Fiber Bragg Grating Strain Sensors in Smart Factories: Review of Opportunities and Challenges

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Abstract Physical parameter monitors are necessary for the conversion of conventional factories to smart factories. The creation of new sensors for monitoring physical parameters in difficult-to-access areas is necessary for this move. In this line, a large number of optical sensors based on integrated optical wave guides or optical fibers have been designed and manufactured over the previous ten years. As a potent tool for real-time monitoring of physical parameters like temperature, pressure, strain, and humidity. Fiber Bragg Grating (FBG)-based sensors have attracted a lot of attention. The main reasons for using FBG sensors in smart factories are immunity to electromagnetic interference and radio frequency; compact in size and offer multiple sensing to different physical parameters; permit remote sensing and are not prone to corrosion. In this paper, a review of FBG-based sensors for strain parameter monitoring and their application in the smart factories is presented. An overview of the historical background is followed by an explanation of the fundamentals of FBG sensing and a discussion of the electromagnetic theory of waveguide modes in optical fibers. Then give a review of current research in FBG strain sensor development. A review of the challenges and applications of FBG strain sensors specifically in smart manufacturing follows.

Keywords Fiber Bragg grating · Optical fiber sensors · Strain · Smart factories · Bragg wavelength · Photo-sensitivity

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1   Introduction

1.1   A Historical Context of Fiber Bragg Gratings

The discovery of photosensitivity in optical fibers has led to the development of numerous devices for a range of purposes [1]. This finding significantly influenced the advancement of sensor and communication systems. The basis for a fiber Bragg grating is often the photosensitivity feature of silica fiber doped with germanium (FBG). When exposed to ultraviolet (UV) radiation, some doped glasses exhibit photosensitivity, which results in a higher refractive index. As a result, when a fiber is exposed to UV radiation, its refractive index changes permanently, with the shape and characteristics of the UV exposure beam having an impact [2].

When a side of fiber is exposed to UV light by the interference of two crossing beams, an FBG with a user-defined central wavelength that is independent of the wavelength of the writing beam is produced. With lengths ranging from millimeters to centimeters, this UV treatment will permanently etch a regular form with a periodicity half the necessary Bragg wavelength into the fiber core. Because the FBGs may be generated with such freedom, Bragg wavelengths that are much beyond the telecommunications wavelength of 1550 nm can be written [3].

2   Literature Survey

Fiber Bragg grating (FBG) strain sensors are a well-established research topic and are also growing their market share because of their high sensitivity and affordable price. Rao et al. [4] looked at a review of FBG strain sensors with an emphasis on the physical principles, interrogation methods, and read-out procedures.

Newly developed high performance single head FBG,categories are highlighted in particular, and to which FBG strain sensors belong. A number of alternative sensing methods are mentioned, such as mode-locked FBG strain sensors splitting. Their operational theory and performance are recorded, and they and those of classic architectures are contrasted [5]. To sum up, certain innovative applications and substantial market sectors for fiber-optic strain sensors are predicted, in addition to the key market players active in this sector.

Fiber-optic sensing is now a practical option for evaluating the effectiveness of civil infrastructure due to substantial advancements in the field [6]. Their unique qualities make them an important choice for civil engineers and a reliable option alternative to conventional sensors [7]. These features include small size, high resolution, great long-distance signal transmission, immunity to electromagnetic and radio frequency fields interference, and the capacity to multiplex a number of probed sensors.

Due to its small size, as stated in [8], the fiber Bragg grating sensor is compactly or superficially connected to a range of materials, including concrete, reinforcing steel, steel sheets, fiber-reinforced polymer (FRP) strips, and others.There has been a lot of recent study on the use of fiber Bragg gratings (FBGs) as optical sensors to monitor structural performance [8]. The foundation of many of these studies is the ability of fiber optic sensors to track the internal strain of structures.

The method for designing wide-range FBG strain sensors described in this study [9] can be used to find extra-large strain in unusual structures. For accurate measurement, the elastic modulus, and adhesive layer thickness are investigated in the wide-range FBG strain sensor's strain transmission rate distribution. The wide-range FBG strain sensor, which is the subject of this study, has been proposed, and its capable of simultaneously experiencing and quantifying the extra-large strain experienced by the unique structure [9]. Although this sensor has potential uses for tracking the structural health of unusual structures, one drawback was that it wasn't used in smart factories.

Zhang et al. [10] examined the design and calibration of a small, multi-component force sensor based on an elastic transducing body and eight multiplexed fiber Bragg gratings. They provided construction instructions for multiplexed multi-component force sensors based on FBG strain sensors. Zhang et al. [10] suggested that due to their multiplexing abilities and immunity to electromagnetic interference, multi-component force sensors may be preferable to fiber Bragg grating (FBG) strain sensors for carrying out these local strain measurements in the control of robots in electromagnetically noisy environments. Despite strides in strain monitoring, the technique not applied in a sophisticated industrial setting.

In [11] they suggested additional research on the application of optical Fiber Bragg Grating (FBG) strain sensors for gear diagnostics. Although it can be extremely useful, the development, justification, and experimental validation of a novel diagnostic approach based on FBG strain sensors for both gear types under various operating conditions, such as speed and load, as well as for local problems of various severity levels, is not yet implemented in smart factory settings.

A number of fiber-reinforced polymer (FRP) packaged optical fiber Bragg grating strain sensors were suggested by [12] in order to fully address the requirements of difficult civil engineering infrastructures. Experimental research is done to examine how well these sensors operate in both common and difficult conditions. Experimentally and conceptually, it has been shown that FRP-packaged FBG strain sensors have significantly higher durability in harsh environments while maintaining the same exceptional sensing performance as the bare FBG sensor. However, this work suffered greatly because these sensors were not used in smart factory settings.

A fiber-optic Bragg Grating (FBG) strain sensor for uniaxial rock compression testing was discussed in [13]. For the cylinder-shaped rock samples, the optical FBG sensors were made by hand and put together. A compression test on a hard rock sample was conducted after a calibration procedure was completed to ensure the mechanical performance of the FBG package. The strain was then measured using both the conventional Bragg grating sensor and the compression sensor. The FBG

strain sensor prototype offered potential uses in structural health monitoring but was not used in a smart industrial environment.

The use of a fiber Bragg grating (FBG) strain sensor for oil and gas derrick health monitoring was suggested by the authors of [14]. The system was composed of the optical interrogator, monitoring program, and FBG strain sensors. When the sensors were fastened to a derrick, the system's performance was evaluated. The outcomes demonstrated the viability of the field application. The work exploited significant electromagnetic radiation immunity benefits of optical sensors, but it had a limitation in that it was not applied in a smart factory environment, which is consistent with the industrial 4.0 characteristics.

In [15] they propose for sustainable industrialization using IoT and big data analysis with machine learning to pave the way for industrial processes that are resource and energy efficient conservation, product development that satisfies both current and future demands, and safe and skill-enhancing employment with low waste generation, execution speed, and cost. Through sustainable practices enabled by the processing and analysis of industrial data using big data and IoT, the verified model is effective in terms of power consumption, latency, and execution time, resulting in a decrease in the creation of industrial waste and an increase in production rate. The study's strengths made use of cross disciplinary technologies like machine learning and the Internet of Things (IoT), but not fiber Bragg grating sensing technique.

A novel, extremely accurate strain measurement technique based on a fiber Bragg grating sensor was also reported in the Moreover Ref. [16]. The sensor is more sensitive than a fiber Bragg grating sensor alone because it combines a fiber Bragg grating with a sensitivity-boosting technique. The suggested strain sensor's ability to detect battery strain has been shown in a test comparing it to bare fiber Bragg grating sensors. This FBG method is essential for extended use in smart factories since it offers battery management systems information on the load placed on power batteries.

In this paper there a review of opportunities and challenges of using Fiber Bragg Strain Sensors in smart factories which are inline with the industrial 4.0 is presented which has more advantages by blending the inherent advantages of FBG sensors and the technological aspect of smart factories having automation and connectivity as its central backbone.

3   Theory of Fiber Bragg Grating Sensors (FBG's)

The essential idea behind an FBG-based sensor is the wavelength change of the perturbed Bragg signal as a result of measurement factors including strain, temperature, and force. Relevant factors are the material's refractive index and grating pitch [15].These gratings work in sensor systems by absorbing light from a Bragg wavelength portion of the spectrum.

FBGs are systems that use the diffraction grating theory and are created by periodically modulating the longitudinal index of refraction of the fiber core [16] The
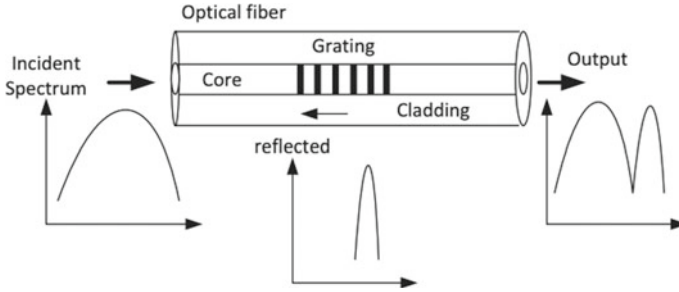
Fig. 1 Structure of fiber Bragg grating [7]

core's refractive index is supposed to vary on a regular basis thanks to the grating. The grating lets light through as The structure's gratings all reflect some light back (Fig. 1).

The refractive index of the optical fiber core (n_{eff}) with respect to the grating length and the period of the grating microstructure (Λ) effectively define the Bragg wavelength (λ_B).

$$\lambda_B = 2n_{\text{eff}}\Lambda \tag{1}$$

The shift in Bragg grating wavelength can be calculated by expanding Eq. (1) in terms of partial derivatives with respect to the temperature, wavelength, and length.

$$\Delta\lambda_B = 2\left(\Lambda\frac{\delta n_{\text{eff}}}{\delta L} + n_{\text{eff}}\frac{\delta\Lambda}{\delta L}\right)\Delta L + 2\left(\Lambda\frac{\delta n_{\text{eff}}}{\delta T} + n_{\text{eff}}\frac{\delta\Lambda}{\delta T}\right)\Delta T$$
$$+ 2\left(\Lambda\frac{\delta n_{\text{eff}}}{\delta\lambda} + n_{\text{eff}}\frac{\delta\Lambda}{\delta\lambda}\right)\Delta\lambda \tag{2}$$
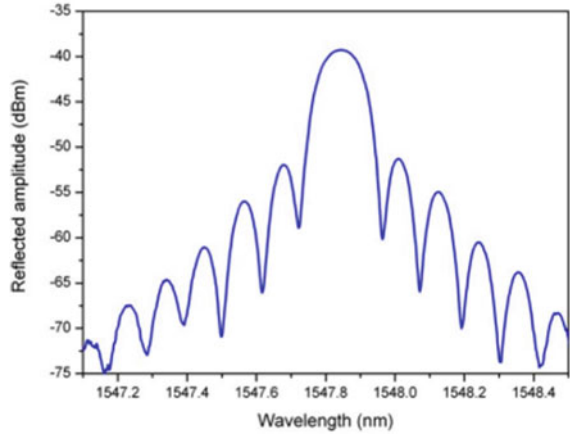
where ΔL is the change in physical length of the grating due to the temperature applied, ΔT is the change in Temperature and $\Delta\lambda$ is the change in wavelength.

As shown in Fig. 2 for a 1 cm long FBG, a uniform FBG acts as a selective mirror in the wavelength region close to the Bragg wavelength to produce a pass-band reflected amplitude spectrum. In reality, a faint Fresnel reflection is produced for each change in the refractive index along the fiber axis. At the Bragg wavelength, they increase phase, creating a broad reflection band bordered by side lobes. The highest peak reflected amplitude is −40 dBm, with a wavelength range of 1547.2–1548.4 nm.

4 Strain Optical Response

Bragg grating is impacted by the strain in two different ways. First, the Bragg wavelength will change due to the alteration in the physical distance between succeeding index modulations. Second, the strain-optic effect will cause a change in refractive

Fig. 2 Spectrum of reflected amplitude of a 1 cm long uniform FBG

index, which will cause the Bragg wavelength to shift [17]. The central wavelength of the Bragg grating varies as a function of strain as follows:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\delta n_{\text{eff}}}{\delta L} + n_{\text{eff}}\frac{\delta\Lambda}{\delta L}\right)\Delta L \tag{3}$$

where ΔL denotes the change in physical length caused by the applied strain on the grating. Provided that the integrated path of the longitudinal strain is given by $\varepsilon_z = \frac{\Delta L}{L}$. Equation (3) can be rewritten as:

$$\Delta\lambda_B = 2\Lambda\frac{\delta n_{\text{eff}}}{\delta L}\Delta L + 2n_{\text{eff}}\frac{\delta\Lambda}{\delta L}\varepsilon_z L \tag{4}$$

Defining

$$\Delta n_{\text{eff}} = \frac{\delta n_{\text{eff}}}{\delta L}L \tag{5}$$

And

$$\Delta\left(\frac{1}{n_{\text{eff}}^2}\right) = \frac{2\Delta n_{\text{eff}}}{n_{\text{eff}}^3} \tag{6}$$

By Substituting Eqs. (5) and (6), Eq. (4) can be written as

$$\Delta\lambda_B = 2\left[\frac{-n_{\text{eff}}^3}{2}.\Delta\left(\frac{1}{n_{\text{eff}}^2}\right)\right] + 2n_{\text{eff}}\varepsilon_z L \tag{7}$$

Having a grating with a particular center wavelength ,λ_B, the shift in the center wavelength is denoted as

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\,\varepsilon_z \tag{8}$$

where P_e is 0.213 for germanosilicate optical fiber and ε_z is the applied strain. Equation (8) can be rearranged and simplified as follows:

$$\Delta\lambda_B = \lambda_B \left(1 - p_e\right) \varepsilon_z \qquad (9)$$

When the Fiber Bragg Grating is strained, its central wavelength λ_B drifts. Equation (9) is a way to express wavelength shift where p_e is the photo-elastic constant, and ε_Z is the strain applied.

4.1 Calibration of FBG Strain Sensors

Calibration for temperature-dependent strain readings is described in [17] using a four point bending test and might be used for this study. Electrical strain gauges are employed for calibration, and a finite element model is provided for comparison. It was presented in a way to calibrate FBG sensors over a wide-range of positive and negative strain values utilizing the four point bending test. It is crucial to know if the strain in that area is constant because electrical or FBG sensors assess an average strain along the gauge length.

5   FBG Strain Sensor Opportunities in Smart Factories

Optical sensors are becoming one of the most important components in a number of industrial sectors, including the manufacturing, civil and energy, medical, automotive, and aerospace industries [18]. The increasing installation of items using optics technology is the main factor driving the global market for distributed optic temperature sensing. In smart factories, fiber Bragg gratings are widely utilized for strain sensing, particularly in hard environments with high temperatures, severe electromagnetic interference (EMI), or highly corrosive environments. During the development and testing of a prototype, strain monitoring is essential. Strain measurements guarantee that parts function as intended and that the apparatus is robust and reliable [18, 19].

When inspecting complicated structures like aircraft and turbines in smart manufacturing, it's crucial to pay particular attention to strain monitoring. Although there are various ways to measure stress, the FBG sensors are the most effective overall for measuring strain [20]. It is possible to assess the dynamic strain in a variety of transportation systems, including automobiles, trains, and airplanes. Dynamic strain testing and vibration stress testing with fiber Bragg gratings have numerous more applications than construction projects and automobiles. Industrial machinery can be equipped with FBG sensors to measure the frequency and amplitude of stress vibrations.

Utilizing some extremely tiny FBG sensors, which can be used in smart electronic sectors, it is possible to monitor the stress in electric circuit boards and other constrained areas. Residual stress monitoring, which is crucial in smart factories, is the measurement of stress during casting, welding, and forming activities. For this use, FBG strain sensors are widely employed. They can also be used to monitor stress during rapid drilling operations in smart manufacturing.

6   Challenges of FBG Strain Sensors

The handling of the FBG strain sensors is difficult due to their fragility, wavelength cross sensitivity, and bulky interrogation devices. Because FBG strain sensors are constructed of fragile optical fiber cables that cannot endure process conditions, they are challenging to install in smart manufacturing environments [21]. Along with these difficulties, using pricey, intricate industrial equipment like oscilloscopes and optical spectrum necessitates a high level of deployment and maintenance skill [22].

Additionally, since both temperature and strain cause a Bragg wavelength shift, temperature strain discrimination is another difficulty that cannot be overcome by a single FBG [23]. The above-mentioned issue, demodulation of amplitude spectrum throughout the curing cycle process, is resolved in practice using two FBGs with different temperatures and/or strain sensitivities [24].

7   Conclusion and Future Scope

The usage of Fiber Bragg strain sensors in smart factories was studied in this paper, which began with a historical review of FBGs before conducting an extensive literature review of FBG-based strain sensors. The physics underpinning fiber Bragg grating optical sensors is also well covered, as is the optical response of FBG strain sensors. These FBG strain sensors are used in smart factories for cars and transportation systems and have applications in harsh environments. However, they are expensive to implement and call for specialist equipment like optical spectrum analyzers and interrogators.

Due to their inherent advantages, more intelligent FBG sensors are predicted to be released onto the market in the near future. To connect these sensors, diagnostic tools, and other associated equipment, optical communication will also be used. Manufacturing will use an increasing number of optical sensors based on FBG to monitor physical characteristics, including strain measurements. The sensing system would also be hooked to a central network, allowing devices to function remotely, gather data, and perform fundamental computer operations. Additionally, future plans must take into account the use of portable, affordable interrogators to improve the demodulation of sensor data.

Fabrication of strain FBG sensors employing phase mask technology and their deployment in a smart manufacturing environment should be implemented in future scope. The simulation in ANSYS Lumerical FDTD and COMSOL software will be implemented.

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