Fiber Optic Distributed Sensing Systems For Harsh Aerospace Environments

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ABSTRACT

Fiber optic sensors have the potential to be used in the very hostile environments necessary for advanced aerospace platforms. This paper reviews some of the key issues associated with the implementation of distributed fiber optic sensors in harsh environments and outlines baseline system designs.

Keywords: Fiber gratings, etalons, demodulation, multiaxis strain

1. INTRODUCTION

1.1. Aerospace Requirements

Virtually any aerospace platform has the potential to benefit from distributed fiber optic sensors that could be used to measure a wide range of parameters. Table 1 lists advanced measurands needed to support single stage to orbit vehicles. As an example of the harsh temperature environments that are associated with this vehicle, Table 2 lists thermal sensor functional requirements. The need for these measurements derives from a series of mission and vehicle health management requirements. In particular, to make this vehicle economically feasible, maintenance and turn-around functions need to approach those associated with modern commercial aircraft. Instead of hundreds or thousands of people supporting a few vehicle launches per year, the numbers should drop to two or three people supporting tens or hundreds of launches for each of hundreds of vehicles. This situation requires the vehicle to be as autonomous as possible with maintenance performed as needed rather than to a cookbook schedule. Further optimized control of the vehicle and improved performance require designers to move away from "launching bricks" to implementing increasingly intelligent vehicles with integral nervous systems.

Shock Position
Thermal Management
Mass Flow
Gas Diagnostics
Slush Hydrogen Gauging
Surface Temperature
Structure Temperature
Rotary Speed
Heat Flux
Skin Friction
Structural Integrity
Fatigue
Acoustic Noise
Engine Unstart Detection
Linear Position
Strain
Air Data
Surface Pressure
Control Position
Acceleration
Torque/Horsepower
Deflection
Catalicity
Engine Mode Transitions
Wear/Erosion
Hydrogen Leaks

Table 1. Advanced measurands that are needed to support viable future single stage to orbit spacecraft

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Location	Temperature (°F)	Heat Flux (BTU/ft^2-sec)	dT/dt (°F/sec)
Actively Cooled Panels Airframe	-200 to +1200	300	1000
Engine Region	-200 to +1800	2400	1000
Leading Edges Airframe	-200 to +1200	2000	1000
Engine Region	-200 to +2000	12000	1000
Passively Cooled Panels Airframe (Metal Matrix Composite)	0 to +1800	15	100
Engine Region (Carbon/Carbon)	+1800 to +3000	55	250
Cryogenic Tankage	-430 to +150	1	500

Table 2. Hypersonic vehicle thermal sensor functional requirements

The case for military and commercial aircraft is equally compelling. Maintenance costs currently are tens of billions of dollars yearly. Diagnostic systems are required that allow for maintenance to be performed when needed. This would allow improved safety by insuring that necessary tasks are performed while reducing costs by eliminating costly and unneeded procedures. Further improvements in safety and performance can be expected by integrating these systems into control systems to improve flight control and assess in-flight damage.

Advanced reusable launch vehicle development programs are being used as test beds to demonstrate the utility of distributed fiber sensor systems. An example of this is the Delta Clipper which had a system of fiber grating based strain sensors integrated into its hydrogen fuel tank. This system initially acted as a redundant backup to a set of electrical strain gages to demonstrate new technology. Initially, some of the program managers were very doubtful about its utility. By the end of the program the attitude had changed from "why use fiber optic grating based strain sensors when we have electrical ones on board?" to "lets scrap the electrical strain gages that perform poorly and only use the fiber optic grating strain gages." Why the change in attitude? Fiber optic grating strain sensors can be embedded directly into a composite hydrogen tank becoming an integral part of the structure, they do not fall off with vibration and shock. Fiber optic grating strain gages do not pose an electrical hazard, they are lighter weight, environmentally superior, easier to install, and can be multiplexed in numbers along a single fiber line. The X-33's hydrogen tank also incorporates fiber grating strain sensors to perform health monitoring [1-3]. The X-33 system employs hundreds of fiber grating strain sensors to perform this task using multiplexed strings of sensors.

As fiber sensors continue to be used and proven in these advanced systems, continuing decreases in cost due to advances in the telecommunication and optoelectronic industries will enable more cost-effective solutions for military fighters, military transports and commercial aviation.

1.2. Components Supporting Fiber Optic Sensor Systems

The basic components comprising a fiber optic sensor system are shown in Figure 1. The key components include a light source, beam conditioning optics, a transducer, a modulator for signal processing, and a detector to convert the light output into an electrical signal. In many cases it is possible to place components into a relatively benign environment reducing requirements on their environmental performance. The key element that must be placed in the hostile environment is the transducer.

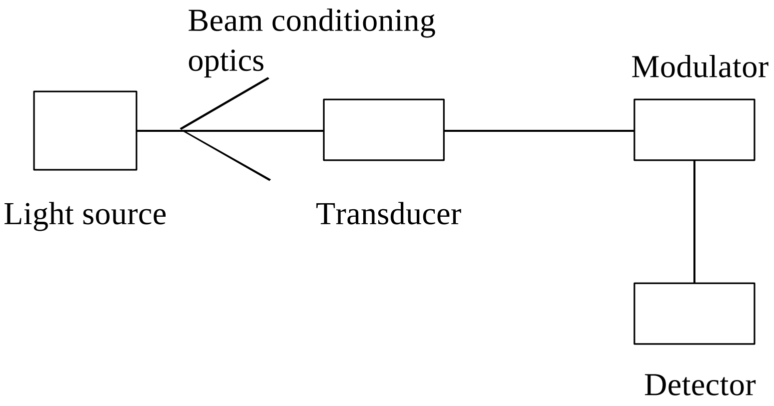


Figure 1. Basic Elements of a fiber optic sensor

The transducer consists of an optical fiber that is usually protected by a coating. The function of the coating is to inhibit deterioration of the optical fiber due to microfractures on its surface and protect against constituents of the surrounding environment such as water vapor that will cause these fractures to propagate resulting in failure. For silica based fibers there are issues associated with softening and deformation of the fibers at elevated temperatures as well as diffusion of the core dopants into the cladding. These processes appear to be dependent on the exact fiber design and dopants used and there is scant data on the operation of these fibers at elevated temperatures for prolonged periods of time. Most telecommunication applications rely on epoxy acrylate coatings which are designed to operate to upper temperature ranges of 80 to 125 °C and to lower temperature ranges of -20 to –50 °C. Failure at the high-end often is in the form of chemical transitions drastically altering the mechanical properties of the coating, eventually resulting in the coating becoming brown and brittle. At low temperatures the coating freezes, often causing the fiber to be severely stressed and prone to fracture. Some special acrylate coated fibers have upper ranges that are on the order of 150 to 200 °C before failure occurs. Polyimide coatings have a wider temperature range and have been used successfully to support strain monitoring in composite hydrogen tanks as well as operation in excess of 400 °C. There are two common types of polyimide materials used. The lower temperature polyimide operates to approximately 300 °C before it becomes soft and tacky and has the advantage of being relatively easy to remove. A higher temperature polyimide retains its integrity beyond 400 °C, although it is much more difficult to remove from the fiber. For situations where still higher operating temperatures are required, aluminum coatings have been used up to 600 °C and gold to in excess of 700 °C.

For some fiber sensors, such as those based on interferometry, the fiber is the primary element of the transducer with potential augmentation from a host material it is embedded into or mechanical amplification. In other cases the transducer itself may be more complex. Two important cases for harsh environments involve fiber etalon and fiber grating based fiber sensors.

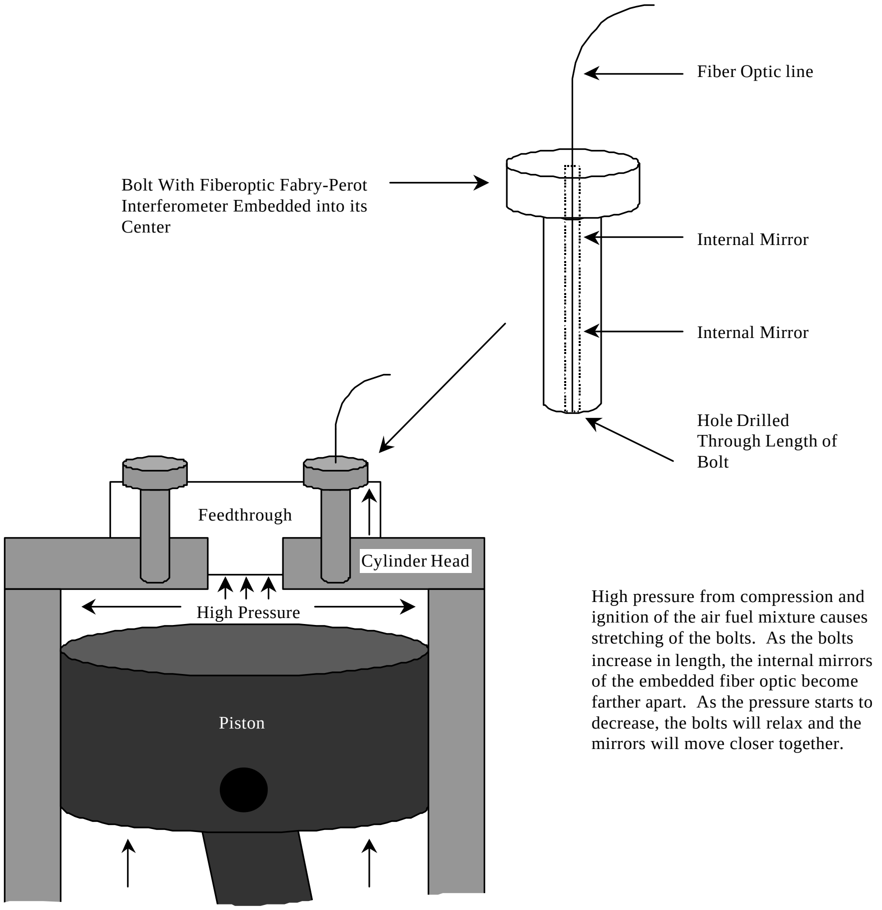
Most other components of fiber sensors can be made to withstand severe shock and vibration environments as evidenced by fiber gyros packaged to withstand being fired in mortar shells and to support drilling operations. The major harsh environment limitation for components other than the fiber transducer is high temperature. For fiber couplers this limit is about 200 °C with some experimental devices performing to 300 °C. Light sources, detectors, and modulators are often limited to low temperature solders. In the case of light sources, most laser diodes are limited to less than 100 °C and only a very few selected light emitting diodes can operate at temperatures above 150 °C. Generally, detectors can be made to operate at temperatures approaching 200 °C. Most integrated optic modulators will fail around 100 °C with some piezoelectric devices operating to somewhat higher temperatures. Specific data on these devices is extremely limited as the commercial market is targeted to 70 °C and many military applications do not exceed 85 °C. Instead, many developers interested in higher temperatures, test commercially available devices themselves and if necessary pay for custom changes which they regard as proprietary to attain higher operating temperatures. For these reasons the nearest term approach to enabling distributed fiber sensors to operate in harsh environments is to locate these components in a relatively cool area and expose only the fiber transducers to the higher temperatures.

2. FIBER SENSORS FOR HARSH AEROSPACE ENVIRONMENTS

2.1. Fiber Etalons

The Fabry-Perot interferometer or etalon consists of two mirrors of reflectivity R_1 and R_2 separated by a distance L. When the wavelength of light transmitted through the etalon is such that an integral number of wavelengths match the length L a resonance condition is established and the mirrors in combination appear to be transparent. Sensors may be constructed by configuring the devices to respond to strain, temperature, or pressure [4,5]. There are a series sensor and demodulation designs that have been implemented using fiber etalons.

One type of fiber etalon that was pioneered at Texas A&M and later at Fiber Dynamics, Inc. involves placing the mirrors directly in the fiber. This type of fiber etalon sensor is called an intrinsic fiber etalon. One of the simplest methods for demodulation of this sensor is simply to look at intensity peaks as the fiber is cycled. To demonstrate the potential range of this method, Texas A&M formed an etalon with 2% mirrors in an optical fiber and ran a temperature cycle from -200 to 1050 °C and did not observe hysteresis or changes in the mirror reflectivity [6]. These sensors have been embedded in composite material [7] to measure strain and in metals to measure ultrasonic acoustic waves [8]. Because these sensors can be used to for high temperature environments, they have been used widely to support electrical generation using natural gas. This has been done by embedding the fiber Fabry-Perot with internal mirrors to the optical fiber directly into a steel bolt by casting with aluminum [9]. Figure 2 shows a schematic of the fiber fabry-perot being embedded into a bolt with aluminum that in turn is screwed into the head gasket of a natural gas engine to monitor strain and piston position. One of the principle advantages of this approach is that the fiber sensor can withstand temperatures well in excess of 300 °F during operation while the piezoelectric sensors it replaces began to have significant breakdowns in performance at this temperature level.



High pressure from compression and ignition of the air fuel mixture causes stretching of the bolts. As the bolts increase in length, the internal mirrors of the embedded fiber optic become farther apart. As the pressure starts to decrease, the bolts will relax and the mirrors will move closer together.

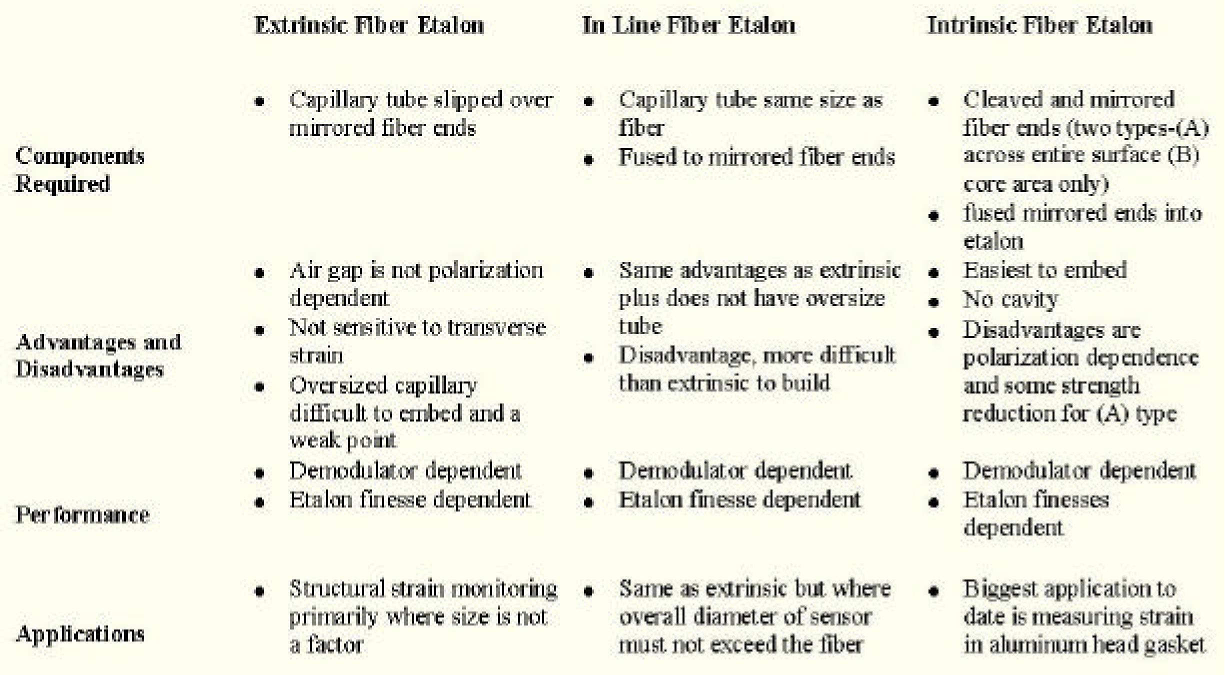
Figure 2. Intrinsic fiber Fabry-Perot etalons have been used to support strain measurements in cylinder heads of combustion engines.

A second type of fiber etalon based sensor consists of fibers with mirrored ends placed in a capillary tube. This is called the extrinsic fiber etalon. This technique was pioneered at Virginia Tech [10-12] and has been commercialized by F&S in Blacksburg, Virginia and FISO in Canada. One of the advantages of this approach is that the fiber between the two mirrors in the intrinsic fiber etalon is subject to birefringence effects that cause polarization rotation and can significantly alter the properties of the etalon. This situation does not occur in the extrinsic etalon which generally has air or another gas between the two mirrors. In addition to being used to support ultrasonics and embedded studies, it has been used to support ground fatigue tests on an F-15 [13]. This approach has also been used to support very high temperature operation by employing sapphire. It is important to note that making single mode fibers out of sapphire is very difficult so reported efforts have been confined to using small sapphire rods acting as multimode optical fibers. The resulting etalons have been used to support very high temperature strain measurements [14]. F&S has made as series of demodulation systems to support the fiber etalon including those based on fringe counting and using coherence for absolute measurement.

FISO makes a series of extrinsic etalon based fiber sensors that come in packages suitable for temperature, pressure, and strain measurement. These commercial packages are specifically designed to support market applications. To support demodulation, FISO also markets a system based on a Fizeau interferometer consisting of a glass wedge placed in front of a CCD array. By using a very low coherence length source, interference only occurs on the CCD array when the glass wedge spacing matches that of the extrinsic etalon spacing. This approach has resulted in a robust, cost effective instrument.

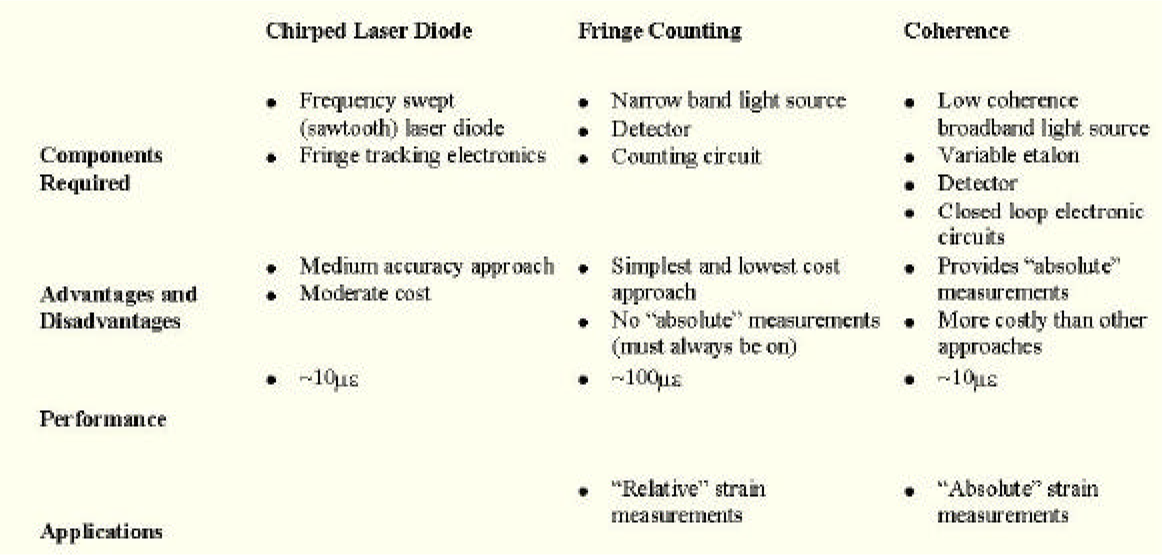
One of the issues associated with extrinsic fiber etalon sensors for embedded applications as implemented by F&S and FISO involves the capillary tube being of a larger diameter than the fiber. This can cause structural problems in parts. Another problem with early designs involved breakage when the sensors were embedded at the point the fiber exited the capillary tube. Both F&S and FISO have improved their designs but the oversize capillary tube remains a problem. The University of Maryland addressed this problem by forming extrinsic fiber etalons with capillary tubes the same size as the fiber diameter, which they called the "in line fiber etalon" or ILFE [15]. The University of Maryland also recognized that in order to make a practical fiber etalon based strain sensor it would also be necessary to measure temperature [16, 17]. Their approach has been to use a combination of a fiber etalon and a fiber grating connected serially.

Table 3 summarizes the characteristics of the three major types of fiber etalons. Table 4 summarizes demodulation systems that may be used to support fiber etalon based sensors.



	Extrinsic Fiber Etalon	**In Line Fiber Etalon**	**Intrinsic Fiber Etalon**
Components Required	• Capillary tube slipped over mirrored fiber ends	• Capillary tube same size as fiber • Fused to mirrored fiber ends	• Cleaved and mirrored fiber ends (two types-(A) across entire surface (B) core area only) • fused mirrored ends into etalon
Advantages and Disadvantages	• Air gap is not polarization dependent • Not sensitive to transverse strain • Oversized capillary difficult to embed and a weak point	• Same advantages as extrinsic plus does not have oversize tube • Disadvantage, more difficult than extrinsic to build	• Easiest to embed • No cavity • Disadvantages are polarization dependence and some strength reduction for (A) type
Performance	• Demodulator dependent • Etalon finesse dependent	• Demodulator dependent • Etalon finesse dependent	• Demodulator dependent • Etalon finesses dependent
Applications	• Structural strain monitoring primarily where size is not a factor	• Same as extrinsic but where overall diameter of sensor must not exceed the fiber	• Biggest application to date is measuring strain in aluminum head gasket

Table 3. Fiber Etalon Sensor Configurations



	Chirped Laser Diode	Fringe Counting	Coherence
Components Required	• Frequency swept (sawtooth) laser diode • Fringe tracking electronics	• Narrow band light source • Detector • Counting circuit	• Low coherence broadband light source • Variable etalon • Detector • Closed loop electronic circuits
Advantages and Disadvantages	• Medium accuracy approach • Moderate cost	• Simplest and lowest cost approach • No "absolute" measurements (must always be on)	• Provides "absolute" measurements • More costly than other approaches
Performance	• ~10$\mu\varepsilon$	• ~100$\mu\varepsilon$	• ~10$\mu\varepsilon$
Applications		• "Relative" strain measurements	• "Absolute" strain measurements

Table 4. Fiber Etalon Demodulation Types.

2.2. Fiber Gratings

2.2.1. Single Axis Strain or Temperature Sensing

A Fiber Bragg Grating (FBG) is a periodic perturbation of the refractive index along the fiber length which is formed by exposure of the core to an intense optical interference pattern [18]. These periodic perturbations or grating, when written onto ordinary single mode fiber, effectively create a single axis strain or temperature sensor on the core of the fiber (Figure 3.) When a broadband light source such as an edge emitting LED (ELED) is guided through the core to the grating, spectral peaks are reflected back and the majority of the light is allowed to pass through. The reflected peak shifts to higher and lower wavelengths with axial strain and temperature changes, thus relating a measurable spectral change to the measurand (Figure 4.) To measure both strain and temperature using fiber gratings written onto single mode fiber, a series of approaches have been used [19-22]. These methods include writing two overlaid fiber gratings at different wavelengths, a loose fiber grating to measure temperature near one bonded to measure strain, and a combination of a fiber etalon sensor with a fiber grating.

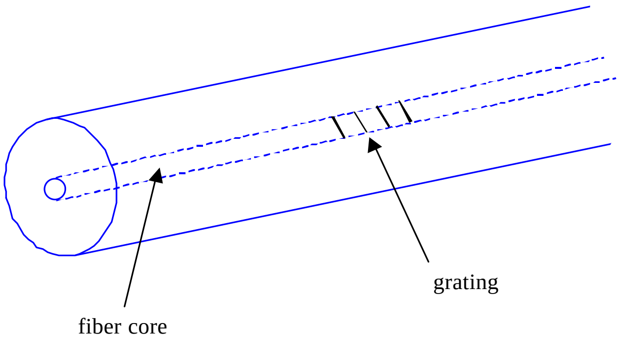
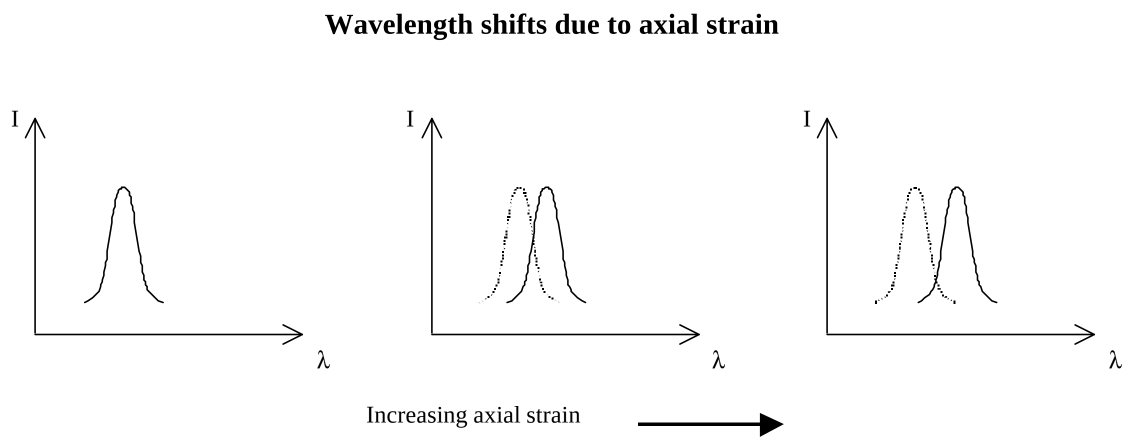


Figure 3. Single grating written onto ordinary single mode fiber to form single axis strain or temperature sensor.



Wavelength shifts due to axial strain

Figure 4. Shifts in spectral peaks reflected from fiber grating sensor due to axial strain or temperature changes.

2.2.2. Demodulation Systems

To demodulate the single grating sensor, three main systems may be employed.

The first of these systems is an etalon-based system. The basic principle of an etalon demodulation system is to “scan” over the wavelength by changing the spacing of two mirrors. Once the spectral peak from the grating is detected, its wavelength is determined by the spacing of the mirrors.

Etalon systems are capable of handling multiple in-line fiber grating sensors and can operate at speeds up to about 100 Hz using systems commercially available today. Examples of etalon based demodulation systems are Research International’s family of Ferret PC cards and systems available from Micron Optics.

The second demodulation system is an optical spectrum analyzer. These diverse systems are widely used for testing because of their ability to show spectrographic details. Optical spectrum analyzers are typically limited in speed to a few Hz.

A third type of fiber grating demodulation system is based on ratiometric approaches involving overcoupled fiber beamsplitter, chirped fiber gratings, or Mach-Zehnder/Michelson interferometers.

A schematic of a chirped fiber grating system is shown in Figure 5. The system works on the principle that the chirped fiber grating filter will attenuate one leg of the output proportional to strain and temperature changes in the fiber grating sensor. Blue Road Research has built several units running from DC to approximately 10 kHz. A faster unit capable of monitoring speeds beyond 3MHz is under development.

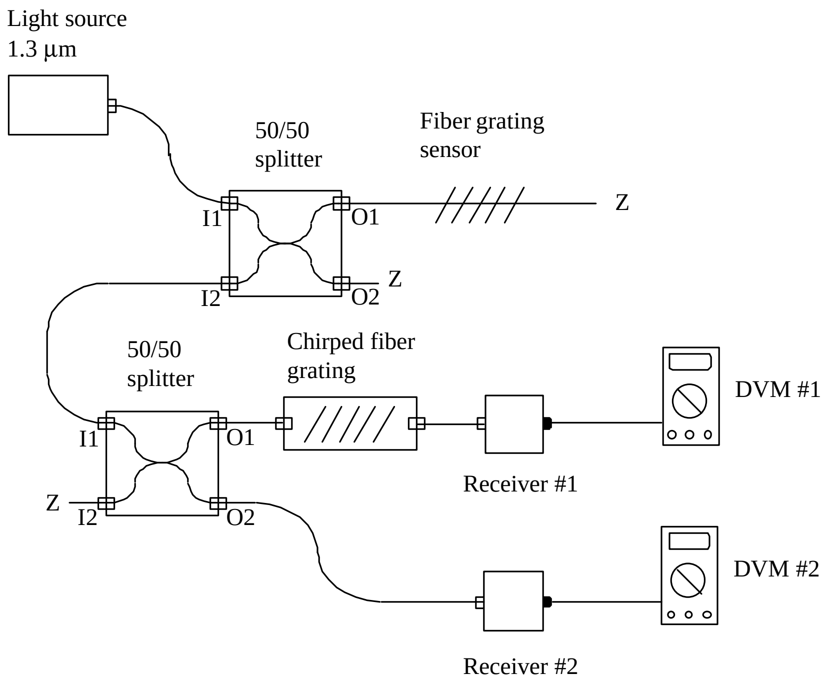


Figure 5. Schematic of a fiber grating demodulation system employing a chirped fiber grating spectral filter. This system has the potential to operate from DC up to well over 1 MHz limited mainly by the receiver electronics and processing.

2.3. Multiaxis Strain Sensing

In many structural applications, it is necessary to measure transverse as well as axial strain. A multiaxis fiber Bragg grating strain sensor uses the same principle as the single axis sensor mentioned previously with the difference that a second grating at a different wavelength is written over the first grating and polarization preserving fiber is used (Figure 6) [23,24].

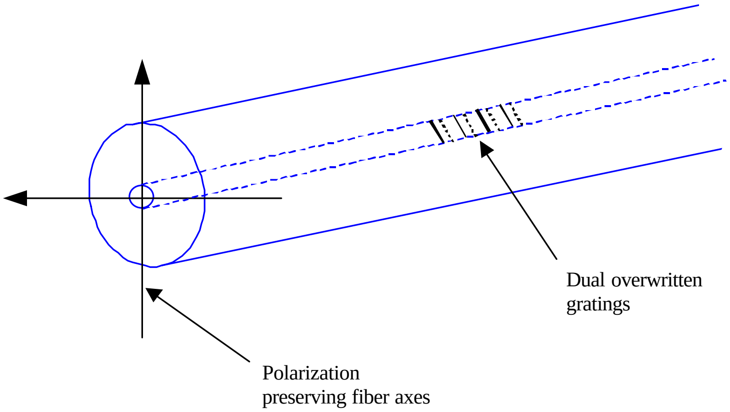


Figure 6. Multiaxis fiber grating strain sensor

This configuration results in four reflected peaks, two for each polarization axis. Similar to the single axis sensor, the reflected spectral peaks from the multiaxis sensor will shift with axial strain and temperature changes. In addition to this, transverse strain can be determined by measuring the peak to peak separation of the two peaks corresponding to the two mutually orthogonal polarization axes (Figure 7.)

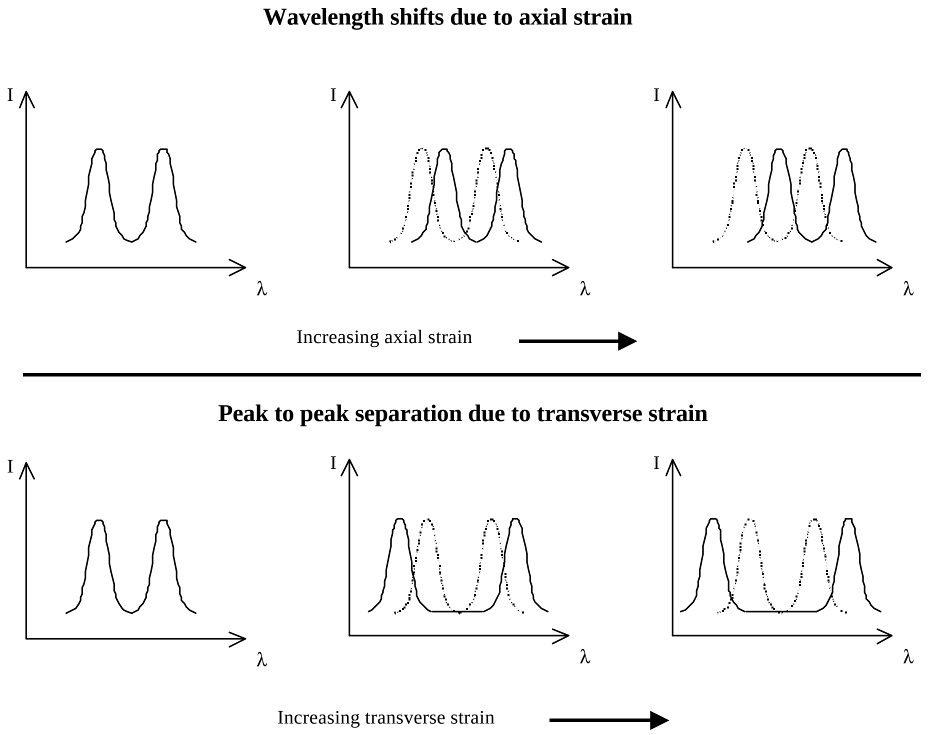


Figure 7. Spectral shifts of peaks due to axial and transverse strain on a multiaxis fiber grating strain sensor.

Some sample data showing the multiaxis sensor response to transverse strain is presented in Figure 8.

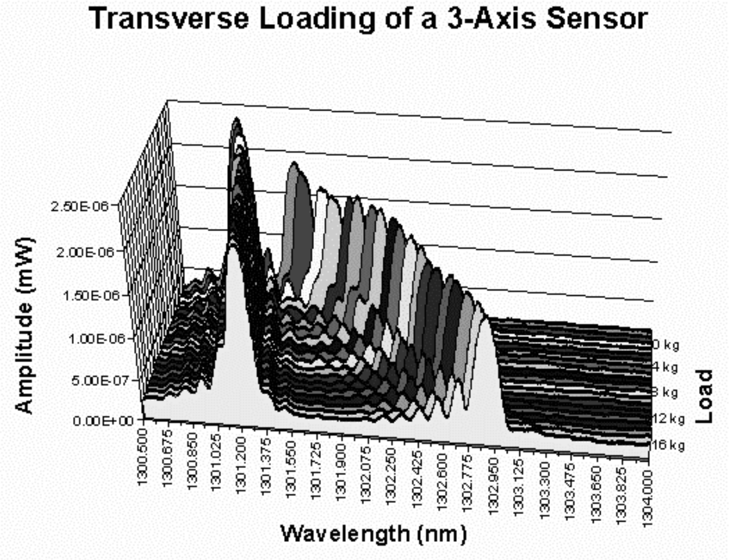


Figure 8. Sample data of the multiaxis sensor’s response to transverse strain.

The information from the four spectral peaks reflected from the multiaxis grating sensor can be used to simultaneously measure axial strain, two mutually orthogonal components of transverse strain, and temperature.

In addition to using a spectrum analyzer, a scanning etalon approach can be used to demodulate multiaxis fiber grating strain sensors. Research International is currently developing the Ferret III scanning etalon-based system for multiaxis strain sensing that is expected to be introduced commercially the second quarter of 1999.

3. SYSTEMS

Fiber etalons, gratings, and interferometers may all be configured to support distributed fiber sensing under harsh environmental conditions. Fiber etalons are usually multiplexed using time division techniques. Fiber gratings are naturally amenable to both time and wavelength division multiplexing while fiber interferometers are often multiplexed using time division multiplexing.

Figure 9 shows a configuration using fiber gratings to support a wavelength division multiplexed interferometric system where pairs of fiber gratings are used to form Michelson interferometers along a single fiber line [25,26]. This single fiber layout is optimized for measuring time varying effects such as acoustics. It is also possible to configure a fiber grating system so that each fiber grating is sensitive to a different environmental effect. Figure 10 shows how this can be done to measure corrosion, multiaxis strain, pressure, temperature and other key parameters. Figure 11 is an illustration of how this system might be used to support launch operations.

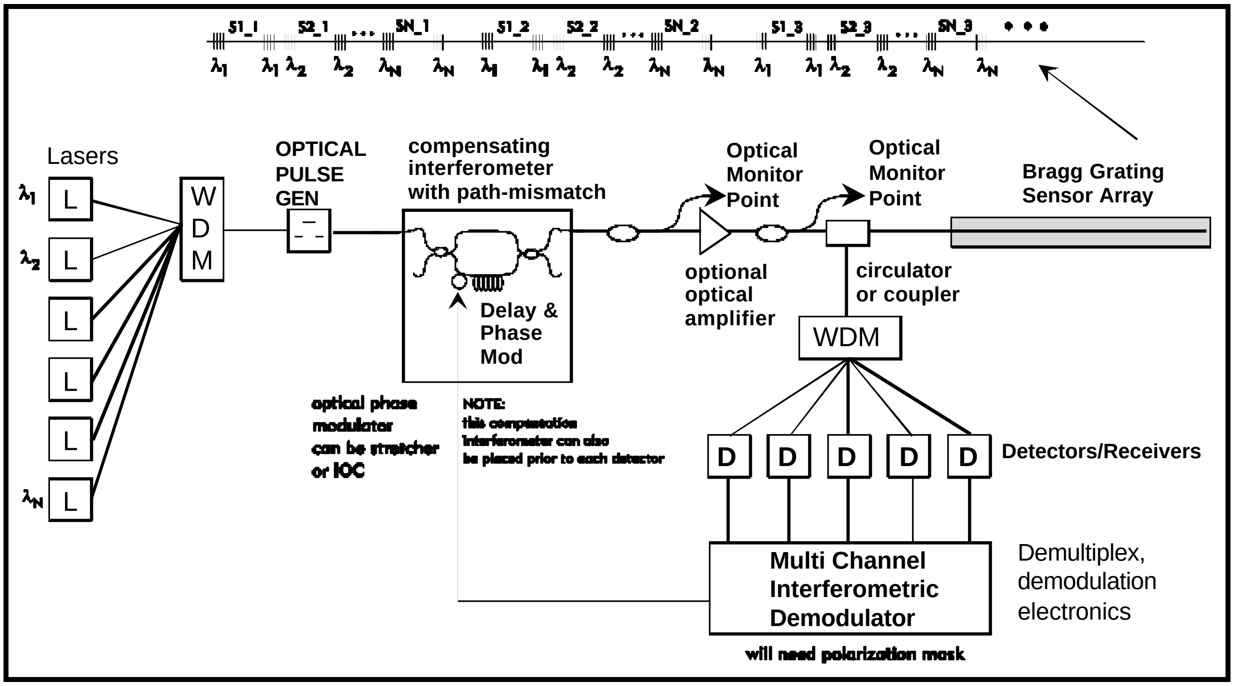


Figure 9. Bragg Grating Interferometric Sensor Array Approach using Multiple Wavelength Simultaneous Interrogation Technique

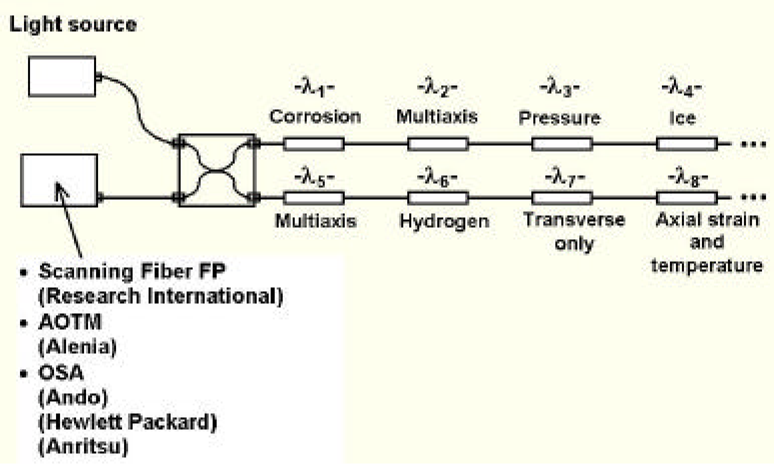


Figure 10. Multiparameter sensing system

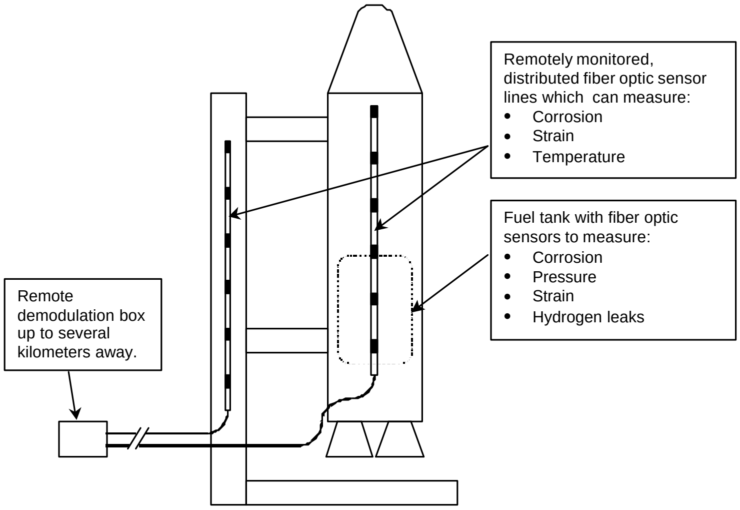


Figure 11. Distributed Sensors in Space Vehicles.

It is possible to combine both fiber gratings configured to measure time varying signals that may be acoustics or vibrations interferometerically with those configured to measure environmental effects directly such as temperature, pressure and strain by combining the two systems presented.

4. SUMMARY

Fiber optic sensors have the potential to measure a range of environmental parameters that meet the future needs of a wide variety of aerospace platforms. Some classes of fiber sensors, including fiber gratings, have the potential to be used in very harsh vibration and shock environments with temperatures at least in the range of 400 to 500 °C.

5. ACKNOWLEDGEMENTS

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