Recent progress in applications of in-fibre Bragg grating sensors

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Abstract

In-fibre Bragg grating (FBG) sensor technology has become one of the most rapidly progressing sensing topics of this decade in the field of optical fibre sensors. FBG sensors are currently emerging from the laboratory to find practical applications. Rapid progress has been made in both sensor system developments and applications in recent years. This article presents a systematic review of recent progress in applications of FBG sensors in large composite and concrete structures, the electrical power industry, medicine, and chemical sensing. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

In-fibre Bragg grating (FBG) sensors have been subject to continuous and rapid development since they were first demonstrated for strain and temperature measurement about 10 years ago [1]. The main reason for this is because FBG sensors have a number of distinguishing advantages over other implementations of fibre-optic sensors, including potentially low-cost and unique wavelength-multiplexing capacity. The transduction mechanism is the modulation of the reflection wavelength of the sensing element, for example, thus avoiding the ambiguity of a phase measurement in an interferometric sensor or the requirement for referencing inherent in an interferometric one. FBG sensors seem to be ideal for realising so-called 'fibre-optic Smart structures' where fibre-optic sensors are embedded in (or attached to) the structure for achieving a number of technical objectives, such as health monitoring, impact detection, shape control and vibration damping, via the provision of real-time sensing.
information, such as strain, temperature and vibration [2]. The general aspects of the FBG sensor technology, including sensing principles, properties, fabrication, interrogation and multiplexing techniques, have been systematically reviewed by the author [3]; the present review concentrates on applications. In recent years, FBG sensors have been demonstrated for measurement of a wide variety of parameters; some FBG sensor systems have been installed in large-scale practical applications and a few FBG systems are commercially available. The applications of the FBG sensor cover a number of important fields. Generally speaking, the FBG sensor technology is approaching maturity after 10 years R&D, although there is still some potential for further improvement in terms of performance and functionality. Efforts are now engaged to realise cost effective FBG sensor systems and to explore more potential applications. Hence, it is considered useful to update the reader with the recent progress in applications of the FBG sensor technology. Several conference review articles on FBG applications with different emphases have been published previously [4–7]. This article aims to provide a comprehensive overview of the FBG sensor technology in terms of recent progress in applications. Following the introduction, the applications of FBG sensors for large composite and concrete structures, the electrical power industry, medicine and chemical sensing, are provided in Sections 2–5, respectively. This article concludes in Section 6 with a brief discussion on some future developments of the FBG sensor technology.

2. Applications to large composite and concrete structures

When compared with traditional electrical strain gauges used for strain monitoring of large composite or concrete structures, FBG sensors have several distinguishing advantages, including (i) much better invulnerability to electro-magnetic interference, including storms, and the potential capability of surviving in harsh environments, such as in nuclear power plants [8]; (ii) much less intrusive size (typically 125 μm in diameter — ideal size for embedding into composites without introducing any significant perturbation to the characteristics of the structure); (iii) greater resistance to corrosion when used in open structures, such as bridges and dams; (iv) greater capacity of multiplexing a large number of sensors for strain mapping along a single fibre link, unlike strain gauges which need a huge amount of wiring; (v) higher-temperature capacity (typically ~ 300°C); (vi) longer lifetime which could probably be used throughout the working lifetime of the structure (e.g. > 25 years) as preliminary accelerated aging tests indicate that FBGs properly exposed and annealed are reliable for long term operation over periods greater than 25 years without degradation in performance [4]. These features have made FBG sensors very attractive for quality control during construction, health monitoring after building and impact monitoring of large composite or concrete structures. After the first demonstration of embedding an FBG sensor in an epoxy-fibre composite material in 1990 [9] and in a simple concrete beam in 1992 [10], a number of applications in bridges, mines, marine vehicles, and aircraft, have been demonstrated.
2.1. Bridges

One of the first monitoring demonstrations for large structures was a highway bridge which uses carbon fibre-based composite pre-stressing tendons for replacement of steel-based tendons to solve the serious corrosion problem [11]. Since composite materials are not well proven in their substitution for steel in concrete structures there is considerable interest to monitor the strain and deformation or deflection, temperature or environmental degradation within such types of composite structures using an integrated fibre-optic sensing system. FBG sensors could be suitable for achieving such a goal. An array of FBGs has been adhered to the surface of a composite tendon and the specially protected lead-in/out optical fibres egress through recessed ports in the side of the concrete girders, as shown in Fig. 1. However, if the FBG sensors could be embedded into the composite tendons during their manufacture, excellent protection for the sensors and their leads would be provided (this has been done recently [12]). A strain-decoupled FBG temperature sensor was installed within each girder to allow for correction of thermally induced strain. A four-channel demodulation system, as shown in Fig. 2, has been developed based on the combination of the linear filter method and an Er-doped fibre laser used for enhancement of the small reflective signal levels from the FBG sensors. In this arrangement a length of Er-doped optical fibre pumped by a semiconductor laser operating at 980 nm serves as the fibre laser whose wavelength is tuned by the sensing FBG and the wavelength shift of the sensing FBG induced by strain change is detected via a bulk linear filter that converts the wavelength shift into intensity change [13]. The measurement range and resolution of this interrogation system are 5 με and 1 με. An accuracy of ~ ± 20 με was demonstrated, which is mainly limited by the Er-doped fibre laser frequency jitter. The maximum measurement bandwidth is about 700 Hz. The transient strain change and static loading associated with passing and parking a 21 ton truck on the bridge were demonstrated, indicating the potential for possible traffic monitoring applications. Also, such a system has been embedded into a concrete bridge by the same research group. Two similar FBG sensor systems using a long-period fibre grating [14] and a chirped fibre grating [7] as wavelength discriminating elements for demodulating the sensor output have been used for replacement of the bulk linear filter and have been field-tested for strain monitoring of concrete bridges recently. These two approaches provide an all-fibre and robust design. In order to obtain more detailed information about the strain distribution in a bridge structure due to damage, an FBG sensor system with up to 60 FBGs has been embedded into a ¼ scale bridge model by the Naval Research Laboratory in USA [5]. This system with a typical response time of 0.1 s is well suited for static strain mapping but not for dynamic strain measurement, due to the constraint of the scanning speed of the Fabry–Perot tuneable filter used for the wavelength-shift measurement.

The preliminary results obtained from these demonstrations are quite encouraging. However, the typical resolution of 1 με/√Hz is not adequate for traffic usage, e.g. the 21 ton truck only generated a strain level of ~ 20 με [11]. The resolution would need to be improved by a factor of at least 10. Recently, a new approach using FBG to form the reflectors in a Fabry–Perot interferometer, interrogated by low-coherence
interferometry to minimise the interferometric phase noise, has been demonstrated to achieve high sensitivity dynamic strain measurement [15]. The configuration of such a system is shown in Fig. 3, which combines FBGs with an all-fibre Fabry–Perot interferometric sensor (FFPI) formed by writing two FBGs with the same central wavelength on a length of fibre. For a single sensor design, the phase change of the FFPI is used for high-sensitivity dynamic strain measurement whilst the wavelength shift of one of the two FBGs protected against strain is used for correction of thermal apparent strain. The wavelength difference between the two FBGs caused by a temperature gradient would be a problem for practical applications as it would degrade the visibility of the interferometric signal. This undesired effect could be reduced by simply selecting the two FBGs with a larger linewidth. Also, as the gauge length of the sensor is normally much less than the size of the structure to be monitored, the wavelength difference caused could be negligible due to small environmental temperature gradients between the two FBGs.
Static strain monitoring is simply obtained by directly measuring the wavelength shift of another FBG sensor which is arranged in tandem nearby the FFPI and has a different central wavelength to the FBGs in the FFPI, although it can also be achieved by the identification of the central fringe position of the interferometric signal when the FFPI is interrogated with a scanned local receiving interferometer [16,17]. This FFPI/FBG combination allows simultaneous measurement of three different parameters—static strain, temperature and transient strain. Multiple FFPI/FBG sensor pairs are wavelength multiplexed for facilitating quasi-distributed measurement.

An experimental system, including two 1 m long FFPIs with central wavelengths of 1531 and 1534 nm and a FBG with a central wavelength of 1555 nm, has been demonstrated. A static strain resolution of better than 1 με over a range of 5 mε, a temperature sensitivity of 0.1°C and a dynamic strain sensitivity of better than 1 nε/√Hz have been obtained. Fig. 4 shows the result for a 10 Hz low-frequency dynamic strain with a heterodyne carrier frequency at 1 kHz. The system cross-talk measured is less than 50 dB. This sensor system, combining the advantages of both FBG sensors and low-coherence interferometry, would be well suited to health monitoring of large-scale structures because quasi-distributed static strain, temperature and transient strain sensing could be simultaneously achieved for both the surface mounted and embedded applications due to the simple profile of these sensors. In addition, this system could be used for detection of acoustic emission from concrete cracks for damage monitoring due to its superior sensitivity as the acoustic emission would generate a dynamic strain [18] that could be detected by the FFPI. An experiment has been carried out to investigate this possibility and the preliminary results show that sub-nε sensitivity can be achieved for high-frequency dynamic strain signal at frequencies of tens of kHz (see Fig. 5 where the heterodyne carrier frequency is 100 kHz). For the dynamic strain application, parallel WDM filters could be used
Another example of the application of the FBG sensor to bridges is for distributed load monitoring of carbon-fibre-reinforced polymer cables used in a cable-stayed suspension road bridge during construction and its behaviour during traffic [19]. The interrogation system based on a CCD spectrometer with a calibrated lamp as the wavelength reference has a resolution of $1 \mu e$ but response time is slow due to the speed limitation of signal processing with software. An FBG sensor system with the combination of a two-mode fibre and an FBG has also been proposed for such an application where simultaneous strain and temperature measurement could be achieved [20].

2.2. Mines

Measurement of load and displacement changes in underground excavations of mines and tunnels is vital for safety monitoring. Multiplexed FBG sensor systems could be able to replace the traditional electrical sensors, such as strain gauges and load cells, which cannot be operated in a simple multiplexed fashion and in a very hazardous environment with strong electro-magnetic interference generated by excavating machinery. An FBG sensor system based on a broadband Er-doped fibre source and a tuneable Fabry–Perot filter has been designed for long-term static displacement measurement in the ultimate roof of the mining excavations and in the hanging wall of the ore body’s mineshaft [21]. A specially designed extensometer with a mechanical level mechanism can cope with the large displacements of up to a few cm.
applied to the extensometer by controlling the overall strain change of the FBG to be less than 1%. This system is currently undergoing its field test.

2.3. Marine vehicles

Advanced composite materials are currently finding an increased interest in marine vehicle design and construction as the introduction of new composite materials can reduce hull weight considerably and is especially attractive for fast vehicles. It is necessary to obtain a complete characterisation of the behaviour of such structures in order to achieve an optimum use of material for reinforcement and cost-effective construction. Approximately, 100 sensors are required for monitoring bending moments, shear force, and slamming force at various positions of a vehicle model and the test results are transferred to a full-scale vessel by appropriate scaling. The FBG
Fig. 6. Schematic of a marine vehicle model with FBG strain and force sensors.

sensor may be an ideal candidate for such a specified application. An FBG system based on the use of a dynamic locking DFB laser for wavelength-shift detection induced by strain has been demonstrated for measurement of the bending moment at the middle of a catamaran model, as shown in Fig. 6 [22]. Two FBGs are mounted at the top and bottom of a stainless-steel beam that is a part of the model. An FBG positioned in the wet deck between the two hulls of the model is used for measurement of the slamming force generated by sea waves. The major advantage and disadvantage of using a DFB laser are its high S/N and limited wavelength tuning range (< 1 nm). A limited range to resolution of ~ 500:1 has been demonstrated which is less than that of most of other interrogation schemes [3]. Advanced FBG systems with improved performance and capacity of multiplexing a very large number of FBGs are needed for this application. Very recently, a 16-channel WDM FBG dynamic strain sensing system with interferometric detection has been demonstrated for approaching such a goal [23]. A strain resolution of < 10 nε/√Hz with a bandwidth of up to 5 kHz has been achieved. This system has been successfully used for the slamming-load tests of a composite panel used in design and fabrication of an air-cushion catamaran ship.

2.4. Aircraft

Advanced composite materials are now routinely being used for manufacturing engineering structures such as aerospace structures (e.g. parts of airplane wings). Compared with metallic materials, advanced composite materials can have higher fatigue resistance, lighter weight, higher strength-to-weight ratio, capability of obtaining complex shapes and no corrosion. Hence, the use of composite materials with embedded FBG systems can lead to reduction in weight, inspection intervals and
maintenance cost of aircraft and consequently to improvement in performance [24]. However, there is a major challenge in realising real-time health and usage monitoring in service with an on-board sensor system. A distributed FBG sensor system could be ideally suitable for such an application. Because FBG sensors are sensitive to both strain and temperature, it is essential to measure strain and temperature simultaneously in order to correct the thermally induced strain for static strain measurement. A number of approaches have been proposed for simultaneous measurement of strain and temperature [3,25,26]. A simple and effective method often used is to employ an unstrained temperature reference FBG, but this approach is not suitable in all cases, e.g. for FBG sensors embedded in composites. This may be due to three possible difficulties: (i) integrating both strain and temperature sensors into the same location within the composite to obtain high spatial resolution, e.g. when an unstrained temperature reference FBG is used; (ii) achieving adequate strain-temperature discrimination accuracy with the dual parameter method, in particular in a multiplexed system; (iii) processing the distorted FBG signal if the FBG experiences a non-uniform strain along its length—this is likely to occur when the applied strain is large. Strictly speaking, local and accurate temperature compensation for static strain measurement with FBG sensors embedded in composites is still a key problem to be solved. At this stage it may be easier to measure dynamic strain rather than static strain as temperature variations are normally much slower than dynamic strain changes and hence would not affect the measurement accuracy. Dynamic strain measurement can be used for vibration and impact mode analysis of the structure, which is highly desirable in practice.

Fig. 7 shows a schematic diagram of a multiplexing system which is, in principle, capable of measuring the two-dimensional dynamic strain distribution of a carbon fibre composite specimen used for aircraft [27]. This (SDM + WDM) topology with a tuneable wavelength filter (TWF) and an interferometric wavelength scanner (IWS) combines the advantages of the series and parallel multiplexing topologies and hence it can create an efficient 2-D distributed FBG sensor network. Both the TWF and the IWS are located immediately after the source rather than in the front of the detector to allow FBG elements with similar wavelengths on all fibre lines to be interrogated simultaneously. In operation, the TWF is used for selection of specified FBG channels with different centre wavelengths along a single fibre line, whereas the IWS, arranged after the TWF, is used to achieve both high-resolution and high-speed wavelength-shift measurement. A step strain change was applied to the composite to simulate a periodic transient strain. The results obtained from the FBGs embedded in the composite were in good agreement with those from conventional strain gauges used as a strain reference (see Fig. 8). This system has a potential multiplexing capacity of up to a few hundred of FBGs with a strain resolution of sub-με and a bandwidth of up to MHz, hence it could also be used for possible detection of acoustic emission either from material degradation (e.g. matrix cracking, fibre break) or from impact of foreign bodies with sufficient impact energy to cause damage and thus to achieve both strain and damage detection with the same system. For such an application, FBGs have been combined with conventional piezoelectric sensors to provide a more simple solution, but piezoelectric sensors may suffer from electro-magnetic interference and shorter lifetime [28].
In general, for FBGs embedded in composites it is ideal to measure all the multiple axes of strain and also temperature at multiple locations, as transverse strain loading may be on the order of the longitudinal strain for many applications. Recently, a technique based on the combination of an FBG and an in-line fibre Fabry–Perot sensor has been demonstrated for simultaneous measurement of axial and transverse strain [29]. As the in-line FP sensor is insensitive to transverse strain, it can be used for axial strain measurement directly and the transverse strain is then obtained via subtracting the axial strain from the output of the FBG which is intrinsically sensitive to both axial and transverse strain. Furthermore, a sophisticated technique of using dual overlaid FBGs written onto polarisation preserving fibre has been proposed to address the subject of simultaneous three-axis strain and temperature measurement, as shown in Fig. 9 [30]. Four effective FBGs are generated with this procedure which includes two FBGs at widely separated central wavelengths and two FBGs corresponding to each polarisation axis of the fibre. The result is that there are four equations in four unknowns that relate the three axes of strain and temperature to the four grating wavelengths. This method could be very effective if adequate strain–temperature discrimination accuracy could be achieved.

Many research groups have demonstrated the ‘simple’ operation of FBGs embedded in large composite or concrete structures for strain measurement; however, further work may be needed in order to realise a cost-effective multi-functional FBG sensor multiplexing system that is able simultaneously to measure static strain, temperature, and dynamic strain with adequate resolution and accuracy. With such a type of system, the FBG sensor would be able to realise its full potential and perhaps to dominate the market for health monitoring of large composite and concrete structures in the future.
Fig. 8. Results of dynamic strain measurement of composites with embedded FBGs: (a) FBG output, (b) strain gauge output.
3. Applications in the electric power industry

Like other implementations of fibre-optic sensors, FBGs are ideal for use in the electrical power industry due to their immunity to electro-magnetic interference. In addition, FBGs can be written onto standard 1.55 μm wavelength telecommunication fibre, hence long-distance remote operation is feasible due to the low transmission loss of the fibre. Loading of power transmission lines, winding temperature of electrical power transformers and large electrical currents have been measured with the FBG sensor.

3.1. Load monitoring of power transmission lines

An excessive mechanical load on electrical power transmission lines, which may be caused by heavy snow, for example, may lead to a serious accident. In particular, for those lines located in, e.g. mountainous areas, there is no easy access for inspection. Therefore, an on-line measurement system is needed to monitor the changing load on the power line. A multiplexed FBG system with more than 10 sensors distributed over a distance of 30 km has been demonstrated, as shown in Fig. 10 [31]. The load change is simply converted into strain via a metal plate which is attached to the line and onto which the FBG is bonded. Obviously, many more sensors are required for such an application. WDM may no longer able to cope with the significant increase in sensor number due to the limited bandwidth of the light source; however TDM could be employed to improve the multiplexing capacity considerably. As the distance between adjacent FBGs is large, high-speed modulation and demodulation would not be required. Overall, this is an excellent example of applying FBG sensors for long-distance remote monitoring in harsh environments.

3.2. Winding temperature measurement

Knowledge of the local temperature distribution present in high-voltage, high power equipment, such as generators and transformers, is essential in the understanding
of their operation and in the verification of new or modified products. Defective or degraded equipment can be detected by continuously monitoring the variations in the winding (the ‘hot spot’) temperature which reflects the performance of the cooling system. The FBG sensor has been demonstrated for such an application where the winding temperature of a high-voltage transformer is measured with two 1550 nm FBGs as sensing and reference elements interrogated via a standard optical spectrum analyser [32]. A measurement accuracy of $\pm 3^\circ C$ has been achieved for long-term monitoring. If WDM is added into this system, real-time multiplexed measurement can be achieved.

3.3. Electric current measurement

Optical fibre sensors exploiting the Faraday effect have been intensively researched and developed for measurement of large currents at high voltages in the power distribution industry for more than a decade [33]. However, problems associated with induced linear birefringence, temperature, and vibration have limited the application of this technique. An alternative method is to measure the large current indirectly by using a hybrid system consisting of a conventional current transformer (CT) and a piezoelectric element (PZ). The CT converts the current change into a voltage variation and then this voltage change is detected by measuring the deformation of the PZ using an FBG sensor [34]. Interferometric wavelength-shift detection method has been exploited for the detection of wavelength-shift induced by the current and a current resolution of $0.7 \text{ A/}\sqrt{\text{Hz}}$ over a range of up to 700 A has been obtained with
Fig. 11. Schematic diagram of the multiplexed FBG-based Fabry–Perot current sensor system.

a good linearity. More recently, the resolution has been further improved by replacement of the FBG with an FBG-based Fabry–Perot interferometer (FFPI) formed by arranging two FBGs with the same central wavelengths along a length of fibre, as shown in Fig. 11 [35]. Figs. 12a and b show the experimental results for measurement of a 50 Hz 12 A current and the performance of the sensor respectively; from Fig. 12b one can see that good linearity has been obtained. Compared with expensive CTs used in industry, these approaches offer a much lower cost alternative as the sophisticated electrical insulation is no longer required.

4. Applications to medicine

The majority of commercial sensors widely used in medicine is electrically active and hence they are not appropriate for use in a number of medical applications, in particular, in high microwave/radio-frequency fields or ultrasound fields or laser radiation associated with hyperthermia treatment, due to local heating of the sensor head and the surrounding tumour due to the presence of metallic conductors and electro-magnetic interference of currents and voltages in the metallic conductors, resulting in erroneous readings. Fibre-optic sensors can overcome these problems as they are virtually dielectric. A range of miniature fibre-optic sensors based on intensity modulation have been successfully commercialised in recent years. Generally speaking, these sensors are all point sensors which can only provide readings over a small volume in the human body. Although passive multiplexing of these point sensors is possible it is difficult to achieve in practice due to limitations on the probe size. By
Fig. 12. Results of current measurement using FBG-based Fabry–Perot interferometry: (a) spectrum of carrier at 5 kHz and current signal for an effective current of 12 A; (b) normalised side-band signal amplitude as a function of effective current at 50 Hz.

Using the unique multiplexing property of the FBG sensor it is possible to realise quasi-distributed sensor systems with a single fibre link. A number of temperature and ultrasound sensing systems have been demonstrated to date.
4.1. Temperature

A novel FBG temperature sensor system has been demonstrated, as shown in Fig. 13, in which high-resolution detection of the wavelength-shifts induced by temperature changes are achieved using drift-compensated interferometric detection while the return signals from the FBG sensor array are demultiplexed with a simple monochromator which offers cross-talk free WDM [36]. A ‘strain-free’ probe shown in the inset of Fig. 13 is designed by enclosing the FBG sensor array in a protection sleeve. The inner diameter of the sleeve is very small (typically 0.5 mm), hence it can support large transverse stress without transferring it to the fibre. The inner diameter is selected to be a few times larger than the diameter of the fibre so that the inner surface of the sleeve does not contact the fibre under the maximum transverse stress condition. The fibre link is connected to the processing unit via a fibre connector, making the probe disposable and interchangeable. A resolution of 0.1°C and an accuracy of ± 0.2°C over a temperature range of 30–60°C have been achieved, as shown in Fig. 14, which meet or exceed the requirements for many medical applications.
Another FBG temperature sensor system using a tuneable Fabry–Perot filter (FPF) has been developed for achieving both wavelength-shift detection and WDM simultaneously, making the system simple and compact, as shown in Fig. 15 [37]. The performance of the probe with four sensing FBGs is tested by placing it in a container inside a NMR machine with a high magnetic field of $\sim 4.7$ T. In situ measurement is achieved by using a $\sim 25$ m long fibre line to link the instrument and the NMR machine. A resolution of $0.1^\circ$C and an accuracy of $\pm 0.5^\circ$C over a temperature range of 25–60$^\circ$C have been achieved. Fig. 16 shows the experimental results obtained by cycling the FBGs from water at room temperature to ice. All the FBG sensors work well and the transitions caused by suddenly changing the temperature of the FBGs are readily seen.
The spatial resolution is mainly determined by the thermal cross-talk between adjacent FBGs due to heat transfer along the connecting fibre (here the length of each FBG is shorter than the interval between adjacent FBGs). It may not be easy to determine the exact value of the spatial resolution by theory due to the relative complexity of the specific heat transfer conditions involved, such as the heat convection between the fibre and the surrounding medium. However, experiments could be used to measure the spatial resolution for specified experimental conditions. For example, an experiment has been carried out to determine the spatial resolution for FBGs exposed in air, in which three 1 mm long FBGs with an interval of 5 mm were scanned through by a heated metal wire with a diameter of 0.2 mm at a constant temperature of $\sim 42^\circ$C, as shown in Fig. 17. It can be seen from the results shown in Fig. 18 that the minimum spatial resolution without thermal cross-talk is approximately between 7 and 8 mm.

A more portable FBG system using a simple CCD spectrometer has also been employed. Compared with the two-systems mentioned above, this approach is more simple and inexpensive [38,39]. The arrangement is similar to that shown in Fig. 13 but the GRIN array has been replaced by a linear CCD array so the Michelson interferometer is no longer required. The spectrum of the FBGs is recorded by a fast A/D converter and the centroid of each FBG can be determined by fitting the FBG profile using a standard Guassian function, and a resolution of 0.1$^\circ$C and an accuracy of $\pm0.2^\circ$C over a temperature range of 20–50$^\circ$C have been achieved, as shown in Figs. 19a and b respectively. The measurement speed is relatively slow (a few seconds

![Fig. 15. Schematic diagram of FBG temperature sensor system with a FP tuneable filter.](image-url)
The FBG sensor can also be used for the measurement of the heart’s efficiency based on the flow-directed thermodilution catheter method in which doctors inject patients with cold solution to measure their heart’s blood output. A flow-directed thermodilution catheter is inserted into the right atrium of the heart, allowing the solution to be injected directly into the heart for measurement of the temperature of the blood in the pulmonary artery. By combining temperature readings with pulse rate, doctors can determine how much blood the heart pumps. Such a type of catheter

Fig. 16. Results of temperature measurement with FBGs operated in a NMR machine.

Fig. 17. Schematic of experimental set-up for thermal cross-talk test for FBG sensors scanned by a heated metal wire.
with an FBG sensor has been demonstrated for replacement of a conventional catheter with a thermistor or a thermocouple [40]. To simulate the change of blood flow due to the size change of the blood vessel when the pump rate is kept constant, a clamp is used to squeeze the tubing, as shown in Fig. 20. The results for both clamped and unclamped cases with a pump rate of 108 rotation/min are shown in Figs. 21a and b. It can be seen that for both the FBG sensor and the thermocouple the time delays have changed from ~0.9 to ~1.1 s due to the partial clamping, corresponding to a relative change of ~10%. Preliminary results show that the optical outputs are in good agreement with the electrical thermocouple. It is also found that as the FBG is longer than electrical sensors, more accurate measurement is achieved due to smoothing of temperature profiles.

4.2. Ultrasound

Similar to temperature monitoring for the assessment of the operating safety of high RF or microwave fields mentioned above, an ultrasound sensor is required to monitor the output power from diagnostic ultrasound equipment used for a range of medical applications (including ultrasound surgery, hyperthermia and lithotripsy). Piezoelectric devices are the most common sensors but suffer from a susceptibility to electromagnetic interference and signal distortion, and the difficulty of direct determination of ultrasound fields in vivo due to the limitation of the probe size. The FBG sensor can overcome these problems and is able to measure the ultrasound field at several points simultaneously due to its unique multiplexing capability. An FBG sensing system
Fig. 19. Results of the FBG temperature sensor system based on a CCD spectrometer: (a) spectrum of sensing and reference FBGs, and (b) experimental results.

Based on interferometric detection with heterodyne signal demodulation has been demonstrated for detection of a focused ultrasound field at a frequency of $\sim 2$ MHz [41]. The maximum frequency range measurable is mainly limited by the length of the
Fig. 20. Schematic diagram of the FBG-based flow-directed thermodilution catheter system. SLD: superluminescent diode; APD1 and APD2: avalanche photodiodes; LPF: low-pass filter; A/D: analogue-to-digital converter.

Fig. 21. Experimental results of simulation for blood-vessel blocking test: (a) with clamping of the tubing, and (b) without clamping of the tubing.
FBG used (typically 4–10 mm) as the wavelength of the high-frequency ultrasound waves needs to be smaller than the length of the FBG. Apart from the wanted wavelength modulation induced by the ultrasound, undesired amplitude modulation of the output signal has been observed. This is because compressional standing waves, set up by the ultrasound in the fibre, only partially modulate the grating (as their wavelength is less than the length of the grating); the grating is subject to a non-uniform strain and hence leads to regions of the grating acting as spectral filters for the back-reflected light from other regions of the grating. As a consequence, an FBG with a length of 1 mm has been used to reduce this amplitude modulation effect [42]. Except for the region where the 1 mm FBG is located, all other regions of the fibre near the ultrasound field need to be desensitised to eliminate the standing waves in the fibre — this is simply achieved by jacketing the fibre. A pressure resolution of $\sim 10^{-3}$Atm/$\sqrt{\text{Hz}}$ has been demonstrated.

5. Applications to chemical sensing

The FBG sensor can also be used for chemical sensing based on the fact that the central wavelength of an FBG varies with refractive index change, i.e. chemical concentration change, via the evanescent field interaction between the FBG and the surrounding chemical. An approach based on an FBG written onto an etched D-fibre has been demonstrated [43] and very recently a modified version based on a side-polished fibre configuration has been reported as a refractive index sensor, allowing fast on-line measurements of chemicals, such as carbon hydrides in petrol industry [44]. Because of the constraint of current interrogation techniques with a typical resolution of 1 pm for static wavelength-shift measurement, the sensitivity obtained is much lower (up to $10^{-5}$) compared with other fibre-optical techniques, e.g. the interferometric method with a sensitivity of up to $10^{-8}$. A new type of fibre grating called long-period grating (LPG) has been discovered to be more sensitive to the refractive index change of the material around the grating cladding when compared with FBGs [45]. As LPGs couple light from the forward-propagating mode into several forward-propagating cladding modes, as shown in Fig. 22, any variation on
the refractive index of the material around the cladding modifies the transmission spectrum properties to generate loss peaks. A sensitivity of up to $10^{-7}$ is possible with further improvement of the interrogation resolution. As LPGs are also sensitive to temperature change, temperature compensation is required. The concentration of a number of chemicals, including ethanol, hexanol, methylcyclohexane, hexadecane [46], and CaCl$_2$, NaCl$_2$ [47], have been tested with LPGs. In principle, any chemical with its loss peak lying in the refractive index range from 1.3 to 1.45 can be detected using such a LPG technique.

6. Discussion

In this article, recent progress in applications of the FBG sensor to large composite and concrete structures, in the electrical power industry, medicine and for chemical sensing has been reviewed. Recent applications have concentrated on the strain mapping of large composite and concrete structures in a surface-attached fashion and this may lead to the development of a major market for FBG sensors if cost-effective FBG multiplexing systems could become available. For the embedding mode of operation in composites, the correction of thermally induced strain is still a difficult problem for high-accuracy static strain measurement, in practice due to limitation of either the spatial resolution or strain–temperature discrimination accuracy, or possible non-uniform strain—this needs to be solved in the future. Also, simultaneous measurement of multi-axis strain and temperature in composites remains as a major challenge for the optical fibre sensors community, due to its complexity.

Preliminary studies have shown that the FBG sensor is a promising technique for use in the electrical power industry and there is no doubt that more application examples can be foreseen, due to the capability of FBGs to be used in high-voltage environments. For medical applications a number of FBG temperature and ultrasound sensor systems have been developed. With further engineering, it is anticipated that these FBG systems could be used for in vivo measurement of temperature or/and ultrasound. Chemical sensing with FBG and LPG sensors represents another active application area where quasi-distributed measurement can be achieved. Apart from the applications mentioned in this article, there have been several other applications of FBGs to physical parameters which can be transduced to strain, such as pressure [48], and acceleration, for example [49,50].

For the instrumentation of FBG sensors, sensor systems based on the edge filter method and the Fabry–Perot tuneable filter method have been commercialised successfully [51,52]. Typical performance of these commercial instruments is summarised in Table 1. It can be seen that the typical resolution and accuracy for wavelength-shift detection are limited to 1 and $\pm 5$ pm or so, corresponding to the strain resolution and accuracy of $1 \mu$e and $\pm 5 \mu$e for a 1300 nm FBG. The maximum number of FBGs that can be multiplexed could be up to 64 but the cost for such a multiplexing system is quite high at this stage. However, it can be anticipated that with the increasing number of uses, cost-effective instruments would be commercially available whilst the fabrication cost of FBGs would reduce considerably in the future.
Table 1

Brief summary of performance of commercial FBG instruments

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<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (of full scale)</td>
<td>0.01%</td>
</tr>
<tr>
<td>Measurement range (strain)</td>
<td>1%</td>
</tr>
<tr>
<td>Accuracy (of full scale)</td>
<td>± 0.05%</td>
</tr>
<tr>
<td>Response time (single channel)</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Temperature range</td>
<td>−70–350°C</td>
</tr>
<tr>
<td>Gauge length</td>
<td>&gt; 10 mm</td>
</tr>
</tbody>
</table>

As a consequence, this could enhance the applicability of the FBG sensor and hence would lead to more new applications.

Although the performance of currently available instruments can meet most practical requirements, especially for structural monitoring, further improvement is still needed for some specific applications where higher strain sensitivity or higher measurement bandwidth is required, such as for acoustic wave sensing. Non-standard FBG sensors, e.g. FBG-based fibre laser sensors [53,54], and phase-shifted FBGs [55,56], have been proposed to address such applications. However, as the application range of these non-standard FBG sensors is limited due to their complexity in fabrication and/or in signal processing, sensor systems with standard FBGs are likely to continue to play a dominate role in fibre grating sensors.

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References


