ALL-OPTICAL SHIPBOARD SENSING SYSTEM

Richard L. Lopushansky
Davidson Instruments, Inc.
P.O. Box 130100
The Woodlands, TX 77393-0100

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ABSTRACT

The U.S. Navy is developing a new class of ships called the Twenty-First Century Surface Combatant (SC-21) ships. The first class of ships in this family will be a Land Attack destroyer that has been designated the DD-21. One of the design objectives for the SC-21 ships calls for a dramatic reduction in the manning levels that can be achieved through the use of a substantial number of shipboard sensors. According to the Navy's SBIR solicitation, "These ships of the future will have an enormous number of sensors on board, perhaps as many as 250,000."

One important requirement for a shipboard sensor system with thousands of sensors is that it be immune to electromagnetic interference (EMI). To address this issue, the Navy is evaluating the potential of using fiber optic sensors in these new ships because fiber optic sensors are immune to EMI and nuclear blast effects. This paper describes the results of an effort funded under SBIR contract N00024-97-C-4148 to demonstrate the feasibility of developing a family of fiber optic sensors that are reliable, inexpensive, and suitable for use in Navy shipboard applications.

1. INTRODUCTION

Optical fibers are fine strands of glass that can transmit light over several kilometers. Fiber optic sensing systems harness light and make useful and precise measurements of force, pressure, temperature, strain, acceleration, and other parameters.

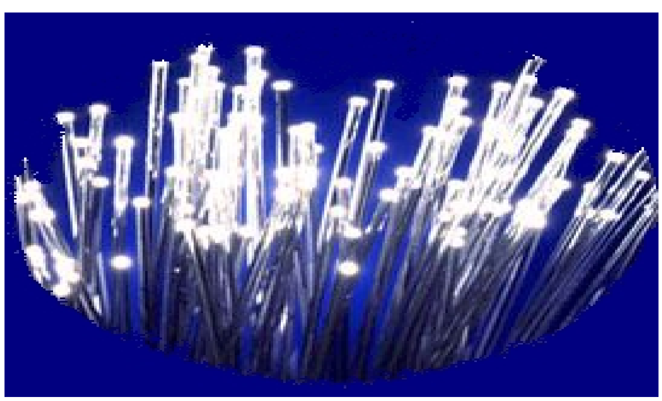

Figure 1 – Strands of Optical Fiber

A fiber optic sensing system consists of a signal processor that transmits light to a passive fiber-optic sensor along an optical fiber as illustrated in Figure 2. The sensors are integrated with mechanical transducers that are affected in some manner by changes in the environment. These changes in the environment cause predictable changes in the characteristics of the light, (i.e. intensity or spectral shift), that are reflected from the sensor back to the signal processor. The modulated light is converted into a signal that conforms to a transmission protocol that is understood by computers in the control system.

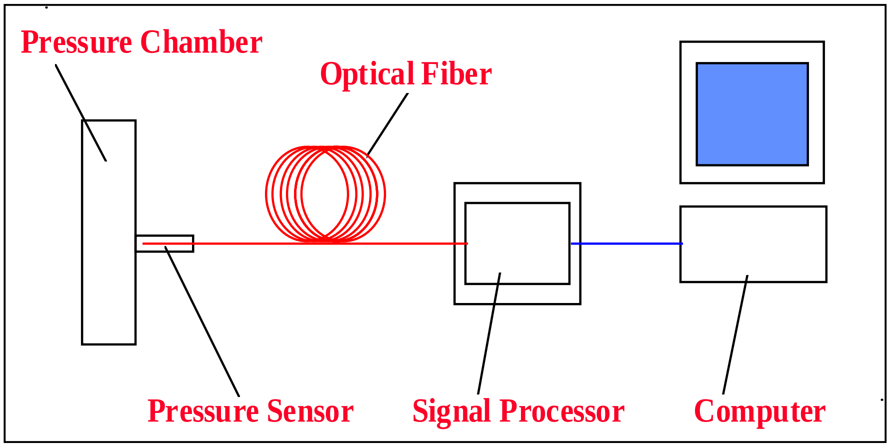

Figure 2 – Fiber Optic Sensing System

Fiber optic instrumentation offers a number of benefits when compared to conventional electronic instrumentation. The following benefits provide compelling justification for using fiber optic instrumentation in various applications:

- Immune to EMI, RFI, and nuclear blast effects
- Immune to grounding problems and lightning strikes
- Inherently safe and suitable for use in highly explosive environments
- Tolerant of high temperatures and corrosive environments
- Suitable for use in wet environments
- Lightweight

Although fiber optic sensing systems offer enormous functional advantages, the cost of the sensing systems has limited their use to very special niche applications. Fiber optic sensing systems have been simply too expensive for most applications, until now.

To illustrate the advances in the application of fiber optic technology one only needs to reflect on a statement made in a report written in 1998 by The National Research Council entitled, "Harnessing Light" that describes advances in the use of optical fiber for information technology and telecommunications. The article states, **"… optical fiber is being installed worldwide at a rate of 1,000 meters every second …".** Consider, too, that today 90% of transcontinental telephone calls are carried over fiber optic cables.

Advances in the production of optical fiber, fiber optic components, computer chips, microelectromechanical systems (MEMS), and in the development of thin film deposition technology have led us to the point where inexpensive fiber optic sensing systems are becoming a reality. **With these advances, fiber-optic instrumentation has the potential to revolutionize the instrumentation industry in the next ten years the same way fiber optic technology has revolutionized the communications industry over the past ten years.**

2. TECHNICAL DISCUSSION

The family of fiber optic sensors being developed for the Navy must survive in a very hostile shipboard environment. Davidson has selected broadband interferometric technology for this application because it offers a number of distinct advantages when compared to other fiber optic sensing technologies. The following features of Davidson's fiber optic sensing system have been demonstrated to the Navy in a prototype system that measured temperature, strain, and pressure:

Large Dynamic Range -- The most important characteristic of Davidson's sensing system is that it has a very large dynamic range, i.e. the system can resolve 1 part in 15,000. This large dynamic range allows the system to resolve less than 0.01% of the full-scale range of a sensor. This will allow very precise measurements to be made when necessary and will allow a universal sensor to be used for most other applications. Universal sensors will minimize the installation, logistics, and life cycle costs of the sensing system.

Multiplexing Capability -- A second important characteristic of the system is the whole family of discrete measurement sensors can be multiplexed with the same signal processor because all of the sensors in the system are based on the same Fabry-Perot sensor concept. Further, because the Fabry-Perot sensor is so fundamentally simple, it is easy to make thousands of precision sensor caps using microelectromechanical systems (MEMS) manufacturing technology. Multiplexing a variety of sensors with a single signal processor is another way that the Davidson system shows promise for low-cost installation.

Insensitivity to Light Losses -- A third important characteristic of the system is its tolerance for power level fluctuations and light losses due to transmission and bending. Intensity-based fiber optic sensing systems need complex compensation schemes to overcome this unfortunate characteristic of optical fiber transmission.

Absolute and Static Measurements -- A fourth important characteristic of the system is that unlike interferometric systems that make use of spectroscopy and require a change from a reference condition, Davidson's innovative system is able to make absolute and static measurements. These characteristics contribute to the ease of multiplexing and to the possibility for long term stability of the sensing system.

Long Transmission Range **–** Preliminary evaluations of the prototype system indicate that a single sensor can operate with a resolution of 0.01% with a transmission range of 5 km.

The intensity of the light transmitted from each Fabry-Perot sensor is modulated according to the interferometric model shown in Figure 3 where d is the cavity length and F is a constant dependent on reflectivity:

$$I(\lambda, d) = \frac{F \sin^2\left(\frac{2\Pi d}{\lambda}\right)}{1 + F \sin^2\left(\frac{2\Pi d}{\lambda}\right)}$$

Figure 3 - Interferometric Model

Davidson uses a broadband light source with a broad spectrum that ranges from 600 to 1000 nm. For any given Fabry-Perot cavity length, the conditioned light that is transmitted to the signal processor has peak intensities at approximately twenty-four discrete wavelengths, $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \ldots \lambda_{24}$. as illustrated in Figure 4.

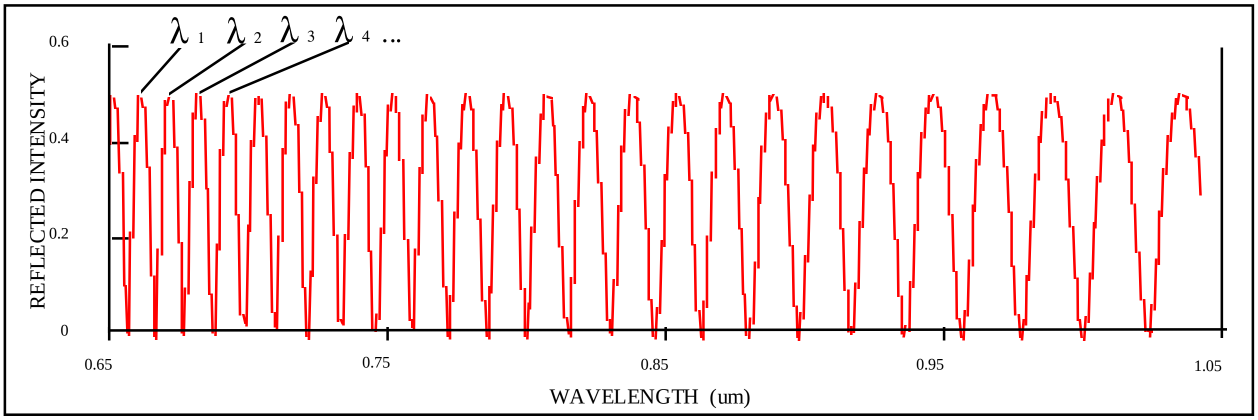

Figure 4 – Intensity of Conditioned Light reflected from the Fabry-Perot Interferometer

The conditioned light is transmitted along the optical fiber to the signal processor where the length of the Fabry-Perot cavity in the sensor is determined by the destructive interference at a second interferometer. Figure 5 illustrates the destructive interference between the two interferometers with different cavity lengths.

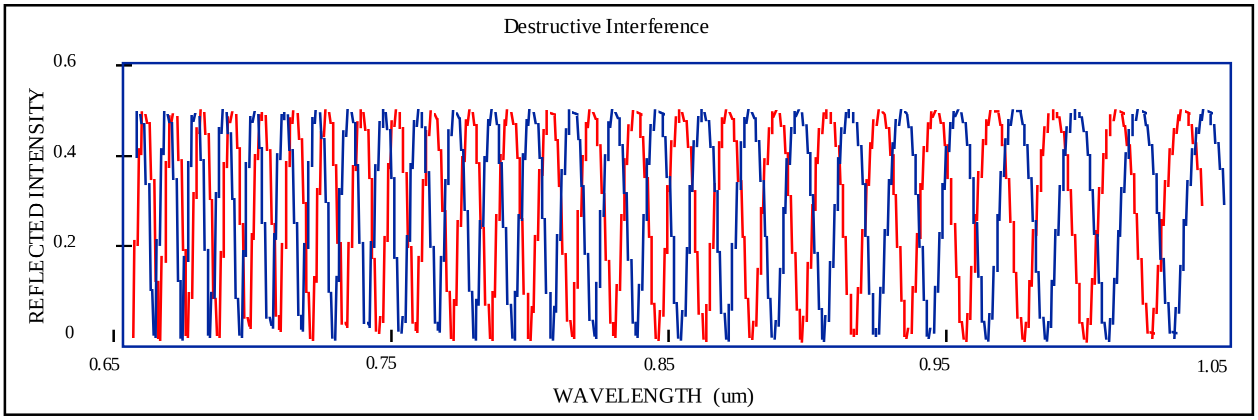

Figure 5 – Destructive Interference between the Interferometers

When the cavity length in each interferometer is matched, there is no destructive interference and maximum light intensity is projected from the second interferometer to the signal processor.

One important feature of Davidson's family of sensors is that any sensor can mate with any signal processor. This requires the whole family of Fabry-Perot sensors to be designed with common features. To achieve maximum resolution, each temperature, pressure, and strain sensor/transducer must be designed so the transducer has a maximum movement or transduction of 14μm over the specified operating range. Each sensor must also be designed to survive the expected worst case conditions, e.g. overpressure. Finally each sensor/transducer must be designed of materials that will survive the environment and fit within any space constraints that may be imposed. A typical Fabry-Perot pressure sensor is illustrated in Figure 6.

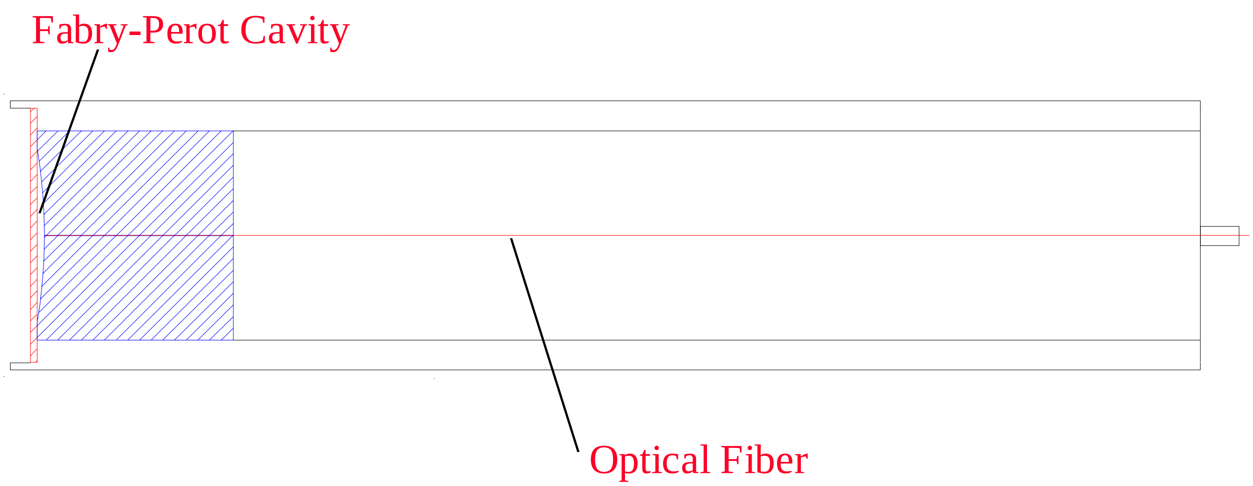

Figure 6 – Fabry-Perot Fiber Optic Sensor

Fabry-Perot pressure sensors can be manufactured using microelectromechanical systems (MEMS) manufacturing technology. The miniature MEMS pressure sensor caps will be about 2 mm square. The MEMS pressure sensor caps will be manufactured by bonding a silicon membrane directly to a micromachined silicon substrate as illustrated in Figure 7.

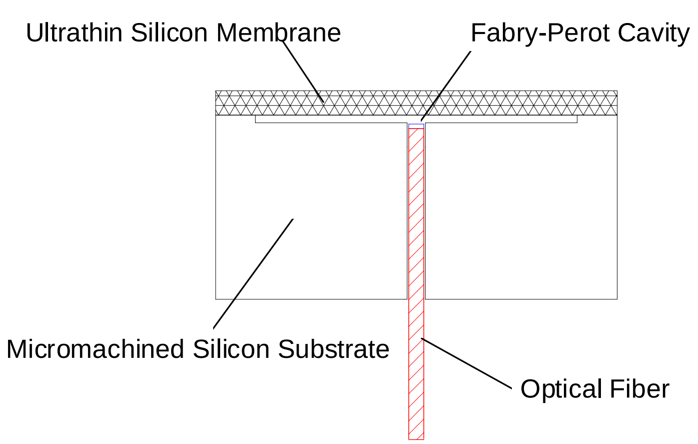

Figure 7 -- Davidson's MEMS Fiber-Optic Pressure Sensor

The sensor cap is 2000μm wide and 1000μm thick. The Fabry-Perot cavity between the membrane and optical fiber is 16μm deep. The MEMS pressure sensor diaphragms will be designed to deflect 2 microns at full pressure. The sensor caps will be fabricated in a basic four-step process:

1. Laser micromachining the substrate wafer
2. Fusion bonding an ultrathin membrane to the substrate
3. Depositing an infrared reflective coating
4. Dicing the individual sensor caps.

3. APPLICATIONS

The sensors being developed by Davidson for the Navy will have application in a variety of aerospace, military, and industrial systems where any of the following conditions apply:

- Immune to EMI, RFI, and nuclear blast effects
- Immune to grounding problems and lightning strikes
- Inherently safe and suitable for use in highly explosive environments
- Tolerant of high temperatures and corrosive environments
- Suitable for use in wet environments
- Lightweight

Davidson is committed to the development of a family of inexpensive fiber optic instruments designed for applications in aerospace, military, power generation, and oil and gas processing.

Navy – Immunity to electromagnetic interference is the driving force that is moving the Navy to the use of fiber optic sensors and the Navy is planning to use such sensors in the SC-21 family of ships illustrated in Figure 8.

Figure 8 – Artist's Concept of the SC-21 Family of Ships

In addition to the SC-21 family of ships, the Navy is exploring the use of fiber optic sensors on the Smart Ship Project, the CVX Carrier Project, the Arsenal Ship Project, and the LPD 17 Amphibious Assault Ship. In addition to shipboard applications, the Navy is also exploring the use of fiber optic sensors for use in towed arrays to measure depth and heading while at sea.

Aerospace - NASA and the military need "fiber optic and integrated-optic sensors and control systems" to achieve optimum engine performance and for advanced aircraft control systems. The aerospace industry is motivated to use fiber optic sensors because they are lightweight, immune to EMI, and tolerant of high temperatures. An excellent example of NASA's work in this field is the Fiber Optic Control System Integration (FOCSI) Program, illustrated in Figure 9, that formed the foundation for NASA's fly by light (FBL) programs.

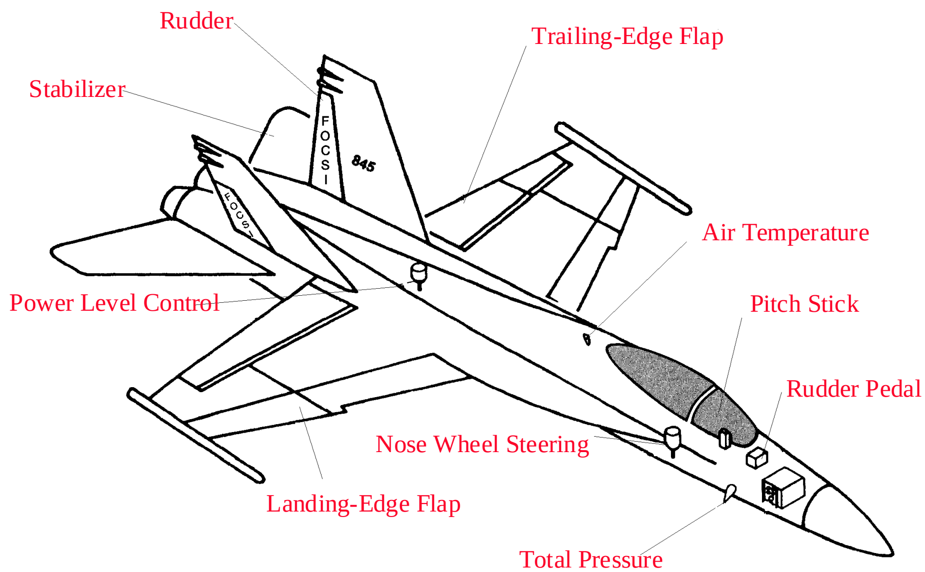

Figure 9 – FOCSI Flight System Configuration

Process Industries - Worldwide, the oil and gas industry spends five-hundred million dollars ($500,000,000) per year on temperature, pressure, and differential pressure transmitters of the type illustrated in Figure 10. Throughout industry, and especially the oil and gas industry, there is significant market potential for a family of "inherently safe" fiber optic based instruments that have low installed cost.

Fiber optic instruments will have immediate application in explosion hazard areas of refineries and chemical plants because the total installed cost will be less. The cost of installing and making a convention transmitter and the related wiring explosion proof is high while the cost of installation of an intrinsically safe fiber optic sensor will be low.

In addition to the inherently safe nature of fiber optics, other features that make fiber optics attractive for use in the process industries include the immunity to EMI, RFI, grounding problems, and lightning strikes. Industry will also find that temperature tolerance and corrosion resistance of the fiber optics will allow fiber optic sensors to be used for applications where conventional sensors simply cannot survive.

Figure 10 – Conventional Explosion-Proof Transmitter – Rosemount Model 1151

In addition to general use wherever pressure, differential pressure, temperature, acceleration, or strain are required for monitoring industrial processes, the use of fiber optic sensors are being explored for a variety of highly specialized industrial applications including the following:

- Monitoring of downhole pressures and temperatures in oil and gas exploration and production.
- Monitoring of subsea pipelines to detect the buildup of hydrates that could reduce or restrict flow.
- Monitoring the combustion performance in engines.
- Performing on-line diagnostics of reciprocating compressors.

4. CONCLUSION

The basic architecture of Davidson's fiber optic sensing system provides a clear path for the development of an inexpensive, robust, high-performance, all-optical sensing system. High-performance fiber optic sensing systems will find immediate use in a variety of military, aerospace, industrial, and commercial applications.

Davidson will leverage the Navy development funding by developing derivatives of the fiber optic sensors for aerospace and industrial use. The Navy will derive cost and performance benefits from high volume use of the fiber optic sensors in aerospace and industrial applications.