ISSN 2278-3091

International Journal of Advanced Trends in Computer Science and Engineering, Vol.2 , No.1, Pages : 107-113 (2013)
Special Issue of ICACSE 2013 - Held on 7-8 January, 2013 in Lords Institute of Engineering and Technology, Hyderabad

Applications of Fiber Bragg Grating Sensors for Measuring Extreme High Temperatures

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Abstract: Fiber Bragg gratings have found many application in sensor systems, e.g. for temperature, strain measurements. Recently, high temperature stable gratings based on regeneration techniques and femtosecond infrared laser processing have shown promise for use in extreme environments such as high temperature, pressure or ionizing radiation. Such gratings are ideally suited for energy production applications where there is a requirement for advanced energy system instrumentation and controls that are operable in harsh environments. This paper will present the measuring of extreme high temperatures using FBG wave analyzer. Because of their small size, passive nature, immunity to electromagnetic interference, and capability to directly measure physical parameters such as temperature and strain, fiber Bragg grating sensors have developed beyond a laboratory curiosity and are becoming a mainstream sensing technology.

Keywords: *fiber Bragg grating sensor, optical sensing, high environment sensing*

INTRODUCTION

Sensing technologies based on optical fiber have several inherent advantages that make them attractive for a wide range of industrial sensing applications. They are typically small in size, passive, immune to Electromagnetic interference, resistant to harsh environments and have a capability to perform distributed sensing. Because of their telecommunication origins, fiber optic-based sensors can be easily integrated into large scale optical networks and communications systems.

Although developed initially for the telecommunications industry in the late 1990's, fiber Bragg gratings (FBGs) are increasingly being used in sensing applications and are enjoying widespread acceptance and use. The FBG is an optical filtering device that reflects light of a specific wavelength and is present within the core of an optical fiber waveguide. The wavelength of light that is reflected depends on the spacing of a periodic variation or modulation of the refractive index that is present Within the fiber core. This grating structure acts as a band-rejection optical filter passing all wavelengths of light that are not in resonance with it and reflecting wavelengths that satisfy the Bragg condition of the core index modulation. The Nobel Laureate Sir William Lawrence Bragg established the Bragg law in 1915, describing with a simple mathematical formula how X-Rays were diffracted from crystals. The Bragg condition, when applied to fiber Bragg gratings, states that the reflected wavelength of light from the grating is $\lambda_B = 2 n_{eff} \lambda_G$ where n_{eff} is the effective refractive index seenby the light propagating down the fiber, and Λ_G is the period of the index modulation that makes up thegrating. A diagram of an FBG is shown in Figure 1. Typically, the modulation of the core refractive index is created by photo imprinting a hologram in the photosensitive glass core of the fiber. Like a photographic film, the core of standard telecommunication optical fiber was found by researchers at the Communications Research Centre Canada to be photosensitive [1]. They found that Germanium, the element that is commonly used to raise the refractive index of silica in the core region of an optical fiber, when exposed to high intensity visible or ultraviolet (UV) light, further increased the core refractive index. By modulating the high intensity light along the length of the fiber core, a modulated change in the refractive index of the fiber core was realized. Typically, this spatial modulation of the writing beam is realized by transmitting the UV light through a special transmission diffraction grating that is precisely etched to null the transmitted zero order [2]. This diffraction grating is often referred to as a phase mask. The light exiting the mask is mostly coupled into the resulting ±1 orders. The interference of these transmitted orders causes a spatial modulation of the beam that is photo-imprinted along the length of the core of the optical fiber.

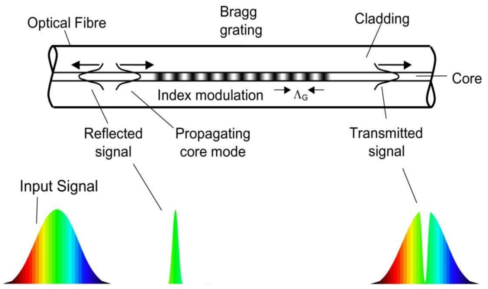


Fig1. Schematic diagram of an FBG having an index modulation of spacing λ_G inside a single-mode optical fiber

In addition to telecommunication applications, the FBG is also ideally suited for sensing purposes especially those requiring monitoring of temperature and stress. Optical components and sources already developed for use in the telecom industry can be utilized for sensing network applications. Being a completely optical device, an FBG sensor is immune to electromagnetic interference (EMI) that often compromises electronic sensors.

The sensing function of an FBG originates from the sensitivity of both the refractive index of the optical fiber and the grating period within the fiber to externally applied mechanical or thermal perturbations. As the light reflected from the Bragg grating is dependent upon the spacing of the index modulation Λ_G and the refractive index n_{eff}, the strain field affects the response of the FBG directly, through the expansion and compression changes of Λ_G and through the strain-optic effect, *i.e.*, the strain-induced change in the glass refractive index. A schematic of a basic Bragg-grating based sensor system is shown in Fig 2.

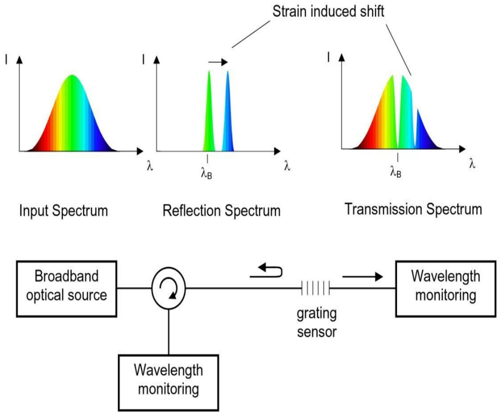


Fig2. Basic Bragg grating-based sensor system with transmissive or reflective detection options.

The temperature sensitivity of the FBG is mainly due to the thermo-optic effect *i.e.*, temperature induced change in the glass refractive index and to a lesser extent, on the thermal expansion coefficient of the fiber. Thus, λ_B shifts by an amount $\Delta\lambda_B$ in response to strain ε and temperature change ΔT by [3]:

$$\frac{\Delta\lambda_B}{\lambda_B} = P_e\varepsilon + \left[P_e\left(\alpha_s - \alpha_f\right) + \varsigma\right]\Delta T \qquad \text{---------1}$$

where P_e is the strain-optic coefficient, α_s and α_f are the thermal expansion coefficients of any fiber bonding material and of the fiber itself, respectively and ζ is the thermo-optic coefficient. Because FBGs can be written to have different resonant wavelengths, they can be multiplexed into a sensor web where different stresses or temperatures can be measured at different locations along the optical fiber length. Making use of this capability, Bragg grating sensors have been integrated into civil structures, aircraft, naval ships, oil pipelines *etc.* as 'smart skin' sensor webs to measure '*in situ*' temperature and stress of these structures. At telecommunication wavelengths near room temperature, λ_B varies with temperature at approximately 10 pm/°C.

GRATING TYPES FOR HARSH ENVIRONMENTAL SENSING

Type I Gratings

Type I gratings were initially formed in germanosilicate fiber, at least for small index changes, by a single UV photon absorption process that excites oxygen deficiency defect centers(ODC) with absorption bands around 244 nm. For large index changes, it is likely that defect formation is also accompanied by densification of the glass matrix. In terms of their applicability within a harsh environment (temperatures >450 °C) Type I gratings are unsuitable as most of the refractive index change is annealed out at these temperatures.

Type II Gratings

Using high peak power pulsed ultraviolet laser sources, such as Krypton Fluoride-based excimer lasers, high reflectivity gratings (<99%) have been inscribed with a single laser pulse [8]. These gratings result from a threshold dependent multiphoton ionization process similar to laser induced damage in bulk optics, hence the gratings are often referred to as 'damage' gratings. Such gratings are stable at temperatures over 1,000 °C and have been used to fabricate grating arrays while the fiber is being pulled on the draw tower [9]. The single shot exposure tends to produce grating structures which can suffer from significant scattering loss. The damage like process also has the tendency to reduce the reliability and mechanical strength of the fiber.

Femtosecond Pulse Duration Infrared Laser Induced Gratings.

The ultrahigh peak power radiation generated by femtosecond pulse duration infrared (fs-IR) laser systems has been used to induce large index changes in bulk glasses for the fabrication of imbedded waveguides [17]. Presently there are two main approaches to inscribing Bragg gratings with fs-IR laser sources. The first approach to be demonstrated, utilized a specialty phase mask that was precision etched to maximize coupling of the incident IR laser radiation into the ±1 orders [19]. Gratings were written in standard telecom fiber and then later in 'non-UV photosensitive' pure silica core fibers [20]. The phase mask-generated sinusoidal interference field results in a non-sinusoidal modulated FBG structure due to the nonlinear induced index change processes [21]. Using the phase mask approach, both Type I and Type II index changes can be induced in silica based glass fibers [8],[11].The second approach to fs-IR laser induced FBGs utilized a 'point by point' writing technique where single pulses from the fs-IR laser were focused within the core region of the optical fiber using a powerful microscope objective. Highly localized changes to the refractive index were generated with each pulse to create each plane of the fiber grating. Subsequent planes were made in a step and repeat fashion by translating the beam using sophisticated high-resolution mechanical translation stages [22].

EXTREME ENVIRONMENTAL SENSING APPLICATIONS OF FBGS

High Temperature

High-temperature resistant FBGs, such as regenerated gratings or those written with femtosecond800 nm laser pulses—will open up opportunities in sectors where harsh environments exist such as power plants, turbines, combustion, and aerospace. Attributes of FBGs written with fs-IR radiation above Ith in both Ge-doped SMF-28 from Corning and pure silica core (fluorine doped silica clad)fibers were studied over a longer term [26]. Bragg gratings with large index modulations (Δn) were inscribed in both fiber types which were then heated to 1,000 ℃ in 100 ℃ increments, 1 hour intervals within a tube furnace. The FBGs were loosely placed to avoid the application of external stresses. Once 1,000 ℃ was reached, the grating temperature was maintained at 1,000 ℃ for 150 hours while monitoring the FBG transmission spectra (see Figure 4). There was no noticeable degradation of the grating strength for the duration of the test and the grating maintained $\Delta n = 1.7 \times 10^{-3}$. Spectra taken initially at room temperature and after 100 hours at 1,050 ℃ are shown in inset of Figure 4. The increase in Δn, noted by the slight elevation in grating reflectivity, is likely a result of the two kinds of index change being written simultaneously. The peaks of the complex interference pattern are sufficiently intense to ionize the glass in the fiber producing an index change that is durable with temperature. In the valleys of the interference pattern, the intensity is below the Type II threshold, however some Type I index change is generated. As the device is annealed, the permanent Type II index change remains while the anneal able Type I index change is erased resulting in a higher Δn contrast. The temperature of the FBG was then increased and kept at 1,050 ℃ for 100 hours during which the Δn decreased slightly from 1.7×10^{-3} to 1.6×10^{-3}. A drift of the Bragg resonance to longer wavelengths of 0.2 nm was detected at the end of experiment. When the fiber is pre-annealed at high temperatures in order to relax residual stresses, Type II fs-IR FBGs are operable up to 1,200 °C [27]. This reflectivity is an order of magnitude higher than what is obtainable using type II UV or regenerated gratings.

For operation in a high temperature environment, an important issue for any silica-based fiber optic sensor is that of sensor packaging. At temperatures close to or above 1,000 ℃ in air, unpackaged standard silica single mode fibers loose almost all of their mechanical strength. While the fibers themselves survive hundreds of hours at 1,000 ℃ [26] when left untouched, any subsequent handling of the fiber after the test is not possible as the fiber becomes extremely brittle. Obviously optical fibers experience severe mechanical degradation when tested in oxidizing atmospheres at high temperature.

Protecting the fiber from exposure to oxygen at high temperature could be achieved by using a suitable package that itself survives the high temperature. The most obvious choice would be a coating on the fiber that is applied after the gratings are written or by writing through the existing protective coating. Metallic coatings are preferred for higher temperature applications, with gold coatings rated for the highest temperature operation of 700 °C, however this rating is not suitable for temperatures close to 1,000 ℃ [28].

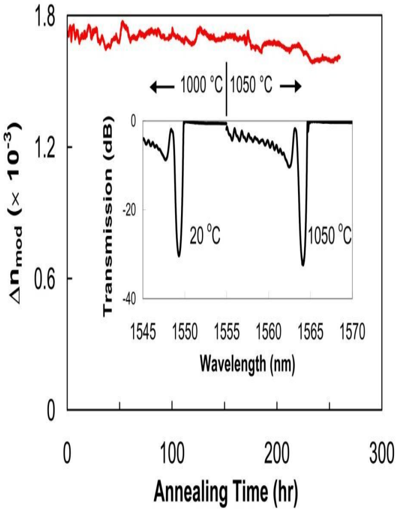


Fig 3. Grating reflectivity expressed as its index modulation (Δn) for a thermally stable grating (red) as a function of time. **(Inset)** Grating spectrum as a function of temperature.

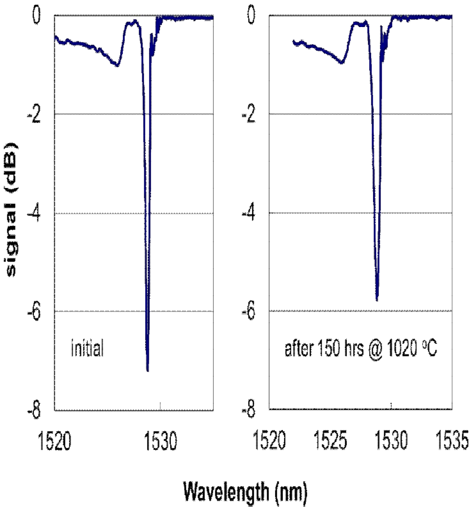


Fig 4. Initial and final room temperature transmission spectra of the FBG in the fiber cane. Final spectrum taken after one week at 1,020 ℃.

Using the fs-IR laser approach, a Type II grating was made in a fiber cane, *i.e.*, a single mode optical fiber with a 400µm cladding [29]. Such a device is considered as a self-packaged FBG device for applications at or above 1,000 °C [15]. The 400µm clad fiber maintained enough mechanical integrity to be easily handled even after 150 hours above 1,000 ℃. Room temperature spectra taken before and after the 150 hours of annealing are shown in Figure 4. In order to test the mechanical strength after the long term annealing, the fiber cane was placed in a tube furnace in air with only the central section of the furnace set at 1,020 ℃. The two side sections of the furnace were set at 400 ℃ in order to preserve the mechanical integrity of the fiber outside the central high temperature zone so that a pull test on the section of the fiber subjected to the 1,000 ℃ temperature could be performed. The fiber was kept at 1,020 ℃ for about 100 h, then the temperature was slowly ramped down to room temperature. After the fiber was removed from the furnace it was proof tested to determine its mechanical state after the high temperature annealing. The fiber was suspended in a vertical position from a support and weights were added to the fiber in 50 gram increments with a 60 second delay time for the application of each new weight. The fiber was tested up to 500 grams force which for the 400 µm diameter corresponds to ~20 kpsi maximum stress. The pristine fiber was proof tested by the manufactures to 100 kpsi. Although the fiber is stiffer than 125 µm diameter SMF fiber, it can normally accept bending radii of less than 10 cm making it suitable for the majority of sensing applications.

For temperatures >1,200 ℃, silica based optical fibers are no longer appropriate. The most successful optical fiber used for high temperature sensing applications is the single crystal sapphire fiber that has a glass transition temperature *tg* of ~2,030 ℃. Unlike conventional single mode optical fibers, sapphire fibers are made in the form of rods absent a cladding layer which makes the sapphire waveguides highly multimode and sensitive to bending losses and mode conversion. With fiber diameters commercially available, beam propagation within the fiber is highly multimode at the 1,550 nm telecommunication wavelengths. An example of available fiber diameters is shown in Figure 5(a). Present sapphire fiber sensors are mostly based on Fabry-Perot structures within the fiber producing a broadband interferometric signal that varies with temperature [31]. Such devices are used effectively as point sensors.

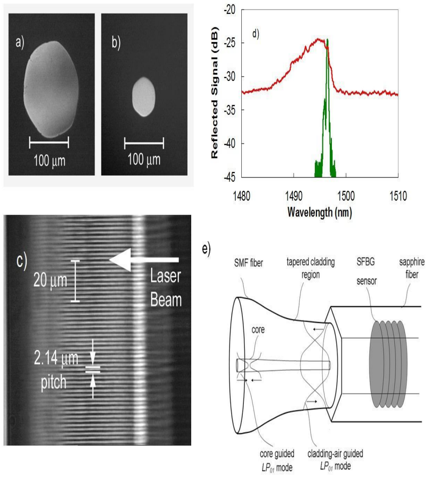


Fig5. Cross-sections of commercially available **(a)** 125 μm and **(b)** 60 μm diameter sapphire fiber are shown; the grating structure inscribed in 150 μm diameter fibre is shown in **(c)**; the corresponding multimode reflection response is shown by the red trace in **(d)**; when using the single-mode field expander shown in **(e)**, the single-mode reflection spectrum shown in green in **(d)** is obtained.

Femtosecond laser inscribed sapphire FBGs (SFBGs) are naturally multimode devices producing a reflection response that is not as sensitive to temperature and strain as the single mode FBG sensor counterparts [28]. The red trace in Figure 5(d)) presents an example of a typical multimode reflection response from a SFBG sensor when interrogated with a multimode coupler and white light source. The multimode reflection spectrum observed with the retro-reflective SFBGs is characterized by a large bandwidth having a complicated structure that consists of a superposition of different modes reflected by the grating. It is preferable to produce a narrowband single mode response, as it increases the sensitivity of the spectral response to changes in temperature and strain. In order to arrive at a single mode response from the multimode SFBGs, they were probed by using an adiabatic fiber taper to expand the ~10 µm diameter single mode into a fundamental mode approaching the diameter of the sapphire fiber (as shown in Figure 5(e)) .The fundamental guided mode of the sapphire waveguide is excited producing a single mode reflection response (green trace Figure 5(d)). In this fashion, single mode reflection responses consistent with existing FBG sensor array interrogators can be generated. SFBGs exhibit no degradation of the grating strength at high temperatures up to 1,745℃ [16]. The SFBG has definite advantages over other sapphire fiber sensors that rely on Fabry-Perot etalons at the fiber tip. Unlike Fabry-Perot sapphire sensors, SFBG sensors with their discrete resonant wavelength could potentially be used as distributed optical sensor arrays up to 2,000 ℃.Gas turbine monitoring is an example where high temperature optical sensing would be useful. Accurate measurement of hot gas working temperatures within a turbine is the critical control parameter that is essential for safe, reliable, efficient, and cost-effective operation of the gas turbine. Inhomogeneous combustion can lead to overheating and considerable damage to turbine blades, however accurate measurements of the blades and vanes within a gas turbine are very difficult [22]. By probing gas temperatures in the turbine exhaust path, temperature distributions within the combustion chamber can be evaluated. Recently several types of high temperature FBG sensors were evaluated for monitoring of hot gas turbine components by placing them on a heat shield tile mounted on the side of the combustion chamber exhaust [30]. Several of the gratings were erased at various temperatures depending on the fabrication technique used: UV-laser induced draw tower gratings annealed out at 250 ℃, weak and strong excimer laser induced Type I gratings at 450 ℃ and 700 ℃ respectively, UV Type II gratings at 900 ℃. Fs-IR laser induced Type II gratings and regenerated gratings were observed to have short term stability at 1,000 ℃, however softening of the fused silica was observed to commence at 850 ℃ which resulted in a drift in the grating response. At 800 ℃, only the femtosecond infrared gratings were reported to have no measurable drift even after a duration of several months.

FBG interrogation wave analyzer

The device covers O-band wavelength ranges and provides simultaneous measurements at very fast response rates and excellent wavelength resolution. High reliability (MIL STD 810E shock and vibration) is achieved through a rugged mechanical design with no moving parts. Periodic calibration is not required. Input/Output (I/O) is provided through a dual port RAM interface accessed through ADD/DAT bus direct connection or serial (RS232 or USB) communications.

FBGA Series employs a highly efficient Volume Phase Grating(VPG) as the spectral dispersion element and an ultra sensitive InGaAs array detector as the detection element, thereby providing high-speed parallel processing and continuous spectrum measurements. As an input, the device uses a tapped signal from the main data transmission link through a single mode fiber, then collimating it with a micro lens. The signal is spectrally dispersed with the VPG, and the diffracted field is focused onto an IngaAs array detector. The control electronics read out the processed digital signal to extract required information. Both the raw data and the processed data are available to the host. This wave analyzer device is Hermetically sealed in order to withstand the extreme environmental conditions.

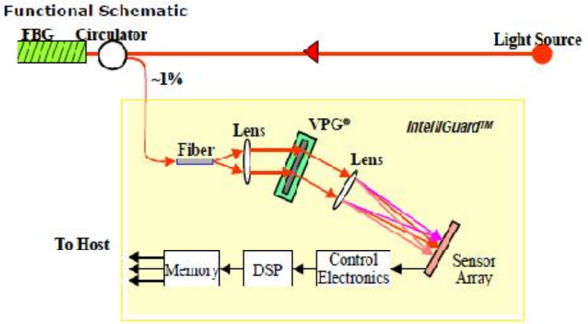
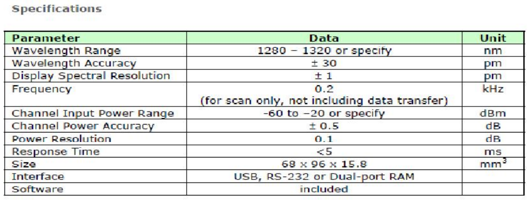


Fig6: Block diagram of FBG wave analyzer device

Key Features

- Ultra fast response time in <5 ms for raw data
- A thermal design enabling battery-operated portable operation
- Min. Frequency of 0.2 kHz
- Wide scanning range
- High dynamic range - 60 dB
- High reliability for use in harsh environment - MIL STD 810E qualified

Table 1 : specifications of wave analyzer device



Specifications

Parameter	Data	Unit
Wavelength Range	1280 – 1320 or specify	nm
Wavelength Accuracy	± 30	pm
Display Spectral Resolution	± 1	pm
Frequency	0.2 (for scan only, not including data transfer)	kHz
Channel Input Power Range	-60 to –20 or specify	dBm
Channel Power Accuracy	± 0.5	dB
Power Resolution	0.1	dB
Response Time	<5	ms
Size	68 x 96 x 15.8	mm^3
Interface	USB, RS-232 or Dual-port RAM	
Software	included	

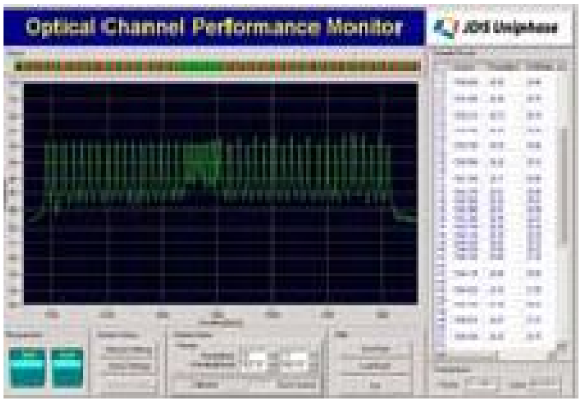


Fig 7: The output of the wave analyzer showing the measurement results.

CONCLUSION

In this paper, some of the recent developments in fabrication and application of fiber Bragg gratings for extreme environment sensing have been presented. For temperatures less than 1,000 ℃. Above 1,200 ℃ extreme temperature with Bragg gratings is relegated to sapphire optical fiber. In the case of sapphire FBGs, these robust devices are suitable for harsh combustion environments such as jet engines, coal gasification reactors, and natural gas turbines for electrical power generation.

FBG wave analyzer device is Hermetically sealed in order to withstand the extreme environmental conditions and for measuring the temperature.

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