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FBG Sensors for Environmental and Biochemical Applications - A Review

Muhammad Arif bin Riza, Yun Ii Go, Sulaiman Wadi Harun, Robert R. J. Maier

***Abstract*— Sensors play a large role in monitoring and ensuring that environmental parameters satisfy industrial requirements. They offer crucial safety measures in the early detection of hazards. Conventional electrical sensors possess several drawbacks that hinder their use in environmental sensing. Research has explored and optimized optical-based sensors because they are more robust, immune to electromagnetic interference and offer multiplexing capabilities for sensor arrays accompanied by ease of modification to cater to different measurands. Fibre Bragg grating is the perturbation of the refractive index imprinted within the core of an optic fibre via an intense UV laser. The gratings, when perturbed by external parameter changes, will induce a shift in their wavelength, indicating detection. With modifications such as hygroscopic coating and different grating profile imprinting, FBG can detect various physical and chemical parameters. Environmental, pharmaceutical and biochemical fields can benefit from FBG sensing because their parameters affect not only their product quality but also the lives of consumers. This review discusses some of the FBG sensors that have been proposed to serve in environmental and biochemical applications.**

***Index Terms*—Biochemical, Bragg Wavelength, Environmental, Fibre Bragg Grating (FBG), Optic Fibre, Sensitivity, Sensor**

I. Introduction

The rapid development of sensors has propelled many industries worldwide towards better efficiency in environmental and process-critical parameter monitoring. Common parameters that all industries monitor for their processes include temperature and pressure. More specific environmental parameters that are important and crucial for most industries include chemical sensing and humidity. Wide variety of sensors are continuously being developed to further enhance sensing capabilities. Electrical-based sensors still dominate the market. However, they are prone to electromagnetic interference, and some may require frequent calibration. To counter these drawbacks, researchers have directed their attention to other modes of sensing in addition to electronics. This is where fibre optic sensing has moved to the forefront; with the discovery of fibre optic sensing in the mid-1970s, thoughts arose on incorporating these sensors in a variety of applications [1].

With the main signal carrier being light instead of electron flow, fibre optic sensors are immune to electromagnetic interference and exhibit light-speed responses in comparison to other types of sensors. The flexibility of a single strand of OF enables its use as a sensor. Optical Fiber (OF) sensing alone has many variants applying different optical mechanisms for sensing modes. In this paper, different OF sensors are discussed, and fibre Bragg grating is the focus of the paper in biomedical and environmental applications. Chemical and humidity monitoring with substantial degree of sensitivity is often required in biomedical industries. For example, the production of tablets involves the compression of water-dissolvable powders. The presence of moisture in the air can cause poor tablet quality and may induce other undesirable features in the product. Lithium battery production requires an exceptionally low humidity to prevent the lithium from reacting with water molecules, which would cause a drop in efficiency for the final product. The flexibility of an FBG enables good monitoring, especially for humidity, and the possibility of simultaneous sensing of more than one parameter [2].

Sensors in biochemical and environmental fields favours precise and active mapping of an area. Multiplexed FBG is an excellent candidate due to its capability in multi-parameter sensing when connected in series. Particularly in pharmaceutical industry, where critical parameters required to be mapped and monitored is humidity and temperature. Having the allocation of FBG humidity and temperature sensors in series within a set region allows regulation of the parameters that can heavily impact the product. FBG sensors have potential in not only in pharmaceutical but other fields as well. This paper discusses some of the notable studies involving FBG sensors and its modification in environmental and biochemical application.

II. Fibre-optic vs. Conventional Sensors

Myriad conventional sensors with different working principles exist in the market. The predominant ones are electrical-based sensors. Sensors that primarily use electrical current as the main principle for sensing, such as micro-

This paragraph of the first footnote will contain the date on which you submitted your paper for review. This work was supported under research grant FRGS/1/2018/TK10/HWUM/02/2.

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electro-mechanical systems (MEMS) and resistive probes, are commonly implemented in many industrial fields. They are used to measure many different parameters. However, these sensing devices rely heavily on electrical flow on their active regions for the detection of the measured parameters. Electron flow is susceptible to electromagnetic interference and has a possibility to damage the device due to electrical flux or short circuits. Most electrical-based sensors are built upon complex circuitry which contributes to high maintenance costs. The complex circuitry causes these conventional sensors to be less robust, and they may have difficulty when embedded within a structure [3, 4]. The drawbacks of these type of sensors are propelling research fields to focus on studying and exploring the research gaps in optical-based sensors.

Optical based sensors are sensors that utilize light as the primary sensing and signal transfer mechanism. Similar to their electrical counterparts, optical sensors have many variations. Additionally, other than fibre Bragg grating sensors, other optical sensor families that are prominent are absorption-based sensors that rely on evanescent waves and interferometers that take advantage of wave interference by two or more rays, which are then interpolated into readable data. Bragg grating sensors have advantages over other optical sensors. Grating-based sensors are often minimal in terms of form and are capable of temperature and pressure sensing without any extra alterations to existing structures. They have the potential to be implemented in long-distance sensing and can be multiplexed with many sensors of different sensing measurands. This allows highly sensitive locational mapping of various parameters in a large area of the environment with low noise [5].

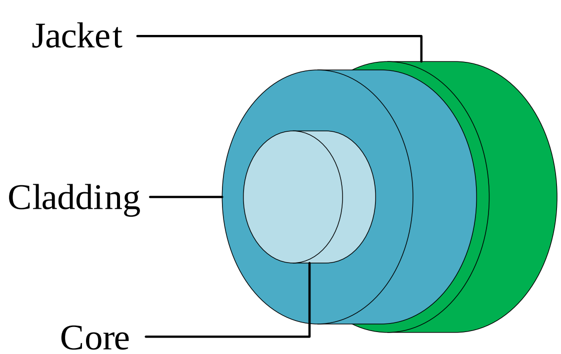

Fig. 1. A cross-sectional view of an optical fiber.

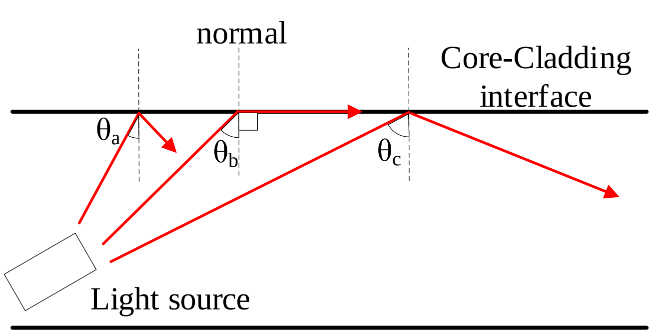

Fig. 2. Light propagation mechanism in fibers.

III. Fibre-optic Principle

The main carriers/modes of signal transmissions in OFs are photons. Light particles or photons behave differently than electrons because they have no mass at rest and negligible mass when mobile [6]. Therefore, the manipulation of light follows laws of optics such as reflection and refraction of light. The possibility of propagating light in this way enables OFs to transmit data, luminescence and signals in the form of alternating frequencies of light. Signal detectors and decoding devices are usually connected at the ends of OFs to decrypt the light signals into electronic signals and then process them into data [7].

The propagation of light down an OF is based on the total internal reflection of light occurring within the core and interface of the cladding. The lower refractive index of the cladding contains the light by refracting it. The cross-section of a typical OF is shown in Fig. 1. OFs are strands of fibres consisting of cladding and cores having different refractive indexes. The cladding of an OF has a lower refractive index, n_{cl} than the core refractive index, n_{co}, allowing light to propagate down the core instead of escaping. Total internal reflection phenomena occur when light is transmitted through from a medium at a specific incident angle. Fig. 2 depicts the transmission of light within an OF, where θ_a, θ_b and θ_c are different incident angles of transmitted light. The reflected light with θ_b travels roughly along the interface of the core and cladding. An angle of 90° is formed between the refracted light path and the normal path. At this angle, θ_b is known as the critical angle. When light has an incident angle greater than the critical angle, it will be reflected back within the core itself. This allows the light to propagate down the core while being contained by the cladding [8].

IV. Fibre-optic Sensing

OFs are commonly applied with plastic or glass fibres due to their clarity and ability to allow light transfer within them. With the latter having better clarity, glass fibres are primarily used for long-distance signal transfer. Telecommunications and data transfer utilize super-clear silica glass fibres for minimum signal power loss due to attenuation. Plastic-based OFs are used for applications that differ from telecommunications. Attenuation losses in plastic OFs are usually in dB/m rather than dB/km as for glass OFs. This shows that signal loss is extensive in plastic fibres compared to silica-based fibres, thus negating its use in long-range data transfer. Short-range data transfer is still viable with plastic OFs, and the desire to use plastic-based fibres rose from their low cost in fabrication, modification and handling. Therefore, integrating plastic OFs within a small device is practical for production cost minimization [9, 10].

Regarding environmental sensing, a common practice used to sensitize a fibre optic is the manipulation of the refractive index within the fibre. The refractive index can change with the deformity of the OF itself by imposing mechanical strain. A change in temperature can also affect the refractive index due to the OF expanding and contracting from heat exposure.

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From these behaviours, OFs can be modified to enable the sensing of other parameters. Such modifications can include the tapering of the OF, thus introducing different environment reactive coatings to the sensitized region of the OF sensor. These coatings may affect the OF sensor in a way that they impose mechanical deformation that reacts with external stimuli or induces refraction index changes of light signals crossing the OF [11].

A. Fibre modification for various sensing techniques

OFs made of either glass or plastic have been used and studied in sensing applications. Modifications and sensitizations of OFs have been attempted by researchers in various ways to achieve a higher accuracy of parameter sensing while maintaining simple and robust configurations. Environmental sensing involves various parameters to be monitored other than temperature and pressure. Chemical concentration, water vapor content, pH, and salinity detections are among the environmental sensing parameters that require modifications to an OF. This section describes some of the different modes of OF sensing for the detection of various environmental elements.

1) Optical absorption-based sensors

Sensing is possible by directly examining the change in optical absorption of the light signal within the OF as the concentration of parametric target. This mode of OF sensing is among the most commonly used modes for chemical-based sensing [12]. For sensitization of the OF, some works taper the OF and apply different chemical sensitive coatings for specific chemical presence detection. Incorporating Gd-doped zinc oxide coatings for ethanol sensing [13], nickel oxide coatings for gas sensing [14], and air hole micro-structured fibre modification tapers [15] are some methods that utilize light absorption-based measurements.

Direct spectroscopic optical absorption-based sensors utilize the evanescent field occurring within an OF. An evanescent field exists along with the light that emanates in a confined optical waveguide. Light is totally reflected internally when travelling from a region with a high refractive index to the surface of a region with a lower refractive index. Along with the light propagation path, an electromagnetic wave exists, and this wave is not reflected together with the light. This electromagnetic field instead penetrates the inter-surface boundary of different refractive index regions. In an OF, the wave that penetrates the interface of the core-cladding surface is called the evanescent wave. This standing wave penetrating outwards from the core decays exponentially with the distance to the outer surface of the core. Since the evanescent field decays at the cladding region down to a near zero value, modifications such as tapering and coating can provide changes to the optical power transmitted over the OF [2, 12, 16].

Through removal of the cladding, evanescent waves proceed further from the core-cladding interface and contact with an analyte (parametric target). The evanescent field facilitates the absorption of light into the analyte, affecting the output power of the light transmission [17]. A study by Anuj *et al.* [18] replaced the tapered cladding of a fibre with graphene for biomedical application. This recently developed OF detects a small change in haemoglobin concentration. A graphene layer allows light that is facilitated by evanescent waves absorbed into the surrounding analyte due to its high absorbance. As the concentration of haemoglobin analyte increased, more light was leaked from the tapered region and absorbed to the analyte, reducing the transmission power of the injected light. Coating nanoparticles and controlling their sizes can influence evanescent wave penetration [19].

2) Interferometry sensors

Interferometry is a powerful optical sensing technique used in OFs for environmental and medical applications. The sensing method in interferometry involves the disruption of light phase properties upon exposure to an external environment. In OF sensing, the light phase changes are detected between two single mode fibres, where one bears a signal of interest (exposed external parameter) and the other carries a reference signal. The mixture of these signals induces a phase difference that can be translated into optical intensity changes [12, 20]. Interferometers have been studied since the 1980s, and several established interferometer configurations are still being studied to date.

A common configuration of an interferometer is the Mach-Zahnder interferometric sensor. An OF is often tapered or stripped via femtosecond lasers to alter the microstructure. This modified microstructure within the OF splits the light source into two parallel paths. One path is the reference path, and the other path carries the signal that was interrupted by the external parameter. These two different paths are then merged back into one combined light path. Since the reference path has fixed light parameters, the exposed path will have a difference in the light signal parameter, inducing notable interference fringes [21]. This principle can be observed via a recent study of bovine serum albumen sensing by Li *et al.* [22]. For sensing the bio-medium, a cuboid-shaped gap is imprinted between the core and cladding of the OF. The gap occupies only half of the whole diameter of the core for the purpose of splitting the light path. Channels are then fabricated from the cuboid gap to the fibre surface. These channels are where the serum enters and flows into the cuboid gap once the sensor is immersed. The light pathway within the core is split on the gap region into a reference path and medium path. The split light recombines at the end of the cubic gap, forming an interference path detected by an optical spectrum analyser.

A Mach-Zahnder sensing configuration, while having excellent sensing performance, lacks mechanical strength without an etching. A Sagnac configuration interferometer was explored because it offers a higher refractive index sensitivity than Mach-Zahnder interferometers [23]. In Sagnac interferometers, the incident light itself is split before being transmitted through a micro-structured region of the OF. The transmitted and split light enters the OF at the same pathway but in opposite directions. This configuration is known to be robust and suitable for sensing in harsh environments such as earthquakes and vibration monitoring [24]. In a Febry-Perot interferometer configuration, partial mirrors are created within the fibre or at the end of the fibre via chemical processes. This causes partial reflectivity to occur on the light ray, creating

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TABLE I
FBG APPLICATIONS WITHIN VARIOUS INDUSTRIES

Environmental/Geological/Oceanography		
Soil Strain sensor [25]	Water grade monitoring in rivers [26]	Water level indicator for river run-offs [27]
Ocean temperature and depth measurement [28]	In-sewer environment humidity and temperature field monitoring [29]	On-site Heavy metal ion detection [30]
Temperature and strain measurements under extreme radioactive environments [31]	Moisture contamination detection in adhesive bonds [32]	Wastewater environment temperature and humidity monitoring [33]
Cryogenic environment long range displacement measurement [34]	Earth crust deformation observation and earthquake [35]	CO_2 monitoring in indoor environments [36]
Soil and geo-grid interaction observation [37]	Magnetic field sensors for harsh environments [38]	Artificial landslide monitoring [39]
Pharmaceutical/Biochemical		
Dental shrinkage profiler [40]	Glucose sensor [41]	Encapsulated force sensor for robotic surgery [42]
Bone integrity monitoring [43]	Sclera force evaluation during a vitreoretinal surgery [44]	Highly sensitive erythrocyte detection [45]
Temperature monitoring of ex-vivo organs during enhanced radiofrequency ablation D [46]	Breathing pattern and respiratory rate monitoring [47]	Quantification of metatarsophalangeal joint quasi-stiffness based on clinical settings [48]
Strain sensor for bone stress analysis during masticatory movements [49]	Simultaneous measurement of cardiac and respiratory activities in human body [50]	Chloroform detection [51]
Carcinogenic chromium(IV) Detection [52]		
Transmission Lines		
Smart sensing bolts in transmission towers [53]	Strain measurement of angle brace of transmission towers [54]	Fatigue life monitoring of transmission lines [55]
Electrical current sensor with temperature compensator for transmission lines [56]		
Communications		
Photonic frequency converter [57]	Wave division multiplexer [58]	Distortion suppressor in radio over fibre communication system [59]
Optical chaos communication enhancement [60]		
Engineering and Structures		
Crack propagation monitoring [61]	Corrosion monitor for rebar [62]	Pipeline safety monitoring [63]
Vehicle tire dynamic control system [64]		
Energy		
Temperature sensor for nuclear reactor [65]	Temperature and strain sensor embedded in glass for nuclear power plant pressure vessels [66]	Vibration monitoring in hydroelectric generator system [67]
Embedded pressure sensor for thermoelectric power plant [68]		

multiple rays. Interference patterns can be observed via the mirror reflected rays [7, 69]. A moisture or chemical sensitive reflective material can be fabricated at the end of the OF. Thus, the change in the refractive index of the sensitive material induces a ray with a different pattern than that of its incident ray. A Fabry-Perot interferometer was recently used by Zhao *et al.* [70] for the measurement of humidity.

3) Fibre grating sensors in various fields

The versatility of fibres permits many different types of modification to suit various types of sensing. The very first fibre Bragg grating was first discovered by Hill *et al.* [71]. FBGs, much like other OF sensors, prevail from their capability to obtain real-time measurements, electromagnetic interference capability, linear output production and multiplexing capabilities. Wavelength filters, multiplexers and de-multiplexers are also possible with FBG [3]. FBG sensors are OFs built in periodic grating within the core. The gratings have different refractive indexes as a result of exposure to high-intensity lasers. The core grating segment is the sensitized point of the OF that causes the modulation of refractive indexes. FBG sensing has been applied in a wide variety of different environmental and biochemical parameters. Table I shows the implementation of FBG in various technological sectors. The involvement of FBG in many fields of industry depicts its good practicality and ease of implementation while delivering substantial sensing performance.

V. FIBRE BRAGG GRATING SENSORS

A. Working Principle

FBG sensing occurs in the region of periodic gratings. The gratings bear different refractive indexes than the core. Upon light injection through the core, wavelength signal perturbation occurs. Only a specific wavelength is reflected

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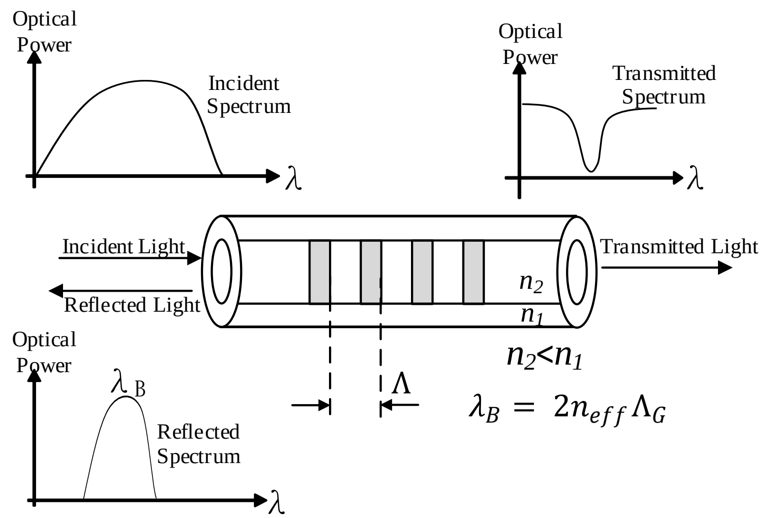

Fig. 3. Fibre Bragg grating principle in OF

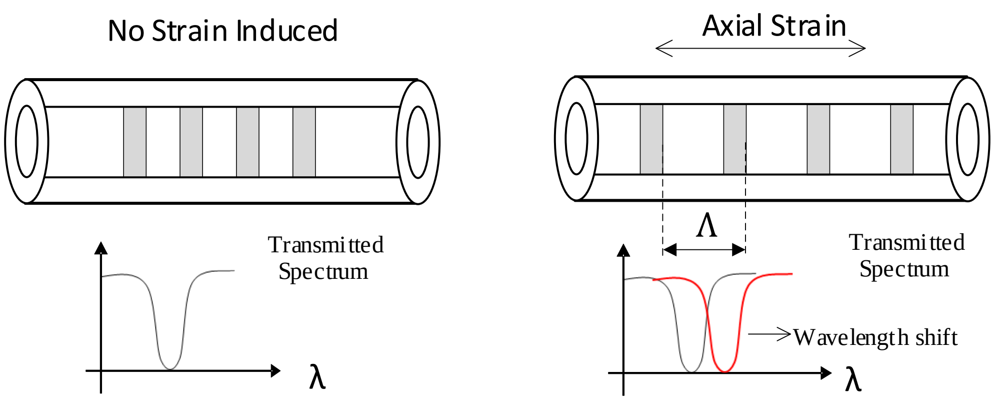

Fig. 4. Strain-induced FBG

back, while another wavelength proceeds through. The reflected wavelengths satisfy Bragg's equation (1):

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda_G \qquad (1)$$

Where n_{eff} is the refractive index of the propagating light through the OF, and Λ_G is the index modulation period, which is also known as the grating profile/pattern. λ_B is the Bragg wavelength [71, 83]. This principle is demonstrated in Fig. 3. The sensing mechanism is observable when the gratings perturb the light wavelength by deformation. Upon deformation of the grating region, the wavelength of the light will experience a shift. Fig. 4 visualizes an FBG upon axial strain induction. This is the principal way for an FBG to be used as a sensor [83]. Generally, an FBG can be used for the detection of strain, temperature and other physical parameters with minimum modifications. For the detection of humidity and other chemicals, a coating of a moisture-sensitive material is often applied [12]. Materials that can induce strain or deform upon water molecule presence in the environment are suitable for coating onto an FBG.

B. Grating Profiles

The perturbed refractive indexes within the core of an OF affects the performance of an FBG as a sensor. Phase masking allows the imprinting of various grating profiles. The grating profiles will largely impact the light signal transmitted across the grated OF. Because the light wavelength modulation largely depends on the grating arrangement within the core of an OF, different grating profiles have been considered and studied for their performance in sensing. Table II shows the depiction of each grating profile.

A common arrangement of grating widely used and established is uniform grating, where the period of each grating is uniformly distributed along the sensitized region of an OF. Gratings of uniform periodicity are often used in conjunction with different coatings for environmental sensing. Based on equation (1), n_{eff} and Λ_G are dependent upon the Bragg wavelength, λ_B. For FBGs, strain induction to the imprinted core will cause a shift in the Bragg wavelength. This can be written as equation (2):

$$\Delta\lambda_B = \lambda_B(1 - P_e)\varepsilon \qquad (2)$$

Upon expanding the strain-optic coefficient, P_e,

$$P_e = \frac{n_{eff}^2}{2}[P_{12} - \nu(P_{12} + P_{11})] \qquad (3)$$

According to equation (3), ν is the Poisson ratio of the

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grated fibre, and P_{12} and P_{11} are the stress-optic tensor coefficients. Based on this equation, any standard OF that obeys Hooke's law will experience a shift in Bragg wavelength upon experiencing axial strain along the fibre [61, 84].

While simple in nature, uniform gratings suffer from side lobes in their optical signal reflection at selected wavelengths. This could cause a misbehaviour of sensing functionalities, especially when multiplexed [20]. Apodization of the gratings has been explored for various applications. In an apodized FBG, the refractive index modulations are written non-uniformly. This consists of modifying the grating intensities to achieve a smoother transition between the grated region and the rest of the OF core.

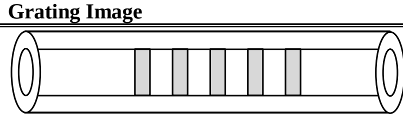
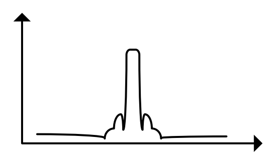
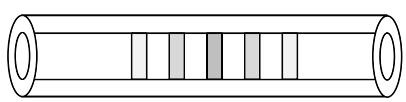
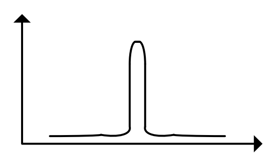
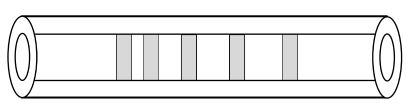
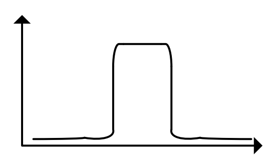
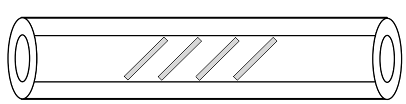
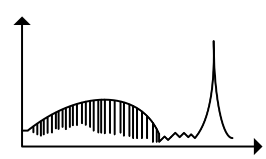
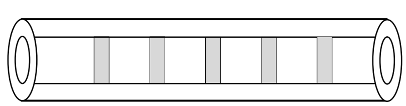
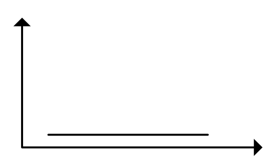
Apodized gratings are core gratings that are modulated non-uniformly. This type of grating profile serves to suppress side lobes occurring within the optical signal spectrum [72]. Various apodization profiles have been explored in an attempt to increase the side lobe suppression ratio (SLSR) of the spectrum. Some of these profiles include Gaussian, Nuttal, and chirped apodization. Apodized gratings with a Gaussian profile have been used within a work that utilizes a di-ureasil coating for humidity measurement [4].

The chirped gratings of FBG (CFBG) can be produced by varying the periodicity of refractive indexes [85]. CFBG reflects different spectra due to the variation of periodicity throughout the grating. The Bragg wavelength variation increment along the grating in a linear fashion allows a broader spectrum than uniform, non-apodized FBGs [85]. Recently, a study incorporating the use of chirped FBG has been performed for pressure monitoring [75]. CFBG have been implanted within rubber, which is then attached within a gasket for gas pressure monitoring. The CFBG reported a very high sensitivity of -267.7 pm/kPa within a sensing range of 0-10 kPa. The linearity obtained with this high sensitivity is 97.93%, which is lower than a metal diaphragm metal pressure gauge (99.99%). This study has proven useful for the application of CFBG as a low-pressure, high-sensitivity sensor.

The most recent FBG profile that has been examined is tilted grating. The refractive index perturbation is imprinted in an angled orientation as opposed to uniform or apodized gratings [86]. Tilted gratings are the perturbation of the refractive index in the fibre core that is tilted at a certain angle between the grating plane and the fibre cross-section. This leads to more complex mode coupling [80]. Application of this type of grating profile has been observed in gas quality sensor development [87]. A study reported successful detection of ethanol and gasoline solutions.

FBGs with extended grating lengths are considered long period gratings. A sensing principle slightly differs from uniform FBG. The wavelength resonance within a long period grating is written as [82]:

TABLE II
VARIOUS GRATING PROFILES OF FBG

Grating Profile	Grating Image	Reflectivity Spectrum	Ref.
Uniform grating			[72-74]
Apodized (varied strength of index modulation)			[72]
Chirped Grating			[75, 76]
Tilted Grating			[77-80]
Long period grating			[81, 82]

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$$\lambda_L = (n_{eff}^{co} - n_{eff}^{cl})\Lambda \quad (4)$$

As written in terms of resonance wavelength, λ_L, n_{eff}^{co} is the core refractive index, and n_{eff}^{cl} is the cladding refractive index. Λ is the period length of the grating. LPG relies on the change in n_{eff}^{cl} and n_{eff}^{cl} upon environmental measurand exposure, which leads to a change in the resonance wavelength Λ value shifting. This may mean that without any coatings, LPG may detect measurands such as temperature that can affect the refractive indexes of the core and cladding without coating; however, the measurement may not be sensitive, and additional modifications can be made for improvement.

VI. Etching of FBG

A common enhancement made to FBG is by stripping its cladding, reducing its diameter and revealing the core. This will allow the FBG to become more sensitive since the core will have less mechanical restriction of strain [88]. Therefore, an FBG, which primarily utilizes strain as its mode of sensing mechanism, etching as close as possible to the core would be advantageous. Since FBGs rely on their grated core for sensing, techniques that can disturb or reduce the core size, such as flame tapering, should be avoided to prevent damaging the grating. D-shaped or side polishing techniques for FBG are preferably etched by chemicals. Corrosive chemicals such as hydrofluoric acid (HF) are capable of stripping the cladding without compromising the core.

Upon cladding reduction, the FBG becomes more susceptible to the surrounding medium of the fibre refractive index changes. This means that a thinly etched fibre close to its core can have perturbations in the propagated light wavelength and intensity. Furthermore, surface irregularities induce light propagation scattering and chirps in the wavelength spectrum of the FBG [73]. Therefore, a proper etching position should be implemented to ensure uniform de-cladding.

In several other studies [5, 89, 90], FBG were typically etched at the end of the FBG fibre. This produces probe-type intrinsic sensors. Etching in such a manner as in Fig. 5a) allows the ambient strain to be minimized while etching, as there is no 'other end' of the FBG contributing to its weight to possibly break the FBG. Therefore, this produces the most uniformly etched FBG fibres, with the possibility of etching as close as possible to the core without any substantial mounting or modified etching stages. The only downside to this etching method is that it prevents the FBG from being multiplexed for multiple point/parameter sensing.

Etching in the middle section of the fibre requires extra effort in minimizing any strain exhibiting on the fibre during etching. A strained fibre during etching can introduce chirping in the Bragg spectrum that may interfere with the performance

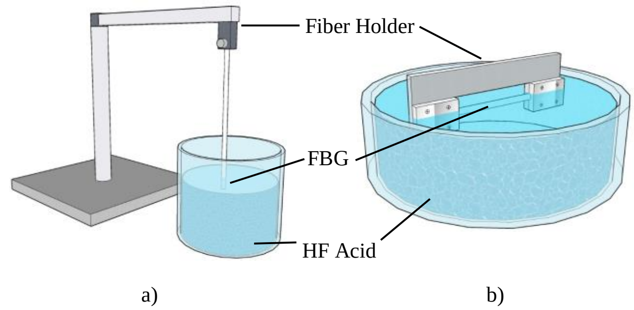

Fig. 5. FBG fibres etched at a) end of fibre and b) etched at middle of fibre with aid of a mounting tool.

of the FBG sensor. This has been demonstrated by a study [73] involving the etching of FBG with the aid of specially designed V-shaped mount for strain reduction to the FBG fibre, as demonstrated in Fig. 5b. The V-mount type allows the fibre to be tested with various strain magnitudes. A loosely held FBG fibre etch produces reflection spectra with multiple broadening peaks, a significant perturbation of reflectivity that can render the FBG less effective for use as a sensor due to the large flux of the peak spectrum. With tight fastening of the FBG during etching, a slight broadening of the reflectivity spectrum is present, with the main FBG peak still visible. FBG with just the right amount of tension produces a uniform wavelength shift retaining its reflectivity peak. Therefore, fibre tension during chemical etching can have an impact on

TABLE III
Various FBG Coatings That Have Been Recently Proposed

FBG Coating Material and Thickness	Grating Profile	Coating Method	Sensing Parameter	Sensing capabilities: Range	Sensitivity	Response Time	Ref.
Agar	Uniform	Mould Coating	Humidity	40-100% RH	0.036-0.051 nm/%	N.A.	[98]
Polyaniline (5µm)	Tilted	Oxidative Polymerization	pH	2-12 pH	40 pm/pH	29 s	[99]
Zinc Oxide	Uniform	Hydrothermal Dip Coating	Humidity	55-80%RH	2.51 pm/%RH	N.A.	[90]
Polyimide (50nm)	Uniform	Dip Coating	Salinity	0%-6%	15.407 nm/RIU	N.A.	[5]
Graphene	Tilted	Dip Coating	Humidity	30-80%RH	0.0185 nm/%RH	0.042 s	[77]
Di-Ureasil	Gaussian Apodized	Dip Coating	Humidity	15-95%RH	22.2 pm/%RH	N.A.	[4]
Strontium titanate ($SrTiO_3$)	Uniform Grating	Pulsed Laser Deposition	Temperature	20-220℃	9.97 pm/℃	N.A.	[74]

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the reflectivity spectrum and should be optimized.

VII. FBG Coating

Since temperature and strain sensing fibres are sensitive to scratches, FBGs require chemical sensitive coatings to enable chemical and humidity sensing. For sensitizing an FBG on a chemical based measurand, FBGs are stripped of their cladding via etching. Table III lists some of the coated FBG sensors for various parameters. This is to ensure that the evanescent field effect is utilized more efficiently due to a core in close contact with a chemical coating. Hygroscopic materials are frequently used as FBG coating materials. These reactive materials, upon exposure to measurand chemicals, will induce axial strain upon the grating periods. Such phenomenon can cause a shift in the transmitted wavelength and enables successful detection of the measurand [91]. Fig. 6 shows a chemical coating surrounding the FBG region that is stripped of its cladding via etching.

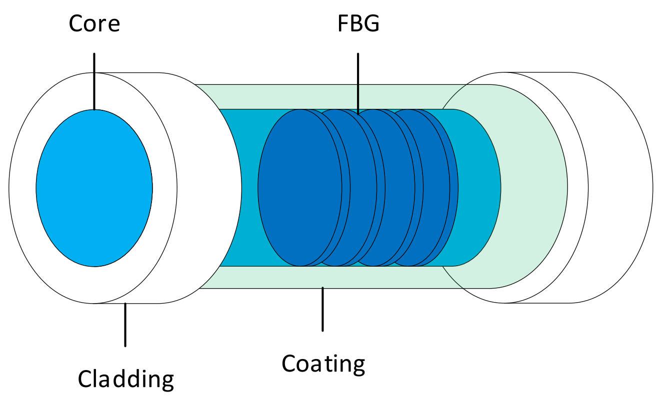

Fig. 6. A cross-section of an optical fiber.

Polymer based materials such as polyimides are suitable chemical reactive hygroscopic materials that have been used for humidity sensing FBGs. Polyimides exhibit exceptional humidity sensing capabilities due to their ability to deform by swelling upon absorption of water molecules. The swelling induces axial and radial strain on the fibre core perturbing the Bragg condition [92]. Polyimides are good for humidity sensing but may be unusable at higher temperatures above 250℃. Usage of 300℃-350℃ for an extended period of time (more than 24 hours) will result in loss of mechanical elasticity of the coating by 10%, and higher temperatures above 350℃ will result in the destruction of the polyimide material [93].

FBG coating with graphene is possible for enhancing sensitivity towards moisture. The high surface-to-volume ratio of graphene oxide (GO) and wide optical wavelength absorption allows it to interact with chemical compounds for sensing purposes. As such, the integration of optic fibres allows GO to allow for chemical and humidity detection. This has been realized recently in a work by Jiang *et al.* [77] that involved GO-coated FBG. The dip-coated FBG-GO exhibited an ultrafast response time of 0.042 s for a sensing range between 15-95% RH. This excellent response time was due to the structure of GO that allows uninterrupted absorption of water within the coating itself.

Organo-silica materials have been implemented as coatings for FBG sensors. One such material is di-ureasil, a material that consists of chains of polyether attached covalently to urea bridges. The material is capable of moisture detection with added advantages such as good optical fibre attachment and good coating durability [4]. Di-ureasil requires synthesis, which involves sol-gel-derived urea linkages before it was dip-coated onto FBG for humidity sensitization [94]. The proposed di-ureasil coatings on FBG have a sensitivity of at least 22.2 pm/% RH within the range of 15-95% RH [4]. The complex synthesis route for this material, requiring many precursors, may overshadow its simplicity and capability to be used as a sensitized coating for FBG.

Chemical property detection has been reported with polyaniline-coated FBG. A pH detector FBG incorporating the use of a conducting polymer, such as polyaniline, has been reported to achieve excellent results. A recent study utilizing tilted FBG with polyaniline coating for pH monitoring achieved ultra-fast response times of 29 s and 40 pm/pH sensitivity. Prior to coating, polyaniline was synthesized via a polymerization reaction between aniline and ammonium peroxydisulfate. The pH detection sensitivity of polyaniline was also tested at different coating thicknesses. The coated FBG at a high thickness of 17 µm exhibits a high sensitivity of up to 82 pm/pH. However, the sensor suffers from a hysteresis error of ±2.91, which is more than twice the error of a 5 µm thick coating. This suggests that a very thick coating may not be applicable for sensitivity enhancement since the detection error will also increase.

An FBG with ceramic-based coating material has been reported with strontium titanate ($SrTiO_3$). The perovskite material $SrTiO_3$ has been widely used as a photocatalyst [95] and for solar cell components [96]. There was recent reported that utilized $SrTiO_3$ as a coating for a temperature sensing FBG [74]. The coating of the material was performed by pulsed laser deposition and yielded a smooth film coating around the grated region. The sensor exhibited a sensitivity of 9.97 pm/℃ for temperatures up to 220℃. The study showed the possibility of coating an FBG that is delicate in terms of thermal and mechanical strength. The coating was smooth, and the FBG region was well protected by the coating itself. However, pulse laser deposition may not be the most cost-effective method because it requires a vacuum environment, and such an environment can only be offered by high-specification physical vapour deposition equipment.

Metallic coatings can also be applied together with grating-based sensors for water molecule sensing. Zinc oxide has been proposed for humidity detection due to its capability of having a high surface-to-volume ratio to allow for more water molecule attachment [90]. Prior to coating, zinc oxides are synthesized via hydrothermal processes. A coating process of zinc oxide is comprised of seeding process and growth process. The seeding process involves dropping the zinc acetate solution onto a tapered FBG while heating on a hotplate at 90℃. The growth process involves another growth solution prepared with zinc nitrate hexahydrate solution and

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hexamethylenetetramine (HMT).

The seeded FBG was then immersed into the solution before annealing at 90℃ for 5 hours before being tested. Over a humidity range of 55-80% RH, the sensitivity of the zinc oxide-coated FBG was reported to be 2.51 pm/% RH, which is more than uncoated tapered FBG (1.36 pm/% RH). The structure of zinc oxide appears to be somewhat flaky, with some rods appearing. This is due to the HMT influencing the growth of the ZnO nanostructure crystals. Typically, the reaction involving the hydrothermal synthesis of ZnO and HMT is as follows:

Dissolution of zinc precursor:

$$Zn(CH_3COO)_2 \rightarrow Zn^{2+} + CH_3COO^{2-} \quad (5)$$

Dissolution of HMT additive:

$$(CH_2)_6N_4 + 6H_2O \rightarrow 6HCHO + 4NH_3 \quad (6)$$

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^- \quad (7)$$

Formation of ZnO:

$$Zn^{2+} + 2OH- \text{->} Zn(OH)_2 \rightarrow ZnO + H_2O \quad (8)$$

A 2:1 ratio of zinc precursor/additive will result in an insufficient amount of OH- ions, which are crucial for ZnO formation [97]. Rods formed from this ratio may not be as long and thin as a 1:1 ratio of zinc precursor/additive. This study may explain why the ZnO nanostructure from [90] presents more flaky and stubby nanorods. The ratio of additives plays a significant role in the effects of the zinc nanostructures, and the correct ratio allows the possibility of tailoring the structure. Such heterogeneous structure opens the possibility of studying zinc oxide with other structures for humidity or chemical sensing because, similar to graphene, zinc oxide can also possess different nanostructures based on its synthesis techniques.

VIII. Biochemical and Pharmaceutical Applications

With the rising need of a reliable and robust biochemical sensors, FBG type optical sensors found its way in various works. Some of these studies are still in preliminary stages but have revealed promising results proving the potential of FBG integrated biological and chemical sensors. Often FBG have been integrated into pharmaceutical applications that assist in enhancing the precision of surgical tools and biochemical compound detections in human body.

A. Biological and chemical sensing

1) Glucose sensor

There have been many glucose sensors developed with different sensor principles. FBG is not an exception for a glucose application as it can be modified to have sensitivity towards glucose molecules. A study [100] in 2016 involved an etched FBG for detection of glucose. The FBG was coated with a reduced graphene oxide layer at post-etch enabling glucose sensitivity. Linear shift in bragg wavelength reported to be betweem 1 nM to 10 mM which as the author of the work claims to satisfy clinical range for detection of glucose in blood.

2) Carcinogenic chromium (IV) metal ion detection

Among the various metal pollution in the environment is the presence of chromium (IV) metal. These carcinogenic metals exists in industrial effluents down to rivers and soil. Chromium metal can have detrimental effects to human health and regions are often sampled, tested and monitored for its concentration. According to Kishore *et al.* [52] current high accuracy testing techniques such as chromatography, atomic absorption spectroscopy and inductively coupled plasma spectrometry requires expensive instrumentation and time consuming analysis process. This raised an interest in the development of FBG sensor that is capable of chromium (IV) detection. An approach have been made by *Kishore* et al. [52], to coat an FBG with specialised hydrogel for chromium detection. This hydrogel acts as a hygroscopic layer on the FBG that swells upon exposure to the metal ion of chromium (IV) inducing wavelength shifts. The developed sensor was reported to be capable of detecting trace amounts of chromium down to 10 ppb maintaining sensitivity at 1.2 pm/ppb. The study was done in environment of 25 ̊C. This is an excellent result for testing in many different rivers. The author of the work have stated that temperature changes are negligible and conforms the statement with another FBG for temperature sensing connected in series with the sensing FBG. It would be more beneficial that the coating is further tested under various temperature mimicking several temperatures of rivers, lakes and sea around the world.

3) Erythrocyte detection

Concentration monitoring of erythrocytes or red blood cells is also possible with a coated FBG. This would be useful in detection of haemorrhages within internal organs or diagnosis of various other blood related disease Another study involving graphene oxide coated with D-shaped micro-structured polymer FBG have successfully reported the sensor performance[45]. The mentioned sensor is capable of having sensitivity of 1pm/ppm which may be sufficient for use in clinical diagnosis. With hygroscopic graphene oxides that can deform when exposed to other measurands than red blood cells, a selectivity study could help in providing further credibility for this technology.

4) Urinary Protein Detection

The presence of protein in excessive amounts in urine may indicate an individual suffering from proteinuria. Kidney damage is imminent when protein exceeds certain values. For the detection of protein, the utilization of an FBG with a nanometre scale silver coating was proposed [86]. The coating of nanometre scale silver was deposited on the FBG via radiofrequency (RF) sputtering. The study reported a protein concentration sensitivity of 5.5 db/(mg/ml) and a limit detection of 1.5×10^{-3} mg/ml. The study ensures the feasibility of FBG coating that is capable of altering the refractive index when exposed to biomolecules for clinical purposes.

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B. *Pharmaceuticals and healthcare*

1) *Dental*

Grating sensors have seen their potential use in the field of dentistry. The accuracy of FBG-based sensors have made them suitable in the profiling of post-gel polymerization shrinkage. Recently, a published work involved an FBG sensor for use in profiling polymerization shrinkage of dental composites [40]. Strain is the primary parameter involved in the profiling of dental polymerization shrinkage. Due to the robustness of an FBG, it can be embedded within a specimen that mimics the characteristics of a human tooth. For mapping purposes, multi-node FBGs were connected in series within a single fibre. In a recent study by Rajan *et al.* [40], three serially connected FBGs were imprinted within Bragg reflectivity wavelengths of 1540 nm, 1550 nm and 1560 nm. The sensors were distributed at 3 different points of the specimen at a uniform gap length of 2 mm between each sensor. Dental composite was then applied and cured with a curing lamp. The obtained spectral response in Fig. 7 shows that the greatest shift of wavelength occurs at 1550 nm peaked FBG, which is situated at the centre of the specimen location wise. The non-uniformity of the shift in wavelength indicates that the dental composite does not cure uniformly. According to Rajan *et al.* [40], the use of FBG for mapping contributes greatly in the field of dentistry and allows for better development of dental composites or application techniques.

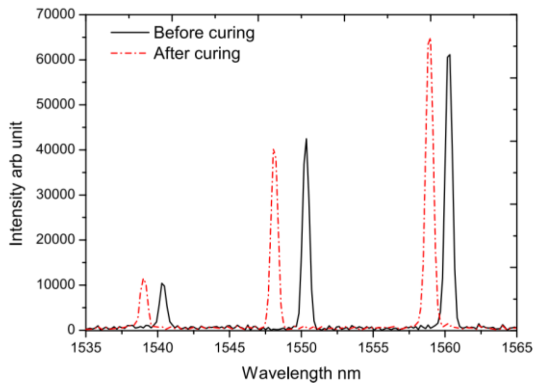

Fig. 7. Spectral response of dental mapping by FBG [40].

2) *Human Breath Monitoring*

The development of an ultra-high sensitive moisture detector for human breath monitoring has been studied using a tilted grating profile FBG (TFBG), as proposed by Jiang *et al.* [77]. Graphene oxide was used as the hygroscopic coating material for the FBG. The tilted FBG used in the study was excessively tilted and was claimed to induce a strong evanescent field. Upon coating with GO, the TFBG exhibits a strong response to relative humidity. It was reported that this study achieved an ultra-fast response time of 0.042 s in the sensing range of 30%-80% RH. Although it is more difficult to fabricate a tilted profile for FBG since it does not follow conventional arrangements of phase masking setups, such remarkable sensing performance reveals the potency of grating-based sensors in use within pharmaceutical fields.

3) *Human bone structural monitoring*

Within the fields of orthopaedics, FBGs have been utilized for monitoring the structural health of human bone cartilage. Recently, Marchi *et al.* [43] utilized an FBG sensor for osteoarthritis diagnosis. The FBG was used in a micro-indentation procedure to distinguish between healthy bone cartilage and osteoporotic bone cartilage. This work has demonstrated the precision and reliability of an FBG strain-based sensor in the orthopaedic field.

4) *Vitreoretinal surgery*

Delicate organs such as the human eye requires high precision when undergoing surgery. Minute deviations in the surgery could lead to loss of vision. Innovations have taken place in favor of enhancing the precision of tools for vitreoretinal surgery. In a study by Patel *et al.* [44], focused on approaching the measurement of scleral forces with the assistance of FBG sensor on a porcine eye model. Scleral forces, at the surgical tool insertion point acts as the allowed magnitude of force allowed to avoid tissue damage during a surgical procedure. The FBG sensor that was tested perform promising results in resolution of approximately 1 mN with a 900 nm diameter FBG based force measurement instrument.

5) *Organ temperature monitoring during cancer treatment*

Various cancer treatments are available and are continuously being innovated to allow for a minimally invasive treatment. A microwave ablation treatment is a thermal dependent process by which tissues are ablated by an applicator at temperature of 60 $^{\circ}$C. Temperature mapping of organ is essential as to avoid damage to other regions of the infected organ during the ablation treatment. Jelbudina *et al.* [101] applied several FBG sensors to map the thermal distribution of a liver in an ex-vivo study. The mapping allows estimation of amount of ablated tissues. For the enhancement of heat distribution throughout the organ tissue, magnetite nanoparticles were injected. The enhanced procedure managed to achieve detection of up to 5 mg/ml density of ablated tissue and can profile temperature distribution over 4.5 cm in length. The author of the work achieved these results with 15 FBGs assembled to several arrays and magnetite nanoparticles for enhanced temperature distribution. It is could be possible to get a more precise and accurate mapping with more FBG arrays assembled. Furthermore, the injection of foreign nanoparticle may be reduced to minimize any risk to the tissue.

6) *Sensing element enhancement in surgical robots*

A critical parameter that involves the precision of surgical robots is the force feedback. The sensitive strain sensing capabilities of a FBG sensor can be embedded within the shaft grooves of a surgical instrument via adhesive encapsulation. This allows the monitoring of more accurate force feedback magnitudes. However, surgical instruments are required to be frequently disinfected. Disinfection of a surgical instruments involves exposure to chemicals. It is a concern that the adhesive may react with the disinfectant chemicals and cause

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harmful effects. Xiong *et al*. [42], have tested this theory by having a FBG strain sensor embedded in adhesive coating exposed to alcohol rich environment. The alcohol concentration exposure mimics the actual disinfection environment common in pharmaceuticals. The adhesive encapsulated FBG was tested on its performance once every 5 days. On the 50th day, the sensor performance begins to drop gradually until completely detached on the 75th day rendering the sensor unusable. From this study, encapsulation method of FBG is still to be investigated before any surgical robots incorporating FBG as its force feedback sensor are ready to enter the market.

IX. Environmental Applications

Environmental parameters are regulated for almost all industries and commerce. Common physical parameters, such as temperature and pressure, are strictly controlled by various sensors. For some environments or processes, moisture content can be more crucial to regulate. Moisture content in the atmosphere or humidity can affect certain processes, leading to unwanted results. This leads to poor product quality or even a hazardous process, placing the environmental safety at jeopardy. Real-time, on-line analyses should be possible with the sensors. This ensures the minimization of reworked batches, which in turn reduces the effort of end-product quality checks and improves overall production efficiency [102]. The World Health Organization (WHO) recommends humidity sensors to have an accuracy of ±5% relative humidity for time- and temperature-sensitive pharmaceutical products (TTSPP) during storage and processing [103]. The relative humidity of most TTSPPs and food-based products should always be within the range of 25%-75% relative humidity to remain stable [104, 105].

A. Field environmental monitoring

Within industrial revolution 4.0, fields of industries continue to widen, and the rise of new infrastructures promotes the increasing requirement of environmental monitoring. For some industries, such as the oil and gas sectors and energy sectors, some key areas require sensors to be immune to EM interference while exhibiting robustness to allow for embedding into structures like pipelines and buildings, or underground for real-time and uninterrupted sensing. Exemplary studies of FBG-based sensors have been proposed involving a loop of FBG wrapped around a pipe to monitor its corrosion and leakage. The FBG exhibited good performance [63].

1) Field humidity evaluation of sewers

In nearly every construction foundations, sewers are built below them. Sewers, which are highly humid underground regions also contributes as a support structure for foundations and buildings above it. Water molecules tend to influence biogenic conversion of bacteria produced hydrogen sulfide (H_2S) into the corrosive sulphuric acid [106]. The sulphuric acid could be potent enough to cause corrosion in surface of the sewers threatening its structural health. Hence, mapping of humidity in sewers can be a step to regulate sewage environments, support sewer maintenance operations and develop mitigation plans for constructions. An approach by Bruno, *et al*.[29] in developing a sewer humidity monitoring system involved the use of a polyimide coated FBG with portable optical sensing interrogator and Raspberry Pi 3 module for remote data transfer. The monitoring system developed successfully mapped the sewer which was in Sydney, Australia with minimal maintenance. It was only after 2 months of which the battery powering the system needs to be replaced. However, from the achievement of this study, it can be said that equipping the system with permanent power supply (alternating current) would be advantageous as it allows for continuous monitoring of the environment. Additionally, with FBG of various other coating, simultaneous monitoring of other parameters may also be possible.

2) Temperature and humidity sensing under radioactive-heavy environments

A major modification to an FBG have been proposed by Pal *et al.* [31] to explore its validity and reliability in sensing under radioactive environments. The design involved a secondary outer cladding made of pure silica instead of the germanium doped silica which common single mode fibers are made of. The reason for this extra cladding is for protection of the gratings from the radiation. Radiation can influence the refractive index of glass which in turn, affects the bragg peak of the grating in the core. The extra cladding was modified onto the FBG by means of modified chemical vapor deposition technique. Pal et al.[31] further shielded the FBG with stainless steel tubing to further minimize bragg wavelength shift towards radiation.

3) Magnetic field sensors

The sensory features of an FBG does not limited to only biochemical detection. With the use of magnetic materials, detection of magnetic field is possible. Apicella *et al.* [38], have proposed of the use of a Fe-Ga allow or galfenol to encapsulate an FBG. In magnetic field detection, the magnetic material undergo deformation which allows the FBG to detect strain. The strain values can be indirectly converted to magnetic field values [38].

B. Geographical mapping

The geographical state of the earth gradually changes overtime. Different regions of the earth boasts its own soil behaviour and earthquake potency. Understanding the geographical and topographical state of a region can help in planning of constructions and mitigation plans. Such type of monitoring may require a sensor of not only of high accuracy but also capable of array configurations or multiplexing. FBG would be among the candidates suitable for use in this type of sensing and several works have been done with geographical sensing in mind.

1) Earthquake monitoring

FBG can be implemented as a seismometer from its strain sensing capability. Zhang *et al.* [35] applied this configuration mode where the FBG is attached between two elastic

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cantilevers and installed in a seismic station. The sensor head of 1 M length was installed beneath bedrocks. The study successfully obtained readings of clear seismic signals and tidal signals. The study was done in locations that are quiet and less active. Monitoring with FBG seismometer in locations that are more active such as near dense population regions may prove to be more challenging. More than 1 sets of FBG and strain meters may be required working in array to help filter out any noises generated by vibrations caused by anthropologic activities.

2) *Artificial landslide monitoring*

Landslides are one of the most dangerous naturally occurred disasters that can happen in certain locations. This due to the disaster being unpredictable and could happen at any time. Zhang *et al.* [39] approached this problem in developing custom sensor rods with FBG sensors attached to them. It is nearly impossible to test these sensors in a real and potent landslides, therefore the work done by Zhang *et al.* [39] on an artificially made landslide. Four separate rods consist of two FBG installed in each was tested. Two rod is made mechanically hard and the other is much softer encapsulation material. The rods were then installed within the soil of an area of which a landslide is to be artificially initiated by digging the lower part of the land. Reported data have shown the softer rods are more sensitive to smaller landslides and their placement further than the landslide potential area is advised. The hard sensors should be installed near the landslide area since these are more rugged in design and detects larger landslides. The outcome of this study allows the areas to be monitored for potential landslides and proved that FBG sensors are usable in such cases.

C. *Ocean observatory application*

The vast coverage of the ocean enveloping almost 71% of the earth's surface requires substantial sensors and techniques for monitoring. An array of sensors with excellent response times and minimal interruptions are preferred, and FBG fits these requirements. Parameters such as salinity, pH, dissolved oxygen, temperature and pressure are among the main parameters of oceanographic study because they can be used to estimate ocean currents, depth and evolution of sea organisms [107]. Tests have been conducted on FBG sensor arrays to monitor the depth of the ocean. Encapsulated FBG as a pressure and temperature sensor was tested within the Yellow Sea in China [28]. The sensor, when compared to a commercial electrical-based sensor, exhibits consistent data on the ocean depth from the acquired temperature and pressure of the sea. It was highlighted that in colder temperature sea water regions, the FBG viewed clearer data compared to its electrical counterparts. Therefore, this recent study has shown the potential and capability of FBG in oceanographic applications.

X. Conclusion

The integration of FBG sensors is feasible within various industrial sectors. With its ease of modification via coating, grating profile modifications and combinatorial use with other types of sensors, FBG offers excellent alternative sensing solutions other than conventional sensors. In line with the United Nation's Sustainable Development Goals (UNSDG), the development of FBG satisfies the industrial requirements of improved sensing capabilities. Furthermore, when focused on the pharmaceutical and healthcare industries, environmental parameter sensing will be more crucial because it may affect the TTSPP quality, which in turn may affect the end user. The possibility for further modification and optimization of FBG opens up wide opportunities for the improvement of sensing capability among the frontline of industrial safety systems.

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