Industrial and medical applications of fiber Bragg gratings

(Invited Paper)

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The uses of optical fibers are numerous, and over the past few decades, they have extended from optical fiber communications to a wide variety of sensing applications. In particular, fiber Bragg grating (FBG) sensors inscribed in single-mode optical fibers offer significant advantages over more conventional electrical sensors and have been successfully deployed in many different industries. In this Review, we review the applications of intrinsic FBG pressure and flow sensors in oil and gas and the deployment of FBG sensing networks in railways. The promising prospect of using polymer FBGs in wearable medical devices is also described.

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Optical fiber communications experienced rapid development, particularly in the last 30 years, after Kao *et al.* proposed the use of optical fibers for communications in their technical paper "Dielectric-fibre surface waveguides for optical frequencies" published in 1966[1]. The use of optical fibers for communications grew tremendously after the attenuation of the single-mode fiber (SMF) at the third window was reduced to ~0.2 dB/km in the late 1970s, which enables long-haul communications. SMFs with a core diameter of only ~8 μm and a cladding diameter of ~125 μm have also attracted tremendous attention from researchers working on optical fiber sensors due to the SMF's mode stability and extremely low propagation loss, together with many other advantages, such as electromagnetic interference (EMI) immunity and non-electrical conductive. The discovery of Bragg gratings in SMFs by Hill in 1978[2], followed by the demonstration of the ease of fabrication of Bragg gratings in SMFs using the transverse holographic inscription technique developed by Meltz *et al.* in 1989[3], spearheaded the development and applications of fiber Bragg grating (FBG) sensors. The availability of specialty optical fibers, which utilize holey microstructures or incorporate dopants into optical fibers, provides more versatility for optical fiber sensing. For example, photonic crystal fibers[4], soft-glass fibers[5], active fibers doped with rare-earth elements (e.g., Er, Yb, Tm)[6], polymer optical fibers (POFs)[7], and multi-core fibers[8] permit the optical, physical, and mechanical properties of a fiber to be modified to suit specific sensing needs. Specialty optical fibers attracted a lot of interest owing to the flexibility of customizing the optical properties, for instance, non-linearity, dispersion, birefringence, and gain, which are essential for fiber sensor and fiber laser developments.

The opportunities provided by FBGs inscribed in standard SMFs and specialty optical fibers are of huge importance to the communications, sensors, and industrial processing industries. FBGs are widely used as wavelength lockers, optical filters, dispersion compensators, reflectors, gain-flattening filters, add/drop devices, numerous kinds of sensors, and fiber lasers in these industries. FBGs are normally fabricated in SMFs by laterally irradiating the core of the fiber with intense UV light[2] to modulate the core index periodically, with a pitch of hundreds of nanometers. Then, 248 nm KrF excimer lasers and 193 nm ArF excimer lasers are commonly used to inscribe FBGs in photosensitive fibers and weakly photosensitive fibers, respectively. FBGs can be fabricated by using either the holographic techniques or the phase-mask technique[9], where the latter does not require precise beam alignment, is much easier to set up, and is therefore a preferred technique for most researchers. However, the holographic technique allows precise control of the grating period to write FBGs at widely different Bragg wavelengths by varying the angle of the two interfering UV beams. In the phase-mask technique, the grating pitch is fixed by the specific phase mask used, and typically, FBGs with a Bragg wavelength range of 1–2 nm can be written by applying tension to the fiber during the writing process. Figure 1 illustrates the schematic figure of writing an FBG in an SMF using the scanning method. More recently, femtosecond lasers[10] with short pulses of high energy are being used to inscribe FBGs in non-photosensitive optical fibers, which induces physical damage or deformation to the core of fiber instead of a light-induced index change.

When a broadband light source is launched into an FBG, a specific wavelength (Bragg wavelength) will be reflected back with a reflectance that depends on the strength of the FBG. The Bragg wavelength is determined by

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

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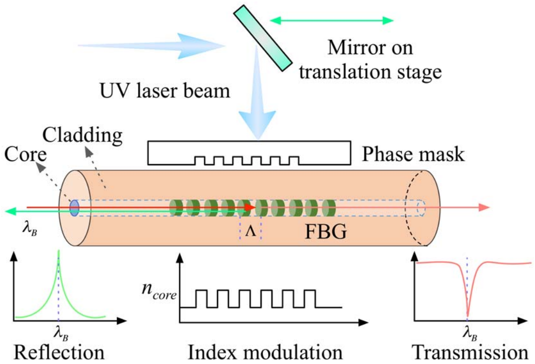

Fig. 1. Schematic of FBG imprinted in an SMF by the phase-mask technique with a scanning UV laser beam.

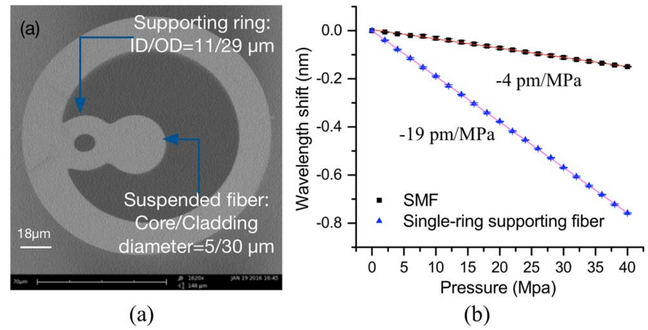

Fig. 2. (a) SEM photo of a single-ring supporting MOF and (b) the pressure response measured using an FBG on this fiber[15].

where n_{eff} is the effective index of the guided mode, and Λ is the grating pitch. The effective index and pitch of the FBG are sensitive to strain and temperature. The relationship of the Bragg wavelength shift with the strain and ambient temperature perturbation is expressed by[11]

$$\Delta\lambda_B = \lambda_B\left[(1 - P_e)\varepsilon + \left(\alpha + \frac{1}{n_{\text{eff}}}\frac{dn_{\text{eff}}}{dT}\right)\Delta T\right], \quad (2)$$

where ε and ΔT are the applied strain and temperature change induced on the FBG, and P_e is the photoelastic coefficient and equals ~0.22 for the SMF. α is the coefficient of thermal expansion. The temperature and strain sensitivities of FBGs in SMFs are experimentally measured to be ~10 pm/°C and ~1.2 pm/με at the operating wavelength of 1550 nm[11].

The many unique features and advantages of FBGs allow FBG-based sensors to be deployed in numerous sensing applications, such as in structural health monitoring of civil structures, condition monitoring of railways, physical parameter measurements in oil and gas, and in medical devices. In this Review, we review some novel FBG sensors for oil and gas applications, successful applications of FBG sensing networks for railway monitoring, and polymer optical fiber Bragg grating (POFBG) sensors that have very promising prospects in wearable medical applications.

FBG sensors can be used in very harsh environments and are being deployed as down-hole sensors in the oil and gas industry to measure temperature, pressure, and flow rate. An FBG inscribed in an SMF is very sensitive to temperature (~10 pm/°C) but relatively insensitive to pressure (3–4 pm/MPa)[12] and cannot measure flow rate directly. FBG-based mechanical pressure transducers were developed to measure pressure with enhanced sensitivity. Similarly, FBG-based flow transducers using the principle of vortex shedding from a bluff body to measure flow rate were developed[13]. However, these transducers are too bulky for down-hole applications.

With the advent of microstructured optical fibers (MOFs) in the 1990s, the capability of fiber-optic sensors has been greatly expanded in terms of sensitivity, resolution, and accuracy. Pressure sensitivity based on an FBG written in an MOF can be enhanced, for example, a higher pressure sensitivity of 12 pm/MPa using a grapefruit MOF[14], 19 pm/MPa using a novel single-ring MOF[15], and ~30 pm/MPa using birefringent MOF[16] were reported. Figure 2 shows the structure of the single-ring MOF and the measured pressure response. Compared with the sensitivity obtained from the FBG on the SMF, an obvious enhancement (~5 times) has been achieved. The pressure responses of these FBGs inscribed in MOF sensors are much higher than those in standard SMFs and therefore can be used to measure pressure directly without the need for mechanical transducers, permitting small and robust sensors to be deployed in down-holes.

An FBG inscribed in a specially doped SMF was developed to measure liquid flow rate at elevated temperatures. We demonstrated that optical fibers doped with cobalt are very efficient in converting light energy to heat and exploited this effect to develop an anemometer. The resolution of the FBG-based anemometer to measure air flow is 0.012 m/s for flow rates of 2 to 8 m/s[17]. This approach was expanded to measure the fluidic flow rate for down-hole applications. Figure 3(a) shows an example of the fluidic flow sensor based on an FBG written on an SMF and heated by Co^{2+}-doped fibers. When the fluid flow passes the heated FBG, a specific amount of heat will be carried away by the fluid, and the sensor's cooling rate, which can be determined by the FBG wavelength shift, is proportional to the flow rate. The sensor, packaged inside a stainless steel tube with an outer diameter of 0.5 mm, was

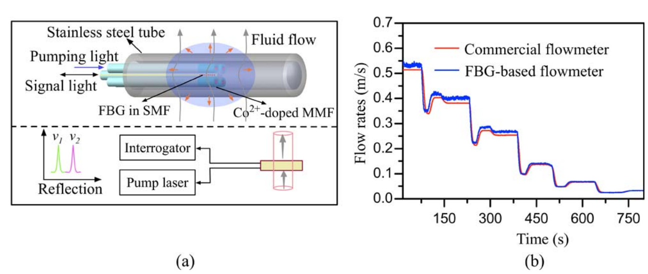

Fig. 3. (a) Schematic figure of the fluidic flow sensor based on an FBG written on an SMF and Co^{2+}-doped multimode fibers, and (b) comparison of the flow rates measured by the FBG-based flow sensor and a commercial flowmeter installed in the test rig.

employed to measure oil flow in a test rig at temperatures up to 130°C. The results were in good agreement with a commercial flowmeter installed in the test rig, as shown in Fig. 3(b). The correlation coefficient between the two independent data is 0.9974. The resolution of the flow sensor is estimated to be 0.002 m/s when measuring the oil flow at a certain laser pumping power. A higher sensitivity can be achieved if more pumping power is launched. Owing to the good resolution and fast response, a slight change in the flow rate can be detected even for a small reduction in the flow velocity, which is clearly seen in Fig. 3(b).

Obviously, long-distance pressure and flow measurements with these small FBG-based SMF sensors can be realized, which is an essential requirement in down-hole applications. Besides pressure and flow measurements, leakage detection of pipelines was successfully implemented with FBG sensing technology[18] to monitor the temperature and strain along oil pipelines. Condition-based maintenance (CBM) strategies are needed to enhance the recovery of oil and gas due to the increasing scarcity of conventional crude oil and natural gas reserves. FBG sensing technologies could play a key role in CBM to provide real-time condition monitoring to ensure safe and efficient running of oil and gas facilities.

The increasing demands for safety, reliability, and efficiency in the railway industry around the world call for the adoption of proactive or preventive maintenance strategies. FBG sensors can be installed on the rail tracks[19] to work as axle counters by measuring the strain induced by the wheel, as shown in Fig. 4.

Compared with the traditional axle counters used in the railway system, which is electrical, FBG sensors are immune to EMI. This is important for sensors employed in railway applications, where most of the equipment and trains operate at a very high voltage. The capability of multiplexing a large number of FBG sensors in a single strand of fiber over a long distance provides an important feature that no other type of sensor possesses. Furthermore, FBG sensors along the fiber can measure a wide variety of different parameters, such as temperature, strain, acceleration, vibration, and weight. The unique features of FBG sensing networks permit the realization of a flexible

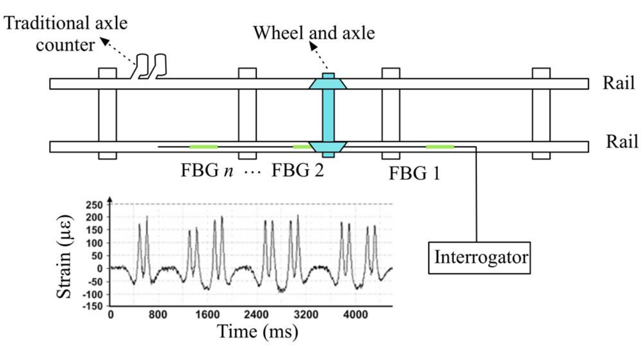

Fig. 4. Schematic figure of FBG sensors installed on the track of railway, where the inset shows the measured strain induced by the wheel.

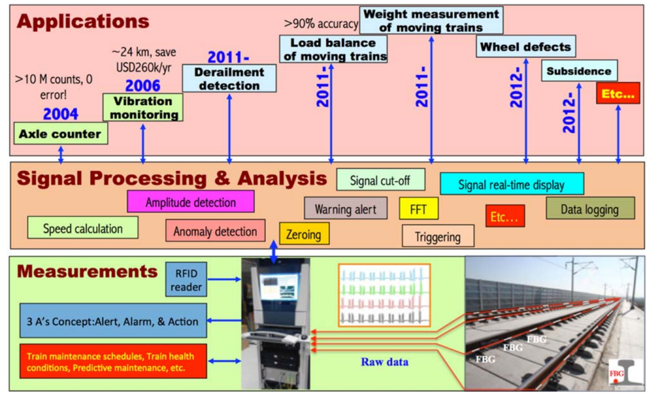

Fig. 5. Rail track-based FBG sensing network for monitoring of various critical conditions of moving trains[28]. The 4-digit numbers in blue indicate the commencement year for that project.

and cost-effective monitoring system for many railway applications[20], as shown in Fig. 5. Several FBG-monitoring systems were installed in Hong Kong[21] for CBM purposes. All trains traveling on the railway lines where the FBG sensors were installed are monitored, and the FBGs' waveforms are analyzed to derive important information about the passing trains, such as the number of axles, vibrations caused by axle boxes and wheel profiles, and train weight.

A train-borne system using a network of FBG-based sensors was developed to monitor critical components of bogies, car bodies, etc. More importantly, conditions of overhead power lines and rail tracks of the entire railway links can be monitored by passenger trains, allowing monitoring to be carried out during service hours. Similar systems have been installed in the Netherlands and Singapore to monitor catenary systems and rail tracks, respectively.

FBG sensing technology has proven to be extremely effective for railway monitoring. The FBG sensing information is wavelength-coded, provides self-referencing, and is virtually immune to intensity fluctuations. FBGs are reflective sensors whose signals can be obtained at either end of the sensors, providing redundancy in the sensing networks. These unique features are particularly important for industries where safety and reliability are major concerns, such as railways.

FBGs are deployed in numerous medical applications because of their small size, non-electrical conductivity, and multi-point and multi-parameter-sensing capabilities. These features, coupled with the fibers' immunity to EMI/radio frequency interference (RFI), make FBG sensors ideal for diagnostic imaging with magnetic resonance imaging (MRI) or computed tomography (CT) systems. FBGs are being used as force sensors to measure deflection and force on needles during MRIs[22]. In clinical operations, FBGs function as the micro-indicator for surgeons to know the applied force inside the blood vessels[23], as small as ∼2 mN. To measure the micro-force, we proposed the use of an FBG inscribed in a microfiber. A resolution of ∼1 mN was obtained for the range of 0–0.65 N in the experiment[24].

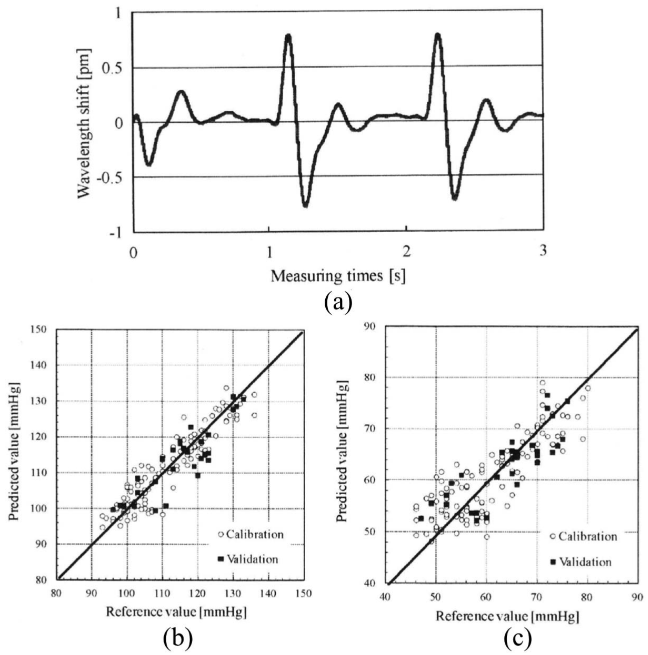

Fig. 6. (a) The pulse wave of filter processing in a wrist, (b) the predicted results of SBP, and (c) the predicted results of DBP in the wrist (© [2015] IEEE. Reprinted, with permission from Ref. [25]).

Some of the latest development efforts are in smart fabrics to measure cardiac and respiratory rhythms and for the prevention of sudden infant death syndrome in newborns. A particularly interesting development being investigated by researchers at Shinshu University is the use of one FBG sensor attached on the wrist to measure the vital signs of humans[25], including heart rate, blood pressure (BP), body temperature, respiratory status, and level of consciousness. They detect the expansion and contraction of arteries by attaching FBGs to the skin surface of the radial artery (wrist) to obtain the pulse waves, which allow them to predict systolic blood pressure (SBP) and diastolic blood pressure (DBP) with good accuracy.

The measured pulse wave in form of wavelength shift is shown in Fig. 6(a), which is processed using the algorithm of partial least squares regression. It can be seen that the BP pulse-induced wavelength shift is very small (<3 pm), and thus, an interrogation with a high resolution is required. The measurement results show good agreement with the reference BP measured by an electronic sphygmomanometer for both SBP and DBP, giving a correlation coefficient ~ 0.9. This is very promising technique to explore FBG sensors as multi-parameter vital sign monitoring device.

However, the aforementioned FBG sensors employed in wearable medical applications are inscribed in glass optical fibers that are not easy to weave into fabrics and that break easily. On the other hand, FBGs inscribed in POFs would be an attractive option. POFs are highly flexible and tolerant of sharp bends, but the single-mode POF necessary for writing FBGs is not commercially available, and writing FBGs in POFs requires a much longer UV irradiation time than in silica fibers. A single-mode POF is difficult to fabricate due to the diffusion of the core dopant to the cladding, making it difficult to control the fiber core's refractive index and diameter. New materials such as TOPAS and, more recently, ZEONEX were successfully used to make single-mode POFs[26], and microstructured POF and FBGs were inscribed in these POFs in less than 30 s[27], instead of the several tens of minutes typically used to inscribe an FBG in a POF made of PMMA. These recent developments in polymer FBGs are encouraging, but more efforts are needed to make FBGs in POF cost-effective and practical to introduce their deployment in wearable medical devices.

In conclusion, the applications of optical fibers have extended beyond optical fiber communications since Charles Kao proposed the use of low-loss glass optical fibers in communications. The many unique features of optical fibers make them attractive to be used as sensors in many industrial applications. In this Review, we gave a review of the industrial applications of FBG sensors in oil and gas, railways, and medicine. These industries have benefitted tremendously from FBG sensors in providing continuous monitoring to ensure efficient, safe, and reliable operation. Research and development are needed to extend the fiber sensors' capabilities, including sensitivity, stability, and multi-functional to other industries. As future prospects, for example, FBGs inscribed on special optical fibers with microstructures are supposed to extend the resonant frequency of vibration for accelerometers, which are vital to improving the performance of railway monitoring. Novel materials of fabricating optical fibers, such as photosensitive dopants for POFs, also provide the opportunity for utilizing POFBGs in biomedical detection; they show higher sensitivity and are more biocompatible compared with silica FBGs. Additionally, as the development of a miniature interrogation based on interferometry, the signal detection of FBGs can be implemented on tiny chips. It is possible to integrate the wireless modules on a chip, which enables the transmission of FBG signals via remote techniques and thus opens the door for wearable and movable devices based on FBGs. Optical fiber sensors coupled with wireless electronics sensors could form a ubiquitous sensor network to play an important role in smart cities to ensure resources are efficiently and effectively utilized.

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