Invited Paper

Fiber Optic Sensing Technology: Emerging Markets and Trends

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ABSTRACT

Recent technical advances in fiber optic sensor technology have brought fiber sensors into the mainstream. Using a wide variety of sensing elements, and interrogation techniques, these devices are finding applications in fields from power line management to homeland security. A variety of fiber sensor technologies, applications, and markets are discussed.

Keywords: Fiber, Optic, Sensor, Market, Bragg, Brillouin, Raman, Interferometer

1. INTRODUCTION

Fiber optic (FO) sensors have emerged from their historic small niche market applications into a complex and growing market. Leveraging developments from telecommunications optics, coupled with falling prices of laser diodes and optical fiber, has led to cost effective fiber optic sensor solutions for a variety of novel applications. Applications range from intrusion protection networks and pressure sensing and temperature monitoring to process-control devices for industrial environments. Nonetheless, fiber optic sensors are well positioned to provide much needed monitoring for a variety of industries.

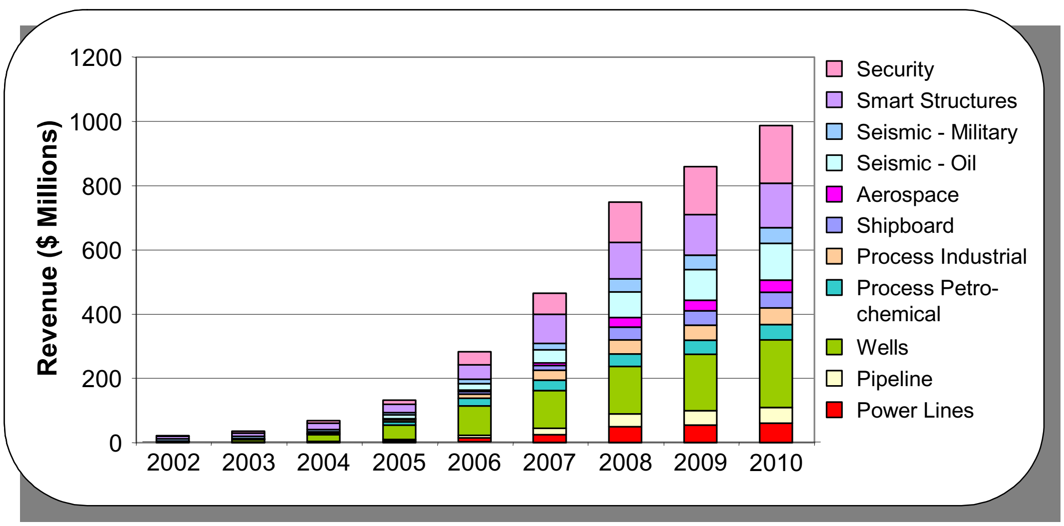

Figure 1: Fiber Optic Sensor Revenue Forecast, 2002-2010, sources: Light Wave Venture, OIDA

The distributed fiber optic (DFO) sensor market is seeing very strong demand from both commercial and government sectors. The distributed sensor market grew 92% in 2005, achieving revenue of ~$130 million (Figure 1). This relatively new market is in the early stages of adoption, with phenomenal performance expected to continuing through 2008. Revenue will level beginning in 2007-2008, with year-over-year growth “down” to ~63%. The revenue for 2010 is on track to reach $980 million.

Applications for DFO sensors are diverse, with the capability to measure various changes including temperature, strain, vibration, chemical and biological agents, and pressure both along the fiber as well as at various measurement points

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along the fiber. The measurements are dynamic and can be quite rapid. DFO sensors are increasingly installed along pipelines to monitor for leaks, pressure and positional changes, are deployed along power lines and structures to detect breakages and strain, and can be an integral part of buildings to provide information on structural health. Similarly, they can be used to monitor the integrity of dams, bridges, roads, and tunnels. These sensors also offer various perimeter security solutions, where they can be either permanently installed or deployed as needed in the field. Shipboard sensing for leak detection and improved security are other applications with healthy interest, as are new concepts for harbor security as fiber optic sensors can be deployed underwater.

The key emerging application markets for distributed fiber optic sensors are oil wells, security, smart structures, and seismic detection (oil industry). These four application areas together will contribute an average of 67% to the total annual revenue through 2010. The balance of the revenue will come from the remaining segments, all of which are also expected to see substantial growth.

2. DISTRIBUTED FIBER OPTIC SENSORS VS. POINT SENSORS

The unique characteristics of fiber optic sensors lend themselves to a wide range of networked applications, many of which are inappropriate for electronics-based sensors. FO sensors can be deployed as an integrated sensor network, capable of dynamically sensing minute changes at multiple points from a great distance, providing unique monitoring opportunities.

Fiber optic sensors also differ from standalone sensors that are networked together. Although FO sensors can be used as individual monitor points, distributed fiber optic sensors can use the entire fiber as a source of information. Also differing from image sensors, deployment of the sensor <u>is</u> the network, capable of monitoring and communicating changes along the entire fiber or fiber group. This makes fiber optic sensors ideal for monitoring building structural health for example, or buried as a perimeter ground sensing network.

This paper focuses on distributed (or quasi-distributed) fiber optic sensors as opposed to point photonic or image sensors. Point sensors often function as single point indicators and are commonly used in medical, industrial, and gyro applications. Point sensors made up about half the total fiber sensor revenue in 2006 but will shrink to about 25% of total revenue by 2010.

3. DISTRIBUTED FIBER OPTIC SENSORS OVERVIEW

Fiber optic sensors have a number of valuable attributes, including small size, light weight, and the ability to be deployed in harsh environments regardless of weather, temperature, or pressure. Fiber optic sensors are also passive; they are not electrically powered which makes them safe even for use around explosives or flammable environments. FO sensors are inherently immune to electro-magnetic interference (EMI) and provide high sensitivity regardless of operating conditions.

When deployed as a sensor network, the fiber operates as both a wide bandwidth sensor network as well as the data link, eliminating the need for additional network systems. Additionally, FO sensor networks can function in a distributed and/or multiplexed operational mode. Their remote sensing capabilities can be further extended through the use of wireless networks.

Sensors can be broadly divided into those that use some form of interferometric interrogation technique and those which depend on other types of detection and measurement. The interferometric technique is by far the larger group and can be further divided into several different types or methods, as shown in Figure 2. The interferometric technique is favored owing to extremely high sensitivity to changes to the media (fiber) so most sensors depend on changes to the fiber or cladding, or changes to quasi-distributed elements like Bragg gratings along the fiber.

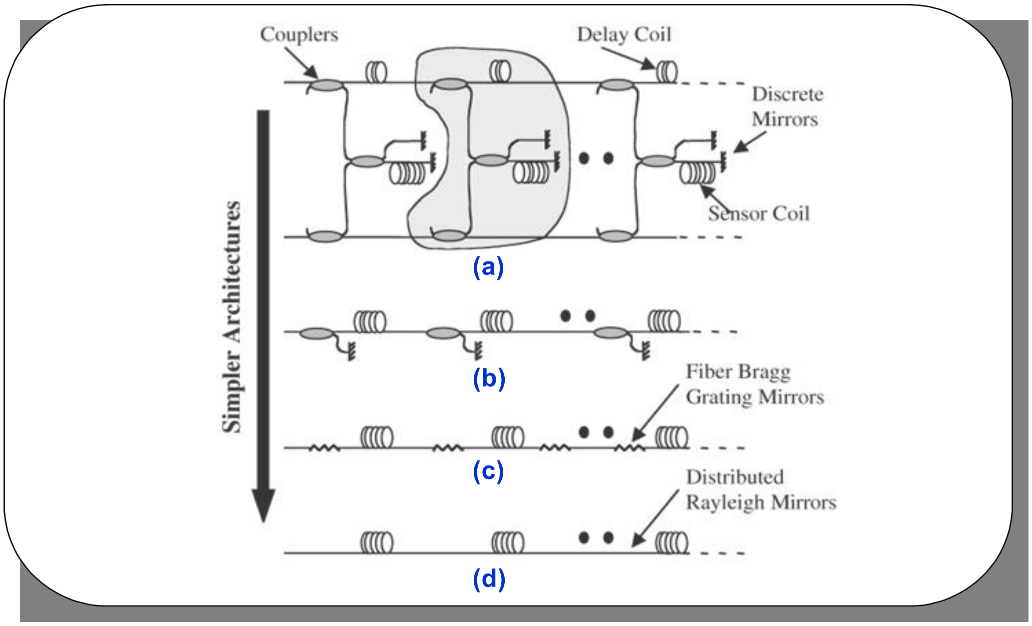

Figure 2 - Interferometric Fiber Optic Distributed Sensor Architectures (a-d), source: NRL–Naval Research Laboratory

Various distributed fiber optic sensor schemes are used in wide area surveillance, including intrusion characterization (vibration signature). Some, such as Raman scattering fiber, are useful for continuous temperature monitoring, while Brillouin scattering sensors can be used for temperature and strain sensing. Interferometric sensors may be deployed over long distances. Bragg gratings can provide hundreds of sense points along the fiber to detect changes in pressure and strain. The environment, the installation requirements, and the changes to be monitored signals help determine the type of fiber optic sensor selected. Typical sensor types and common applications are shown in Table 1.

Table 1: Fiber Optic Sensors and Typical Applications

Technology	Parameters Monitored	Application
Speckle Pattern / Modal Interference	• Pressure • Vibration	Wide Area Surveillance, traffic monitoring
Microbending / Evanescent Wave	• Pressure • Vibration • Chemical	Wide Area Surveillance, process monitoring
Interferometric (including Rayleigh scattering)	• Pressure • Vibration	Wide Area Surveillance, hydrophonic, high resolution applications.
Bragg Grating	• Strain • Temperature	Smart Structures, pipeline, powerlines.
DTS (Raman Scattering)	• Temperature	Surveillance, Smart Structures
DTSS (Brillouin Scattering)	• Strain • Temperature	Surveillance, Smart Structures, oil well
Free Space Absorption	• Chemical	Surveillance, process monitoring
Biophotonic Fluorescence Absorption	• Bio-chemical	Surveillance, process monitoring
Sources: Light Wave Venture, OIDA		

The basic principle of fiber optic sensors is that a change applied to the fiber causes a variation in the reflected light. Light sources can be pulsed, CW, or swept wavelength lasers. The type of fiber sensor will determine how environmental changes are manifested. Most sensors work on some form of interferometric effect, either between modes (speckle), Bragg reflection, scattering, or fiber interferometers. In some sensors, the changes occur as a result of absorption by the cladding of target agents changing the effective index of the fiber.

3.1 Interferometric Distributed Sensors

Interferometric fiber optic sensors use a variety of distributed architectures and use different techniques to detect extremely small phase changes in light caused by the length or the modification of the path that the light has traversed; longer paths take more time. Bragg gratings are one type of interferometric optic sensor. A more complicated system can also be accomplished using optical splicing to insert couplers, mirrors, and delay coils (Figure 2a). Fewer components can also be used (Figure 2b), but some splicing is still required. These spliced architectures require a great deal of assembly which impacts the total cost of the network. In comparison, fiber Bragg gratings are much simpler to manufacture and deploy. Alternatively, detection of Rayleigh scattering within a fiber allows any point of the fiber to act as a sensor, and lends itself to dynamic applications as well.

Although the Rayleigh backscattered signal can be measured for amplitude variations, examining the phase of the signal provides information of the path length variation. Extracting the Rayleigh scattering from the background signal, Figure 3, then examining the phase shifts of the very high frequency signal translates to extremely fine resolution on the order of picometers.

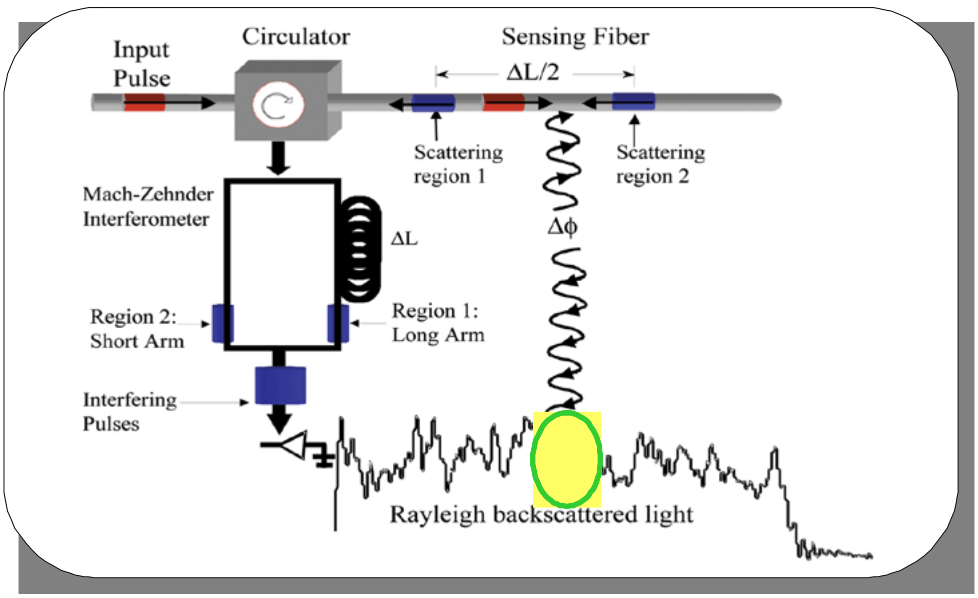

Figure 3: Rayleigh Scattered Signal Detection, source: NRL–Naval Research Laboratory

Rayleigh scattered fiber optic sensor arrays are very high accuracy vibration and strain sensors. Demonstrated over several kilometers, 10km and 20km systems appear feasible. The fiber for a Rayleigh scattered system can also have specialized coatings applied to the fiber to increase the coupling from a particular location(s), providing a much less expensive fiber cable than a fiber with multiple Bragg grating. The cost is in the analysis system itself, making this fiber optic sensor system moderate to high in price. However, it is a highly sensitive system offering incredible resolution, with intrusion signature capability, that can be deployed for harbor hydrophone security (Figure 4) as well as for seismic and oil well applications. The disadvantage is that in amplifying the signal to obtain the Rayleigh scattered signal, noise is amplified as well. Distinguishing the signal depends in part on the background noise floor.

3.2 Speckle Pattern Modal Interference

Pressure or vibration applied to multimode fiber changes the mode profile of the carried light resulting in a variation in “speckle” to appear at the output. Speckle pattern modal interference is very sensitive, with various changes causing specific patterns which enable pattern recognition detection.

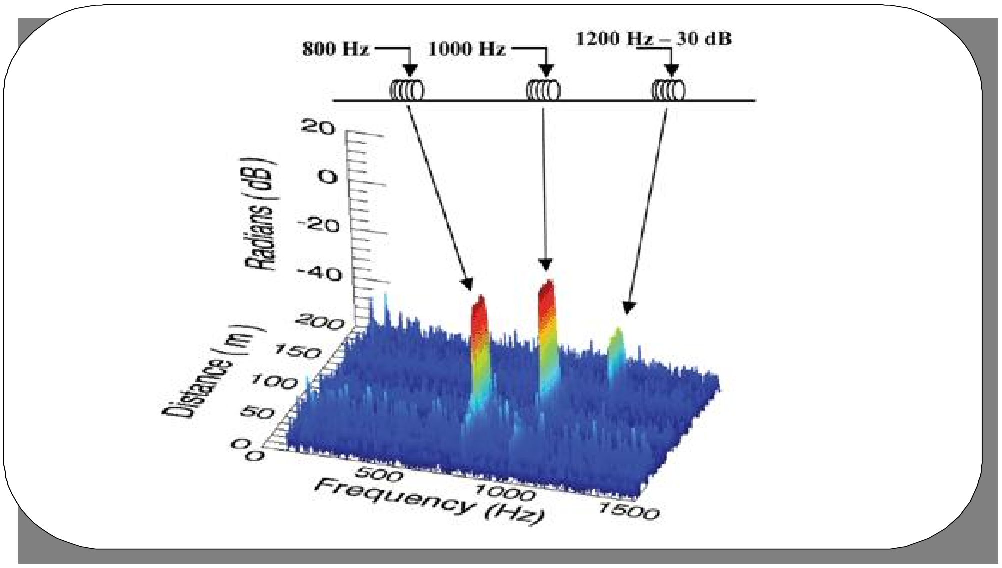

Figure 4: Rayleigh Interferometric Fiber Optic Distributed Sensor used for Hydrophonic Applications, source: NRL

Modal interference fiber sensor systems can be installed for a variety of perimeter protection applications. They can be buried, installed along a fence (including gates), under the capstones of a wall, or on a roof. They function as a very sensitive alarm sensor, minimizing false alarms from events such as wind and animals through digital signature recognition algorithms. They provide for continuous sensing along the fiber and are insensitive to weather and the environment. The maximum zone length is typically around 5km (~3miles). Modal interference fiber sensor systems offer high sensitivity coupled with low cost.

The disadvantages of these systems depend primarily on the sophistication of the signature detection algorithm, but in all systems, simultaneous events decrease sensitivity and modal interference fiber sensor systems offer limited distance coverage. They are good at detecting pressure changes, but cannot sense chemical or bio-agents.

3.3 Bragg Grating Sensor Arrays

Fiber optic sensors can also operate as an array of discrete sense points, where the fiber itself is modified to create multiple sensing locations. One technique for creating multiple sense points along a fiber is to create multiple Bragg gratings, Figure 5 below.

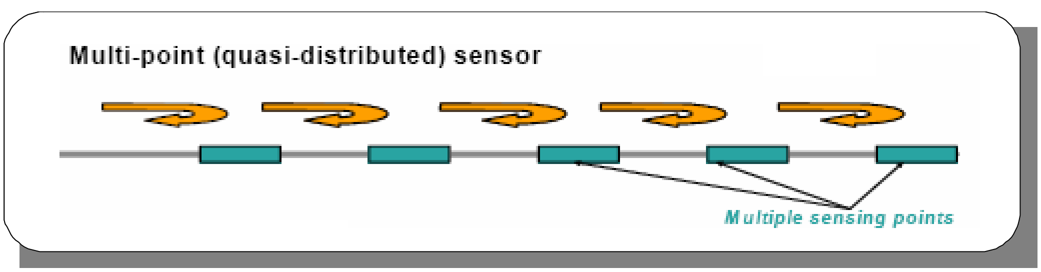

Figure 5: Multi-Point Fiber Optic Sensor Array, sources: MCH Engineering

Multiple Bragg gratings can be created along a single-mode fiber so that each point responds to different specific wavelength. When a Bragg grating exists in an optical fiber, it reflects a very narrow bandwidth of light at a specific wavelength within the transmission spectrum. As a result, fiber Bragg gratings (FBGs) can be created for multiple wavelengths at multiple locations within a single fiber.

Each Bragg grating along the cable becomes an individual sensor point and operates at a unique wavelength. The light source for the fiber is a tunable laser that continuously sweeps through the operating wavelength range(s). A broadband receiver is used for detection, with changes from an individual wavelength correlating to a change at that sense point location. FBGs can be arrayed serially along the fiber, in parallel fibers after a splitter, or some combination of serial and parallel.

Bragg grating sensors are sensitive to temperature, pressure, and strain. In a fiber array, hundreds of Bragg grating sensing points can be supported and interrogated, leveraging WDM technologies and architectures. Discrete points along the fiber can be sensed, even over lengths up to 25km. These systems can offer very high resolution and can be used for monitoring functions based on strain or temperature characterization.

Bragg grating sensing systems are typically more expensive than multimode sensing systems. They are often used in civil structures and increasingly in oil wells. They can be used as a distributed temperature sensing system, but when used for strain sensing, their temperature sensitivity can make it more difficult to recognize or categorize events. Most applications have been for static monitoring; it is possible, however, to accommodate dynamic monitoring.

One application of Bragg grating fiber sensor arrays is in pipeline monitoring. Although one array can cover approximately 25km, multiple arrays can be used to cover hundreds of kilometers. For very remote sites, data can be transferred via solar power wireless transmitters.

3.4 Raman and Brillouin Scattering

In addition to Rayleigh scattering, there are also Raman and Brillouin scattering. Raman scattering can be used for distributed temperature sensing (DTS), where a change in amplitude of the scattered peaks indicates a change in temperature. Brillouin scattering can be used for distributed temperature and strain sensors (DTSS), with phase shifts in the Brillouin peaks indicating temperature shifts. Both Raman and Brillouin can be used for continuous monitoring in a distributed sensor network.

Both Raman and Brillouin systems provide sensitive temperature monitoring. The measurement time is long, greater than five minutes, but this acts as an 'averaging' function which greatly reduces the false alarm rate. These sensor systems can be used to detect leaks in pipelines where, depending on the type of pipeline, either a rise or drop in temperature would indicate a leak.

These systems avoid some of the temperature/strain cross-talk of other systems and therefore are more suitable for environments where both parameters may be changing regularly. These systems are regularly used in pipeline monitoring where temperature changes indicate leakage (higher temps for oil, fuel, and brine; lower temperatures for LNG, LPG and gas).

The advantages of Raman and Brillouin systems are their sensitivity and their fiber cable length of up to 25km. The disadvantages include sensitivity to vibration, measurement time, and cost of the analysis system.

3.5 Fiber Chemical/Bio sensors

A potential enhancement to the Bragg grating method involves coating the FBG with specific biomolecules or with a chemically sensitive cladding to create sensors that can be used for chemical or bio-agent detection (Figure 6). This would potentially add to the functionality of FBG sensor networks. The more common method for chemical or biologic

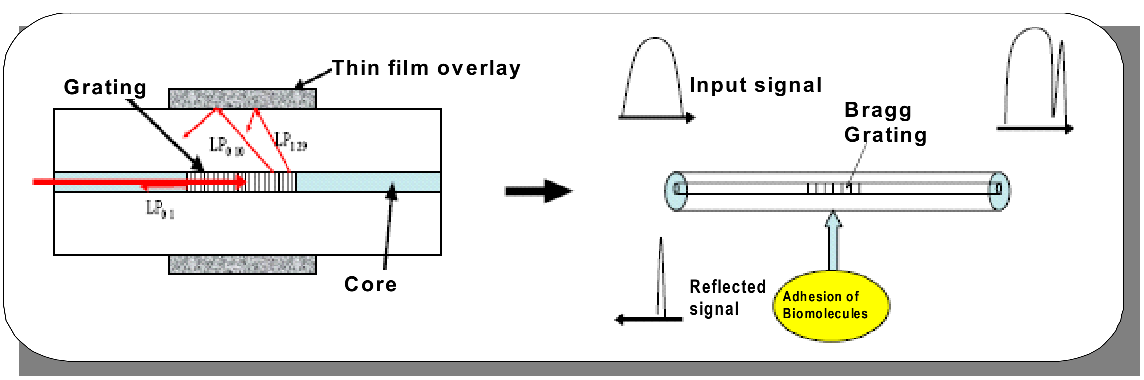

Figure 6: Biomolecular Modulated Bragg Grating Sensors, source: Lefebvre, LxSix

agent detection uses sensors that take advantage of evanescent waves to detect changes in fiber cladding due to environmental changes. These devices work by detecting effective index changes (interferometrically) or by detecting stimulated fluorescence.

4. DISTRIBUTED FIBER OPTIC SENSORS OUTLOOK

Pressing needs for wide area surveillance systems exist, capable of improving intrusion detection in sensitive and critical areas, along with improved border security and asset protection. Given the homeland security requirements alone, there will likely be a legislative push that translates to more dollars for DFO sensor investment.

The distributed fiber sensor market is young and faces competition from the understood image surveillance market and from wirelessly networked point sensors (known as Motes). Field experience and awareness is growing, however, with progress being made in the oil well and pipeline monitoring sectors and the established smart structure market. Emerging sophisticated security markets are present with strong interest in fiber optic sensor deployments.

Many FO sensor networks are either heavily customized or vendor proprietary. As a result, fiber optic sensor network installation experience is still at the learning stage and most vendors do not supply complete solutions that include setup, calibration and maintenance. Furthermore, there has not been the development of platform or volume manufacturing approaches that enable growth in other industries.

Notwithstanding these caveats, growth for the fiber optic sensor market is forecasted to be strong for the commercial markets, with domestic and international government investments likely providing an additional boost. Fiber optic sensors have reached an inflection point where technology, pricing, and needs have converged. The industry should prepare itself to bring the tools to pluck the golden apple–and not lose it for want of a ladder.