Gold and Steel Protected FBGs Enable Robust Sensing in Harsh and High Temperature Environments

Technica Optical Components */ 3657 Peachtree Rd, Suite 10A, Atlanta, 30319, USA*
Kevin Hsu, Andrei Csipkes, and Tommy Jin
info@technicasa.com, www.technicasa.com

Many demanding measurement applications in harsh environments would benefit greatly by using fiber Bragg grating (FBG) sensing technology, given its numerous well-known advantages such as absolute temperature measurement, rapid response, multiple sensing points on a single fiber strand with minimal mechanical burden and intrusion, as well as the critical properties of EMI immunity, spark free, and chemical inertness. However, the high temperatures, corrosive chemicals and high mechanical stress often encountered in harsh environments impose serious challenges on the glass fiber coating. Of the various coating candidates, gold-coated FBG sensors not only offer the mechanical protection and hermetic seal needed in harsh environments, the enhanced sensitivity through plasmonic effects is also particularly useful for bio-chemical measurements.

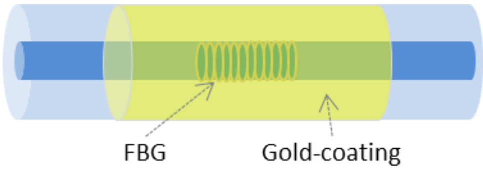

Fig.1 Schematic of a gold-coated FBG

Fig.2 Photos of Technica "T25 Gold Coated FBG": Gold-Recoating on Single Mode Fiber

Often in harsh environments the operating temperature can be quite high. Typical FBG sensors can endure temperatures in the range between ~300^{o}C to ~700^{o}C depending on grating types [1-3]. Various promising techniques have been developed to increase the temperature limitations of FBGs, including micro-structured FBGs (fs-FBGs) written by femtosecond (fsec) IR lasers and regenerated fiber-Bragg gratings (i.e., chemical-composition gratings (CCGs, RFBGs, regen-FBGs)) that can operate stably to ~1,050°C for silica-based fibers, close to the transition temperature of the material (~1,200°C) [3-5]. These techniques also work for up to 1,900°C for sapphire waveguides.

To fully utilize the maximum temperature range of the FBG sensors, and to prevent from chemical corrosion and mechanical fatigue, metallic fiber coating materials are usually applied. Aluminum, copper, and gold coated fibers can withstand a wide range of temperatures, with aluminum-coated fibers rated from -269°C to +400°C, copper coated fibers rated from -269°C to +500°C, and gold-coated fibers rated from -269°C to 750°C, though for most applications the gold coated fibers will continue to protect the fiber to 1,000°C. The high-temperature performance of gold-coated FBG sensors, combined with excellent corrosion resistance and the ability to be soldered or brazed, makes these sensors ideal for many demanding sensing applications, such as in power plants, turbines, combustion process, aerospace, and deep-well oil/gas exploration, hot pipelines, etc.

To meet the demand of these applications, Technica has developed reliable processes to end-strip or window-strip acrylate, polyimide, aluminum, copper, and gold coated fibers, fabricate the high-temperature FBGs, and then recoat with acrylate, polyimide, or gold coating. This fabrication process allows for varying lengths of window stripping with very controllable and repeatable stripping length control. The gold recoating process that follows the process of writing the FBGs provides very good adhesion between the gold recoating layer and the bare fiber glass surface, and can endure 100 KPSI pull force on the gold fiber containing the FBG sensor, prior to exposure to the high temperatures. Furthermore, in addition to offering gold-coatings on its high-temperature FBGs (T98 and T160) [11,12], Technica can also provide gold-coating on its standard FBGs (T25) [13]. Being naturally hermetically sealed and mountable by standard metal bonding techniques, gold coated fiber based standard FBGs make for the ideal optical circuit device or sensing core component, the focus of another paper.

Fig.2 shows photo examples of (a) gold recoating over original gold-coated fiber and (b) gold recoating over a stripped junction of a gold-coated fiber. The gold recoating proves to have durable adherence and uniformity in all cases.

Whether written with Excimer Lasers or Femtosecond Lasers, FBGs will shift in wavelength when first exposed to high temperatures as the supporting fiber structure settles into the new environment. ~~Customers~~ Users who can calibrate these temporary effects in the field can choose from a wider range of FBGs and FBG Array options. However, applications requiring that a pre-calibrated plug-and-measure high-temperature FBG sensor is delivered in the field are in need of an industrial grade product that has been pre-annealed. For high temperature applications Technica applies an additional annealing step to the FBGs at a temperature of 100ºC above the specified maximum temperature (Technica's present annealing limit is 1,200ºC). During the annealing process a proprietary manufacturing technique is applied to partly or entirely erase and regenerate the FBG, permanently altering the molecular structure of the single mode fiber waveguide at the location of the FBG, a process yielding a very stable and settled component for field use. Once the FBG or FBG array is installed and in operation above 300ºC, the acrylate and polyimide coating will vaporize leaving almost no residue, while for fibers with gold coating said coating would remain stable to 750ºC, above which it too will begin changing its properties and ultimately melting above 1,000ºC, all while the High-Temperature FBGs that have been written into these fibers will continue working. When robust fiber protection is needed during FBG sensors field operation to 1,000ºC, the FBG or FBG array can be inserted into a steel tube that can easily withstand 1,000ºC, open or seal-capped at one end, and transitioned into standard pigtails terminated with FC/APC or other customer specified connectors at the other end. Here the key is the low-friction surface of the steel tube interior. As a reference, Table-1 below lists the typical performance range of Technica's T98 and T160 high-temperature FBG sensors.

Parameter	Specifications
Wavelengths / Tolerance	1460 to 1620 nm, +/-1 nm; 980, 1060, 1310 nm, other
Reflection BW (FWHM)	0.1 nm to 2.0 nm; other opt.
Reflectivity %	>40%; other options
FBG Length	5 mm - 10 mm
SLSR	15 dB; other options
Response Time	1 ms
Maximum Temperature Options	Up to +300°C Up to +500°C Up to +700°C Up to +850°C Up to +1,000°C
Fiber Coating and Protection Options	Polyimide, Gold, Steel, Bare Fiber
Fiber Type and Cladding Diameter Options	Single-Mode Non-PM / PM 125 (std), 80, 50µm DIA
Sensor Configurations	Single-Ended, Double-Ended, or Multi-Sensor Array
Fiber Pigtail Length	1 m, other options
Fiber Bend Radius	> 17 mm, other options
Optical Connector	FC/APC, or custom

Table.1. Typical performance parameters of the T98 and T160 high-temperature FBG sensors.

Finally, for temperatures up to 1,900ºC Sapphire rods serve as a good candidate material. In this case the FBG is written by fsec laser technique. However, Sapphire fiber in actuality comes in 100 or 75 um diameter rods (no cladding, no coating) and its highly multi-mode nature introduces very high-loss when attempting to couple light into a single-mode fiber. Such associated technical challenges in optical coupling and packaging of Sapphire fiber will be resolved in due time.

Gold-coated FBG sensors have also enabled a powerful bio-chemical sensing approach by utilizing the surface plasmon resonance (SPR) effect. Such label-free bio-chemical sensing has become quite promising because of the high sensitivity and rapid response of the underlying FBG sensors. Various techniques have been developed in order to allow the guided optical field to have effective interaction with the gold coating, including reducing fiber cladding by tapering or side polishing, writing tilted FBG (T-FBG) (Fig.3(a)), or applying long-period FBG (LP-FBG) (Fig.3(b)). The SPR sensors based on T-FBG (T75) [14] and LP-FBG (T30) [15] are practical and efficient without compromising the fiber mechanical integrity while side-polishing technology promises to bring significant other benefits.

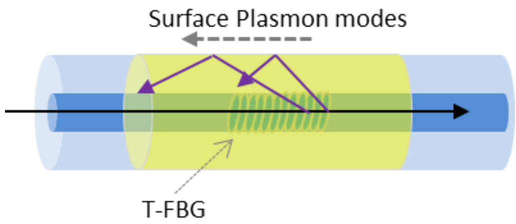

Fig. 3(a) Gold-coated Tilted-FBG. The arrows in purple color represent cladding modes.

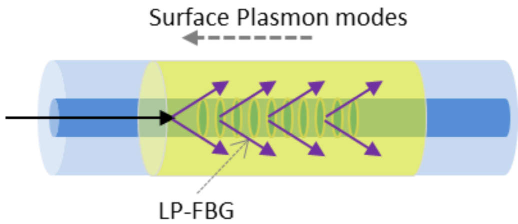

Fig. 3(b) Gold-coated Long-Period-FBG. The arrows in purple color represent cladding modes.

The competitive advantages of gold-coated FBGs, such as sensitivity, compactness, remote sensing capabilities, in the context of bio-chemical sensing, are particularly useful for integration into cell culture equipment for in situ whole cell sensing, and for real-time analysis of cellular behavior [6-8]. By taking advantages of the existing fiber-optic communication technology, both the fiber devices and the interrogation equipment can be highly cost-effective compared to the more complex and bulkier custom designed optical sensing platforms. The wavelength shift of the SPR on gold-coated T-FBG has been found to be an efficient technique for revealing the electrochemical activity of the surface localized bacterial cells in electro-active biofilms (EABs), thereby opening up a multitude of opportunities for monitoring EABs in various hard-to-reach environments [9].

Another approach to access the gold coating is to utilize the scattering of visible broadband light source through the standard telecom FBG and detect the subsequent effect with the gold coating [10]. Specifically, a broadband visible light source is launched into the gold-coated standard telecom FBGs, Bragg scattering occurs at the grating region and light is scattered in the cladding, creating an evanescent field at the interface between the cladding and the surrounding medium. The gold layer further enhances the evanescent wave. When the FBG sensor is exposed to an analyte surrounding the sensing area, absorption occurs at specific wavelengths corresponding to the analyte's absorbing wavelength. A spectrometer can be used to measure the output absorption spectrum.

Summary

The high-temperature FBG sensors fabricated by annealing, regenerative and femtosecond laser writing techniques have demonstrated unique advantages in providing multipoint and multifunction measurement capabilities in high-temperature applications. However, properly designed fiber sensor packaging is also critical for maintaining FBG sensor's integrity, survivability, functionality, and durability. The ability to manufacture high-temperature FBGs with subsequent protection in strain-locked gold coating and loose tube steel allows Technica to offer unique and practical solutions for fiber-optic sensing in high-temperature and harsh environments (T98 ad T160). Furthermore, the gold-coated FBGs represent a new sensing element for many new and useful bio-chemical sensing (T75). Hermetically sealed and mountable using metal bonding techniques this new family of FBG sensors enables new applications and solves several existing limitations of other sensors (T25).

References

[1] K. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," J. Lightwave Technol. 15, pp. 1263–1276, 1997.
[2] T. Erdogan, et al., "Decay of ultraviolet-induced fiber Bragg gratings," J. Appl. Phys. 76, p. 73, 1994.
[3] Stephen J. Mihailov, "Fiber Bragg Grating Sensors for Harsh Environments," Sensors 2012, 12, 1898-1918;
[4] B. Zhang and M. Kahrizi, High-temperature resistance fiber Bragg grating temperature sensor fabrication, IEEE Sens. J. 7, pp. 586–591, 2007.
[5] J. Canning, et al., Optical fibre Bragg gratings for high temperature sensing, Proc. SPIE. 7503, p. 75032N, 2009.
[6] Y.Y. Shevchenko and Jacques Albert, "Plasmon resonances in gold-coated tilted fiber Bragg gratings," Optics Lett., V.32, No. 3, pp.211-213 (2007)
[7] Y.Y. Shevchenko et al., "Surface plasmon resonance fiber sensor for real-time and label-free monitoring of cellular behavior," Biosensors and Bioelectronics V.56 pp.359–367 (2014).
[8] C. Caucheteur, et al., "Near-infrared grating-assisted SPR optical fiber sensors: design rules for ultimate refractometric sensitivity," Optics Express, Vol. 23, No. 3, pp.2918-2932 (2015).
[9] Y. Yuan, et al., "Electrochemical Surface Plasmon Resonance Fiber-Optic Sensor: In Situ Detection of Electroactive Biofilms," Anal. Chem., 2016, 88 (15), pp 7609–7616
[10] P. T. Arasu et al., "Absorbance properties of gold coated fiber Bragg grating sensor for aqueous ethanol," J. Europ. Opt. Soc. Rap. Public. 9, 14018 (2014)
[11] Technica Optical Components, LLC, "T98 High Temperature FBG Sensor to 1,000 ^{o}C" http://technicasa.com/t98-high-temperature-fbg-sensor/
[12] Technica Optical Components, LLC, "T160 High Temperature Multipoint FBG Sensor to 1,000 ^{o}C" http://technicasa.com/t160-high-temperature-multipoint-fbg-sensor/
[13] Technica Optical Components, LLC, "T25 Gold Coated FBG Sensor" http://technicasa.com/t25-gold-coated-fbg-hermetic-seal/
[14] Technica Optical Components, LLC, "T75 Tilted FBG Sensor" http://technicasa.com/t75-tilted-fbg-sensor-2/
[15] Technica Optical Components, LLC, "T30 Long Period Grating (LPG)" http://technicasa.com/t30-long-period-grating-lpg/