INTRODUCTION

The Fiber Optic Sensor System (FOSS) Program is a Navy research effort for developing a generic sensor technology that has a wide variety of applications in Navy weapon systems. Fiber optic sensors can detect a wide range of energy fields by exploiting their effects on the optical signal in a fiber optic waveguide. The transduction mechanisms employed by these sensors result in either phase or intensity changes in the light propagating in the core of the fiber. Fiber optic sensors can detect changes in temperature; electrical, magnetic and acoustic energy fields; and linear or rotational accelerations. Fiber optic sensors offer several significant advantages over conventional sensors including inherently high sensitivity, intrinsic safety in hazardous environments, immunity to electromagnetic interference, geometric flexibility and light weight. Another advantage is the ability to optically multiplex fiber optic sensors which offers the potential to reduce the cost of systems that require large numbers of remotely located sensors.

This paper provides an overview of fiber optic sensor technology and various multiplexing techniques for distributed fiber optic sensors, and then discusses the application of this technology for an intruder detection.

FIBER OPTIC SENSOR SYSTEM OVERVIEW

The structure of a typical optical fiber is illustrated in Figure 1. The central portion, or core, is made of a higher refractive index glass than the surrounding cladding glass. The resultant optical fiber waveguide is covered by a buffer material to protect and preserve its pristine state. An outer jacket material can then be designed to be sensitive to a particular energy field.

Light, injected into the core of an ideal fiber, will be confined to the core through the length of the fiber (Figure 2). However, if light in the core intersects the core-cladding boundary at a grazing angle greater than the critical angle, it is scattered into the cladding and ultimately lost. The core-cladding boundary is simply a line of demarcation between the core glass, which has one index of refraction (n1), and the cladding glass, which has another index of refraction (n2). The difference between n1 and n2 may be as little as one-and-one-half percent.

Three basic types of fiber are illustrated at the bottom of Figure 2: step-index multimode in which the core and cladding have constant, but slightly different, indices of refraction; graded-index multimode in which the index of refraction of the core decreases parabolically with the radial distance r, to allow the different spatial modes to propagate with nearly the same velocity; and typical single-mode step-index with a core diameter of only a few microns.

Phase-modulated (i.e., interferometric) sensors are by far the most sensitive of those being developed by the FOSS Program. For discussion purposes, an acoustic sensor will be used to explain the operation of the Mach-Zehnder interferometer shown in Figure 3. Light from a single-mode laser diode is divided between the arms of the interferometer by a fiber optic coupler. Acoustic pressure variations on the sensing fiber produce changes in the optical path length relative to the reference fiber. The resulting optical phase shift is converted to an intensity modulated signal at the output of the second fiber optic coupler which recombines the light from the two arms. A photodetector converts this signal into an electrical output proportional to the acoustic field excitation.

The sensing fibers can either be jacketed by specific coating materials or wound on specialized mandrels to increase the scale factor of the sensor (i.e., to enhance its response to the desired energy field). By proper selection of the jacketing or mandrel material, sensors can be made uniquely responsive to one particular field and insensitive to all other fields. Figure 4 shows the coatings used for some selected fiber optic transduction mechanisms with coated-fiber sensors. An acoustic sensor has a compliant elastomer coating that is responsive to varying acoustic pressure and amplifies the effect of this strain on the fiber while simultaneously providing adequate isolation from thermal effects. Magnetic sensors would use some type of magnetostrictive metal while an electric field sensor would typically have a PVDF coating.

There are also sensing techniques for modulating the intensity of the optical beam. Intensity-modulated sensors use off-the-shelf multimode components that can transmit high optical power from commercially available LED's. These sensors have many advantages: they are very simple and reliable; have no moving parts; and should be low-cost since they use multimode optical fiber, light sources, and photodetectors. Figure 5 shows some examples of intensity-modulated sensors.

The FOSS Program is exploiting the unique advantages of both phase- and intensity-modulated sensors. Phase-modulated sensors offer high sensitivity and geometric versatility but are still using state-of-the-art technology. Intensity-modulated sensors, on the other hand, use available technology and simple construction techniques, and are thus relatively low in cost. Very-high-performance, high-sensitivity devices will probably require interferometric sensors. As designs become standardized however, the "sophisticated" interferometric technology will supplant the intensity-modulated sensors.

Fiber-Optic Sensor Multiplexing Techniques

An additional advantage of fiber optic sensors is the ease of multiplexing a large number of sensors on a few number of fibers. These
Multiplexing techniques can be divided into two broad categories: distributed sensors and multiplexed sensor networks. In case of distributed sensor systems, these techniques can be further divided into "intrinsic-distributed" sensing where a single fiber is utilized to form an extended sensor and "quasi-distributed" sensing which uses discrete fiber or non-fiber sensor elements arranged in a linear array. Intrinsic-distributed sensors utilize either the basic loss or scattering mechanisms in a single fiber which forms an extended sensor. Interrogation of this extended sensor using an optical time domain reflectometer (OTDR) permits the spatial variation to be resolved within a few centimeters along the fiber length (Figure 6). By enhancing the sensitivity of the fiber to specific measurands (stress, temperature, pressure, etc.) at specified locations, a change in the slope of the detected backscatter signal versus time can be measured. The location can be determined by the time delay, and the magnitude of the parameter being measured is determined by the change in the slope of the backscattered signal. The returned optical power can depend on various parameters other than optical loss. These include scattering coefficient, fluorescence, stimulated emission, and polarization properties of the light. Figure 7 shows an example of an intrinsic-distributed sensor using mode-mode coupling. The simplest quasi-distributed sensor system is shown in Figure 8, where discrete sensing elements are spliced into a long fiber at certain intervals to provide localized variations in the loss, backscattering, fluorescence, etc. These elements can either be fiber optic or conventional sensors which vary in transmittance or reflectance in response to the parameter being measured. Since the discrete element can be tailored to measure a specific energy field, multisensor correlation is possible. The major limitation of distributed sensors is the fact that attenuation is cumulative; the light level at the most distant sensor depends on the sum of the losses at each sensor along the fiber. This limits the number of sensors which can be used in a practical system.

For large arrays of interferometric sensors, a multiplexing approach must be used. Figure 9 shows the basic configuration for interferometric fiber optic sensor (IFOS) arrays. Two basic requirements dictate the design of IFOS systems: the approach must allow for the demodulation of the interferometric signals and it must use a multiplexing and demultiplexing interrogation system to minimize the number of fibers between the passive sensor array and the electro-optics module. A number of interrogation techniques are possible including time- and frequency-division multiplexing.

One architecture for a time-division multiplexed IFOS array is the tapped serial array (TSA) shown in Figure 10. Pulsed light from the laser source is launched into a long fiber which forms a series of sensor elements, $S_i$. A small fraction of the optical power is tapped off at each sensor. If the width of the input pulse is less than the optical propagation delay through each sensor, the output obtained from the array consists of a series of pulses which are separated in time. When this pulse train is applied to the compensating interferometer, it coherently mixes the pulses obtained from consecutive sensors and provides an output pulse carrying the interferometric information of interest. Time-division demultiplexing of this output pulse train can then be used to address each sensor. Other time-division multiplexing techniques are shown in Figures 11.4

The generic approach to frequency-division multiplexing (FDM) relies on an emission-frequency modulated laser source to interrogate a passive array of slightly unbalanced interferometric sensors. When this light interrogates the sensor, the path imbalance creates a large amplitude optical phase shift in the interferometer outside the signal band. This large amplitude signal carries as sidebands the signal of interest. Figure 12 shows the architecture used to implement this scheme for a four-sensor array. Two lasers, each modulated at a different carrier frequency, interrogate two sensors. The four sensor outputs are then combined in such a way that each output fiber carries only one signal from each laser. The output signals are then separated by the frequency demultiplexer and demodulated to obtain the signal of interest. As shown in the lower half of Figure 12, this network can be expanded to $N \times N$ matrix. The size of the matrix is limited by the optical power at the detector required to achieve the desired sensitivity.

Fiber Optic Sensors for Intruder Detection

Fiber optic sensor technology is ideally suited for use in hostile environments where area coverage and multisensor correlation are critical. The detection of intruders in a protected area is one such application!

The revolutionary potential for fiber optic sensors for intruder detection lies in its demonstrated ability to multiplex numerous sensors capable of detecting different energy fields onto a single optical fiber to be processed at a console removed from the protected area (Figure 13). Incorporating cross-correlation techniques into the processing stage to look for known intruder characteristics offers the ability to significantly reduce false alarms. For example, by using a novel non-linear displacement-to-strain transduction mechanism for monitoring DC measurands, a single interferometer can be used to monitor a number of sensors. In this configuration (Figure 14), a linear strain in the primary sensing element is transposed non-linearly into axial fiber strain. A displacement dither, $\omega$, is superimposed on the transducer. The measurement frequency is then upshifted from D.C. to the dither frequency. If the dither frequency is moderately high (>100 Hz), low frequency perturbations of the interferometer caused by environmental drifts do not affect the output signal. By using different dither frequencies, a number of sensors can be multiplexed on a single interferometer. Intruder emanations that might be sensed using this technique include acoustic, seismic, thermal and motion.

Intrinsic-distributed sensors are particularly attractive for use in applications where monitoring a single measurand is required at a large number of locations. Examples of this include temperature monitoring in fire or intrusion detection systems. Quasi-distributed sensors that measure different parameters can be used to correlate a specific event thus reducing the false alarm rate. This type of system is particularly attractive for intruder detection applications such as perimeter defense systems. "Spoof-proofing" might be possible by the intrinsic properties of fiber optic technology such as
as EMI immunity, no external radiation, "DC-to-light" operation, as well as the multisensor correlation discussed above.

Summary

This paper has provided an overview of fiber optic sensors and optical multiplexing techniques. Fiber optic sensors are sensitive, lightweight, lend themselves to multiplexing and are suitable for use in harsh environments. Sensor development results have clearly shown the potential of this exciting new technology for a wide range of applications, including intruder detection.

References


BASIC PHENOMENOLOGY
AMPLITUDE MODULATION

Figure 5

Received optical power, $I_r$ a Scattering coefficient (elastic/nonelastic)
- Fiber attenuation
- Fluorescence
- Stimulated emission

Figure 6

Multiplexing of Interferometric Fiber Sensors: Conceptual Diagram

Figure 7

Figure 8

Figure 9

Figure 10