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Fiber Optical Sensors for Monitoring the State of Objects and The Environment

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Abstract. The article describes new approaches to measuring environmental parameters and technical devices in monitoring systems, based on the use of the capabilities of fiber-optic systems with various methods of processing an optical signal. It is shown that the use of such systems will significantly simplify the measurement process, as well as obtain new possibilities for measuring and analyzing physical quantities. Recent developments in optical fiber array sensors are reviewed, including quasi-distributed strain measurement using Bragg gratings, chirped grating systems, intra-array sensing concepts, long period array sensors, and interferometric sensor systems based on grating reflectors.

Keywords: Fiber optic sensors, light guide, laser radiation, sensor, spectral analysis, spectroscopy, quasi-distributed measurement, interferometer.

Introduction

In the field of monitoring and safety, fundamentally new fiber-optic sensors are becoming increasingly common, devoid of a number of significant drawbacks inherent in electrical analogs. Instead of electric currents, such sensors use an optical signal for their operation. As in the case of electrical analogs, the principles of signal conversion or generation may differ, however, all types of fiber-optic sensors have a number of undeniable advantages, among which the following can be distinguished [1]: insensitivity to electromagnetic fields; explosion and fire safety due to the absence of electric currents; possibility of remote control without using additional signal conversion and amplification devices; small size; chemical inertness; usually high sensitivity and measurement accuracy.

The fiber light guide, which is the basis of any fiber-optic sensor, is a quartz thread structured in diameter. In the simplest case, the light guide consists of a modified quartz core with an increased refractive index and a reflective shell made of unalloyed quartz glass. Depending on the application, the core can be doped with various elements: germanium, nitrogen, erbium, tin, etc. Thanks to the additives, the light guide itself and sensors based on it acquire certain production and operational properties: increased sensitivity to temperature, luminescent properties, increased thermal stability and increased photosensitivity, which is technologically necessary for creating a number of fiber-optic sensor elements.

All fiber-optic sensors can be roughly divided into two main types: distributed and point.

Distributed sensors use the properties of the fiber itself along its entire length. Localized impact on any part of the sensitive light guide can be fixed in magnitude and location. It is these sensors that are now widely used for monitoring long pipelines.

Point sensors represent a structurally modified or combined section of a fiber light guide and allow monitoring parameters at a specific point or local area of the object (Fig. 1). The third type of sensors is often distinguished - quasi-distributed (Fig. 2).

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Such sensors consist of an array of point sensor elements combined by one light guide and one conversion device. In the system under consideration, a typical representative of quasi-distributed sensors can be strain sensors combined in series into a single fiber line (Fig. 3).

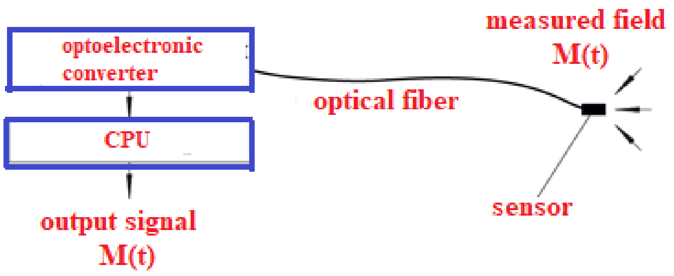

Fig. 1. Fiber optic point sensor structure

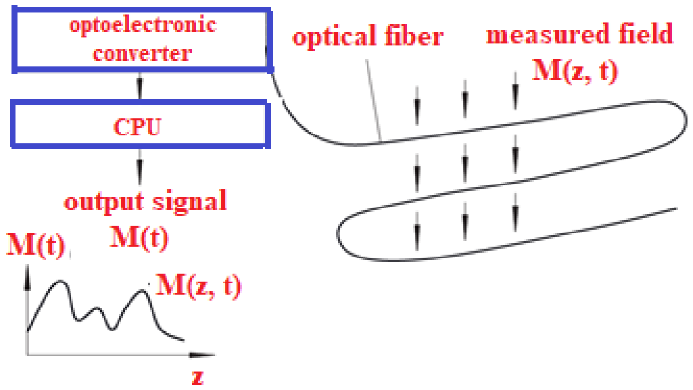

Fig. 2. Distributed fiber sensor structure

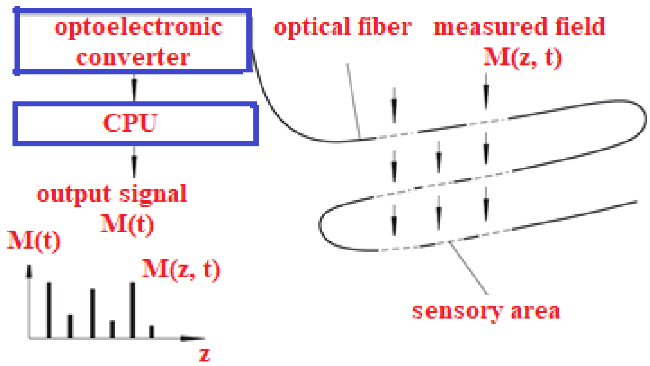

Fig. 3. Quasi-distributed fiber optic sensor system

Such sensors, possessing all the advantages of point sensors, including high measurement accuracy, allow one-time control at various points of the object or provide conditionally continuous monitoring of extended objects.

By the principle of operation, fiber-optic sensors can be divided into several main types: scattering sensors, interference sensors, based on intra-fiber gratings [2].

Below are the principles of operation of various fiber-optic sensors and their application for monitoring objects, including underwater and surface structures.

The sensors on the scattering.

This type of sensor is synonymous with the term "distributed fiber sensors". The principle of their operation is based on the analysis of the backscattering or forward scattering signal in the fiber. In all such

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systems, a short light pulse is used, the scattering of which is recorded by the receiving equipment. By the time of arrival and the value of the received signal, you can determine the magnitude and location of the impact on the reference fiber.

The accuracy of determining the amount of impact on the fiber and its location depends on the pulse duration and the accuracy of determining the signal amplitude.

To improve accuracy, multiple averaging over many dimensions is used, which can increase the survey time to several minutes. As with interference sensors, distributed systems can be based on different effects: Rayleigh and Raman scattering, Mandelstam-Brillouin scattering, and so on.

The simplest version of the scattering sensor is the "Rayleigh reflectometry" system based on the analysis of scattering from small fiber inhomogeneities. Such devices are used in telecommunications to analyze the parameters of a fiber communication line, as well as to search for fiber breaks. Working as a distributed sensor, the system responds to thermal and mechanical stresses on the fiber. However, the accuracy of such measurements is low.

Systems based on Raman and Brillouin scattering are more interesting from the point of view of measurements. In both cases, it is not the scattered signal at the radiation wavelength that is measured, but the frequency-shifted Stokes and anti-Stokes components, which arise in the first case on thermal molecular vibrations, and in the second case, on a sound wave (Fig. 4).

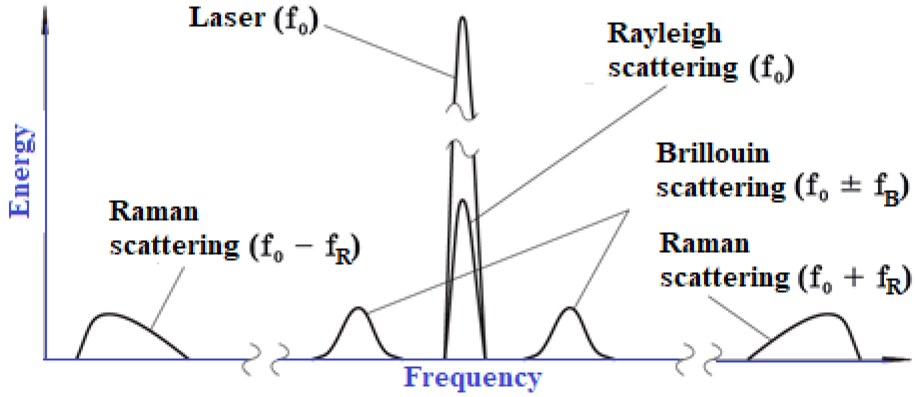

Fig. 4. Different types of scattering spectra

The amplitude of the anti-Stokes component of Raman radiation depends significantly on the temperature, while the Stokes component practically does not change. It is the ratio of the Stokes and anti-Stokes components that determines the temperature effect on the section of the fiber light guide. Mechanical action has almost no effect on the Raman effect in the light guide.

The most promising method is Brillouin reflectometry. In contrast to Raman, the ratio of signals of the Stokes and anti-Stokes components does not change with changes in temperature or in the presence of deformation. However, the frequency shifts of these components changes. Any influence (mechanical or thermal) changes the density of the substance (and hence the speed of sound in it), which determines the value of the Brillouin frequency shift. A notable feature and important advantage of Brillouin sensors is the independence of the measurement results from the signal amplitude, since it is the frequency shift that is measured, which significantly increases the reliability of the data obtained. Although the optical frequency shift is relatively small (gigahertz range), the use of special equipment allows for high-precision measurements.

Sensor systems of this type can be used to measure temperature and mechanical deformations. For example, the accuracy of modern temperature measurement systems of this type reaches several tenths of a degree, and determining the location of the impact is less than a meter. The total length of the sensor can reach several tens of kilometers. These properties make it indispensable for continuous monitoring of long pipelines. Any leak of oil or gas from the pipeline changes the temperature of the surrounding pipeline material. The oil heated for transportation increases the temperature at the leak site. Modern algorithms for analyzing the temperature distribution along the pipeline make it possible to uniquely identify the leak with high accuracy. In addition, mechanical deformations of the pipeline can also be identified. There are no

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analogues of such control systems. Currently, fiber-optic scattering sensors are being actively implemented in the oil and gas industry to monitor the integrity of oil and gas pipelines.

Interference fiber optic.

Fiber-optic interferometers - the basis of such sensors - are based on the well-known light interference effect, when two light signals interact with each other, amplify or extinguish each other. The effect depends on the phase of the incoming optical signal, which varies with a change in the distance traveled by the light beam, namely, with a change in the so-called optical path.

Interferometric sensors are based on the analysis of the interaction of two such beams propagating along one or two arms of the interferometer. One of the "arms" can be a reference with a fixed incoming phase of the light beam. Any impact on the second leads to a change in the phase of the second beam and, consequently, the output signal. The principle of construction of fiber interferometers is the same as that of their "volumetric" analogs - schemes developed long before the appearance of a fiber-optic light guide. These can be Fabry – Perot and Sagnac schemes or two-arm Mach – Zander, Michelson, etc. interferometers (Fig. 5a). As an example, we can consider the operation of the Mach – Zehnder interferometer, which is used in modern optical seismic sensors (Fig. 5b).

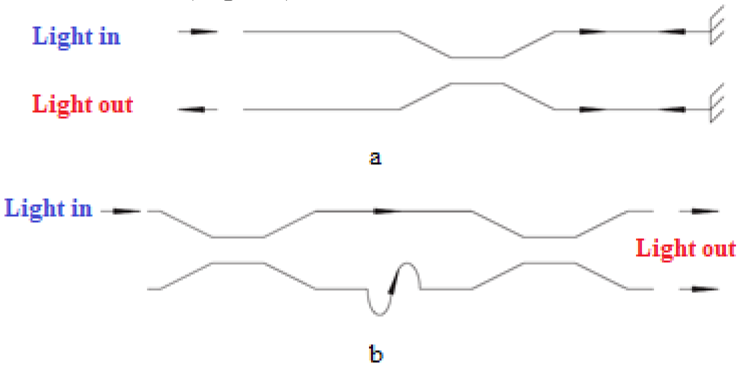

Fig. 5. Two-arm fiber interferometer: a - Michelson; b - Mach - Zander

Light from a coherent (laser) source is fed to the input of the interferometer ("Light in"), and then through an optical splitter it enters the two arms of the interferometer. The output signal is summed by means of a splitter and recorded by a photo detector ("Light out"). When one of the interferometer arms is affected, the optical path of the light signal passed through it changes, which affects the phase of the light at the exit. The phase change is recorded by a photodetector after the interaction of light beams from different arms of the interferometer.

A feature and at the same time a significant advantage of such sensors is their extremely high sensitivity. A change in the phase of light can be recorded with a high accuracy equal to a change in the optical path of only 10^{-9} m. It is the high sensitivity of interferometers, along with a large dynamic range, that makes them promising for use in seismic bottom stations. At present, active work is underway in the world to develop a new generation of optical seismic sensors replacing outdated electrical analogs that do not meet the requirements of modern geo-prospecting, continuous monitoring of the hydro- and lithosphere.

Sensors based on intra-fiber gratings.

Grid sensors are representatives of point sensors, and being easily combined into arrays, they form a quasi-distributed system. The sensor is based on the so-called Bragg, or long-period, refractive index grating.

This is, as a rule, a small (3 ... 20 mm) section of the fiber light guide, in the heart-fault of which a periodic structure is formed, which is an alternation of regions with higher and lower refractive indices along the fiber. The lattice period determines its type and principle of operation.

The Bragg grating has a period comparable in order of magnitude to the wavelength of the sensor reference signal. Such a grating has the unique property of reflecting light in a narrow spectral range with a maximum at a wavelength λ_B, determined by Bragg's law:

$$\lambda_B = 2\Lambda n, \quad (1)$$

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where Λ is the lattice period; *n* is the average refractive index of the fiber for the mode propagating in it.

A typical transmission spectrum of a Bragg grating is shown in Fig. 6. A change in the ambient temperature leads mainly to a change in the refractive index of the fiber material. This, in turn, is reflected in the change in the reflection wavelength.

A portable narrow-band spectrometer is used to analyze the signal from the Bragg sensor.

The application of mechanical forces to the grid also leads to a change in its period. This effect is the basis of optical load cells that are widely used for monitoring the condition of complex engineering structures. Simultaneous temperature control allows you to take into account the temperature deformations of the object, increasing the measurement accuracy. In addition, the Bragg sensor, if necessary, can be optimized for measuring pressure, etc. Bragg sensors, having all the advantages of fiber-optic sensors, are extremely light and small in size - only 0.12 mm in diameter and 3...5 mm in length, high sensitivity and low inertness of indications. They can be installed in hard-to-reach places.

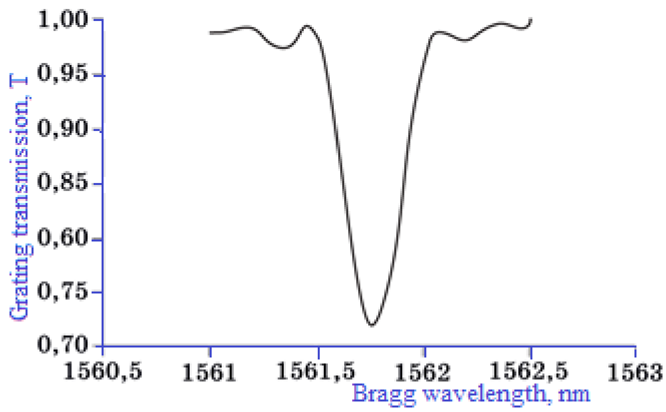

Fig. 6. Typical transmission spectrum of a Bragg grating

However, as mentioned above, the most remarkable feature of Bragg sensors is the ability to combine them into arrays using a single input light guide and a single analyzer unit. The resonant (Bragg) wavelength is a unique property of the sensor.

It is thanks to the unique properties that a large number of modern sensor systems for monitoring the state of structures are based precisely on fiber-optic Bragg sensors - the most promising, reliable and convenient ones.

Separately, it should be said about the new possibilities in determining the chemical composition of contaminants that have appeared due to the development of Raman spectroscopy.

For a long time, Raman spectroscopy was in the background after infrared spectroscopy due to the complexity of taking the Raman spectrum and its processing. The advent of lasers, more accessible and sensitive CCD matrices, holographic filters, and the use of Fourier transforms in devices marked the beginning of the revival of Raman spectroscopy as the main means of non-contact non-destructive analysis of substances.

The most advanced Raman spectrometers are single modules with computer control, automatic laser blocking, automatic calibration procedures and a wide range of spectral libraries. These advantages make the acquisition and use of Raman spectra a routine process.

Taking into account the high sensitivity of the method, the narrowness of the lines in the spectrum, and the absence of the requirement for destruction of the sample under study, the Raman method is suitable for constructing systems for identifying substances on its basis.

Much of the work on fiber Bragg grating sensors has focused on using these devices to provide a quasi-distributed point measurement of strain or temperature. The strain response arises from both the physical elongation of the sensor (and the corresponding partial change in the grating pitch) and the change in the fiber index due to photoelastic effects, while the thermal response arises from the inherent thermal expansion of the fiber material and the temperature dependence refractive index. The shift of the Bragg wavelength with strain and temperature can be expressed using

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$$\Delta\lambda_B = 2n\Lambda\left\langle \left\{1-\left(\frac{n^2}{2}\right)\left[P_{12}-\nu\left(P_{11}+P_{12}\right)\right]\right\}\varepsilon + \left[\alpha + \frac{\left(\frac{dn}{dT}\right)}{n}\right]\Delta T \right\rangle \quad (2)$$

where ε is the applied deformation, P_{11} coefficients are the Pockel coefficients (piezo) of the optical stress tensor, ν is Poisson's ratio, α is the coefficient of thermal expansion (CTE) of the fibrous material (for example, silica), and ΔT is the temperature change. The factor $\{(n^2/2)[P_{12} - \nu(P_{11}+P_{12})]\}$ has a numerical value of ≈0.22. The measured deformation characteristic at constant temperature is equal to

$$\frac{1}{\lambda_B}\frac{\delta\lambda_B}{\delta\varepsilon} = 0.78\times10^{-6}\,\mu\varepsilon^{-1}. \quad (3)$$

This sensitivity gives a practical estimate of the lattice shift with a strain of 1 nm per 1000 at a distance of 1.3 m. In silica fibers, the dn/dT effect predominates in the thermal response, which accounts for 95% of the observed shift. The normalized thermal sensitivity at constant deformation is

$$\frac{1}{\lambda_B}\frac{\delta\lambda_B}{\delta T} = 6.67\times10^{-6}\,°\mathrm{C}^{-1} \quad (4)$$

A wavelength resolution of 1 pm (0.001 nm) is required (at λ_B≈1.3 μm) to resolve a temperature change of T≈0.1 °C or an elongation change of 10^{-6}. While this wavelength resolution is achievable with laboratory instruments such as spectrum analyzers and tunable lasers, the ability to resolve changes in this order with small package electro-optical units is a challenge, and it has been the focus of much research work in the field of array sensors (Fig. 7).

The nature of the output signal of the Bragg gratings gives these sensors built-in self-regulation capability. Since the information read is encoded directly into wavelength, which is an absolute parameter, the output signal is not directly dependent on overall light levels, splice and coupler losses, or source power. This is widely recognized as one of the most important benefits of these sensors.

Although a wide variety of methods have been demonstrated to monitor Bragg wavelength shifts, only a few methods seem to be reducible to practical, cost-effective measurement systems for use in "real" applications.

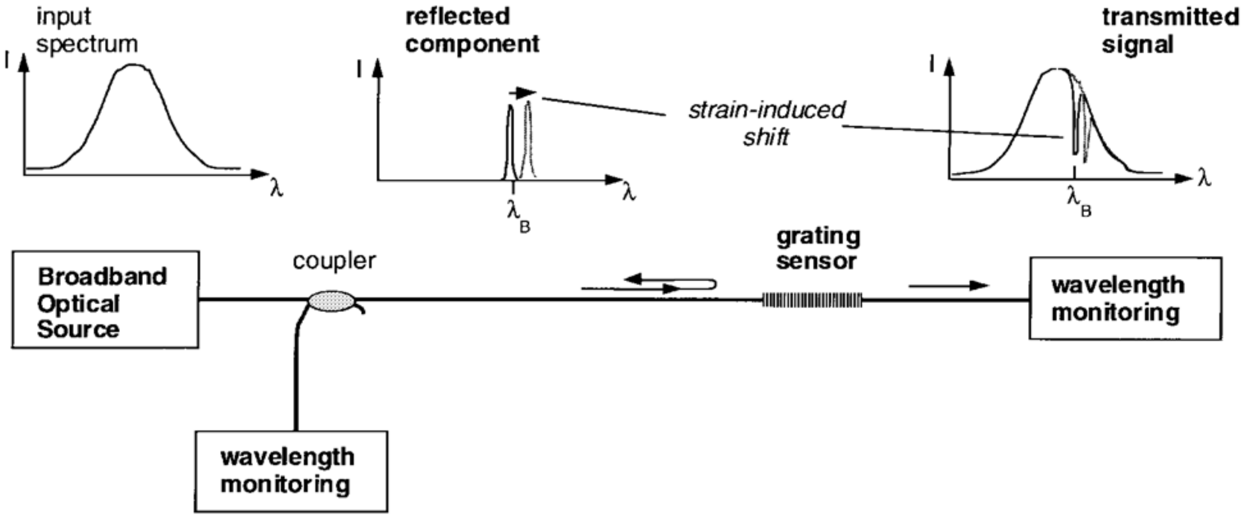

Fig. 7. Basic sensor system based on Bragg grating with the possibility of transmission or reflection

Sensors on chirped gratings.

Most lattice-based sounding methods use only the most basic FBG properties; namely, the nature of wavelength coded devices. However, newer sensors based on chirped and other specialized lattice structures are possible, and several examples have been reported in the literature.

The initial interest in chirped gratings was associated with their potential for dispersion compensation in telecommunication systems with high data rates [3]. Several methods of making chirped Bragg gratings have been demonstrated. Until recently, chirped fiber Bragg gratings were found to be inadequate for their

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intended purpose. However, as is often the case in technology, ideas in one area find application in another. In particular, the grating types originally developed for dispersion compensation needed only minor modifications to be used in the development of a new brand of strain and temperature sensors.

Sensors with a long-period gratings.

In 1995, Vengsarkar et al. introduced a new type of fiber-grating device to the optical community [4]. Long-period fiber grating (LPG) is a periodic modulation of the refractive index of the core recorded in a single-mode fiber using UV irradiation through an amplitude mask. A typical LPG has a λ period of hundreds of microns, a length of approximately 1-3 cm, and a modulation depth of 10^{-4} or more. LPG transmits light from the core to the shell with a certain wavelength.

$$\lambda_i = \left[n_{01} - n_{clad}^{(i)}\right]\Lambda \qquad (5)$$

where n_{01} is the effective index of the core mode, and $n^{(i)}_{clad}$ is the effective index of the i-axisymmetric cladding mode. The light in the cladding decays rapidly due to losses at the cladding / air interface, leaving a series of loss bands or resonances in a controlled manner. Since, depending on the index of the environment $n^{(i)}_{clad}$, surrounding the shell, the part of the fiber on which the lattice is located usually remains without a polymer coating after production. A single grating can have multiple resonances over a wide wavelength range, as illustrated by the transmission spectrum shown in Fig. 8.

LPGs were originally developed for use as notch filters [5] and have been used to attenuate gain in erbium doped fiber amplifiers (EDFA) [6]. However, LPG also presents unique opportunities as fiber optic sensors. The center wavelengths of LPG resonances are critically dependent on the difference in refractive indices between the core and cladding, and therefore any change caused by deformation, temperature or changes in the external refractive index can cause large shifts in the wavelengths in the resonances.

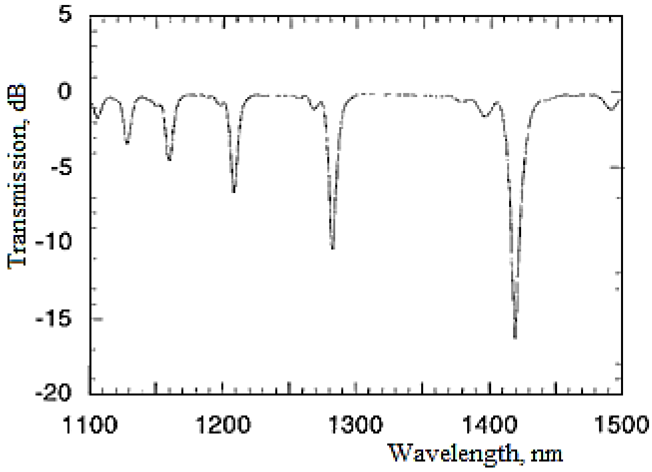

Fig. 8. LPG transmission spectrum. The grating is written in AT&T DSF fiber Λ = 225 microns.

In terms of strain and temperature measurement, LPGs are unique among fiber grating sensors in the sense that LPG resonance at a given λ wavelength can have very different sensitivities depending on fiber type and grating period. The deformation and temperature characteristics of the resonance of a long-period grating can be either positive or negative, depending on the differential responses of the core and cladding [7].

LPG has been used in several sensor systems and has certain advantages. It is the only short thickness fiber optic sensor whose sensitivity can be selected for a specific application, and its multiple resonances can be used to measure multiple parameters simultaneously. Challenges associated with the widespread use of devices in structural sensing include the development of suitable coatings for fiber protection, refining interpolation techniques for resonances, and narrowing of LPG resonance bands to enable multiplexing of sensors. Finally, this review did not investigate the area of environmental monitoring using the sensitivity of LPG to the ambient refractive index, but its application should become increasingly important [8].

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Interferometric sensors on Bragg gratings.

An additional use of Bragg gratings is the formation of interferometric sensor elements [9]. In this case, the gratings simply serve as reflectors defining the interferometric paths.

One of the first multiplexing techniques demonstrated for interferometric gratings was based on the use of internal partial reflectors, which were formed by mechanical joints between the fiber segments of the grating [10]. This resulted in low reflections in the range of a few percent, which is necessary to achieve low crosstalk with this approach. The reflectivity obtained with the mechanical connection was found to be unstable and lossy, which limits the applicability of the method. However, the advent of fiber Bragg gratings has provided a practical means for creating reliable low insertion loss internal particle reflectors. Fig. 9 illustrates the configuration [11].

In addition to simply acting as full or partial reflectors, the wavelength selective nature of gratings provides unique capabilities and configurations that must be realized. The most obvious extension of this is the implementation of WDM / TDM interferometric arrays [12]. It has also been demonstrated that the use of gratings can allow selective interrogation of overlapping "nested" interferometers implemented in conventional fiber paths [13]. This sensor concept can be used to form adaptive sensor arrays or to implement specialized sensor configurations such as gradient and vector sensors.

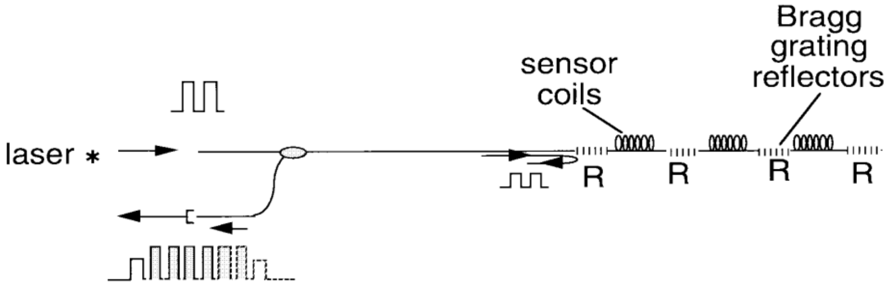

Fig. 9. Sequentially multiplexed interferometric sensors based on reflectors on the inner array.

Nesting multiple interferometers using common fiber optic paths provides some flexibility in the design of interferometric sensors, especially for differential, vector and spatially varying quantities. Nested interferometric arrays based on this concept are possible and useful for forming adaptive arrays in which the spatial properties of the array are controlled by the polling wavelength.

There are other interesting possibilities for the implementation of new interferometric sensors, such as Michelson and FP elements using chirped grating reflectors [14].

Conclusions

Using production and operational advantages of fiber-optic sensor elements, it is possible to create a continuous integrated monitoring of natural-technical systems, characterized by high efficiency, informativity and accuracy issued by the state parameters of such systems, which in turn provides the optimal decision-making for the prevention of emergency situations of natural and technogenic character [15]. There has been a great deal of interest in research and development in fiber array sensors over the past few years, and this aspect of fiber sensor technology is currently one of the most exciting growth areas in this field. Much of this work is dictated by the need to develop distributed strain sensor systems for use in intelligent design systems. We haven't discussed any very important developments that have occurred in the field of measurement systems testing, but it should be noted that fiber Bragg array sensors are being successfully applied in real-world applications such as infrastructure and composite materials monitoring, and commercial systems are beginning to appear. There are some interesting possibilities for developing sets of multi-parameter sensors based on FBG. Bragg gratings are also currently being investigated for use in fiber laser sensor configurations that can be configured for applications with ultra-high strain sensitivity.

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