Small-Diameter Thin FBGs Ideally Suited for Embedded Sensing in Composites

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For many advanced embedded-FBG sensing applications it has become necessary and critical that the sensing fibers have small dimension, light weight, and low bend sensitivity in order to allow easy embedding with minimal compromise on the strength of the host materials. Specifically, fiber-optic sensing applications typically use a standard single-mode fiber (SMF) where the core/clad/coating diameters are ~8/125/250 μm. However, when the standard SMF sensors are embedded inside composite materials, the mechanical performance of the composites could be compromised due to local stress concentration.

Driven by increasing demands in mechanical testing and structural health monitoring (SHM) purposes, small-diameter (thin) SMFs have been developed in order to decrease the size mismatch between embedded FBG sensors and the composites. This development was pioneered by Takeda et.al. and Hitachi Cable [1], and has now become particularly useful for applications not only in the aerospace industry but also in robotics, medical devices, and micro-mechanics. Fig.1 illustrates a visual comparison between a standard 125 μm cladding diameter SMF and a thin fiber of 40/52 μm cladding/polyimide-coated diameter embedded in carbon fiber-reinforced plastic (CFRP) laminates. Applications of thin FBG sensors with cladding diameters ranging from 40 to 50 um have been investigated theoretically and experimentally [2-13]. It was shown that the thin FBG sensors are less intrusive at stress heterogeneities, and exhibit linear strain and temperature responses with sensitivity coefficients almost the same as those of the standard-diameter FBG sensors. Studies have also shown that FBGs in small-diameter fibers experienced slightly less induced birefringence than those in standard fibers for the same embedding conditions [8,9]. The intensive development of thin FBG sensing in composites in the aerospace industry [14,15] has advanced to the realization of autonomous sensing-healing systems [16] and a recent successful demonstration of large-scale SHM of a composite aircraft wing [17].

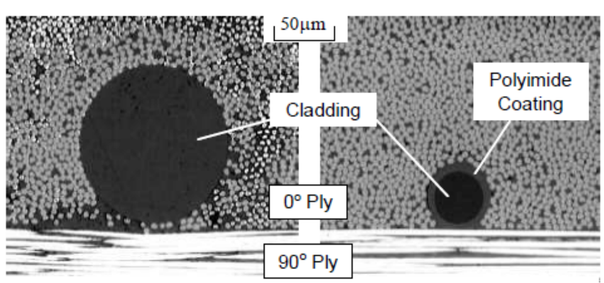

Fig.1. Standard SMF (left) and thin optical fiber cross-section embedded in a CFRP lamina [1].

To meet the growing needs of thin FBG sensors for advancing SHM in composite materials and a variety of other applications, Technica has developed thin single-mode fiber-based FBG sensors (T60) for a wide range of optical specifications and coating requirements (Figs.2-4). Fabricated directly in bare fiber and coated with acrylate, polyimide, or metal, these sensors are ultra-small and durable for use in tight spaces with minimal intrusion. When metalized (most commonly with Au), these FBGs can be encapsulated into hermetically sealed devices as well. The small-diameter fibers containing these FBGs have correspondingly smaller core, higher NA and higher cut-off wavelengths to significantly reduce macro-bending sensitivity. Table-1 presents the results of bend-loss measurements of the 50 μm and 80 μm cladding diameter SMFs. Indeed it is impressive that even at a bend diameter of 0.9 mm the loss is very low.

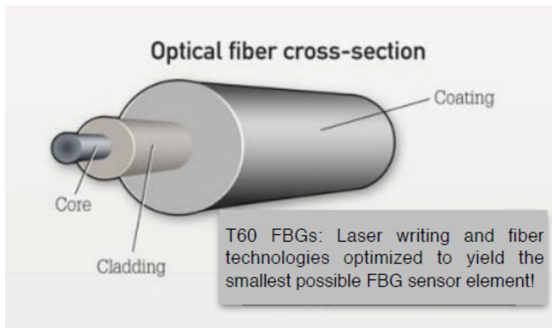

Fig.2. Optical fiber cross-section.

	Core	Cladding	Coating
Standard	8.2 μm	125 μm	250 μm
Thin	7.8 μm	80 μm	125 μm
Ultra-Thin	4.0 μm	40 μm	90 μm

Fig.3. Thin fiber options for acrylate coat fiber.

	Core	Cladding	Coating
Standard	8.2 μm	125 μm	150 μm
Thin	7.8 μm	80 μm	100 μm
Ultra-Thin	4.0 μm	40 μm	55 μm

Fig.4. Thin fiber options for polyimide or metal coated fibers.

Thin Fiber Type	3 mm Coil Diameter		0.9 mm Coil Diameter	
	5 Turns: Measured	1 Turn: Average	5 Turns: Measured	1 Turn: Average
50 μm cladding SMF	Negligible loss	Negligible loss	0.5 dB	0.1 dB
80 μm cladding SMF	0.1 dB	Negligible loss	0.6 dB	0.12 dB

Table.1. Thin fiber bend-loss measurements.

These thin FBG sensors yield excellent wavelength to temperature and wavelength to strain linearity. Their small-size and fast response time make them useful and uniquely fitting for in-process control of advanced composites manufacturing and real-time monitoring of high performance vehicles for space, air, water and land. New applications are emerging in energy, medical, and robotic sectors.

The T60 FBG is designed to make handling and installation fast, easy and intuitive. It delivers the many advantages inherent to all FBG based sensors. Equally sensitive compared to most traditional strain and temperature sensors but immune to electromagnetic interference (EMI). The precise FBG structure written into these specialty fibers' core in producing the T60 yields a simple transducer configuration of high resolution, linearity, and measurement repeatability, as well as high side-lobe suppression ratio (SLSR) for clear signal processing (Fig.5). As the T60 sensors can be provided in arrays of various lengths and with a flexible number of FBGs, they are well suited for projects that require high-density and large-scale monitoring. Additionally, splicing techniques for connecting the thin fibers with normal SMF28-compatible fibers also exit to facilitate further processing and system integration.

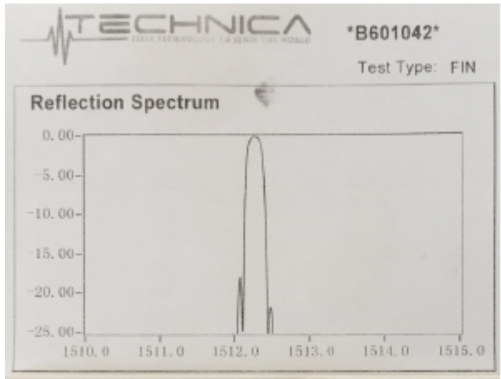

Fig.5. Typical thin FBG reflection spectrum with high side lobe suppression.

The T60 is a rugged low-cost FBG with stable operation for highly accurate long-term use, and have been field-proven in many customers' applications worldwide. Table-2 below lists the typical range of available performance parameters of the T60 thin FBG sensors.

Parameter	Specifications
Wavelengths / Tolerance	1460 to 1620 nm, +/-0.5; 980, 1060, 1310nm, other
Reflection BW (FWHM)	0.1nm to 0.8nm; other opt.
Reflectivity %	>70%; other options
FBG Length	1-24 mm
SLSR	15 dB; other options
Response Time (for Strain, Temperature)	0.01 ms, 0.1ms
Temperature Range / Sensitivity (Acrylate, polyimide, metalized)	-40 to +85°C; ~10 pm/°C -40 to +275°C; ~10 pm/°C
Strain Range / Sensitivity	10,000 microstrain; 1.2pm / microstrain
Fiber Type	Single-Mode Non-PM / PM
Fiber Coating	Acrylate, polyimide, metal
Fiber Pigtail Length	1 m, other options
Fiber Bend Radius	>17mm
Optical Connector	FC/APC, or custom

Table.2. Available performance parameters of the T60 thin FBG sensors.

In addition to SHM in composite materials, there are new and exciting applications that can benefit from the thin FBG sensing technology, including shape sensing development in continuum robots [18], embedded sensing in 3D printed structures [19], and touch/force/shape sensing in medical robotics [20].

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