

Fiber Bragg Grating Sensors in Industry 4.0

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Abstract

Review of the Fiber Bragg Grating (FBG) sensor technology's state-of-the-art. In the past three decades, FBG sensors have drawn a lot of attention because of their key benefits, which include immunity to electromagnetic interference, lightweight, compact size, high sensitivity, huge operation bandwidth, and excellent multiplexing capabilities. Temperature and strain are the two most extensively researched sense physical variables. This paper focuses on the operation of fiber bracket grating sensors and their integration in industrial 4.0, extending to the latest real-time applications in the oil and gas industry, cargo ship handling systems, and structural health monitoring systems for industrial applications in aerospace. Studies and reviews of the many benefits of fiber Bragg grating demonstrate that it outperforms conventional sensors in terms of sensitivity, cost, weight, and electromagnetic interference.

Introduction

Fiber optic technology has surely developed and changed over the past three decades. As a result of the developments in optical fibre, the term telecommunication has come to be understood as referring to optical fibres and associated components. Optical fibres are used in the quickly expanding field of fiber sensors in addition to their use in telecommunications [1]. One of the sensing fields in optical fiber sensors that have advanced the fastest this decade is the Fiber Bragg grating (FBG) sensor technology. Due to FBG sensors currently leaving the lab and entering the real world, both the FBG research and deployment of sensor systems have advanced quickly in recent years [2].

In developing technologies, Fiber Bragg grating is crucial for optical communication and sensing applications. The discovery of photo-sensitivity in optical fibres [2] had a significant influence on the advancement of sensor and telecommunications systems, resulting in a variety of devices being created for various uses. The photo-sensitivity property of silica fibre doped with germanium is often the foundation upon which a fibre Bragg grating (FBG) is built. The term "photo-sensitivity" describes how ultraviolet (UV) light exposure causes a permanent refractive index change [2,3].

Fibre optic sensor (FOS) systems for process control, environmental monitoring, and structural monitoring were reviewed by Willsch et al. in [4]. The study focused on advances in fibre Bragg grating (FBG) sensing for wind turbines, aerospace, structural health monitoring, and railroad applications, as well as advancements in chemical sensors and interrogation methods, as well as the FBG applications in transportation. The researchers further studied fibre optic sensors in 2011 with an emphasis on German industry and research [4]. The study emphasized the advancements made to

FBG technology as well as how they could spin off businesses, helping it move from a lab setting to an industrial setting. This is typical of FBG and other in-fibre grating technologies used all around the world. Several industry pioneers have already put test cybernetic production systems in place (production of equipment: household appliances, cars, machinery, and equipment). Industry 4.0 was introduced in Germany in 2011, and governments from industrialized nations all over the world have subsequently backed it vigorously [5]. The changes brought about by the twenty-first century will happen gradually over several decades in organizations due to the significant investments required to establish new cyber-production solutions. FBG sensors can monitor a wide range of physical, chemical, and environmental factors, such as temperature, pressure, shape, location, and chemical composition. Fiber Bragg sensors can be used to measure things that conventional electrical-based sensors cannot because of measurement requirements like high electromagnetic energy or radiation levels, extreme temperature, extremely small size, or large sensor count [6]. In this paper, a review of the integration of Fiber Optic sensors based on the fibre Bragg grating technique will be presented, starting from the reviewing of literature, the theory behind FBG, the integration of FBG sensors in industrial 4.0 and finally, the applications due to its integration of FBG.

Literature Survey

Recently, Industry 4.0-based manufacturing processes have drawn a lot of interest from many researchers, with a major focus on several areas such as sustainability, organizational structure, lean manufacturing, product development, and strategic management within the manufacturing industry. Researchers have looked into the interaction between various optimum control models and an Industry 4.0-based smart manufacturing system [7]. The advantages, difficulties, and risks of implementing smart factories have been thoroughly examined, but the integration of FBG-based sensors in an industrial 4.0 setting has been neglected despite its numerous advantages.

The determination of the roles of optical fiber sensors in the domain of the fourth industrial revolution is discussed in [8]. It embarks on the complex systems and their sensing capabilities. The principal sensing is discussed, and a survey of industrial 4.0 is narrated. The conceptual view of how optical sensing can contribute to the progress of industrial 4.0 is based on the vision and sensing attributes. In this study context, optical sensing was best positioned to make a significant contribution to the gradual emergence of the new paradigm, Industry 4.0, weighted to its enormous potential [8]. The discussion further had an emphasis on optic fibre sensing through fibre Bragg grating; however, a design or implementation of a prototype was not incorporated, which was a major downfall and probable applications which would use the Fiber Optic Sensors (FOS) as a major tool for sensing physical parameters.

In this section, fiber Bragg grating sensors' capabilities and characteristics are assessed with an eye toward hydraulic machinery and systems. In an effort to produce high-quality outputs, the hydropower sector is utilizing this technology [9]. Data for numerical models that could be used as digital twins of important assets, increasing the sector's relevance within Industry 4.0. Before using it,

fibre needs to be confirmed. Bragg grating sensors' ability to function well underwater for extended periods of time with little maintenance. Their scalability and simplicity of degradation attracted the author's attention [9-10].

The following is a simplified modal analysis as a first step in validating the potential of this sort of beam; a partially submerged beam is proposed. Hydro-power technology is a type of technology that is used to generate electricity from water. The beam's position is measured using Bragg grating sensors' natural frequencies, which dampen vibrations in a variety of situations. The outcomes are contrasted by featuring reliable waterproof electronic strain gauges and a laser vibrometer. The existence of several sensors in a single fibre enables excellent spatial resolution, which is critical to the success of the system[9]. Determining vibration patterns with precision is a major concern in this market, hence the use of sensors with fibre brags grating technique.

In [10], the authors employed different kinds of sensors in the health diagnosis of agricultural structures, which was desirable for detecting cracks, concrete corrosion, spilling and delamination. They proposed that agricultural structures are prone to environmental damage due to frequent exposure to water, organic effluent, and farm chemicals [10]. The prototype in this research used different kinds of sensors, such as fibre optic sensors based on fibre Bragg grating technology and piezoelectric sensors, which were reviewed depending on the transmission speed and cost-benefit analysis. The drawbacks in [10] involved the installation of the sensors in the agricultural farm structures, technical constrains and the preference of using traditional inspection methods. Further to these drawbacks, the optical fiber sensors were not deployed to the crosscutting domain of industrial 4.0 technology.

The fabrication of force sensors is based on tri-axial fibre, as described in [11]. When inserting the catheter, the doctor needs to be aware of the force on the catheter tip. Bragg grating with a flexible structure designed on FBG force sensor suited for cardiac catheterization. The FBG fibre study was simulated in ANSYS, and its sensitivity and toughness were assessed. Three FBGs were used in conjunction with the interrogator to collect wavelength signals. The proposed design has the shortcomings of not being deployed in a real-world environment and not being integrated with Industrial 4.0 to meet the increasing demands of smart sensing in Industrial 4.0.

In [12] the recent advancements in the development of sensors for structural health monitoring (SHM) at high temperature environment discussed the usage of sensors in several applications in the industrial 4.0. The section emphasis on Industrial 4.0 focused on the interconnectivity, automation, machine learning and acquisition of real-time sensor data[12], further discussed the importance of real-time structural health monitoring for components of the fourth industrial revolution and also demonstrated the development, applications and recent advancements of existing sensors. The review did not elaborate much on the utilization of FBG sensors in Industrial 4.0, and no physical parameter which utilized an FBG sensor was discussed.

In the oil and gas business [13], fibre-optic sensor technology has revolutionized the monitoring of

wells and reservoirs. The passive nature of fibre optic sensors, their aptitude for cost-effective installations, and the ability to measure along the fibre length have all contributed to this development. Fiber optic sensors put in oil and gas wells provide information that adds to increased efficiency, safety, and final recovery. Moreover, FBG sensors were used for logging fields and seismic exploration in the oil and gas industry to collect sensor data for physical parameters such as temperature, pressure and acoustic waves in a hostile environment; however, a linkage of the sensor usage and industrial 4.0 was not discussed [13].

A further narration to the use of FBG as an enabling technology for oil and gas sensor data logging and health monitoring of pipeline applications [14]. Over the previous years, the oil and gas industry has had an increase in fibre optic sensor technology to monitor the bottom wells of oil reserves [14]. The reservoir pressure and oil temperature are the main physical parameters in reservoir engineering. Many traditional sensors employed to monitor oil wells utilize conventional sensors, which became unreliable at high temperatures and were not accurate. The FBG optic sensors have proved to have high accuracy at high operating temperatures, making them ideal for working in down-holes and conducting measurements at high temperatures. The downside of the research was the use of expensive interrogators, and sensor data was not used in the decision-making processes of industrial 4.0 applications. However, some merits involved the pressure and strain sensing techniques used in the FBGs.

The penetration of fiber Bragg grating sensors into typical industrial operations, such as the amenities and services industry, mining, and the oil and gas business, has been very limited despite the fact that the technology has been developing for more than 40 years [15], as well as the cost and complexity of FBG sensor networks. Furthermore, only a small number of applications, including safeguarding industrial assets and tracking structural health, which are not addressed in depth in [15], have seen substantial advancements in FBG sensing and interrogation due to the lack of industry standards. Detailed analyses of FBG-based sensors intended for physical security applications are provided, as well as their applications in industrial processes, along with a study of fiber-based opto-acoustic sensors used in structural health monitoring.

Over the years, the primary objective of research in the field of fiber Bragg grating sensing has been the development of sensors with better sensitivity at various wavelengths. For applications with a relatively low frequency, such as those in the process control industry, this is not the most crucial factor to take into account[16]. However, the appropriate dynamic range, suitable packing, and networking capabilities are the most crucial parameters to be considered [17].

This reference focuses on the adoption of the integration of FBG sensors in industrial 4.0. setting to enhance sensing and exploit its advantages.

Theory of Fiber Bragg Grating Sensors and Industrial 4.0

Fiber Bragg Grating

The grating-based advancements in spectral modulated fibre sensors, like the fibre Bragg grating, hold the greatest promise (FBG). Since 1989, when FBGs were first used for sensing applications, they have attracted significant interest and have undergone continuous, quick development. Using FBG's technology, which has been around for some time now. Numerous concepts and demodulation algorithms have been developed for a range of measurements and applications. To produce Fiber Bragg Gratings, the refractive index in the single-mode optical fibres' core is periodically changed [18].

FBG-based sensors have also gained popularity as sensing tools, and they are used for everything from chemical sensing to structural monitoring [19]. Any modification of the fibre's physical characteristics, such as strain or temperature, alters the fibre index or grating pitch, which alters the Bragg wavelength [19]. Therefore, by figuring out the grating's highest reflectivity wavelength, learning more about the sensing physical parameters is observed, which can be deployed in harsh environments not suitable for conventional sensors.

FBGs are predominantly engraved on photosensitive fibres, and photo-sensitivity occurs, irreversibly changing the refractive index of the fibre's core when exposed to light of a specific wavelength and intensity. When light from a broadband source is launched from one side of the fibre, only a particular wavelength meeting the Bragg condition will be reflected; the other light will be transmitted, as shown in Fig. 1. This happens because Bragg reflection occurs in every region with a modified refractive index [20]. When light reflects at interfaces where the refractive index varies, it is referred to as a "Bragg reflection."

Fiber Bragg Grating (FBG) is based on contra-directional couplings. In the case of single-mode fibre, the propagating core mode is reflected in the identical core mode propagating in the opposite direction. In most cases of moderated FBGs, the coupling of Bragg reflection is dominant compared to the cladding-mode couplings, even though it is possible for the core mode to be coupled with the counter-propagating cladding modes in cases that include strong gratings and blazed grating [21].



Figure 1: Fiber Bragg Grating Structure

FBG sensors, which rely much on the diffraction grating theory, are systems where the longitudinal index of refraction of the fibre core is periodically modulated. The grating is designed to achieve a regular variation in the core's refractive index. Using an optic fibre as a sensor, the perturbation is

measured as the light travels through the grating, with each grating layer reflecting back a portion of the incident light of a particular wavelength [22]. The refractive index of the optical fibre core (n_{eff}) with respect to the grating length and the period of the grating microstructure (Λ) effectively defines the Bragg wavelength (λ_B).

$$\lambda_B = 2n_{eff} \Lambda \quad (1)$$

Any changes of (n_{eff}) or (Λ) causes a shift in Bragg grating wavelength λ_B which can be computed by expanding Eq. (1) in terms of partial derivatives with respect to the temperature, wavelength and length.

$$\Delta\lambda = 2\Lambda \delta n_{eff} + n$$

$$\delta\Lambda \Delta L + 2\Lambda \delta n_{eff} + n$$

$$\delta\Lambda \Delta T + 2\Lambda \delta n_{eff} + n$$

$$\delta\Lambda \Delta\lambda$$

$$^B \delta L$$

$$_{eff} \delta L$$

$$\delta T^{eff} \delta T$$

$$\delta\lambda$$

$$(2)$$

$$_{eff} \delta\lambda$$

where ΔL is the change in the physical length of the grating due to the temperature applied, ΔT is the change in Temperature, and $\Delta\lambda$ is the change in wavelength. Furthermore, the optical response of fiber Bragg grating to the shift in wavelength is denoted as:

$$_{eff} \delta\lambda$$

$$\Delta\lambda_B$$

$$= 2\Lambda \delta n_{eff} + n$$

$$\delta\lambda$$

$$\delta\Lambda \Delta\lambda \quad (3)$$

The refractive index actually changes very negligibly as a result of wavelength changes. Additionally,

the wavelength shift has no impact on the periodic spacing of the index modulations in fibre. Thus, by neglecting the wavelength effects, Eq.(2) can be written as

$$n_{eff} \delta L$$

$$\delta T$$

$$n_{eff} \delta T$$

$$\Delta \lambda = 2 \Lambda \delta n_{eff} + n$$

$$B$$

$$\delta L$$

$$\delta \Lambda \Delta L + 2 \Lambda \delta n_{eff} + n$$

$$\delta \Lambda \Delta T (4)$$

where ΔL is the change in physical length of the grating due to the temperature applied, ΔT is the change in Temperature of the Fiber Bragg Grating.

Reflectivity of Fiber Bragg Grating

The Bragg reflection theory serves as the foundation for FBGs-based sensors. Erdogan's Coupled Mode Theory (CMT) estimates the reflectivity obtained in FBG at each grating inside the fibre.

Consider an optical fibre with an average refractive index (n_0) that has been fashioned into a uniform Bragg grating. The expression for refractive index profile can be denoted as

$$n(z) = n_0 + \Delta n \cos$$

$$2\pi z$$

$$(5)$$

$$\Lambda$$

where Δn is the length of the fibre's longitudinal axis, z is the distance and is the magnitude of the induced refractive index perturbation. For a constant modulation amplitude and time, the reflectivity of a grating-based CMT is given by:

$$\Omega^2 \sin^2(sL)$$

$$R(L, \lambda) = \Delta k^2 \sinh^2(sL) + s^2 \cosh^2(sL) (6)$$

where $R(L, \lambda)$ is the Reflectivity (with functions of grating length L and wavelength λ). The coupling coefficient is denoted as Ω , $\Delta k = k - \pi/\lambda$ is the detuning wave vector, the propagation constant is $k = (2\pi n_0)/\lambda$ and $s^2 = \Omega^2 - \Delta k^2$.

The coupling coefficient, Ω , is expressed as the index perturbation's sinusoidal variation along the fibre axis.

$$\pi \Delta n$$

$$\Omega = \lambda M_p (7)$$

where M_p is the fibre mode power's per cent. There is no wavevector detuning at the middle wavelength of the Bragg grating, and $\Delta k = 0$. As a result, Eq. 7 provides the expression for the reflectivity of FBG.

$$R(L, \lambda) = \tanh^2(\Omega L) (8)$$

FBG becomes more reflective as the induced index of refraction increases. Similar to this, the reflectance will rise as the grating length does. As the induced index of refraction changes, so does the level of reflectivity. Similar to this, the grating's reflectance rises as it gets longer. The side lobes of the resonance are caused by numerous reflections to and from the opposite ends of the grating region. The general formula for a grating's approximate full width at half-maximum bandwidth, or (λ_{FWHM}) , is given as :

$$\lambda_{FWHM} = \lambda B s$$

$$\Delta n^2$$

$$s$$

$$+$$

$$2n_0$$

$$1/2$$

$$N$$

$$(9)$$

where N is the number of the grating planes. The parameter s is ≈ 1 for strong gratings (for gratings with near 100 % reflection) and ≈ 0 for weak gratings.

FBG's Sensing Mechanism

The FBG sensor operates on the basis of wavelength shift. According to coupled mode theory, the grating period and effective refractive index of the fibre are two physical characteristics that affect Bragg wavelength [23]. Only when the period of the gratings or the effective refractive index of the FBG is altered by a physical parameter to be monitored, such as temperature, strain, humidity, pressure, etc., does the wavelength of the reflected spectrum shift to the left or right of the central wavelength [23]. The amount of external perturbation delivered to the FBG can be determined by the wavelength change that can be observed under the Bragg condition.



Figure 2: Wavelength shift due to external perturbation

Basics of Industrial 4.0.

The emergence of information and communication technologies has been manufacturing is only one of many industries that are creating new realities. Consequently, a manufacturing idea known as the fourth industrial revolution industrial revolution (sometimes referred to as "Smart Manufacturing," "Industry 4.0," and There is now a connected factory [24-25]. This idea is referred to as Industry 4.0 (4IR), and in this article, we are opting for the deployment of FBG-based sensors in the sensing layer of Industrial 4.0. In light of this, Industry 4.0 demands the finest technology that can offer advanced information and communication in manufacturing industries.

The term "Industry 4.0" refers to a fourth industrial revolution that follows the first three that have already occurred. During the first industrial revolution, these included the utilization of steam power; during the second, electricity; and finally, during the third, automation [26]. 4.0 was defined ex-ante, as opposed to preceding industrial revolutions, which were defined ex-post, and was based on a German government concept. The term "Industry 4.0," which denotes a German government initiative to retain the competitiveness of its industrial sector, first appeared during the Hanover Fair in 2011. The technological foundation of Industry 4.0 is comprised of cyber-physical systems, which allow for the merging of the real and virtual worlds. This necessitates the use of sensors that can accurately represent the real environment in the virtual one, as well as data processing, analysis, and communication systems.

Industry 1.0 emerged in the late 18th century as a result of the advent of mechanical industrial facilities [27]. Machinery powered by steam and water was created to assist employees in the huge manufacturing of commodities. Industry 2.0, which manufactured electrically powered machinery, first appeared at the turn of the 20th century. Electrical energy served as the primary energy source for the industry, and it employed a mass manufacturing process. The creation and manufacturing of numerous electronic devices at the turn of the century gave rise to Industry 3.0. This is crucial because automated devices reduce effort, speed up processing, improve precision, and, in certain

cases, completely replace humans.

The introduction of mechanical industrial facilities led to the development of Industry 1.0 in the late 18th century. To aid workers in the massive production of goods, water and steam-powered machinery was developed. At the start of the 20th century, industry 2.0 emerged and produced electrically driven machinery [28]. The industry used a mass manufacturing technique, and electrical energy was used as the main energy source. At the turn of the century, the development and production of a variety of electronic devices gave rise to Industry 3.0. This is important to automate the machines, which leads to less work, faster processing, higher precision, and, in some cases, total human replacement. Industry 4.0 is now driving growth in the telecom and internet sectors. There have been paradigm shifts in manufacturing and conventional manufacturing processes as a result of the usage of cutting-edge information and manufacturing technology. The Fourth Industrial Revolution has had a far-reaching impact on various industries such as transportation, steel, textile manufacturing, glass making, mining, and agriculture [29].

Integration of FBG-Based Sensors in Industrial 4.0

The term "Industrial 4.0" refers to a trend being observed in manufacturing- ing technologies that involve automation and data sharing, including cyber-physical systems, the Internet of things, cloud computing, and cognitive computing, as well as the development of the smart factory [30]. It is distinguished by, among other things: 1) even greater much more automation than in the third industrial revolution; 2) the fusion of the physical and digital worlds through cyber-physical systems, enabled by Industrial IoT; 3) the switch from a central industrial control system to one where smart products define the production steps; 4) closed-loop data models and control systems; and 5) personalization as well as customization of products (meant to also include needs of the customer) [30].

The dynamics of systems for the interchange of matter, energy, and outside-world knowledge are strongly related to complexity in Industry 4.0. Their visibility and the ability to closely monitor the external and internal factors that affect their evolution depend on the existence of a large and diverse market [31]. This allows for a more thorough evaluation of their current situation and the development of a strategy for maintaining a desired performance level. Industry 4.0 demands an intelligent and interconnected network that improves intelligent production. FBG sensors can gather and evaluate data for effective decision-making, and self-optimization is conceivable for automation in manufacturing processes. Through industrial automation, all specialized product solutions and assembly procedures can be improved. In the upcoming years, the sector is expected to implement asset management technologies[32]. Asset monitoring technologies and solutions are heavily relied upon by the supply chain industry for effective supply lines, which generates significant demand for sensors. As the industry switches to in-process sensors as a management tool, FBG Sensors can be used for process and condition monitoring [32,33]. Soon, several businesses will use this technology extensively for process management. FBG Sensors will present a substantial opportunity for

advancement in the automation of manufacturing processes through the Industrial Internet of Things (IIoT) [33].



Figure 3: Pyramid for industrial restructuring linked to the idea of Industry 4.0.[6]

The FBGc sensors and actuators are the main topics of the top layer of the automation pyramid. Essentially, it consists of manufacturing and product assets and components that FBG sensors can address, find, and identify, turning them into information carriers. To put it another way, this layer tries to "sense" what needs to be perceived, connect what needs to be connected, and lay the foundation for the next tier of the pyramid [34].

A layer of services and systems that enable the new ways the value chain is managed inside the industrial 4.0 setup follows the connected layer of FBG-based sensors and actuators. This layer is anticipated to deal with concerns like managing systems and keeping an eye on the health of assets like machinery, buildings, infrastructure, and so forth. In order for Industry 4.0 to function, it must also address chances to enhance, comprehend, and build new capabilities [35].

The third layer, which facilitates new applications and capabilities, focuses on connectivity. As a result, IoT and Internet Protocol (IP) service models are made possible, enabling new capabilities like asset tracking, preventive/predictive maintenance, and smarter applications. Here, the data and monitoring systems are connected with the assets as well [35].

Depending on the circumstance, the fourth layer makes substantial changes to the business model using the skills, services, data, and intelligence. By combining data and insight from smart systems and those of others with complementary techniques that are tapping into whole new client categories, new services that constitute a significant change in the core business also emerge from this sector.

FBG Sensors as a Drivers of Industrial 4.0

The development of intelligent manufacturing has had a significant and long-lasting impact on the direction of manufacturing globally. Physical and cyber-technologies are combined in Industry 4.0-based smart factories, increasing the complexity and accuracy of the merged technologies and enhancing the performance, quality, controllability, management, and transparency of manufacturing processes in the Internet-of-things era [36]. Advanced low-cost sensor technologies are crucial for gathering data and using it for efficient performance by supply chains and manufacturing companies. Data collection on various devices across manufacturing processes can be greatly expanded thanks to various low-power/low-cost sensor types.

The various industrial revolutions over time have significantly altered the way some industries use technology. Manufacturing industries have generally improved as a result of the incorporation of automation and mechanization into industrial processes [37]. Industrial systems and processes have

become smarter as a result of advanced Internet technologies. The drivers of Industry 4.0 include technological developments that have improved productivity. Tipping points describe the effects of emerging technologies. The development of agricultural methods, transportation, and economic expansion were the three main turning points of the Third Industrial Revolution. Business procedures improved as a result of the development of Industry 4.0, and new business architecture models appeared[38]. The following are Industry 4.0's key tipping points, which include optimized lean production, analysis of data, increasing end users' demand, enormous data available and conventional sensors.

The tipping points focus on replacing the conventional sensors with fibre Bragg grating sensors for the benefits of immunity to electromagnetic interference, no electric power usage, and non-corrosive real-time scenarios. FBG sensors link machines, people, and gadgets by measuring physical parameters caused by perturbations inside the industrial 4.0 factory setting [38]. These sensor nodes can keep an alert on processes, cut expenses, and warn people when something is harmful. Numerous sensor networks and the associated parts frequently generate large amounts of data. A key factor in the development of contemporary civilization in the manufacturing industry is that Industry 4.0, the forerunner of smart factories, has access to a variety of cutting-edge technologies, including cloud computing, big data analytics, artificial intelligence, advanced robotics, and 3D printing and in this case the integration of FBG sensors in the physical layer [38].

Fiber Bragg Gratings Applications in Industrial 4.0

The Fiber Bragg Grating sensors have enormous potential and offer opportunities across many productive sectors, including logistics, aviation, transportation, healthcare, energy, oil and gas production, and manufacturing. Therefore, a variety of use cases will cause industry executives to become aware of and think about the potential of the Fiber Bragg Grating Sensors in the Industrial 4.0 setting. After all, an industry only needs a small change in productivity to generate enormous revenue, so for example, the role adoption of Fiber Optic Sensors might be quite beneficial; as an example, even a 1% gain in productivity can result in enormous revenue benefits like a reduction in the cost of aviation fuel [39]. Industry must accept and adapt to the Industrial Internet of Things in order to enjoy these potential financial gains.

Oil and Gas Industry

The monitoring of wells and reservoirs in the oil and gas industry has undergone a revolution because of fibre optic sensor technologies. This advancement is the result of fibre optic sensors' passive nature, ability to be installed affordably, and potential for measurements throughout the fibre length. Information gleaned through fibre optics [40]. The installation of FBG-based sensors in oil and gas wells significantly improves efficiency, safety, and final recovery. The use of fiber optic sensor technology to monitor well bottoms has rapidly increased over the past five years in the oil and gas

sector. The considerable advancement in the glass chemistry sector made it possible to fit up to 20 fibres into a very small cable slot, which helped to advance the analytical applications and design powerful bottom well sensors [40]. For measuring temperature, acoustics, and strain, each fibre can be converted into a completely distributed sensor (DTS), or they can be used to query many point sensors like pressure gauges and geophones.

Cargo Ship Handling Systems

The efficiency and cost-effectiveness of sea transport methods are under pressure. Modern commercial ships' designs must take fibre optic technology, especially the Fiber Bragg Grating technique, into consideration in order to accomplish this [41]. The updated standards for modern ships mandate increased reliance on electrical equipment, automation, and control to improve circulation and cut crew workload.

A single FBG sensor thread can be used to measure a wide range of physical parameters, including some electrical and non-electrical values in ship systems, which are pivotal in Industrial 4.0 applications. FBG sensor's immunity to all electrical interference and their capacity to thwart corrosion are two of optical fibre technology's most significant benefits over conventional technology [41]. Additionally, this type doesn't necessarily require an electrical path because a fibre optic sensor only needs a light source, an optical fibre to transmit data, a sensing element, and a detector in its most basic form.

Industrial Applications in Aerospace

The usage of FBG sensors in the aviation industry spans a variety of tasks, including hard landing detection, hydraulic temperature and pressure monitoring, and oversight of fuel monitoring systems [42]. Optical fiber sensors can be used to monitor spinning parts and other important components, including the strain on the landing gear. The aerospace industry would boost its attention on industrial 4.0 applications, hence enhancing safety and extending the lifespan of aircraft[42]. The benefits of the optic fibre sensors make them perfect for aircraft applications, including their light weight, immunity to electromagnetic interference, ease of multiplexing, lack of drift, and high level of maturity.

Nuclear Radiation Industries

Conventional measuring instruments are not suitable for nuclear applications in such conditions, where temperatures are very high, together with chemical pollution and significant levels of electromagnetic interference [43]. Additionally, the destructive consequences of neutron bombardment on materials include thermal output drifting under high radiation as the two metals that make up the thermocouple gradually transition to other elements. It is predicted that fibre Bragg

grating sensors, which are produced using a pattern created by ultraviolet radiation, can tolerate radiation in low-flow nuclear situations for long periods of time, which makes them ideal for usage in industrial 4.0 environments.

Liquid Level Monitoring in Industries

Both systematic and random errors could affect the accuracy of the method for taking liquid-level readings in industrial tanks [44]. Fibre optic sensors based on fibre Bragg grating (FBG) technology may be utilized to measure the liquid level due to their advantages of being non-corrosive. Each sounding pipe of the tank should have a liquid-level fibre optic sensor installed vertically on it. These Optical sensors are made of a coil of fibre wrapped around a cylinder tube. Optical liquid level sensors for the intended measurement. Reading the fluid level is the important data entry to the approved tables, and Fiber Bragg Grating Sensors systems operate on the same principles as sensors described on the inner draft reading system.

Conclusion

In this review paper, the possible role of integrating fiber Bragg Grating sensors in industrial 4.0 is discussed. It embarks on the introduction of the fourth industrial revolution and FBG sensors coupled with a literature survey, which centres on the role of applications of FBG sensors in different scenarios. Furthermore, an introduction and theoretical aspect of FBG and Industrial 4.0 have been discussed. The study has concentrated on the FBG sensors that have been deployed for physical parameter monitoring in several use cases, including oil and gas industries, cargo ship handling systems, industrial applications in aerospace, and nuclear radiation industries, which would drive the Industrial 4.0 integrating the FBG sensors. The future focus of this research will be the development of FBG prototyped sensors and their deployment in real-time industrial settings to gather sensor data and support the transition of conventional factories to smart factories, which is how industrial 4.0 will be realized.

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