Fiber Bragg Grating: Technology and its Applications in Fiber-Optic Strain Sensing

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Abstract: *In this paper, we will see how Fiber Bragg grating technology has developed and taken the fiber-optics to a whole another level. A brief overview of Fiber Bragg Grating technology and its various applications in the field of Optical sensing is discussed in this paper. The advantages of FBG sensors, its drawbacks, rectification of issues and measurement of different parameters or we can say the interrogation techniques are also covered. A vast description on the FBG based strain sensors in fiber-optic sensing is given covering all the main factors related influencing the phenomenon.*

Keywords: optical devices, Fiber Bragg grating, stress and strain in fiber optics, optical sensors, interrogation techniques

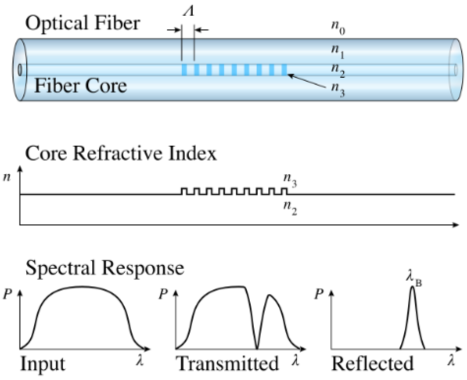
1. Introduction

In modern times, Fiber Bragg grating based sensors are evolving rapidly. Being beneficial in various technological and structural aspects as discussed here, these are winning over all the other sensors of its fields. Commercially, these sensors are slowly getting accepted, looking at its flexibility in the design fabrication both for the single-point and multi-point sensing, lesser cost and relatively greater sensitivity. However, this technology is not yet utilised and fully known by everyone and its advantages are still not yet recognized by many, but the ones who have proper knowledge and interest in the field of photonics and its related studies understand the worth of these such sensors. Properties like compact size, immunity to the electromagnetic interference (EMI), light-weight and many others are examples of the advantages of Fiber Bragg grating based optical sensors. Fiber optic communication is technique in which we send the pulses of Infrared waves via Optical Fibers for the transmission and exchange of information. This technology has grown over a large scale over the years and its usage is increasing day by day because of its flexibility and secure transmission over larger distances. This development of Fiber optic communication has been a major reason for the overcoming of fiber optic sensors. These fiber optic sensors have been proven beneficial over others because of its properties which we will see later. Many factors are responsible for the fiber-optic sensing using FBG, which influence its functionality. Some factors including the reflection and sensitivity proves to be a drawback if not rectified the issues it faces. Hence some interrogation techniques are proposed to rectify such issues which we will study in detail.

2. Fiber Bragg Grating Technology

In Photonics and Optical Fiber Sensing, the most preferred technology to be considered is Fiber Bragg Grating (FBG), for their strong reflected signal and simple architecture. Basically, FBGs are the microstructures of few millimetres of in length, commonly used as the reflector which filters certain wavelengths and reflects all others. In this way it acts as a barrier to certain undesired waves. Hence, being a resonant structure, it acts as a narrow band filter. The optical fiber core has a diameter of 125 micrometres, and with a protective coating or primary coating, this diameter becomes 250 micrometres. This fiber core allows the light ray of diameter of approximately 8 micrometres only to travel through it. The refractive index of the fiber core in longitudinal direction results in the formation of these such wavelengths.

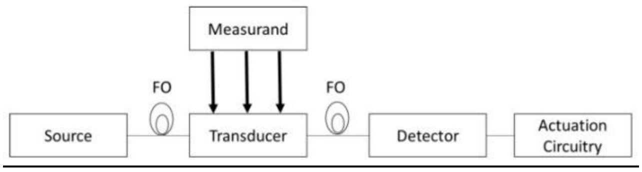
The term Fiber Bragg Grating came from a law, proposed in 1913 called Bragg Law, which was the confirmation that the real particles existed at atomic scales. The credit for the discovery of this Bragg law of X-ray diffraction goes to Sir William Lawrence Bragg (1890-1971), the Australian-British physicist and X-ray crystallographer. His discovery proved to be so successful that even today his discovery is used for the study and crystal structure and architecture determination. To be more specific, in the thin film research, his principle is used. In addition to this, they provided a tool which helped in studying the crystals called as X-ray and Neutron diffraction. In this way, later in 1915, a very talented duo, Sir Bragg and his father won the Nobel Prize for their priceless contributions in Physics and in the development of X-ray crystallography.



Here, a pictorial example of Fiber Bragg Grating is shown. In this image, a structure of a positive-only index change Fiber Bragg Grating can be observed. We can see a slight change of the refractive index along the core from the refractive index profile of the fiber core. The splitting of incident broadband signal into the two components that is, transmitted and reflected, about the Bragg wavelength which is observed in the spectral response.

3. Fiber optic sensor simplified architecture

Due to the compact size and light weight of FBG sensors, these are preferred a lot in modern times. The key advantages of fiber optic sensors are such that these propose the immunity to electromagnetic interference (EMI), low attenuation and a very less power consumption. The properties of these sensors like the accuracy, the spectral range of operation it proposes, shelf life and many others prove how beneficial these are. Moreover, these sensors can be used in remote sensing purposes also. These can be used in many extreme environmental conditions like either extreme temperature, or extreme voltages or excessive corrosion or many others because of their dielectric properties.



Here in this figure, can see a simplified architecture of fiber optic sensor. The optical source (LED, LASER and LASER Diode), fiber optic cable, transducer for conversion of initial signal obtained from the source to another signal of different characteristics (which is performed with proper measurements), optical detector for the detection of this modified signal and at the end some processing units like oscilloscope altogether forms the fiber optic sensor. But the way they are beneficial in the fiber optics, since these are costlier than other cables, not everyone and everywhere they are currently seen, and hence many researches are going on from the decades to suppress and lower the cost of these cables.

Now a days, a large market share has been grabbed by the optical sensors due to their so many advantages which we have already seen above such as size, weightage, rigidness and so on. As the optical fibers are non-conductive in nature, lightning will not affect the FBG with voltage fluctuations or power surge. If we go in the depth of these sensors, the small form factor and the compatibility for non-invasive remote sensing also makes them unique. One more benefit of optical sensors is like they don't need the electrical connections to function. FBGs' are highly sensitivity to the environmental parameters such as physical, chemical, biomedical, and electrical parameters, so they can be used for structural health monitoring in civil infrastructures, aerospace, energy, and maritime areas, in which the encoding of the information related to the measurands is performed by the Bragg wavelength shift of FBGs.

Initially, FGBs were the sensors majorly used for the strain and temperature sensing, but after many of the researches and modifications in the structures of these sensors, these sensors were made capable of multi-functioning that is sensing of various parameters like pressure, vibration, displacement etc. Now we will see what makes these FBG strain sensors so special and will understand some concepts related to these sensors.

3.1 FBG sensors for strain sensing

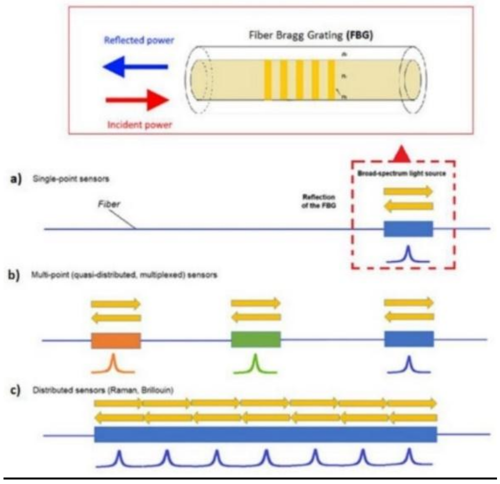
Before going into the depth of strain sensing, Let's see understand some concepts about the strain. The investigation begins with the analysis of the measurand (that is strain). The basic definition which every student has learnt is force applied per unit area is stress. Mathematically we can define the strain as the amount of deformation of the material in the direction of the applied force divided by the material's initial length. Strain can be measured by measuring the deformation created by the applied force. Now the measure of this applied force per unit area is termed as Stress, which we will further understand in detail later. The strain is a normalised measure of the disturbance created between the particles in matter because of the applied stress with respect to the initial length. Whenever an action is performed on any rigid body to deform it on the particle level, the strain is observed. This action can be of any form such as rotational, translational etc. Physically, the strain is a tensor quantity, that is it can be varied with respect to both magnitude and direction. Strain can be decomposed into its two components, normal strain and shear strain. Normal component is observed when the deformation is perpendicular to the face of the body, whereas the shear component is observed when parallel deformation takes place. The normal strain is termed as tensile strain if the length of body increases after deformation, and if it gets reduced, then this strain is termed as compressive strain. So, in this way, tensile strain occurs when deformation is positive and compressive occurs when deformation is negative. In short, both are opposite in nature to each other, the important factor we saw in the formation of strain is stress. In a continuous material, the stress possesses the internal forces which is exerted by the particles on each other or on the adjacent one across an imaginary plane of contact that separates them, which results in the deformation of the material and we term it as strain. This stress does not always harm the material as the stress is reversible. But the condition is that it must not exceed the threshold value of that particular material. If this happens, then the material will be deformed permanently or its crystal structure of the material will be changed. The unit of stress is that of pressure whereas the strain is a dimensionless unit.

Now, as we have seen all the basic terms related to the strain sensing, the phenomenon by which this sensing occurs can be understood. So, the FBGs acts as a strain sensor due to variation in the period of microstructure and of the Bragg wavelength, caused by the deformation of the optical fiber.

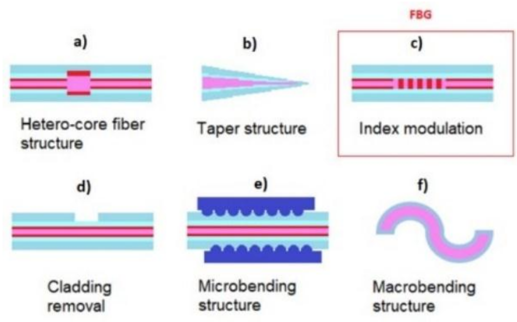
So, as we have briefly covered several concepts related to the stress and strain, now we will move on to the main categories of fiber optic strain sensors, where the fundamental role of the FBGs are assigned as single-point sensors where the periodic modulation of the refractive index is performed to obtain the sensing head.

3.2 Optical Fiber Devices for Strain Sensing

Optical strain sensors are used in the compressive strain or tensile strain sensing in fiber optics. There are many alternative sensors available like mechanical or electronic strain sensors, but because of the factors like insensitivity to EMI, wide temperature range and many more, they prove to be more beneficial than others in the photonics community. In addition to these, they also do not require electronic cables like others hence acts as an insulating material in high voltage applications, increasing the dependability. Fiber optic strain sensors are classified into three types: single-point sensors, quasi-distributed sensors (multiplexed sensors) and distributed sensors. Single-point sensors are comparatively smaller in size, durable with higher accuracy, which are usually connected to a fiber-optic cable of high bandwidth. These single-point sensors are multiplexed and placed at desired locations along the cable to build a quasi-distributed measurement. Distributed sensors uses fiber-optic cables in measuring strain along the entire length of the desired material.



In this figure, some structures of single-point sensors are covered. The Bragg gratings can be calculated using a method called Micro-fabrication method, in which we determine the Bragg gratings by performing refractive index modulation along the direction of beam penetration. From the figure, we can infer that not only by the micro-fabrication method that is refractive-index modulation for FGBs, they can also be measured using many more structures like Hetero-core fiber, Taper, Cladding Removal, Micro-bending and Macro-bending structures as shown.



4. Classifications of the Fiber-Optic Sensors and its key performance factors

The key performance factors of the FBG strain sensors are generally the same as the fiber-optic sensors. There are some key factors responsible for the performance of Fiber-Optic sensors which include the relation between variation of sensor output and its correspondingly varying measurand. Sensitivity is another key factor for the performance. If a sensor is good in quality, it will always have high sensitivity, so that a very slight variation can be detected depending on the variation in output, which is usually larger in magnitude.

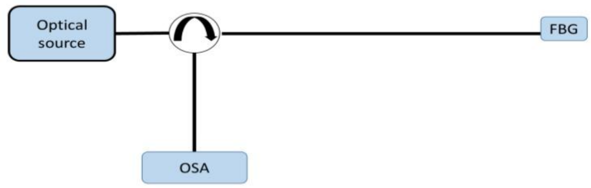
So many other factors also exist with which we can classify the FBG strain sensors. Starting with Attenuation spectrum which is based on the wavelength in the operation point. Next is the Dispersion spectrum which represents the refractive index based on the wavelength in the operation point. So, these spectrums represent the attenuation and refractive index in the point of operation. Then comes the type of modal propagation which depends on the operating principle of the sensor and it is classified into two of its types that is unimodal (single) and multi-modal (many modes) propagations. Within the cable or the guided path, this propagation is of only type that any one among the previous two mentioned types. This propagation is dependent on the sensor operating principle. Then comes the important one that is the mantle's properties which includes the threshold resistance, radiation resistance in highly radioactive environment and the last that is threshold temperature in which it can work. In fiber-optic sensing, a major term "scale factor" which can be defined as the sensitivity of the sensor, is observed if the sensor output varies linearly with the measurand output. Next is the geometrical and physical properties of the guiding structure which can be any like optical fiber or waveguide or anything. These properties majorly depend on what the material is being used, the core and dimensions of the cladding, the refractive index profile (step or graded) and the cutting wavelength for modal operation depending on its type.

4.1 Additional figure of merits of FBG

A term 'Resolution' is a figure of merit of FBGs which tells the sensor capability to detect minute variations in the measurand. 'Resolution factor' is defined as "the variation in output value caused by the variation in measurand magnitude which is equal to the uncertainty of output itself". Often the term resolution is correlated with the term "dead band", which most of the times is indicated as sensitivity, which is not correct. There is a unique case in optic-sensing when the sensor operates with a measurand in the zero proximity. In this case, the term 'threshold' plays its role as the threshold is the minimum output shown by the measurand which is often different to those cases when this measurand the output to be null. FBG sensors are characterised in two categories in terms of measurement which is 'accuracy' and 'bandwidth' of the measurement. With the accuracy, the output power can be measured at the receiver ignoring the system noise levels. Then comes the bandwidth which detects the variation in the calculated magnitude is observed. Corresponding to the measurement bandwidth, some of the other figures of merit of FBGs are system bandwidth, sensor ability and dynamic range. The system bandwidth is the required bandwidth to analyse the system, whereas the stability is the maximum variation to occur in the output value in any of the absolute, relative or reduced value with same measurand magnitude. This sensitivity keeps the sensor operating characteristics unaltered for a longer period of time like for months or even years. The dynamic range is the ratio between the maxima and minima of the measurand value with the required accuracy (dB).

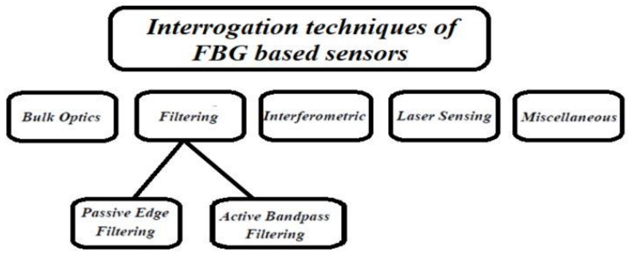
5. FBG Strain Sensors Interrogation Techniques

Interrogation techniques are the techniques with which one can gather the information related to the measurand which is encoded in the spectrum, generated by FBG sensors. The spectral change, is mainly associated with either the Bragg's wavelength shift or with a change in either the optical exciting power or in the FWHM (Full-width half maximum). In the figure here, a basic set up is shown with which we can detect these variations. Here, the FBG is given the broadband optical input via circulator. Then, a conventional optical spectrum analyser (OSA) is connected to the circulator in which the reflected beam is redirected to it.



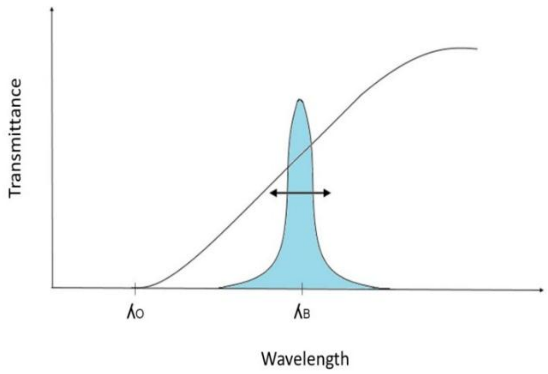
The main drawback of this technology is that the commercial OSAs are not suitable for the dynamic measurement purposes, as these are slightly costlier and slower. Moreover, they have some issues with the resolution and sensitivity also as they have a typical resolution in the range of tens of picometers whereas the sensitivity of these strain sensors is in the order of some picometers for one micro-strain. So, to improve the issues related to resolution and sensitivity, particular algorithms are needed to be implemented.

This is why, to improve FBG interrogation technique, so many demodulation techniques have been considered and implemented, achieving highest resolutions in terms of spectral detection. Depending on the main principle adopted in the detecting scheme, as depicted in figure shown below, we can classify the interrogation techniques of FBG sensors into five categories:



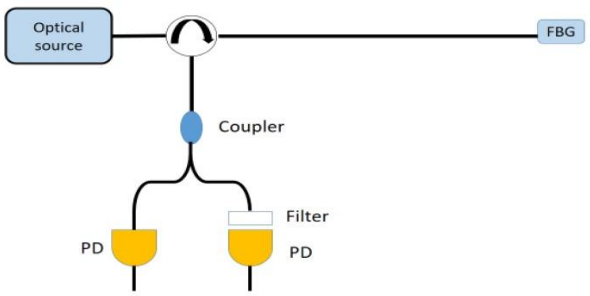
5.1 Classification of the interrogation techniques of FBG sensors

In FBG sensing, the most common interrogation techniques are the filtering and interferometric techniques, in which the wavelength shaft is converted to change the electrical signal and, in this way, the sensing is done. To implement this filtering and interferometric technique, a photo-diode replaces the OSA. This diode is given the optical signal from reflected spectrum of the FBG. Filtering techniques can further be divided into two types that is passive edge and active bandpass filtering. As inferred from the figure, in passive edge filtering, an optical filter is showing a linear attenuation around the wavelength of interest, which can be used as an interrogation technique. Changing the FBG spectrum will result in the variation in the output power.



Filter transfer function and FBG spectrum response.

The optical signal received by photo-diode is proportional to the central wavelength of the input spectrum. The optical power is varied by the shift of the sensor wavelength as per the slope of the filter. In this technology, the sensitivity to the variation in the source power is proved to be a drawback of this technology and to overcome this limitation, a new filtering technique that is an improved Passive Edge filtering is imposed where we could detect the reference signal also.



As inferred from the figure, the coupler divides the input spectrum power at the receiver into two parts where the branch for reference purpose includes only a photo-diode so as to receive the unaltered spectral power, while the other, which includes filter and photo-diode both, acts as the same explained above. As a result, as indicated by the equation, the ratio of the power received from the two photo-diodes, is proportional to the Bragg's wavelength shift and creates variations in the source also.

$$I_S / I_R = A(\lambda_B - \lambda_b + B)$$

Where I_s is the filtered sensor spectral intensity, I_R is the unfiltered sensor reference intensity, A is a constant depicting slope of the filter and B is a constant arising from the nonzero reflection bandwidth of the FBG. One of the references FBGs is matched with the sensing FBG while the second one presents a small offset which tells us that the strain could be retrieved after the detection, by subtracting these two signals.

Example of experimental set-up for passive edge filtering interrogation technique with reference signal measurement. Alternatively, just like the spontaneous emission (ASE) source (which has smaller bandwidth, about 20 nm), it is possible to take advantage of a large bandwidth light source, rather than implementing a filter before the detector. The function of an ASE source is such a way that it proposes a power spectrum where the slope of the optical power decreases linearly. A shift in the Bragg's wavelength is directly converted into a varying receiving optical power. This model can be simplified into a system containing of an FBG head sensor with the Bragg's wavelength lying linearly in the spectrum of a photoreceiver. We can have another passive filtering interrogation technique which use a Wavelength Division Multiplexer (WDM) coupler as shown in the figure. The WDM is placed at the receiver input in which the spectral power is split according to the wavelength into two parts. Then a photodiode is also placed in each branch receiving the optical power.

6. Conclusions

Fiber Bragg Gratings (FBGs) are the fundamental elements upon which most of the fiber optic sensors are based. Inferring from the above theory, we can hereby conclude that Fiber Bragg Grating (FBG) is a very fast-growing technology gaining fame in its field for so many advantages. FBGs have now become a fundamental technology and a key element in the optical sensing. Whenever set to a specific wavelength of light, the FBG acts as an invisible reflector inside the core of the optical fiber which reflects the waves of certain wavelength and reflects the rest. So, in this way in optical fibers, blocking and rejections of certain waves can be performed. We saw some of the interrogation techniques to alter the problems like sensitivity and reflections. We can multiplex dozens of FBGs on a single fiber using different wavelengths.

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