Miniature Fiber Bragg Grating Sensor Interrogator (FBG-Transceiver™) System For Use in Aerospace and Automotive Health Monitoring Systems

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ABSTRACT

Fiber Bragg grating sensors (FBGs) have gained rapid acceptance in aerospace and automotive structural health monitoring applications for the measurement of strain, stress, vibration, acoustics, acceleration, pressure, temperature, moisture, and corrosion distributed at multiple locations within the structure using a single fiber element. The most prominent advantages of FBGs are: small size and light weight, multiple FBG transducers on a single fiber, and immunity to radio frequency interference. A major disadvantage of FBG technology is that conventional state-of-the-art fiber Bragg grating interrogation systems are typically bulky and heavy bench top instruments that are assembled from off-the-shelf fiber optic and optical components integrated with a signal electronics board into an instrument console. Based on the need for a compact FBG interrogation system, this paper describes recent progress towards the development of a miniature fiber Bragg grating sensor interrogator (FBG-Transceiver™) system based on multi-channel integrated optic sensor (InOSense) microchip technology. The hybrid InOSense microchip technology enables 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 in applications where size, weight, and power are critical for operation. The sponsor of this program is NAVAIR under a DOD SBIR contract.

Keywords: Integrated optics, hybrid PLC, fiber sensors, structural health monitoring, nondestructive inspection, aerospace, military, miniature, and ordnance.

1. INTRODUCTION

Fiber optic sensors form part of our everyday life and can be found in systems from Mars to Manhattan. One of the most widely used and accepted type of fiber optic sensors is the Fiber Bragg grating (FBG) sensor. FBG sensors are a proven structural health monitoring technology utilized for the in situ monitoring of advanced structures in aviation, aerospace systems, civil structures, and the petrochemical industry. Because of its lightness, micron-size transducers, and immunity to electromagnetic interference, it can be easily casted, embedded, or surface mounted on a structure. The FBG sensors can be produced in glass or plastic optical fiber to meet harsh environmental conditions and structural demands for a variety of applications. The sensor fibers are packaged in strong, rugged materials to withstand harsh environments such as embedded in fiber composite structures, in transatlantic fiber cable installations, tow-array sonar, and missile fiber guiding systems. In addition, it offers the ability to distribute multiple sensors on a single fiber strand. A major drawback of FBG sensor technology is that today’s commercially available FBG sensor interrogation systems are bench-top laboratory instruments that are too bulky and heavy to be permanently installed in aerospace or automobile applications.

Because of the need for a compact, low weight, low power FBG interrogation system, Redondo Optics, Inc. under a Navy sponsor SBIR program [1] is currently in the process of developing a family of miniature FBG interrogation (FBG-Transceiver™) systems that uses ROI’s proprietary integrated optic sensor (InOSense™) 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, wavelength

Photonics in the Transportation Industry: Auto to Aerospace
edited by Alex A. Kazemi, Christopher S. Baldwin, Proc. of SPIE Vol. 6758

Proc. of SPIE Vol. 6758 67580B-1
demultiplexing filters, FBG sensor signal demodulators, and signal processing IC-electronics packaged in a miniaturized, environmentally qualified, hermetically sealed 2-cm x 2-cm x 5-cm single fiber FBG-Transceiver™ system suitable for the in-situ installation and long term operation in aerospace, automotive, and industrial applications where size, weight, and power consumption are a critical requirement for the installation of structural health monitoring systems.

2. THE FBG-TRANSCEIVER™ SYSTEM

The FBG-Transceiver™ system is a compact, multi-channel FBG sensor interrogation unit that uses ROI’s proprietary integrated optic sensor (InOSense™) microchip technology as an optical bench to integrate the functionality of all of the key passive and active optoelectronics components such as the light guides, splitters and couplers, light source, photodetectors, wavelength demultiplexing, FBG sensor signal demodulators, and signal processing IC-electronics of conventional bench-top FBG sensor interrogators in a miniaturized, telecommunications standard, small form factor single fiber package. The FBG-Transceiver™ unit, shown in Figure 1, is a bi-directional, transmit and receive, FBG transducer communications unit that uses the principle of wavelength division demultiplexing (WDDM), commonly used in WDM telecommunication networks, to separate each of the received FBG sensor signals and interrogate the status of each of the individual sensors in an array of (1 to 40) FBG transducers distributed along a single optical fiber in real time. [2]

Fig. 1 ROI’s family of single channel, five-channel, and twelve-channel integrated optic FBG interrogation (FBG-Transceiver™) devices.
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 filter structure, in which the wavelength encoded optical signature of 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 InOSense™ 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. The target performance specifications of the FBG-Transceiver™ system are shown in Table 1.

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

<table>
<thead>
<tr>
<th>Model No</th>
<th>FBGT-100</th>
<th>FBGT-500</th>
<th>FBGT-1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBG Sensing Channels</td>
<td>1</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Monitoring Mode</td>
<td>Stress-strain, temperature, pressure, vibration, and acoustics</td>
<td>Wavelength division demultiplexing (WDDM)</td>
<td></td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>1530 nm to 1580 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Power</td>
<td>Max (-)0.5 dBm</td>
<td>Max 0 dBm</td>
<td>Max 5 dBm</td>
</tr>
<tr>
<td>Minimum Sensor Spacing</td>
<td>2 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength Resolution</td>
<td>1 pm @ 100 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength Accuracy</td>
<td>± 1 pm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength Repeatability</td>
<td>± 1 pm @ 100 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor Sampling Rate</td>
<td>0.1 Hz to 20 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal Processor</td>
<td>Microcontroller – Sensor calibration and T compensation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Communication</td>
<td>USB, Ethernet, Wireless, Bluetooth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical Connector</td>
<td>FC/APC or Custom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Display</td>
<td>LabView Graphical Interface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Supply</td>
<td>12 V/500 mA</td>
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<td></td>
</tr>
<tr>
<td>Weight</td>
<td>0.25 ounce</td>
<td>0.5 ounce</td>
<td>1 ounce</td>
</tr>
<tr>
<td>Dimensions</td>
<td>18.5 mm x 18.5 mm x 50 mm</td>
<td>55 mm x 55 mm x 20 mm</td>
<td>55 mm x 55 mm x 20 mm</td>
</tr>
</tbody>
</table>

### 3. HYBRID INTEGRATED OPTIC SENSOR (INOSENSE™) MICROCHIP TECHNOLOGY

Planar lightwave circuit (PLC) technology has emerged as the new optical platform of choice for integration and large scale manufacturing of optical components. The technology draws on the excellent heat-dissipation and mechanical properties of silicon wafers. Optical component designers use the silicon substrate as an optical bench to integrate unpackaged optical components, such as lasers, photodiodes, and micro-optic elements in die form, onto the PLC chip and then re-package the chip in a single unit. Precise micro-machine features on the PLC chip allow the passive mechanical alignment and attachment of the different opto-electronic components, all accurate enough for reliable communication between the components and the outside world.
The optical communication between the components is accomplished by micron-size, optical waveguide circuits written on a thin film of glass deposited onto a silicon wafer. These waveguide circuits are used to guide light, in a manner similar to an optical fiber, through the chip, and perform passive (light guiding) and active (wavelength separation, wavelength filtering, light amplification, switching, modulation, etc.) functions in a manner similar to integrated electronic circuits. Today, high performance PLC chips, as with electronic IC microprocessors, are commercially produced using a variety of mass producible semiconductor technologies. The net result is the integration of sophisticated, multi-element photonic subsystems into mass-produced PLCs.

For designers of aerospace and automotive optical components and sensor systems, the most exciting feature of PLC technology is its influence on the size, weight, and environmental reliability of the device. Freeing each of the individual components from their individual, hermetic package results in 10 times or more reduction in subsystem size and weight. Of course, eliminating excess packaging also reduces the likelihood of subsystem failure because of the interconnect failure.

In its simplest form, ROI’s InOSense™ microchip integrates a temperature- and power-stabilized broadband semiconductor light source that is monolithically integrated to the InOSense™ 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 InOSense™ 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 InOSense™ microchip. The received light signal is guided internally though the microchip, using waveguide routing structures, to the 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 InOSense™ 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 array waveguide grating (AWG) architectures. The wavelength selective WDM structures allows the transmission of a particular FBG wavelength ($\lambda_i$) while reflecting, or separating, all of the other ($\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_n$) 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 2. This principle forms the basis of the FBG sensor demodulator in the InOSense™ microchip.
4. PHOTOSENSITIVE SPIN-ON-Glass (PSOG™) PROCESS

Planar lightwave circuits are optical devices fabricated using silicon wafer processing technology. PLC’s are typically fabricated on silicon wafers using common semiconductor processes and materials, which make them attractive from a mass manufacturing and cost point of view. The predominant method is based on the chemical vapor deposition of silica onto silicon, commonly referred to as silica-on-silicon (SOS) technology. In this method, a series of silica films are deposited onto a silicon wafer to produce a three-layer waveguide structure consisting of: 1) bottom cladding or buffer layer, 2) a high index core layer, and 3) top cladding (see Figure 3). After the bottom cladding and core glass layers are deposited, the wafer is heat-treated to the consolidation temperature of the glass. The next step involves the use of high-resolution photolithographic techniques to define the waveguide structures on the surface of the film followed by etching the waveguide channels. This step produces single mode waveguide structures, typically 4-micrometer to 8-micrometer square channels on the core layer of the device. The next step involves the deposition of the cladding layer followed by complete glass densification of the device. Once the wafer is produced, the individual chips are diced and polished producing typically a set of 50 to 75 InO Sense™ chips on a 6-inch wafer. The polished chip is then connected to the optical fibers and ready for use. For PLC packaging, heat transfer and temperature control are two key factors that contribute to the design solution. Packaging plays a critical role in yield, cost and reliability of this technology.

ROI has developed its own well-established PLC fabrication method based on photosensitive spin-on-glass (PSOG™) technology. ROI’s PLC production method is similar to the SOS technology with two differing steps: 1) deposition of the silica film is achieved via a solution process, and 2) definition of the waveguide structure is achieved by an etchless direct lithography step. ROI’s PSOG™ process allows the lithographic production of gradient index (GRIN) waveguide structures. GRIN waveguide structures are key in the production of the InO Sense™ chip since it allows the fabrication of adiabatic, gradial variations of the refractive index along the propagation plane of the waveguide as well as in the horizontal and vertical planes of the waveguide structures. The GRIN waveguide structures are used to produce the taper
mode adapters used to enhance the mode coupling efficiency from the SLED source to the waveguide, and also to produce taper structures used for the WDM wavelength separation and demodulation of the FBG sensor signals.

Fig. 3 PSOG™ Planar Lightwave Circuit Fabrication Process

ROI’s adiabatic mode coupling waveguide structures allow the complete control of the light confinement strength along the light propagation axis of the waveguide structure. This is accomplished by gradually controlling the refractive index of the PLC waveguide structure at any location of the three-dimensional space of the waveguide, as shown in Figure 4. In ROI’s transverse-transfer mode coupling waveguide structures, the core and the surrounding vertical and horizontal cladding material each have a refractive index profile that is gradually controlled in the direction of light propagation. For these types of structures, it is possible to tailor the velocity of light propagating through the core of the waveguide and the light confinement strength of the waveguide for any given cross section. Such waveguide structures can be used for mode matching an input or output of a high $n$ optical device, such as the SLED die, to the low $n$ of the PLC waveguide. They can also be used in the construction of reflective taper structures to maximize the coupling efficiency of incoming light from the WDM filter to a tapered waveguide. Using this approach, complex adiabatic waveguide structures can be produced to achieve close to 100 % efficiency of optical transfer power from an optical device to a GRIN-PLC waveguide structure. These types of adiabatic structures are key to the design of the InOSense™ microchip and to maximize the power budget efficiency of the chip.

Fig. 4 GRIN adiabatic mode coupler waveguide structures

5. PRELIMINARY DEMONSTRATION OF OPERATING PRINCIPLE OF MINIATURE FBG-TRANSCEIVER™ SYSTEM

To demonstrate the operating principle of the miniature fiber Bragg grating sensor interrogator FBG-Transceiver™ technology, a proof-of-concept prototype unit was developed based on ROI’s proprietary multi-channel integrated optic sensor (InOSense™) microchip technology. ROI designed and produced a state-of-the-art signal processing electronics
CMOS PC board used to interrogate the status of the distributed FBG transducers, to demodulate the FBG optical signatures, and to transmit this information via USB data communication to a remote control station. A user-friendly Visual Basic data acquisition software program was developed to display the status of the FBG sensors in real-time. The FBG-Transceiver™ optics block and electronics board were packaged in telecommunication’s standard common form CM (1.8 cm x 5-cm x 5-cm) single fiber bi-directional transmission package, as shown below in Figure 5.

![5-Channel FBG-Transceiver™ Unit](image)

Fig. 5 Preliminary prototype of multi-channel FBG-Transceiver™ System for the Structural Health Monitoring

To test and characterize the performance of the InOSense™ microchip wavelength-to-intensity, demodulator a test bed was assembled as shown schematically in Figure 6. In this setup, a broadband light source, ASE or SLD, is used to couple into the InOSense™ microchip (DUT) from either the input port or the output port of the chip. The input port of the chip is the waveguide where the SLD source is integrated to the chip, and the output port of the chip is connected to the single fiber pigtail. This fiber pigtail is used to connect to the FBG sensor array using a fiber-mating adapter. To monitor the light guiding and demodulation properties of the chip, an optical spectrum analyzer (OSA) is used to connect at either the output port of the chip, or at each of the detection ports, i.e., D1, using an optical fiber to pick up the light transmitted, or reflected, at each of the detection ports.

![Test set-up for testing and characterization of multi-channel InOSense™ microchip](image)

Fig. 6 Test set-up for testing and characterization of multi-channel InOSense™ microchip.

Using this test setup, the optical properties of the InOSense™ microchip demodulator could be characterized while simultaneously optimizing the alignment position of the light source and photodetector channels. The first step in the measurement process was to observe the light transmitted through the InOSense™ microchip from the input to the output ports of the chip. Figure 8 shows the broadband spectra of the SLD source when connected to the chip. As shown in this figure, the SLD source shows –25 dBm of power with an almost flat top in the range of 1550 nm to 1600 nm.
nm. The half width maximum of the SLD is about 60-nm’s. This figure shows the light intensity power transmitted from the InOSense™ microchip for the interrogation of the FBG sensor array. Similar spectra were observed when light is transmitted from the input port to the first photodetector port as picked up by the collection optical fiber. Figure 7 also shows the FBG reflection spectrum, from an array of five gratings surface-mounted on one of the cantilever test-beds, when illuminated with the SLD source thru the InOSense™ microchip and monitored with the OSA at the fiber coupler output connection prior to being received by the InOSense™ microchip.

![Figure 7](image)

**Fig. 7** Transmission spectra of broadband source and reflection spectra of five sensors FBG array.

The next step involved testing the response of the FBG-Transceiver™ detection channels as a function of the FBG sensors peak wavelength position when the sensor array was exposed to increasing bending stress in the cantilever test-bed. To accomplish this test, the SLD source was connected back to the input port of the InOSense™ microchip, and the fiber sensor array was connected to the output port of the chip. To cross-calibrate the intensity response of the demodulation detector, the peak wavelength position of the FBG sensor was simultaneously measured via the fiber coupler signal split using the OSA. This test setup was used to interrogate the strain status of the FBG sensor array upon bending of the cantilever beam, as shown in Figure 8(a). The plot in this figure shows a linear correlation between the peak position of the FBG sensor and the light intensity measured by the demodulation detector channel. The results in this plot show a displacement on the peak wavelength position of the grating of approximately 1.87-nm, corresponding to approximately 1558- strains. Similarly, the dynamic peak wavelength, strain, response of one of the FBG transducers in the fiber FBG sensor was monitored by exciting vibration modes on the cantilever beam incorporating the surface mounted FBG transducers. Figure 8(b) shows the response of channel 1 of the InOSense™ microchip upon the excitation of vibration modes onto the cantilever beam. The vibration of the cantilever plate is clearly monitored in real time using the WDM demodulation principle of the FBG-Transceiver™ device.

![Figure 8](image)

**Fig. 8** Passive and dynamic wavelength demodulation properties of channel 1 of InOSense™ microchip.

These results clearly demonstrate the fundamental operating principle of the passive demodulation of the FBG-Transceiver™ device. By using both the hybrid InOSense™ microchip to monolithically incorporate a broadband source to analyze the reflected, narrow-band spectral signature of an array of FBG transducers, and the wavelength WDM filters that only allows that portion of the spectrum related to a particular FBG sensor to be transmitted though the
demodulation filter into the photodetector, while reflecting back the remaining analyzing light source into the subsequent detection channels, the passive and active spectral signatures of the FBG sensor array can be monitored in real-time, as shown in Figure 9.

Fig 9. Response of five-channel FBG-Transceiver™ to small perturbations to cantilever test bed
6. SUMMARY

The results presented in this paper described preliminary work towards the development of a miniature fiber Bragg grating sensor interrogator (FBG-Transceiver™) system based on multi-channel integrated optic sensor (InOSense™) microchip technology for applications where size, weight, and consumption power are critical for operation. The preliminary test results of the FBG-Transceiver™ device conclusively demonstrated the demodulation principle of the hybrid InOSense™ microchip for the accurate measurement of the peak wavelength shift of the FBG transducers when the sensors are exposed to passive and active events. The hybrid InOSense™ microchip technology enables 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, single fiber package suitable for the long-term structural health monitoring in aerospace and automotive applications.

7. ACKNOWLEDGMENTS

Redondo Optics acknowledges the support of this work from the U.S. Navy under an SBIR contract No. N68335-06-C-0206.

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