Fully Integrated Miniature Multi-Point Fiber Bragg Grating Sensor Interrogator (FBG-Transceiver™) System for Applications where Size, Weight, and Power are Critical for Operation

E. A. MENDOZA, J. PROHASKA, C. KEMPEN, S. SUN and Y. ESTERKIN

ABSTRACT

Redondo Optics Inc. (ROI), is in the process of developing a miniature fiber Bragg grating sensor interrogator (FBG-Transceiver™) system based on ROI's proprietary multi-channel integrated optic sensor microchip technology for applications where size, weight, and power are critical for operation. The FBG-Transceiver technology is based on the integration of all of the functionalities, both passive and active, of conventional bench top FBG sensor interrogators systems, packaged in a miniaturized, low power operation, 2-cm x 5-cm small form factor (SFF) package suitable for the long- term structural health monitoring of current and future NAVY tactical solid fuel rocket motors. The FBG-Transceiver¬ system uses active chip-on-submount (CoS) optoelectronic components monolithically integrated to the integrated optic microchip, a microprocessor controlled CMOS-PC signal processing electronics board capable of processing the FBG sensors signals related to stress-strain and temperature as well as acoustics and ultrasound. ROI is in the process of developing a family of FBG-Transceiver systems for single channel and multichannel FBG sensor interrogation at 20-kHz sampling rates per sensing channel.

Key Words:
Integrated Optics, hybrid PLC, fiber sensors, structural health monitoring, nondestructive inspection, aerospace, military, miniature

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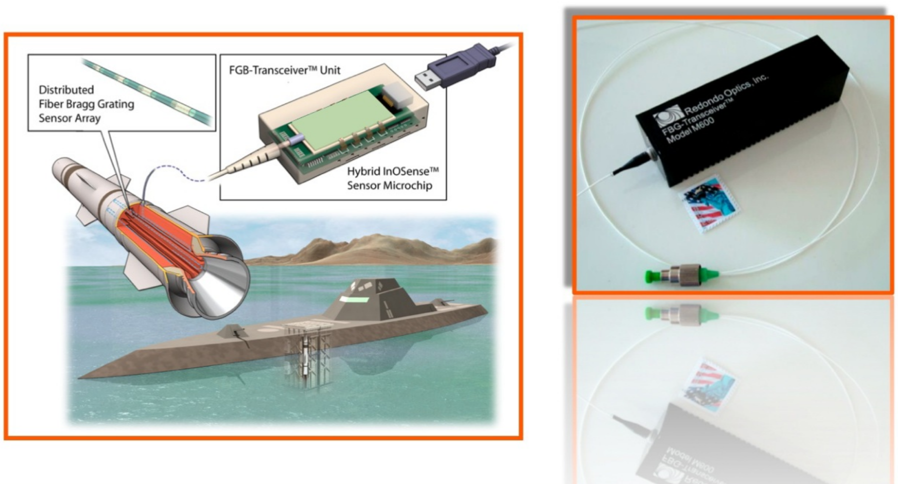
Edgar Mendoza, John Prohaska, Connie Kempen, Yan Esterkin, Sunjian Sun, Redondo Optics Inc.811 North Catalina Ave, Suite 1100, Redondo Beach, CA 90277;

INTRODUCTION

Advanced infrastructure systems are integral to the social, political, and economic well being of a nation. Facets of infrastructure systems affect the quality of buildings and structures, the air we breathe and the water we drink, our access to energy (e.g., electricity, oil, and gas), and communications, inter-modal transportation systems, and disposal of waste. Because these systems are so pervasive, complex, and inherent to our lives, and because of the continued and ever-increasing threats of environment and global terrorism, they need to be secured and made smart. In recent years, Fiber Bragg Grating (FBG) technology has been accepted as a new kind of sensing element for structural health monitoring (SHM) for the in situ monitoring of advanced structures in aviation, aerospace systems, civil structures, and the petrochemical industry. The cost of FBG sensor production, the availability of high-quality FBG demodulation system, practical sensor embedding and packaging techniques are the cores for FBG sensors to be widely popularized for real time monitoring of infrastructure systems.



ROI's FBG-Transceiver™ based on its patented hybrid integrated optics microchip technology enables the most cost effective production of miniature, multi-channel, FBG interrogation systems for applications where performance, size, and weight are critical for operation.

Figure 1. Multi-Channel Fiber Bragg-Grating Sensor Interrogation Unit (FBG-Transceiver™) Based on ROI's InOSense™ Microchip Technology for the Real Time Structural Health Monitoring of the Navy's Future Ordnance.

The U.S. Department of Defense and specifically the U.S. Navy has identified fiber Bragg grating sensor technology of strategic relevance for the development and implementation of critically demanding smart operational platforms. A mission of the U.S. Navy is to maintain a high level, failure-free, ordnance readiness at all times. Although the Navy's ordnance safety and reliability program consistently operates at a level of readiness above expected goals, primarily attributed to the outstanding maintenance efforts by Navy personnel. It is achieved through a considerable drain of manpower hours. Furthermore and more importantly, the reliability of future operations that may be compromised by aging ordnance equipment stored under harsh conditions and prolonged periods are an ongoing concern. Consequently, a significant issue for the Navy's ordnance readiness depends on close scrutiny of the environmental and structural integrity conditions of the equipment at all times. Future readiness and reliability of the Navy ordnance requires investing in advanced technology today. For this reason, future ordnance such as tactical missile solid rocket motors could be potentially instrumented with embedded sensors to provide real-time structural health monitoring of the missile system at all times.

Because of the need for a compact, low weight, low power FBG interrogation system, Redondo Optics is currently developing a family of miniature FBG interrogation (FBG-Transceiver™) systems that uses ROI's proprietary integrated optic microchip technology as an optical bench to integrate all the functionalities of the key passive and active optoelectronics components of conventional FBG interrogation systems, such as the light guides, splitters and couplers, light source, photodetectors, FBG sensor signal demodulators, and signal processing IC-electronics packaged in a miniaturized, environmentally qualified, hermetically sealed single fiber FBG-Transceiver™ system suitable for the in-situ installation and long term operation in civil, petrochemical, and aerospace industrial applications where size, weight, and power consumption are a critical requirement for the installation of structural health monitoring of critical infrastructure systems.

THE FBG-TRANSCEIVER™ SYSTEM

ROI's FBG-Transceiver™ is a miniature, multi-channel fiber Bragg grating sensor interrogation system that offers a reliable, and cost affordable FBG sensor interrogation system solution for applications where weight, size, and power are critical for operation. Based on the integration of state-of-the-art monolithic planar lightwave circuit technology with automated telecommunications optical components packaging, and CMOS electronics, results in the production of a next-generation, high performance, environmentally robust, miniature FBG sensor interrogation device. Redondo Optics has developed engineering prototypes of a single channel and a multi-channel FBG-Transceiver™ devices that currently uses for demonstration to selective customers and strategic partners, as shown in Figure 2.

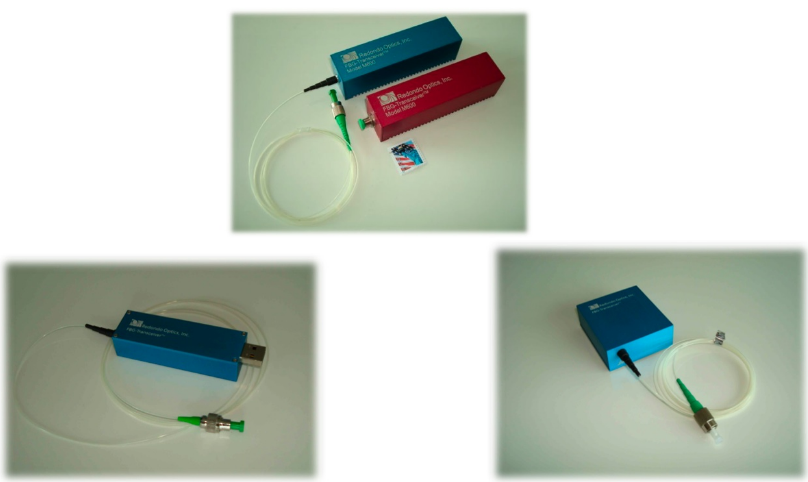


Figure 2. Single Channel and Multi-Channel FBG-Transceiver™ Devices.

Compared to conventional bench-top FBG interrogation devices, ROI's FBG-Transceiver™ system has many advantages. These include: 1) no moving parts, or complex fiber optic connections that are typically sensitive to motion, shock, vibration, and the moisture and temperature environment; 2) all optoelectronic components are integrated on a monolithic hybrid optical microchip, that surface mounts to a CMOS electronics board that is hermetically sealed in a 2-cm x 5-cm small form factor (SFF) standard telecommunications package; 3) the FBG-Transceiver™ is produced using standard automated manufacturing practices common in the semiconductor IC and telecommunications components industries that translate into a manufacturable low cost device allowing the possibility to be disposed with every tactical missile test operation; 4) the system can be battery operated enabling operation for a period of one year, and 5) uses standard data communications protocols that facilitates integration to any communication network. The target performance specifications of the FBG-Transceiver™ system are shown in Table 2.

Table 1. Target performance specifications of multi-channel FBG-Transceiver™ system.

Model No	Units	FBGT-100	FBGT-500	FBGT-1200
Sensing Channels		1	5	12
Monitoring Mode		Stress-strain, temperature, vibration, and acoustics		
Monitoring Principle		Wavelength division demultiplexing (WDDM)		
Wavelength Range	nm	1520 - 1570		
Bandwidth (FWHM)	nm	60		
Output Power	dBm	Max (-) 0.5 dBm	Max 0 dBm	Max 5 dBm
Wavelength Resolution	Hz	5 pm @ 100 Hz		
Wavelength Accuracy	pm	± 5 pm		
Wavelength Repeatability	Hz	± 5 pm @ 100 Hz		
Strain Range		≤ 10,000 µstrains	≤ 4,000 µstrains	≤ 2500 µstrains
Temperature Range	°C	0 °C to 400 °C		
Sensor Sampling Rate	Hz	2-kHz	20-kHz per channel	10-kHz per channel
Signal Processor		Microcontroller – Sensor calibration and T compensation		
Data Communication		USB or (Optional - Ethernet, Wireless, Bluetooth)		
Optical Connector		FC/APC or Custom		
Package		Hermetically Sealed Single Fiber Package		
Data Display		LabView Graphical Interface		
Power Supply	mA	5V/500 mA	12 V/500 mA	12 V/500 mA
Weight		75 gr	115 gr	115 gr
Dimensions	mm	18.5 mm x 18.5 mm x 50 mm	29 mm x 29 mm x 110 mm	29 mm x 29 mm x 110 mm

The principle of operation of an FBG sensor is based on the environmentally induced wavelength shift, associated with changes in stress-strain, temperature, vibration, pressure, etc., of the active peak wavelength of the grating that is attached to the structure under evaluation. ROI uses a passive demodulation technique, based on dispersive filters, in which the wavelength encoded optical signature of the each of the FBG transducers in the array is transformed into an electrical signal at each of the photo receivers by means of the optical properties of the dispersive filter. A microprocessor controller mounted on a CMOS-PC board processes the transformed electrical signal carrying the information from each of the FBG sensors, and transmits the process signals to a remote station via a USB data communication interface. The complete electrical power budget for the FBG-Transceiver™ unit is estimated at approximately ≤ 0.1 Watts, allowing the use of the same USB communications port to provide power to the unit. The complete monolithic integrated optic microchip and signal processing IC-electronics unit is packaged in a single fiber, telecommunications grade, small form factor package to produce a miniature multi-channel FBG-Transceiver™ system that can be used to monitor the status of FBG transducers embedded or surface mounted on the structure.

MONOLITHIC INTEGRATED OPTIC SENSOR MICROCHIP TECHNOLOGY

In its simplest form, ROI's integrated optic microchip integrates a temperature- and power-stabilized broadband semiconductor light source that is monolithically integrated to a PLC microchip to illuminate and interrogate the status of each of the FBG transducers distributed along the sensing fiber. The light source is guided internally through the PLC microchip, using waveguide structures, and coupled to the sensing fiber that connects to the FBG-Transceiver™ SFF package. Each fiber grating distributed along the sensing fiber reflects a portion of the light source broadband spectrum, determined by the Bragg condition of the grating, and transmits the remaining light to the next grating. The returned, wavelength-encoded light signal from each of the distributed FBG sensors is received and processed by the PLC microchip. The received light signal is guided internally though the microchip, using waveguide routing structures, to individual photodetectors assigned to monitor a specific wavelength from each of the distributed FBG transducers.

Two types of wavelength division multiplexing (WDM) waveguide architectures are used in the PLC microchip for the spectral separation of the individual wavelengths of each FBG sensors in the fiber sensor array. One type, used with the low channel count (< 12-channels) FBG-Transceiver™ units, uses wavelength selective dispersive filter structures, the other type, used with the high channel count (> 12 channels) FBG-Transceiver™ units, uses a custom graded index array waveguide grating (GRIN-AWG) architectures. The wavelength selective WDM structures allows the transmission of a particular FBG wavelength (λ_1) while reflecting, or separating, all of the other (λ_2, λ_3, λ_n) FBG sensor wavelengths to the respective detection channels. This process is repeated, wavelength specific, at each photodetector to achieve a wavelength demultiplexing PLC structure. WDM filters are commonly used in long haul fiber optic telecommunication networks to either mix (multiplex) or separate (demultiplex) large numbers of communication wavelengths. By carefully selecting the spectral optical bandpass properties of the filter, the peak wavelength shift, environmentally induced, optical signal from each of the FBG sensors is converted into a linear intensity variation, directly related to the physical state (peak wavelength position) of the FBG sensor at the photodetector element, as shown in Figure 3. This principle forms the basis of the FBG sensor demodulator in the FBG-Transceiver™ system.

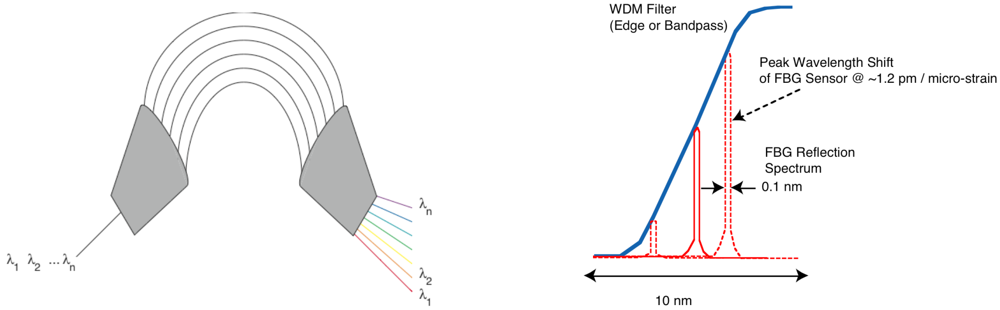
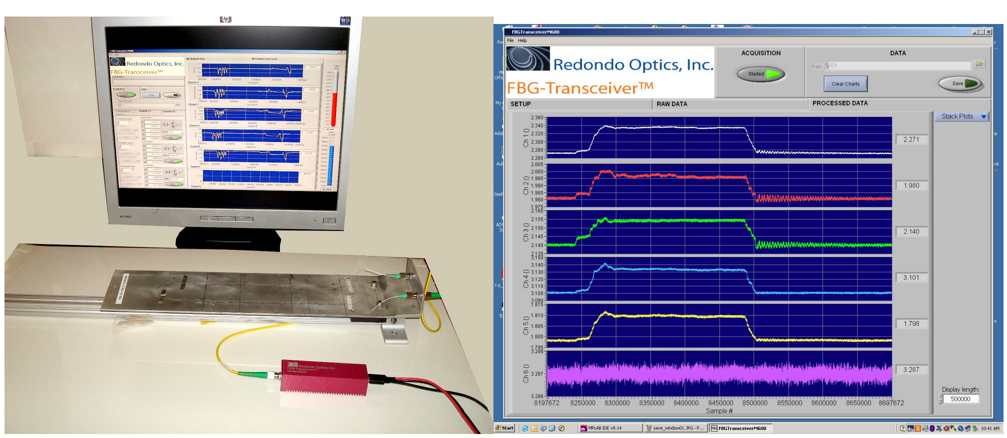


Figure 3. Integrated broadband and narrowband WDM filter structures for passive wavelength separation and demodulation of FBG sensor signals.

DEMONSTRATION OF OPERATING PRINCIPLE OF MINIATURE MULTICHANNEL FBG-TRANSCEIVER™ SYSTEM

To test and characterize the performance of the multi-channel FBG-Transceiver™ prototype, a test bed was assembled by surface mounting an array of five FBG sensors on a cantilever test plate. The cantilever test plate allows inducing variations in the strain state of the FBG sensors as a function of an external induced perturbation. In this case a small progressive, upward or lower, displacement of the cantilever test plate allows monitoring the strain condition of the FBG sensors attached to the structure. To monitor the status of the FBG sensors, the sensor fiber is connected to the multichannel FBG-Transceiver™ system using a mating sleeve, and in turn this system is connected to a computer via a USB communication port. A LabView graphical user interface (GUI) is then use to initialize the system and establish communication with the FBG-Transceiver™ unit. Pressing the run button on the software screen initiates data acquisition and display of the five FBG sensor channels in real time as shown in Figure 4. Pressing the save button, stores all collected data in a text file.



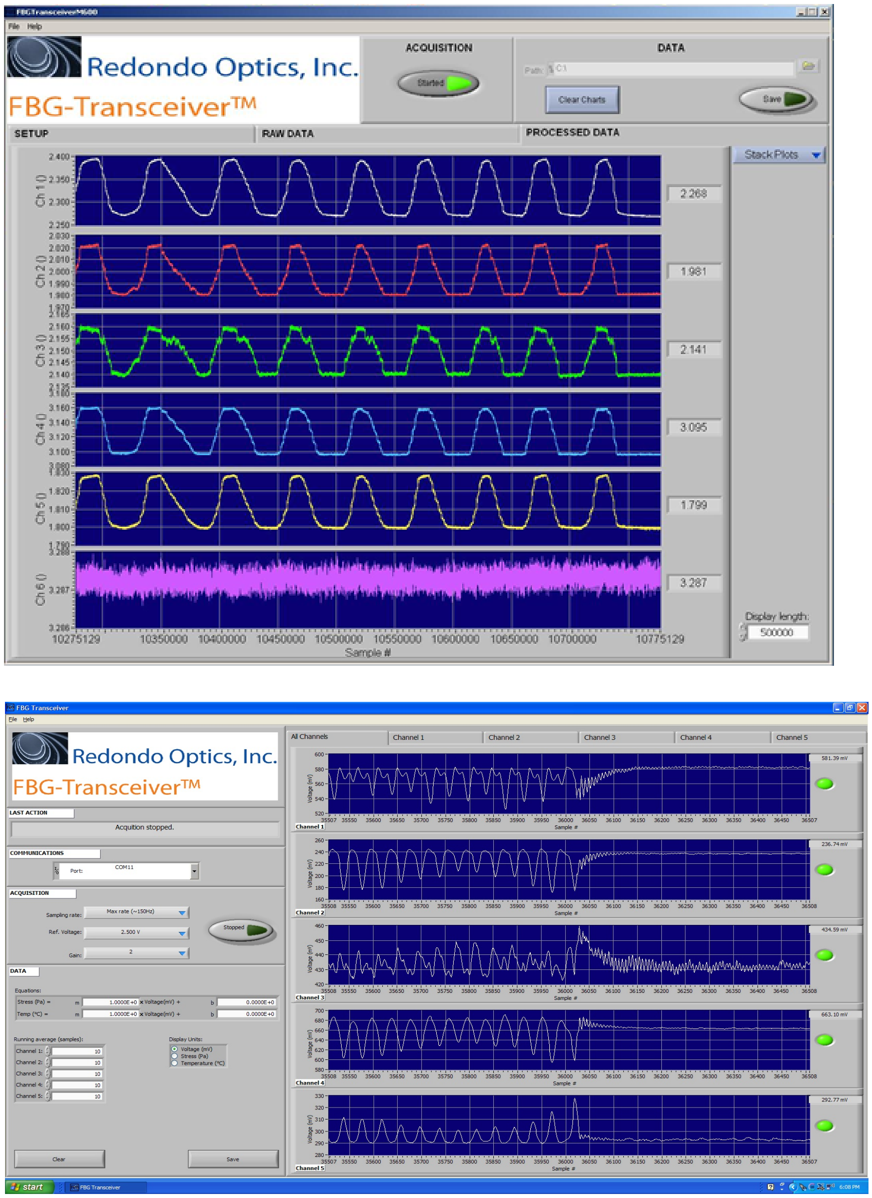


Figure 4. Passive and active response of Miniature multi-channel FBG-Transceiver™ System for the Structural Health Monitoring.

SUMMARY

The results presented in this paper described on going work towards the development of a miniature multi-channel fiber Bragg grating sensor interrogator (FBG-Transceiver™) system based on monolithic integrated optic sensor microchip technology.

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