IV NDT Panamerican Conference
Buenos Aires – October 2007

AAENDE
Asociación Argentina de Ensayos No Destructivos y Estructurales

Overview of fiber optic sensors for NDT applications

Alexis Méndez
MCH Engineering, LLC
1728 Clinton Ave., Alameda, CA 94501 (USA)
alexis.mendez@mchengineering.com
Tel: +1 (510) 521-1069

Tom Graver
Micron Optics Inc.
1852 Century Place, Atlanta, GA 30345 (USA)

Abstract

Over the last few years, optical fiber sensors have seen an increased acceptance as well as a widespread use for structural sensing and monitoring in civil engineering, aerospace, marine, oil & gas, composites and smart structure applications. Optical fiber sensor operation and instrumentation have become well understood and developed. Fiber sensors are attractive sensing devices for non-destructive testing (NDT) applications given their small size, lightweight and dielectric glass construction that renders them immune to electrical noise and EM interference—unlike most conventional electronic sensing systems.

To date, fiber sensors have been embedded inside composite materials to determine curing, internal stresses and deformations as well as to detect the onset of cracks and damage. Surface mounted devices allow for the on-line monitoring in real time of deformations and strains in a variety of test specimens. Furthermore, some specific fiber sensor types allow for multi-point sensing at different locations using a single fiber, or even continuous, distributed sensing of temperature and strain based on Raman and Brillouin scattering systems.

In this paper, we will review the operating principles, sensor types, benefits and applications of optical fiber sensors for NDT of materials and structures in different fields such as composites, aerospace, civil engineering, oil & gas and others.

I. Introduction

The field of fiber optics has undergone a tremendous growth and advancement over the last 25 years. Initially conceived as a medium to carry light and images for medical endoscopic applications, optical fibers were later proposed in the mid 1960's as an adequate information-carrying medium for telecommunication applications. Ever since, optical fiber technology has been the subject of considerable research and development to the point that today light wave communication systems have become the preferred method to transmit vast amounts of data and information from one point to another. Among the reasons why optical fibers are such an attractive are their low loss, high bandwidth, EMI immunity, small size, lightweight, safety, relatively low cost, low maintenance, etc.

1.1 Optical fiber structure & characteristics

At the heart of this technology is the optical fiber itself. A hair-thin cylindrical filament made of glass that is able to guide light through itself by confining it within regions having different optical indices of refraction. A typical fiber structure is depicted in Fig. 1. The central portion—where most of the light travels—is called the core. Surrounding the core there is a region having a lower index of refraction, called the cladding. From a simple point of view, light trapped inside the core travels along the fiber by bouncing off the interfaces with the cladding, due to the effect of the total internal reflection occurring at these boundaries. In reality though, the optical energy propagates along the fiber in the form of waveguide modes that satisfy Maxwell's equations as well as the boundary conditions and the external perturbations present at the fiber.

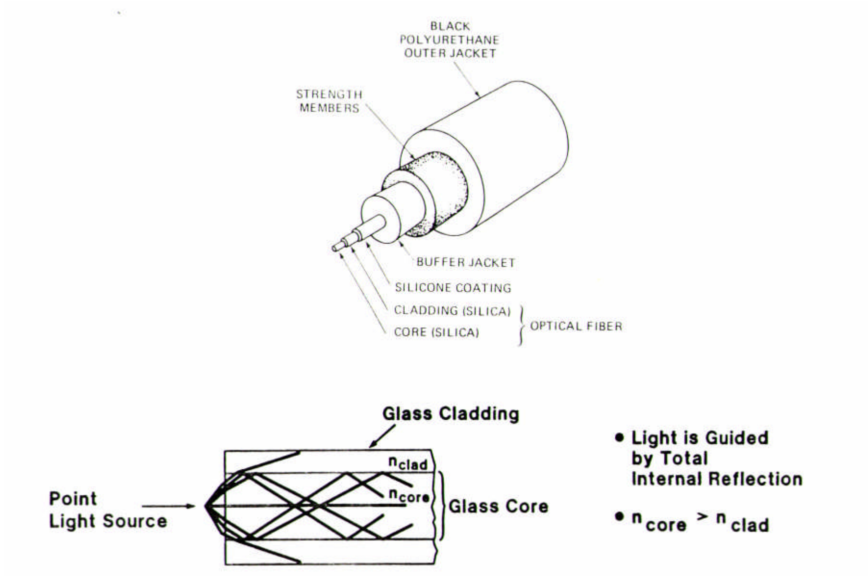


Figure 1. Schematic of an optical fiber

1.2 Introduction to Optical Fiber Sensors: operating principle

Optical fibers are also attractive for other applications such as in sensing, control and instrumentation. In these areas, optical fibers have made a significant impact and are being the subject of substantial research over the last few years. In general, for these applications fibers are made more susceptible and sensitive to the same external mechanisms against which fibers were made to be immune for their effective operation in telecommunications. In its simplest form, an optical fiber sensor is composed of a light source, optical fiber; sensing element and a detector (see Fig. 2). The principle of operation of a fiber sensor is that the sensing elements modulates some parameter of the optical system (intensity, wavelength, polarization, phase, etc.) which gives rise to a change in the characteristics of the optical signal received at the detector.

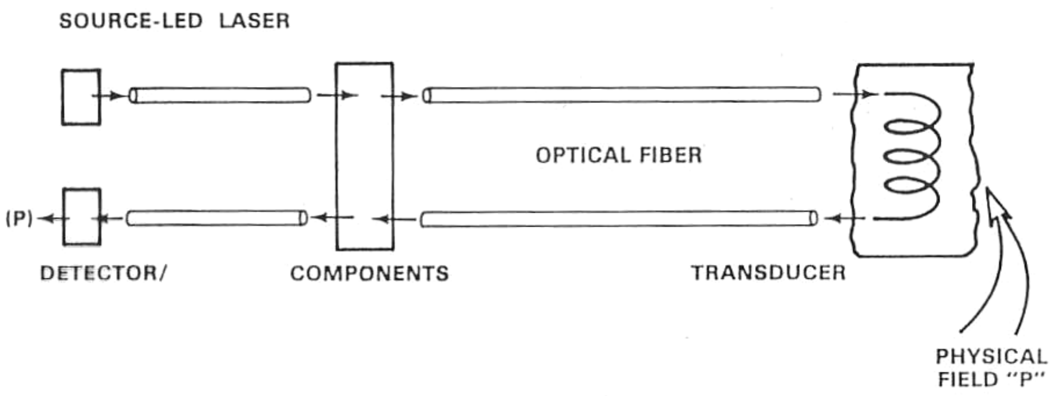


Figure 2. Basic elements of an optical fiber sensor

The fiber sensor can be either an intrinsic one—if the modulation takes place directly in the fiber—or extrinsic, if the modulation is performed by some external transducer as depicted in Fig. 3.

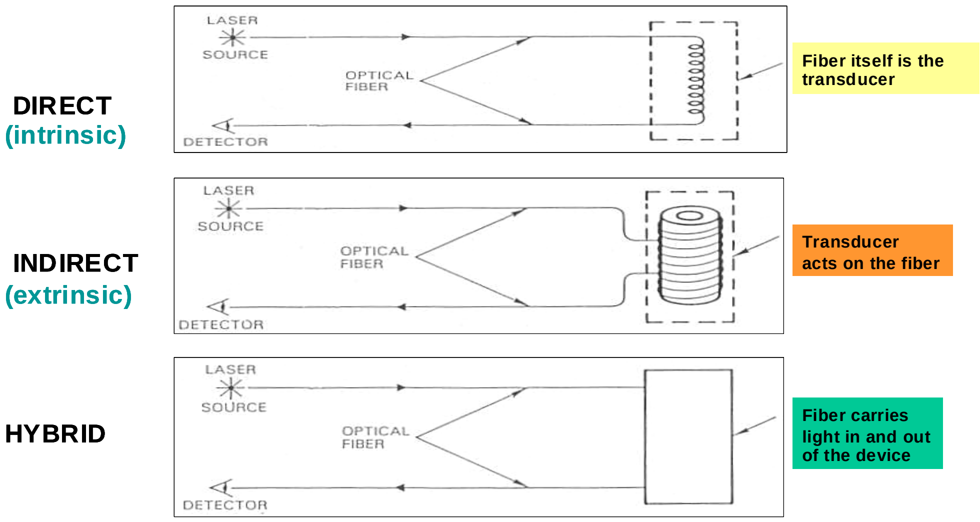
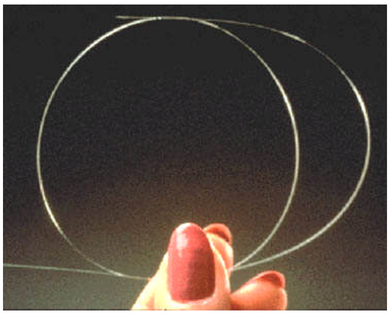


Figure 3. Classification of optical fiber sensors

1.3 Benefits & advantages

Optical fiber sensors offer attractive characteristics that make them very suitable and, in some cases, the only viable sensing solution. Some of the key attributes of fiber sensors are summarized in Table 1 below.

Table 1. Advantages of optical fiber sensors



- *Galvanic isolation*
- *EMI immunity*
- *Intrinsically safe*
- *Passive: no need for electrical power*
- *Possibility of remote, multiplexed operation*
- *Small size and lightweight*
- *Integrated telemetry: fiber itself is a data link*
- *Wide bandwidth*
- *High sensitivity*

1.4 Fiber optic sensor classification

To date, several different types of fiber sensors are commercially available to measure parameters such as pressure, temperature, refractive index, displacement, gas concentration, and several others [1]. Others are at a high stage of development allowing for a reliable and accurate measurement of stress and strain, electric current, vibration, sound, flow, etc. In the sections to follow we will explain how optical fibers can and are being used to measure diverse parameters in different applications.

Table 2. Types of fiber optic sensors

- ***INTERFEROMETRIC***
  - *Measure optical phase difference between two lightwaves (Sagnac, Micahelson, Mach Zehnder)*
- ***INTENSITY***
  - *Alteration of the guided light power*
- ***RESONANT***
  - *Measure optical resonant frequency of an optical cavity (Fabry-Perot)*
- ***POLARIMETRIC***
  - *Measure state of polarization of guided lightwave*
- ***SPECTRAL INTERFERENCE***
  - *Measure frequency of lightwave interfering with a periodic structure (fiber Bragg grating)*

2. Optical fiber Bragg grating sensors

Fiber Bragg gratings (FBGs) have—over the last few years—been used extensively in the telecommunication industry for dense wavelength division de-multiplexing, dispersion compensation, laser stabilization, and erbium amplifier gain flattening, all at 1550 nm. In addition, FBGs have been studied for a wide variety of mechanical sensing applications [2-7] including monitoring of civil structures (highways, bridges, buildings, dams, etc.), smart manufacturing and non-destructive testing (composites, laminates, etc.), remote sensing (oil wells, power cables, pipelines, space stations, etc.), smart structures (airplane wings, ship hulls, buildings, sports equipment, etc.), as well as traditional strain, pressure and temperature sensing. The main advantage of FBGs for mechanical sensing is that these devices perform a direct transformation of the sensed parameter to optical wavelength, independent of light levels, connector or fiber losses, or other FBGs at different wavelengths. The advantages of FBGs over resistive foil strain gauges include:

- *Totally passive (no resistive heating),*
- *Small size (can be embedded or laminated),*
- *Narrowband with wide wavelength operating range (can be highly multiplexed),*
- *Non-conductive (immune to electromagnetic interference),*
- *Environmentally more stable (glass compared to copper), and*
- *Low fiber loss at 1550 nm (for remote sensing).*
- *Potential for very low cost due to device simplicity and high volume telecommunication usage.*

2.1 Operating principle

A fiber Bragg grating is wavelength-dependent filter/reflector formed by introducing a periodic refractive index structure, with spacing on the order of a wavelength of light, within the core of an optical fiber. Whenever a broad-spectrum light beam impinges on the grating, will have a portion of its energy transmitted through, and another reflected off as depicted in Fig. 4 The reflected light signal will be very narrow (few nm) and will be centered at the Bragg wavelength which corresponds to twice the periodic unit spacing Λ. Any change in the modal index or grating pitch of the fiber caused by strain, temperature of polarization changes, will result in a Bragg wavelength shift.

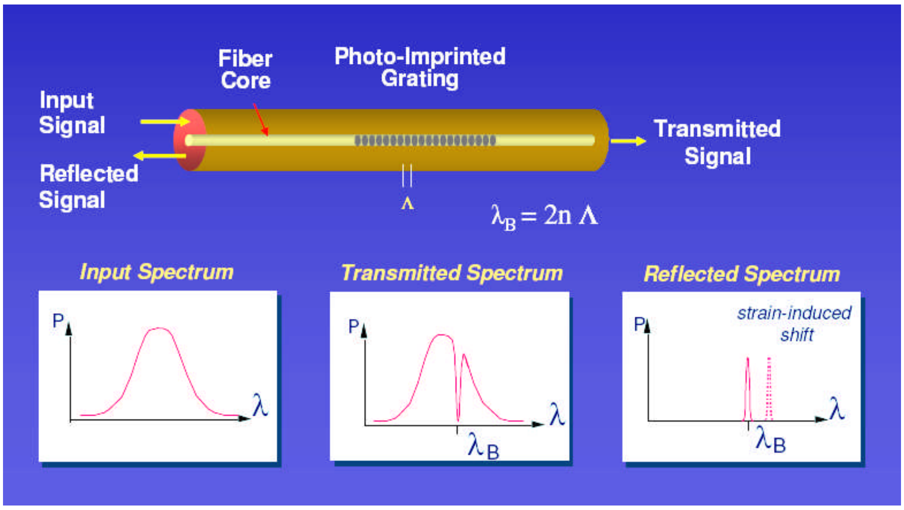


Figure 4. Transmission and reflection spectra of a fiber Bragg grating

Mechanical stresses can be measured using FBG by properly mounting them on or embedding into the substrate of interest. One of the advantages of this technique is the fact that the detected signal is spectrally encoded, so that transmission losses in the fiber are of no concern.

A fiber Bragg grating with a refractive index profile:

$$n(\mathbf{r}) = n_o + n_1 \cos(K \bullet r) \quad (1)$$

Where n_o is the average index, n_1 is the amplitude of the grating (typically 10^{-5} to 10^{-2}) and $\mathbf{r}$ is the distance along the fiber, allows light with wavevector $\mathbf{k}_i$ to be scattered in a direction given by the diffracted wavevector $\mathbf{k}_d = \mathbf{k}_i - \mathbf{K}$. Here $\mathbf{K}=2p/\Lambda$ is the grating vector, its direction is normal to the grating planes. Λ is the grating period. If the diffracted wavevector matches that of the free wave at the incident frequency, strong Bragg diffraction into the $\mathbf{k}_d$ direction occurs. The value of Λ needed to reflect light guided in a single-mode fiber core is given by the first order Bragg condition:

$$\Lambda = \lambda_b/2n_m \quad (2)$$

FBGs are attractive for sensing applications due to the dependence of their spectral shift as a function of grating separation change with external effects. They are commonly used in harsh environment applications as a replacement to standard resistance electrical strain gauges. This is especially helpful in environments such as high-temperature or highly corrosive. It is also possible to use fiber Bragg gratings to sense other environmental parameters such as pressure chemical reaction by using an additional transducer instead of using Fiber Bragg grating itself.

In general, the temperature sensitivity of a grating occurs principally as a result of the temperature dependence of the refractive index in the fiber material and, to a lesser extent, to the thermal expansion in the material which changes the grating period spacing. Typically, the fractional wavelength change in the peak Bragg wavelength is of the order of 7-8pm/°C. This corresponds to 0.012nm/°C @ 1550nm.

The fiber Bragg Grating is written directly into the core of the optical fiber. Fiber Bragg gratings physically function through two main components. The first component is the actual physical change of the glass fiber itself. Whether it is by temperature or strains the fiber itself is expanding or contracting due to the environmental load. The optical change that occurs is a change in the refractive index of the fiber due to that strain loading. Mechanical strain shifts the Bragg wavelength by physically increasing or decreasing the grating spacing by mechanical strain and by changes in the refractive index due to the strain optic effect. For axial loads, the fractional wavelength change is typically 78% of the applied strain, which translates to 11.8nm, at 1% strain @ 1550nm.

Figure 5 illustrates the aspect of a novel, commercial FBG strain sensor. The device is rugged and designed for use in diverse field applications. The FBG sensing element is pre-stretched and mounted on a protective metallic carrier flexure. The strain sensor can be surface mounted to test specimens of interest using epoxy bonding or spot welding techniques. This, in practice, becomes the optical fiber equivalent of a conventional foil strain gage sensor.

Figure 5. Photograph of a commercial fiber Bragg grating strain sensor. Fiber is pre-mounted on a metallic carrier (photo courtesy of Micron Optics Inc.)

3. Applications for Non-Destructive testing

3.1 Civil structures

Since the infrastructure of civil engineering works around the world is in a state of deterioration due to aging of its materials, excessive use, overloading, weathering, lack of maintenance and proper inspection. It has become increasingly important in the last few years to determine the safety of a structure by the non-destructive evaluation (NDE) of its strength and integrity. This assessment is essential for the repair, retrofit, rehabilitation, life extension or replacement of the structure in question. Furthermore, it would be very useful to develop means for the feedback and control of the state of health of a structure.

Optical fibers, because their small size and lightweight, offer the possibility to be embedded within cement or concrete without affecting their properties and used as sensitive, but rugged, transducers of mechanical perturbations. The basic principle behind embedded fibers to characterize the state of a material or structural specimen is that light sent through the fiber has its intensity, phase, wavelength or polarization altered by changes in the mechanical and thermal states of the surrounding host. The first proposal on the application of optical fiber sensors embedded in concrete buildings and structures was given by Méndez et al. [8], who described the potential applications of this approach along with a study on the fundamental issues regarding its practical implementation.

Given their attributes, sensors made out of optical fibers have the capability to be embedded, prior to curing, into reinforced concrete elements and structures such as buildings, bridges, dams and tanks for the NDE of structural integrity and the measurement of the internal state of stress. In other instances, sensors can simply be surface-mounted onto concrete or steel surfaces. Once installed, the fiber sensors can provide high-resolution temperature and strain measurements, detect the onset and growth of cracks, as well as to monitor creep and thermal stresses. In addition, the actual location of a fault can be determined by interrogating the back-reflected signal coming from the fiber, using optical time-domain reflectometry (OTDR) techniques or by means of distributed sensing systems based on Raman or Brillouin scattering.

All this information can ultimately be used to provide "real-time" information on the state of a specific concrete element or structure by means of a built-in damage detection and evaluation system based on a grid of optical fiber sensors embedded within the structure during its construction. Having such capability renders the structure or building more "intelligent" and leads into the so-called smart structures, whereby a certain degree of self-inspection and control is provided thanks to the use of sensors and actuators in a closed-loop fashion.

For instance, Fig. 6a depicts the installation of fiber strain sensors on the girders of a reinforced concrete bridge, while Fig. 6b shows an elongation fiber sensor during the process of embedment into concrete prior to curing.

a) b)

Figure 6. a) Surface mounted fiber strain sensors on a bridge girder and, b) sensor embedment into a concrete slab prior to curing.

The fundamental applications envisioned for FOS within the field of civil engineering can be grouped into three main areas, namely:

- Structural monitoring and damage evaluation
- Experimental stress analysis
- Management and control of systems and service installations

The first group explores the incorporation of single- and multi-mode fiber sensors within structural concrete elements such as beams, columns, arches, slabs and others, so that stress, strain, flexure, bending, curing, cracks and creep in concrete can he measured individually, as well as the deflection and bending of structures as a whole. Table 3 below, summarizes specific applications in this area.

In the field of experimental stress analysis, fibers would make sensitive and versatile sensors for the measurement of mechanical characteristics of structural members in experimental studies. This might be particularly useful with structures and members having complex shapes for which analytical solutions can be difficult to obtain. An answer can be obtained by measuring experimentally the state of stress in a model. Another example would be to use a grid of fiber strain sensors embedded in the runways of airports to evaluate the stresses on the pavement during the landing and take-off of airplanes. The 2-D stress mapping obtained in this fashion would be helpful in the redesign and maintenance of such pavements. Furthermore, embedded fiber optic strain sensors would enable structural engineers to compare between measured and designed values of stress, bending moments and deflection. From this information more accurate design factors can be determined which would make structures safer and more economical to build.

Table 3. Civil structure applications of optical fiber sensors

Bridges:

- Stress monitoring of long spans (>1km) with hundreds of sensors
- Tracking behavior in high stress conditions (earthquake, heavy traffic, high wind)
- Long-term stress& vibration monitoring
- Embedded sensors in concrete beams and pilings
- Embedded/surface sensors on cables for suspension structures
- Surface-mounted sensors on steel components in expansion joints
- Strain sensing on steel girders

Dams:

- Stress & vibration monitoring
- Footing settlement
- Temperature monitoring during curing

Tunnels:

- Monitoring of strains and stresses
- Crack detection and monitoring
- Settlements

Reservoirs:

- Precise reservoir water level monitoring for dam flow control
- River level and flow monitoring for improved flood control

Hillsides:

- Monitoring of gradual shift in soil and rock
- Detection and prediction of possible landslides

The third set of applications considers that building services and installations (such as heating, air conditioning, lighting, electricity distribution and consumption, security, fire alarms, etc.) can be operated more efficiently and economically using fiber optic sensors that monitor and measure the state of affairs of pertinent parameters. For instance, reading of the pressure, flow and temperature of water pipes could be used to regulate the temperature and distribution of running water by controlling valves, pumps and boilers as required. Similarly, the temperature in rooms, hallways and offices could be monitored and controlled automatically. Electric currents could be controlled and regulated according to demand. Fibers coated with special heat-sensitive coatings could be used as distributed heat sensors for use in fire alarm systems. And the list goes on. In this fashion, integration of all the information supplied by a network of fiber and regular sensors into a single processing center within the same facility would result in a "smart building".

3.2 Composites materials

The use of optical fiber sensors embedded within composites for the measurement of internal strain and the detection of structural damage in aerospace applications has proved to be an effective non-destructive evaluation (NDE) technique and become the subject of substantial research [2,3,7].

Given its small size and lightweight, optical fiber sensors can be easily surface mounted or embedded into the matrix material of a composite element or structure. Discrete sensors can be placed at strategic locations inside or outside the composite section under study. In the case of FBGs, a continuous fiber lead with an array of fiber gratings can be embedded into the composite material and routed around various regions of interest. This approach is particularly attractive when dealing with long sections such as airplane wings, fuselage bodies, composite pipes, yacht masts, and many others.

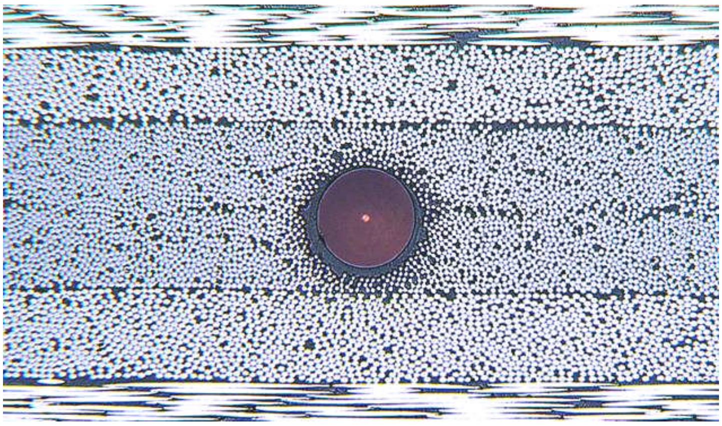


Figure 7. Carbon Fiber Reinforced Polymer Composite with embedded fiber optic Bragg grating sensor (source; Daimler-Benz).

Once installed, fiber optic strain sensors would allow the measurement of surface and internal strains and stresses, detect the onset and location of cracks, determine the loads acting on a given structural element, measure vibrations and determine internal pressure fluctuations in tanks and vessels. Furthermore, coupled with the use of fiber temperature sensors, it would be possible to monitor the curing process of composites and assess their residual stresses. Once embedded, they could monitor both temperatures and strains acting on the composite during its installation and deployment, as well as over its entire service life.

4. Conclusions

Optical fiber sensors are a practical and real sensing technology alternative to more conventional NDT techniques. Among the primary benefits for using fiber sensors are their immunity to electrical noise and EM immunity coupled with their small size that allows for direct embedment into concrete and composite materials. Sensors, interrogation instruments, and installation methods are improving, but need to continue to improve for widespread, mainstream adoption. The number of commercial companies offering fiber-optic based sensing gear is increasing as their adoption in NDT and SHM applications continues to emerge. Nowadays, fiber sensors have been used in civil engineering, aerospace, naval, geotechnical, composite, automotive, oil and gas and several other industries. Further diffusion and growth is expected in the future.

References

1. Jose Miguel Lopez-Higuera, Handbook of Optical Fibre Sensing Technology, John Wiley & Sons Inc., 2002. ISBN 0-47182-053-9. 828 pp.
2. Raymond M. Measures, Structural Monitoring with Fiber Optic Technology, Academic Press, 2001. ISBN 0-12-487430-4. 716 pp.
3. Eric Udd, Fiber Optic Smart Structures, John Wiley & Sons Inc., 1995. ISBN 0-471-55448-0 671 pp.
4. Farhad Ansari and Stein Sture, Nondestructive Testing of Concrete Elements and Structures, American Society of Civil Engineers, 1992.
5. Farhad Ansari, Applications of Fiber Optic Sensors in Engineering Mechanics, American Society of Civil Engineers, 1993. ISBN 0-87262-895-7. 230 pp.
6. Farhad Ansari, Fiber Optic Sensors for Construction Materials and Bridges, Technomic Publishing Co., 1998. ISBN 1-56676-671-0. 267 pp.
7. Brain Culshaw, Smart Structures and Materials, Artech House, 1996. ISBN 0-89006-681-7. 207 pp.
8. A. Méndez, T. F. Morse and F. Méndez, "Applications of Embedded Optical Fiber Sensors in Reinforced Concrete Buildings and Structures", Proc. SPIE, Vol. 1170, pp. 60-69. September 1989.