

Progress in miniaturization of a multichannel optical fiber Bragg grating sensor interrogator

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ABSTRACT

An effort to develop a miniaturized multichannel optical fiber Bragg grating sensor interrogator was initiated in 2006 under the Small Business Innovative Research (SBIR) program. The goal was to develop an interrogator that would be sufficiently small and light to be incorporated into a health monitoring system for use on tactical missiles. Two companies, Intelligent Fiber Optic Systems Corporation (IFOS) and Redondo Optics, were funded in Phase I, and this paper describes the prototype interrogators that were developed. The two companies took very different approaches: IFOS focused on developing a unit that would have a high channel count and high resolution, using off-the-shelf components, while Redondo Optics chose to develop a unit that would be very small and lightweight, using custom designed integrated optical chips. It is believed that both approaches will result in interrogators that will be significantly small, lighter, and possibly even more precise than what is currently commercially available. This paper will also briefly describe some of the sensing concepts that may be used to interrogate the health of the solid rocket motors used in many missile systems. The sponsor of this program was NAVAIR PMA 280.

Keywords: Bragg Grating Sensors, Optical Fiber Sensors, Health Monitoring

1. INTRODUCTION

The US Navy has expressed a need for self-sensing ordnance. This need is particularly acute with regard to solid rocket motors, since it is known that aging of propellant can lead to significant degradation in weapon performance and catastrophic failure. The Navy's mandate that tactical missiles be stored for extended periods of time on board ship, without periodic, land based, inspections, also points to the need for self-sensing missiles.

Classical approaches used to predict and detect material degradation have been, respectively, to develop aging models that can be used to predict the state of a material, given an assumed or measured environmental history, and use of non-destructive testing methods such as ultrasound and X-ray. Both approaches, as currently practiced, are inadequate to meet the needs of a real-time, self-sensing health monitoring system. Thus, in recent years efforts have been devoted to investigate an entirely new approach to meet the goal of self-sensing ordnance - the use of embedded sensors.

The use of embedded sensors is attractive for many reasons. By placing a sensor inside a weapon (vs. having to peer through a thick metallic housing), the sensor is in direct contact with the energetic material, and thus in a better position to monitor subtle changes in properties. Also, the sensor is always present in the weapon, and thus the weapon's health can always be queried, thus meeting the goal of making the ordnance self-sensing. Current efforts in the solid rocket motor community are mainly focused on using embedded, *passive*, strain and stress sensors to monitor small perturbations in the strain and stress fields in propellant indicative of damage.

Two main classes of sensors are currently under development in the solid rocket motor community; strain gage based bond-line stress sensors, and optical fiber strain sensors. It has been demonstrated that multiple bond -line sensors, in conjunction with finite element analysis, can be used to infer the presence of debonds and cracks in the propellant.

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Advantages of this method are that it relies on mature technology and uses physically robust components. Drawbacks include difficulty in placement during manufacture, use of electrical components, cost (~\$1000 per system), and difficulty of ingress for the wires.

In terms of optical fiber sensors, the main type of sensor being investigated is the Bragg grating strain sensor. The development of optical fiber sensors for health monitoring of solid rocket motors is not as developed as bond line sensor methods, but the basic idea is to either cast the optical fiber in place during manufacture or glue the fiber along the bondline. In either case, the basic idea is that by monitoring small perturbations in the strain field, one can infer the presence of damage. The main advantages of optical fiber Bragg grating sensors are high sensitivity (they can measure down to the sub - micro-strain level), they can be multiplexed (several hundred sensors can be incorporated into a single fiber), are insensitive to electromagnetic interference, do not introduce electrical pathways into the motor, and are free from drift. Finally, it has been demonstrated that they can be used to detect ultrasound, and thus may be used in an active sensing scheme.

One of the major hurdles in the use of Bragg grating sensors for health monitoring of tactical missiles has been the large weight and size of the sensor interrogator – commercial units weight around 10 kg. While it is possible to have the interrogator be separate from the motor, it would be much more desirable if the entire health monitoring unit would reside on the missile, thus making it truly self-sensing. To this end, a Small Business Innovative Research program was initiated to see how far optical and electronic technology could be pushed to significantly reduce the size and weight of a Bragg grating sensor interrogator. The goal of each company in the Phase I effort was to demonstrate that their technical approach could lead to a significant reduction in size and weight of the interrogator, and each company delivered a prototype unit. This paper summarizes the results from the Phase I effort by Intelligent Fiber Optic Systems Corporation and Redondo Optics.

2. Intelligent Fiber Optics System Corporation (IFOS) Approach - use of an arrayed waveguide

The path taken by IFOS for their prototype was to incorporate: 1) an erbium doped fiber amplified spontaneous emission source (EDF ASE) to illuminate the gratings; 2) a special arrayed waveguide grating (AWG) to separate the various wavelengths; 3) discrete photodetectors for each channel; 4) a data acquisition board to acquire the signals and process the data. Most of the components used were commercial-off-the-shelf.

An EDF ASE source was used due to its extended bandwidth, fiber compatibility, and low degree of polarization, compared to, for example, a superluminescent diode (SLD). While the low degree of polarization was important to reduce polarization dependent accuracy effects in the photo-detectors and other components, the relatively large size of commercially available EDF ASE sources (optics and electronics integrated in one package) implies that future versions of the interrogator may use other, more compact integrated sources.

As mentioned above, IFOS decided to use an arrayed waveguide grating to separate the wavelengths. Although IFOS has already commercialized an all fiber interrogator, it was determined that there would be few advantages to an all fiber approach when many channels must be interrogated. In Figure 1 is shown the use of an AWG to separate different wavelengths at the input. The standard version of these devices are widely used in the telecom industry, and are very small and inexpensive.

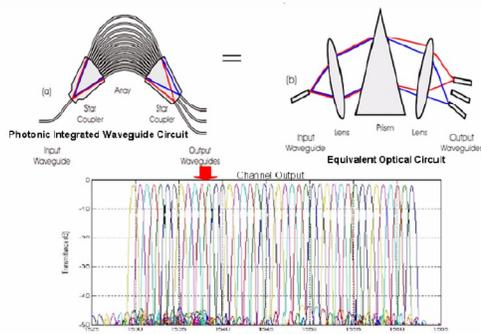


Figure 1. Operation of the AWG.

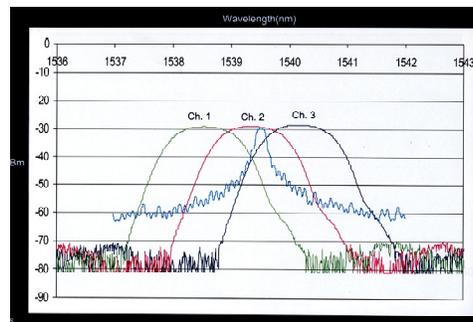


Figure 2. The reflection spectrum of a typical grating overlaps several adjacent channels in the

In Figure 2 it is evident that the reflection spectrum of a typical Bragg grating will overlap several of the channels - taking advantage of this feature, the ratio of amplitudes in the various channels are used to compute the actual wavelength, resulting in increased precision and accuracy. The precision of the prototype unit is shown in Figure 3, where subpicometer resolution is demonstrated. The layout of the prototype, excluding the light source, is shown in Figure 4. It is evident that significant additional miniaturization is possible. The IFOS design provides very high speeds (0 to MHz and over).

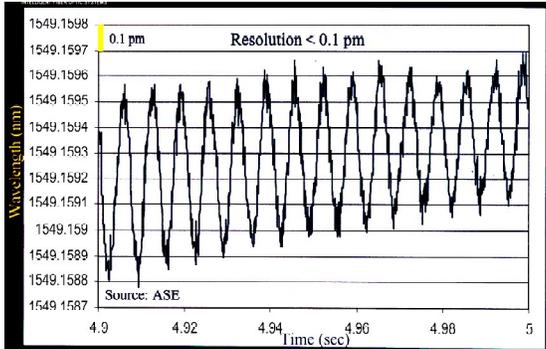


Figure 3. Output for one of the channels. Sub-picometer resolution is possible.



Figure 4. Layout of the 8 channel prototype.

3. Redondo Optics Approach - planar waveguide and edge filters

The path taken by Redondo Optics was to use discrete wavelength edge filters to discriminate between the gratings, and design and fabricate an integrated optics chip which would incorporate the source, filters, and optical waveguides. In Figure 5 is shown the basic concept.

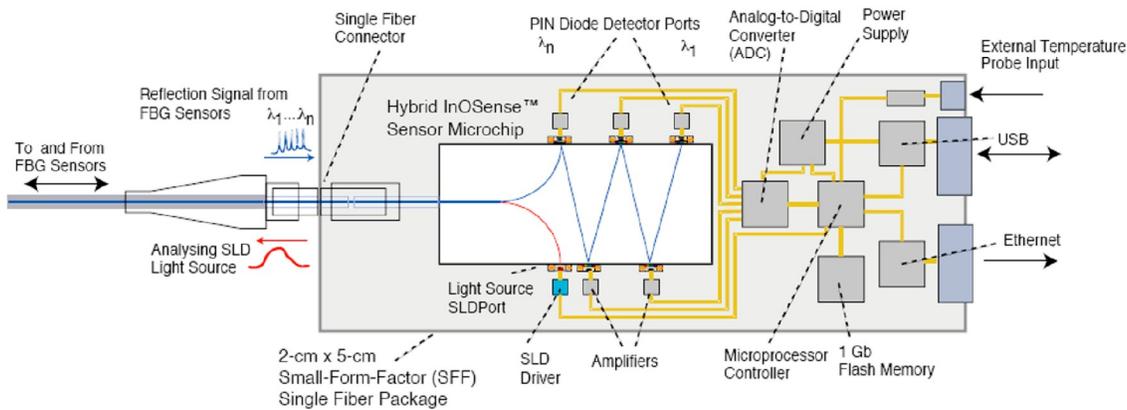


Figure 5. Basic layout, showing how the light source, waveguides, and detectors fit onto a single chip.

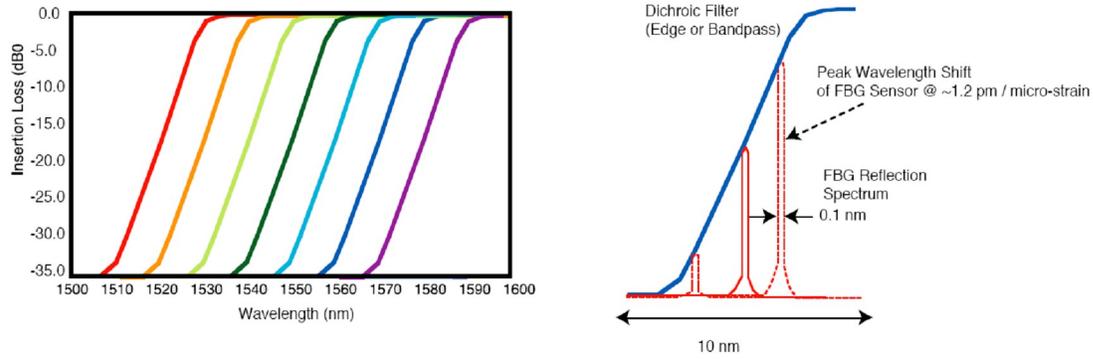


Figure 6. Edge filters are used to select each Bragg wavelength.

A superluminescent diode (SLD) is used to launch the light into the fiber containing the Bragg gratings. The reflected light is routed, via waveguides, to five different detectors, in front of which is an edge filter whose center wavelength corresponds to that of a grating. Figure 6 shows how the edge filters are used to provide an output proportional to the wavelength shift. The outputs from the detectors are amplified, fed into an analog to digital converter, and processed using a microcontroller. All the electronics are contained in a single board smaller than 4 by 4 cm.

Figure 7 shows the geometry of the waveguides in more detail. While using an incident angle of 45° would lead to a more compact package, this design would require custom-made filters. Thus, for the Phase I prototype zero angle waveguides were used. Figure 8 shows the layout of the hardware.

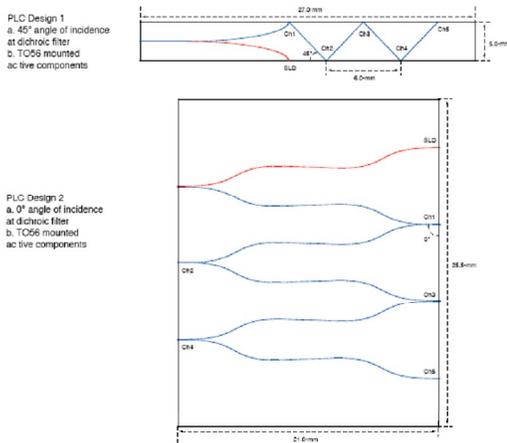


Figure 7. Geometry of the waveguides.

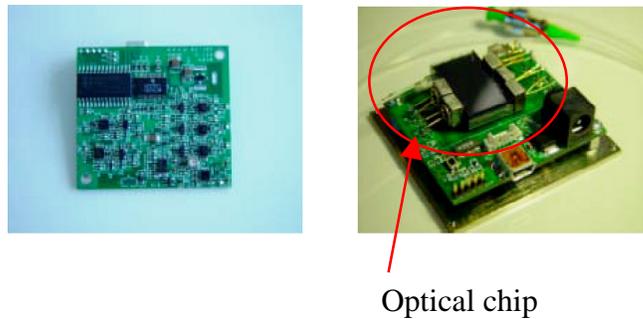


Figure 8. Layout of the hardware. The optical chip lies on top of the electronics board.