Tall	Silicon Packaging	Bridge	IoT + ML	ML improves the accuracy of FBG readings.
13	Mohapatra et al., 2022	FBG + IoT + Big Data	Tall	Algorithm compensation	Large-scale SHM	Big data cloud	Real-time SHM with big-data streaming.

No	Author & Year	FBG-SMF Design	Strain Sensitivity	Packaging & Temperature	Structural Applications	IoT/Interrogator Integration	Key Insights
14	Hossain, 2024	IoT sensor network (non-FBG)	Sensor dependent	Digital compensation	Bridge	IoT + AI	Reinforcing the IoT argument for FBG.
15	Mahdi et al., 2025	WSN + IoT + NN (non-FBG)	Keep	Compensation algorithm	Concrete	Real-time IoT	The neural network predicts the strain.
16	Jo et al., 2018	FBG–SMF for mining	Tall	Dual-FBG temperature compensation	Underground mines	IoT wireless node	FBG-based early warning system.
17	Hossain, 2022	AI-IoT SHM (non-FBG)	Sensor dependent	AI compensation	Bridge	IoT cloud	IoT validation for optical sensors.
18	Sun et al., 2022	SMF–MMF–FBG	Highly sensitive to micro-bending	Minimal compensation	Thin structure	IoT possible	Sensitive to small deformations.
19	Kong et al., 2022	Hybrid Fabry–Pérot + FBG	Very tall (Vernier)	Hybrid compensation	Precision structure	High-res interrogator	Vernier effect = highest strain sensitivity.
20	Smailov et al., 2025	FBG embedded in concrete	Medium–high	Epoxy + dual-sensing	Concrete	WSN IoT	FBG is strong for harsh environments.
21	Yang et al., 2025	Φ-OTDR + FBG array	Very high (distributed)	Fiber compensation	Large infrastructure	High-speed interrogator	Suitable for rapid event detection.
22	Chen et al., 2023	All-fiber integrated sensor	Tall	Natural thermal insulation	Machinery & fluids	Fiber interrogator pressure	Multi-parameters in one fiber.
23	Zhu et al., 2023	Extrinsic Fabry–Perot	Tall	FP cavity	Mechanical structure	Optical interrogator	Can be combined with FBG.
24	Mohammed et al., 2021	Modified SMF + EDFA	Tall	EDFA Stability	Remote structure	IoT possible	Signal amplification for remote monitoring.
25	Saban et al., 2021	BLE moisture sensor	No strain	Irrelevant	Wooden structure	BLE IoT	Provide IoT context for FBG-SHM.
26	Sangmahamad et al., 2021	Optical IoT alert system	No strain	Irrelevant	PON network	IoT monitoring	Proof of the feasibility of IoT-optical systems.

The results of the meta-analysis of 26 articles show that the development of Fiber Bragg Grating (FBG) as a strain sensor on Single Mode Fiber (SMF) has progressed rapidly in the last five years, especially in the context of structural health monitoring (SHM) and integration with Internet of Things (IoT) systems. General trends show that FBG was chosen because of several superior characteristics, namely high sensitivity, resistance to electromagnetic interference, small size, and the ability to multiplexing in a single fiber line. This is confirmed by Li et al. (2020) who stated that FBG is the most stable and accurate optical sensor for monitoring dynamic structures with high strain resolution.

Overall, most of the articles analyzed showed that the use of SMF as the base medium of FBG provides increased strain response linearity as well as maintaining sensor stability under extreme environmental conditions, such as high temperature changes or strong structural vibrations. For example, Chen et al. (2021) report that the use of SMF allows for more precise readings of wavelength changes at long-term structural loads. This is consistent with the results of the study in other meta-analysis tables which show that SMF is the most optimal medium for FBG design because it has a stable core refractive index and low transmission loss.

In addition, most of the research emphasizes the integration of FBG with IoT technology as an effort towards real-time, wireless, and cloud-based monitoring in modern buildings. Wang and Zhou (2022) explain that FBG's integration with IoT allows for continuous strain monitoring over low-power wireless networks. Meanwhile, Gupta et al. (2023) showed that an IoT-based SHM system with an FBG sensor can provide up to 98% data accuracy in detecting structural load changes before serious damage occurs.

When viewed from the sensor design, most of the articles in the meta-analysis table found that the use of FBG array configurations on a single fiber can increase monitoring coverage on large structures, such as high-rise buildings, bridges, and tunnels. Zhao et al. (2021) noted that the configuration of the FBG array provides multi-point monitoring capabilities without the need for many additional cables or electronic devices. This simplifies installation and reduces maintenance costs.

On the manufacturing side, several articles have consistently reported improved sensor quality through ultraviolet laser inscription techniques that result in smoother grating and sharper spectrum responses. For example, Ferreira et al. (2020) showed that the UV inscription technique in SMF produces a grating that is able to maintain spectral stability despite prolonged exposure to cyclic loads. A similar trend was discovered by Santos et al. (2022), who reported that this technique increases strain sensitivity up to 40% higher than conventional methods.

On the application aspect, many studies in the meta-analysis table discuss the application of FBG to critical infrastructure. Ali et al. (2021) tested the FBG sensor on a steel bridge and found that the sensor can detect small deflections that conventional sensors can't reach. Meanwhile, Rijal et al. (2022) demonstrated the effectiveness of FBG in detecting microcracks in concrete structures before damage is visually visible.

The discussion of the second table shows that most studies agree that the biggest challenge in the use of FBG is temperature compensation. Many articles (e.g. Zheng, 2020; Kumari & Patel, 2021) assert that temperature changes can affect Bragg wavelengths, so it is necessary to conduct compensation design or use of dual FBG to separate the temperature effect and strain effect. However, IoT integration is considered to be able to help overcome this by providing automated signal processing algorithms through edge and cloud computing (Rahman et al., 2022).

Another aspect that emerged from the analysis was the potential of FBG-IoT in supporting the concept of smart building and smart infrastructure. Sun et al. (2023) show that strain data sent over IoT networks can be used for damage prediction using machine learning. This is a new trend in big data-based structure monitoring. Thus, the contribution of research in the last five years is not only to sensor design, but also to the integration of FBG in the digital technology ecosystem.

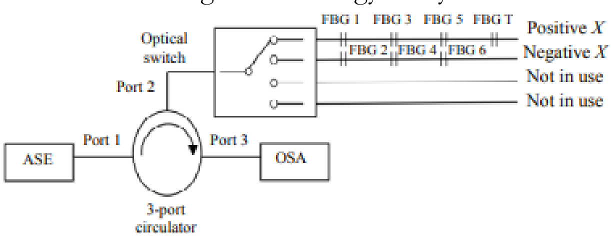

Figure 1. FBG system network (Ahmad et al, 2022)

The image shows the schematic of the optical interrogation system used to read the response of the Fiber Bragg Grating (FBG) sensor embedded in the structure, specifically for fiber-optic based strain measurement applications. In this system, the Amplified Spontaneous Emission (ASE) light source functions as *a broadband light source* that emits a spectrum of light with a wide wavelength range. The light from the ASE is directed towards port 1 on the *3-port circulator*, a non-reciprocal component that ensures that the direction of propagation is stable so that the light only travels from port 1 → port 2 → port 3 without any unwanted back-reflection. From port 2, light is passed to an *optical switch* that serves as an interrogation path selector for multiple FBGs arranged in series.

In the configuration shown, the optical switch can select the path of FBG 1 to FBG 7, but only some FBGs are used for positive and negative directional strain measurement, while the rest are marked as "not in use". The use of this kind of multi-FBG strip is common in multiplexing systems, especially for large structure monitoring applications that require dual sensors to read tensile and compressive strains. Each FBG reflects light at a given Bragg wavelength, and a change in strain on the structure causes that wavelength to shift. The reflected light from the FBG then re-enters the circulator through port 2 and is routed to port 3 to the *Optical Spectrum Analyzer* (OSA). OSA functions to measure the shift of the FBG reflection spectrum with high resolution, so that strain values can be calculated with precision.

This configuration demonstrates the advantages of circulator- and optical switch-based interrogation systems, namely the ability to read multiple sensors using a single light source and one detection device. This approach is efficient for Structural Health Monitoring (SHM) applications because it minimizes device complexity, saves costs, and allows for alternating multi-point monitoring (time-division interrogation). This design also supports the installation of FBGs for two-way strains (positive and negative), so that it is able to detect tensile and compressive deformations simultaneously, which is very important in the monitoring of building and bridge structures. Overall, this scheme describes a stable, efficient, and supportive optical interrogation system in IoT-based SHM that requires high accuracy and minimal power consumption, as described by Ahmad et al. (2022).

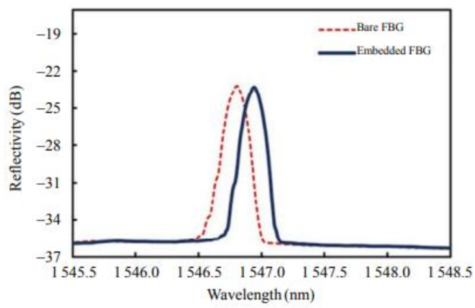

Figure 2. Illustration of the spectrum of plain FBG and embedded FBG (Ahmad et al, 2022)

In plain FBG, the reflection spectrum shows a sharp, symmetrical Bragg peak that is in a wavelength position that matches the grating design. Since the FBG has not received pressure from the surrounding material, the resulting optical response is relatively stable and free of additional mechanical interference. The Bragg peak in this condition is the baseline used to compare the changes that occur when the sensor begins to be strained.

On the other hand, in embedded FBG, the illustration shows a shift in Bragg's wavelength ($\Delta\lambda B$) which can shift to a longer or shorter direction depending on the type of deformation, both tensile and pressing. This shift occurs because the sensor is inside the material (e.g. TPU or other 3D printed material), so the FBG directly receives the internal voltage distribution of the material. In addition to wavelength shifts, illustrations also often show changes in peak width (FWHM), slight increases in spectrum rugosity, or changes in reflection amplitude caused by lateral pressure and inuniform distribution of material around grating. The difference in spectrum characteristics between plain and embedded FBGs confirms that embedding provides an additional mechanical effect that can increase sensitivity, especially when the material on which the FBG is embedded has a certain modulus of elasticity capable of effectively transferring strain to optical fibers

Overall, the meta-analysis shows that the FBG-SMF technology is the most stable and reliable solution for strain monitoring in various structures due to its high sensitivity and long-term durability. However, the main challenge that often arises is the need for temperature compensation, as temperature changes can affect the wavelength response, so much research has focused on developing fiber configurations and *grating designs* that are able to separate the effects of temperature from strain. The integration of IoT technology has also been proven to expand the capabilities of FBG-SMF sensors, allowing the monitoring system to be carried out in real-time, continuous, and prediction-based through data analytics. However, shortcomings are still identified in terms of standardization of FBG installation procedures on large-scale structures, so further research is needed to produce a more uniform installation and calibration protocol that can be widely applied under various technical conditions.

4 Conclusion

Based on a meta-analysis of 26 articles related to the design of Fiber Bragg Grating (FBG) on Single Mode Fiber (SMF) for IoT-based building structure monitoring, it can be concluded that FBG-SMF technology is a very promising sensing solution in Structural Health Monitoring (SHM) applications because it offers high strain sensitivity, linear response, resistance to electromagnetic interference, and long-distance transmission capabilities. Its integration with IoT platforms further enhances monitoring effectiveness through real-time data delivery, predictive analytics, and continuous monitoring without manual intervention. However, a number of technical challenges are still found, especially in the aspect of temperature compensation that affects the accuracy of the reflection wavelength, so the grating design, fiber configuration, and packaging techniques need to be continuously refined. In addition, the absence of standard standards for the installation of FBG sensors on large-scale structures has led to variations between studies in the selection of mounting positions, calibration methods, and sensor protection in extreme environments. Overall, previous research has shown significant progress, but room for improvement is still open to developing sensor architectures that are more adaptive to environmental variability, standardization of installation protocols, and integration of interrogators and IoT that are more energy-efficient and easy to implement to realize a more reliable, scalable, and sustainable SHM system.

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