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DETECTION

Contents

Fiber Sensors

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Introduction

The growth in the fiber optic communications and optoelectronics industries has led to the development and commercialization of many types of optical components. Fiber sensor devices and systems are a major user of such technologies. This has resulted in the development of commercial fiber sensors that can compete with conventional sensors. Fiber sensors are capable of measuring a wide variety of stimuli including: mechanical (displacement, velocity, acceleration, strain, pressure); temperature; electromagnetic (electric field, magnetic field, current); radiation (X-ray, nuclear); chemical composition; flow and turbulence in liquids; and biomedical. The main advantages of fiber sensors are that they are low cost, compact and lightweight, robust, passive, immune to electromagnetic interference, and highly sensitive.

Fiber sensors can be grouped into two basic classes: intrinsic and extrinsic. In an intrinsic fiber sensor the sensing is carried out by the optical fiber itself. In an extrinsic sensor the fiber is simply used to carry light to and from an external optical device where the sensing takes place. Point fiber sensors are localized to discrete regions; quasi-distributed sensors utilize point sensors at various locations along a fiber and distributed sensors are capable of sensing over the entire length of fiber.

A basic fiber sensor system, as shown in Figure 1, consists of a light source, fiber sensor, optical detector, and signal processing electronics. A measurand causes some change (intensity, phase, polarization, spectrum, etc.) in the light propagating through the sensor. This change is detected and processed to give an output signal proportional to the measurand. A large part of fiber sensor research concerns the development of fiber sensors sensitive to particular measurands and appropriate signal processing techniques. We describe some of the most important fiber sensors and also consider quasi-distributed and distributed sensing, including the use of multiplexing techniques.

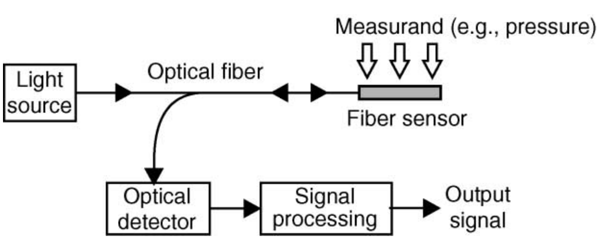

Figure 1 Basic fiber sensor system.

Intensity-Based Fiber Sensors

The intensity modulation (IM) of light is a simple method for optical sensing. There are several mechanisms that can produce a measurand-induced change in the optical intensity propagated by an optical fiber. Perhaps the simplest type of IM fiber sensor is the microbend sensor shown in Figure 2. The sensor consists of two grooved plates between which passes an optical fiber. The upper plate can move in response to pressure. When the fiber is bent sufficiently, light escapes into the fiber cladding and is lost. The greater the pressure on the plates the more loss occurs.

Coupling-based fiber sensors are useful for measurement of displacement or dynamic pressure. Transmission and reflective configurations are possible as shown in Figure 3. The transmission coupling-based sensor consists of two fibers with a small gap between them. The amount of light coupled to the second fiber depends on the fiber acceptance angles and the distance between the fibers. One of the fibers can move in response to vibration or pressure thereby changing the distance between the fibers and hence the coupling loss. The reflection-based sensor operates in a similar fashion, where light is reflected from a flexible diaphragm back into a collecting fiber. The reflected light intensity changes as the diaphragm is flexed. Once the coupling relationship between the input fiber, diaphragm and collecting fiber is known,

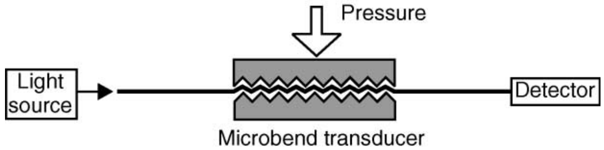

Figure 2 Microbend fiber sensor. The transducer moves in response to pressure and in doing so changes the bending radius of the fiber and thereby the fiber loss.

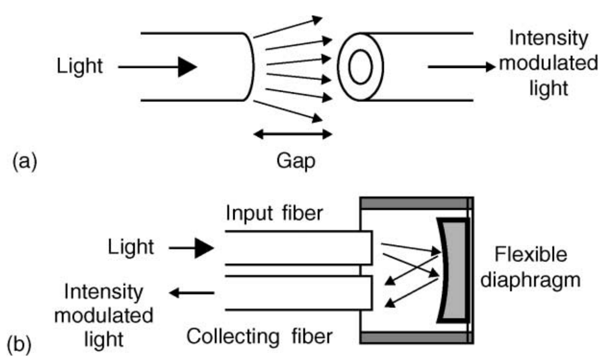

Figure 3 (a) Transmission and (b) reflective coupling-based fiber sensors.

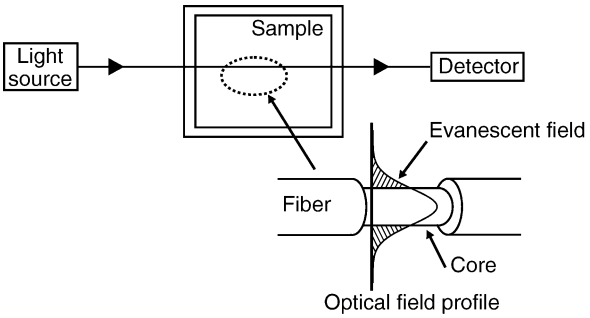

Figure 4 Evanescent wave fiber chemical sensor.

intensity changes can be related to the applied displacement or pressure.

Evanescent wave fiber sensors exploit the fact that some of the energy in the guided mode of an optical fiber penetrates a short distance from the core into the cladding. The penetration of light energy into the cladding is called the evanescent wave. It is possible to design a sensor where energy is absorbed from the evanescent wave in the presence of certain chemicals as shown in Figure 4. This is achieved by stripping the cladding from a section of the fiber and using a light source having a wavelength that can be absorbed by the chemical that is to be detected. The resulting change in light intensity is a measure of the chemical concentration. Measurements can also be performed in a similar fashion by replacing the cladding with a material such as an organic dye whose optical properties can be changed by the chemical under investigation. Evanescent wave fiber sensors have found many applications in the biomedical field, such as blood component meters for detection of cholesterol and uric acid concentrations in blood.

A linear position sensor based on time division multiplexing is shown in Figure 5. It uses a square-wave modulated light source, optical delay loops and an encoded card. The delay loops separate the return signal from the encoded card by a time that is greater than the pulse duration. The encoded return signal can be decoded to determine the card position and velocity.

Interferometric Sensors

Interferometric fiber sensors operate on the principle of interference between two or more light beams to convert phase differences to intensity changes. Common configurations used include Michelson, Mach–Zehnder, and Sagnac interferometers, polarimetric systems, grating and etalon-based interferometers and ring resonators. Interferometric fiber sensors have extremely high sensitivity and are able to resolve path differences of the order of 10^{-6} of the light

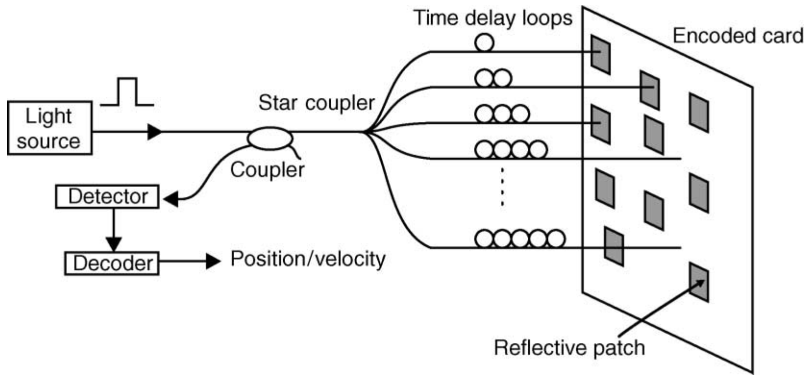

Figure 5 Linear position sensor using time division multiplexing.

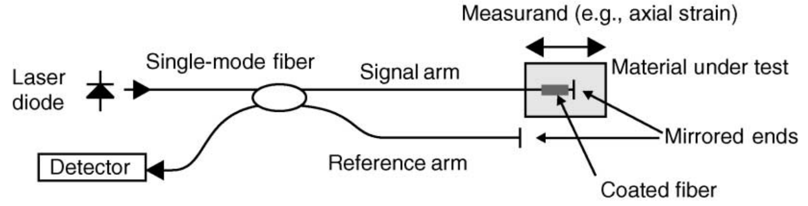

Figure 6 Michelson interferometric strain sensor. Part of the signal arm is embedded in a material, such as concrete (in civil engineering structures) or carbon composite (used in the aerospace industry).

source wavelength. To realize high sensitivity, spectrally pure light sources such as semiconductor lasers must be used. In addition, single mode fibers and components are used to maintain the spatial coherence of the light beams. Factors that affect the performance of interferometric sensors include the optical source phase noise and the polarization states of the interfering light beams.

In two-beam interferometric sensors, such as the Michelson interferometric strain sensor shown in Figure 6, one of the light beams travels through a fiber where its phase can be modulated by the measurand. The two reflected beams recombine on a detector, the output of which is of the form $1 + V \cos \phi$ as shown in Figure 7. ϕ is the relative phase shift between the return beams and V the interferometer visibility. Compensating techniques must be used to ensure that the interferometer sensitivity is maximized. Active techniques involve the insertion of an active device, such as a fiber stretcher, in one of the interferometer arms to control the mean phase difference between the beams. Passive schemes have the advantage in that no active components are required, but usually involve complex signal processing schemes such as active homodyne or synthetic heterodyne demodulation. The sensitivity of the fiber to the measurand can be further improved through the use of specialized coatings.

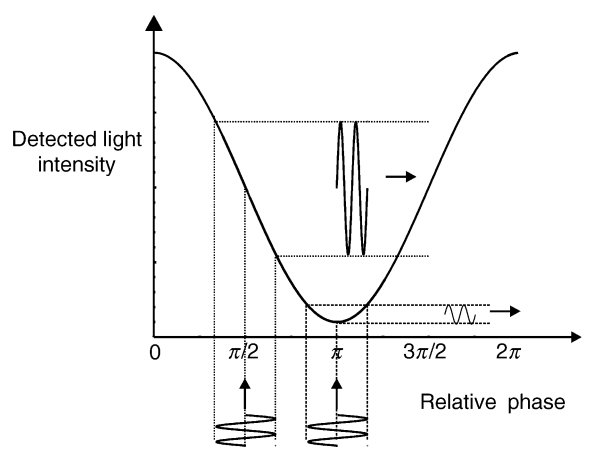

Figure 7 Two-beam interferometer transfer function. The sensitivity is maximized when the mean phase difference between the detected light beams is an odd integer multiple of $\pi/2$. When this is the case the interferometer is said to be operating in quadrature.

Compact interferometric sensors can be constructed using intrinsic or extrinsic Fabry–Perot type configurations, the most common of which are shown in Figure 8. If the Fabry–Perot cavity reflectivities are $\ll 1$, then it can be considered to be a two-beam interferometer.

Polarimetric fiber sensors relate changes induced in the polarization state of light to the measurand.

These sensors usually use high birefringence (Hi-Bi) fiber. The phase difference between the two orthogonally polarized modes of Hi-Bi fiber is given by

$$\phi = \Delta\beta l \qquad [1]$$

where $\Delta\beta$ is the fiber (linear) birefringence and l the fiber length. Both $\Delta\beta$ and l can be changed by the measurand. A polarimetric strain sensor using Hi-Bi fiber embedded in carbon fiber composite, is shown in Figure 9. Light from a linearly polarized He–Ne laser is launched into the Hi-Bi fiber, through a half-waveplate and lens. The waveplate is used to rotate the light plane of polarization so that it is at 45° to the principal axes of the fiber. This ensures that half of the input light power is coupled to each of the fast and slow modes of the Hi-Bi fiber. The output light from the Hi-Bi fiber is passed through a polarization beamsplitter. The beamsplitter separates the light into two orthogonally polarized beams, which are then detected. The output from each of the detectors is given by $V_1 = I_0 \sin^2\phi$ and $V_2 = I_0 \cos^2\phi$, respectively, where I_0 is the input light intensity. The state of polarization (SOP) of the output light from the Hi-Bi fiber is given by

$$\mathrm{SOP} = \frac{V_1 - V_2}{V_1 + V_2} = \cos^2\phi + \sin^2\phi \qquad [2]$$

It is a simple matter to calculate the SOP, from which ϕ can be determined. The form of eqn [2] is very similar to the two-beam interferometer transfer function, shown in Figure 7.

A polarimetric electric current sensor based on the Faraday effect is shown in Figure 10. The Faraday effect provides a rotation of the light's polarization state when a magnetic field is parallel to the optical path in glass. If an optical fiber is closed around a current-carrying conductor, the Faraday rotation is directly proportional to the current. By detecting the polarization rotation of light in the fiber, the current can be measured.

Linearly polarized light is equivalent to a combination of equal intensity right and left circularly polarized components. The linear state of polarization of the polarized laser light rotates in the presence of a magnetic field because the field produces

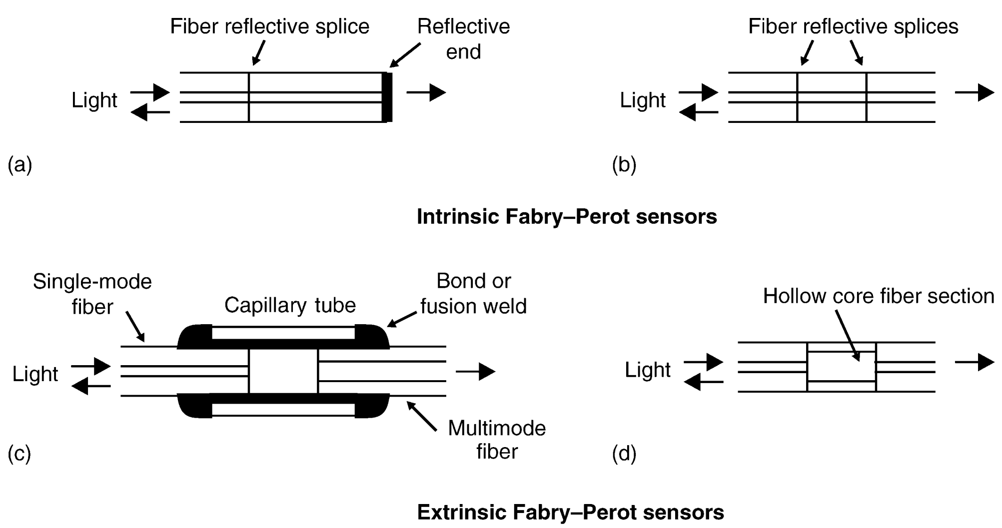

Figure 8 Interferometric fiber Fabry–Perot configurations.

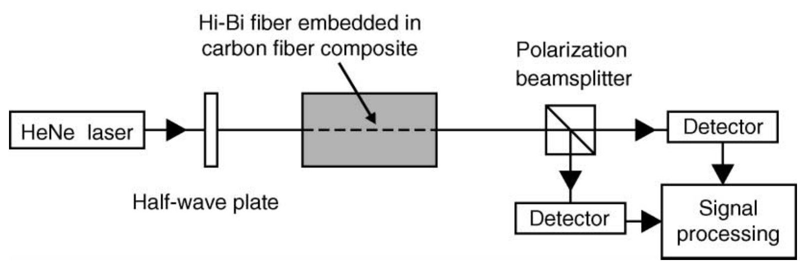

Figure 9 Polarimetric strain sensor system.

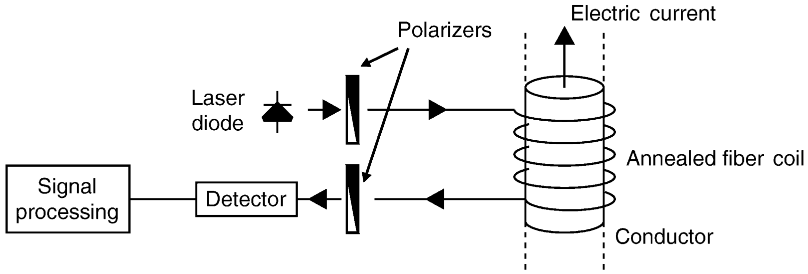

Figure 10 Polarimetric electric current sensor system.

circular birefringence in the fiber. This means that right and left circularly polarized light will travel at different speeds and accumulate a relative phase difference given by

$$\phi = VBl \qquad [3]$$

where V is the Verdet constant (rad Tesla^{-1} m^{-1}) of the glass, B the magnetic field flux density (Tesla), and l the length of the fiber exposed to the magnetic field. In the polarimetric current sensor, the polarization rotation is converted to an intensity change by the output polarizer. The output to the detector is proportional to $1 + \sin(2\phi)$, from which ϕ and the current can be determined.

The linear birefringence of conventional silica fiber is much greater than its circular birefringence. To make a practical current sensor, the linear birefringence must be removed from the fiber and this can be achieved by annealing the fiber. Annealing involves raising the temperature of the fiber, during manufacture, to a temperature above the strain point for a short period of time and slowly cooling back to room temperature. This reduces stresses in the glass, which are the principal cause of linear birefringence, and also cause physical and chemical changes to the glass. Waveguide-induced birefringence cannot be removed by annealing, but can be significantly reduced by twisting the fiber.

White light – or more accurately low-coherence – interferometry utilizes broadband sources such as LEDs and multimode lasers in interferometric measurements. Optical path differences (OPDs) are observed through changes in the interferometric fringe pattern. A processing interferometer is required in addition to the sensing interferometer to extract the fringe information.

The processing of white light interferometry signals relies on two principal techniques. The first technique involves scanning the OPD of the processing interferometer to determine regions of optical path balance. The second technique involves determination of the optical spectrum using an optical spectrum analyzer. The resulting fringe pattern fringe spacing is then related to the OPD of the sensing interferometer.

An example of the optical path scanning technique is shown in Figure 11a. The sensing interferometer is designed such that its OPD is much greater than the coherence length of the light source, so at its output no interference fringes are observed. The output of the sensing interferometer is fed to the processing interferometer. The OPD of the processing interferometer is scanned using a piezoelectric fiber stretcher driven by a suitable scanning voltage. As the processing interferometer is scanned, interference fringes are observed at two distinct points as shown in Figure 11b. The first set of fringes occurs when the OPD of the processing interferometer is within the coherence length of the optical source (close to zero). The second set of fringes occurs when the OPDs in the two interferometers are equal. The OPD in the sensing interferometer can be determined by measuring the OPD in the processing interferometer between the two positions of maximum visibility in the output signal from the detector. This, in turn, can be related to OPD changes due to the action of the measurand, in this case strain.

Sagnac interferometric sensors can be used to create highly sensitive gyroscopes that can be used to sense angular velocity (e.g., in aircraft navigation systems). It is based on the principle that the application of force (e.g., centrifugal force) will alter the wavelength of light as it travels around a coil of optical fiber. A basic open-loop fiber gyroscope is shown in Figure 12. The broadband source (e.g., superluminescent diode) is split into two counter propagating light beams traveling in the clockwise and anticlockwise directions. The polarizer is used to ensure the reciprocity of the counter propagating waves. The inherent nonlinear response of the gyroscope can be overcome by using a phase modulator and signal processing techniques. In the ideal case the detector output is proportional to $1 + \cos\phi_s$. The Sagnac phase shift ϕ_s between the

two returning beams is given by

$$\phi_s = \frac{8\pi AN\Omega}{c\lambda_0} \qquad [4]$$

A is the area enclosed by a single loop of the fiber, N the number of turns, Ω the component of the angular velocity perpendicular to the plane of the loop, λ_0 the free-space wavelength of the optical source, and c the speed of light in a vacuum. Sensitivities greater than 10^{-8} rad/s and dynamic ranges in excess of 40 dB have been achieved with open-loop fiber gyroscopes. More advanced gyroscopes can greatly improve on this performance.

Fiber Grating Sensors

Many types of fiber gratings can be used in sensing applications including Bragg, long-period, and

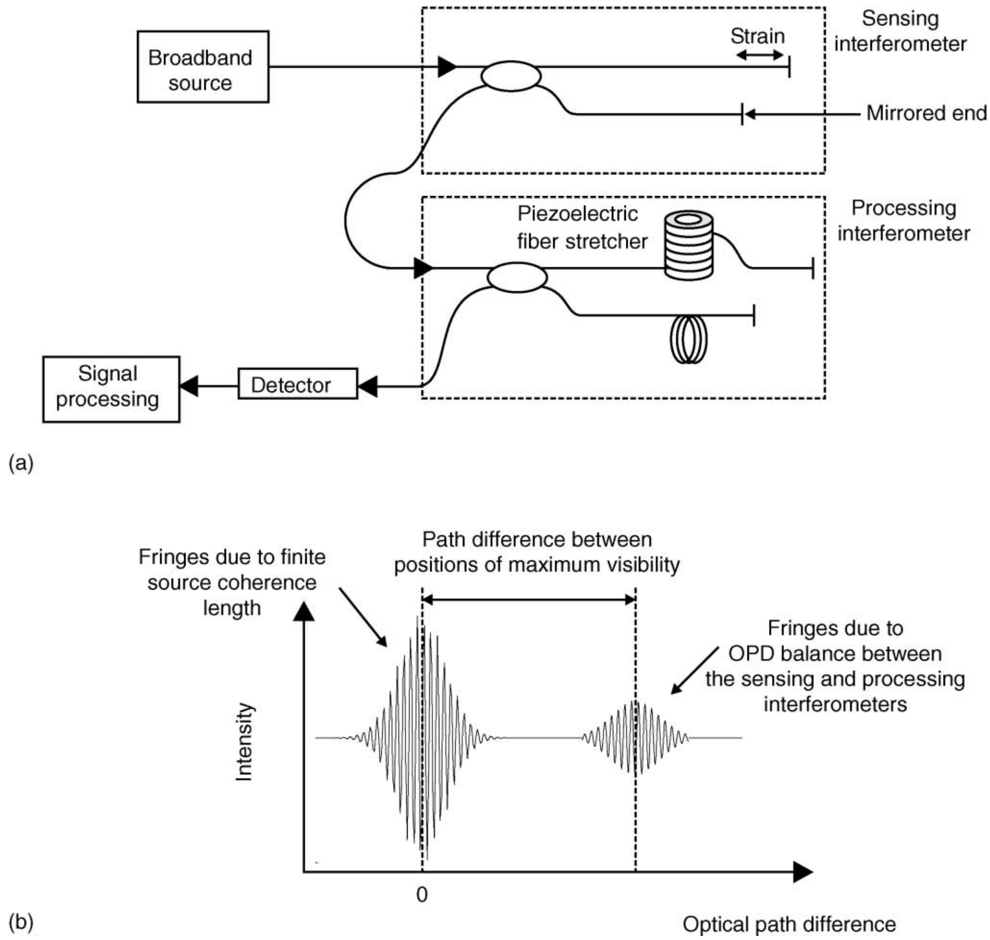

Figure 11 Low-coherence interferometric sensor. (a) Schematic diagram. (b) Output of the scanned processing interferometer.

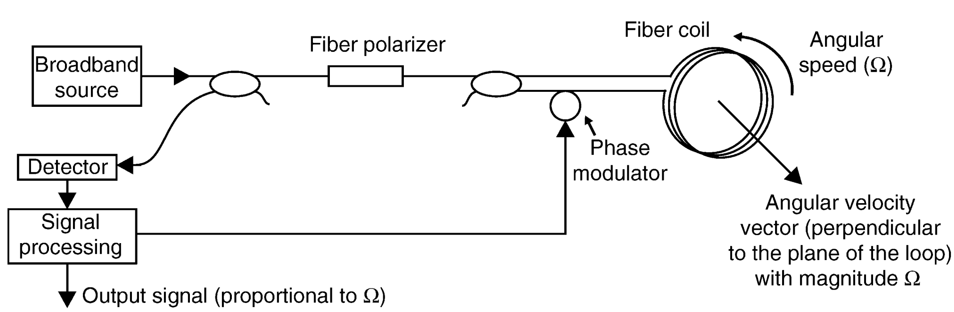

Figure 12 Basic open-loop fiber gyroscope.

chirped gratings. Because fiber gratings are small and have a narrow wavelength response, they can be used for both point and quasi-distributed sensing. They can be embedded in composite materials for smart structure monitoring and also in civil engineering structures such as bridges.

Fiber Bragg gratings (FBGs) are the most popular type of grating sensor. A typical FBG consists of a short section (typically a few mm) of single-mode fiber with a periodic modulation (typically 100s of nm) of the core refractive index. The index modulation causes light in the forward propagating core mode to be coupled into the backward core mode. This causes the FBG to act as a highly wavelength-selective rejection filter. The wavelength of peak reflectivity is the Bragg wavelength $\lambda_B = 2n_{eff}\Lambda$, where n_{eff} is the effective refractive index of the guided mode in the fiber and Λ the index modulation period. Both n_{eff} and Λ can be changed by an external measurand, resulting in a shift in λ_B.

The basic principle of FBG sensors is the measurement of an induced shift in the wavelength of an optical source due to a measurand, such as strain or temperature. A basic reflective FBG sensor system is shown in Figure 13. A broadband light source is used to interrogate the grating, from which a narrowband slice is reflected. The peak wavelength of the reflected spectrum can be compared to λ_B, from which strain or temperature can be inferred. The shift in the Bragg wavelength $\Delta\lambda_B$ with applied microstrain $\Delta(\mu\varepsilon)$ and change in temperature ΔT, for silica fiber is given approximately by

$$\frac{\Delta\lambda_B}{\lambda_B} \approx 0.78 \times 10^{-6}\Delta(\mu\varepsilon) + 6.67 \times 10^{-6}\Delta T \qquad [5]$$

A wavelength resolution of ~1 pm is required (at 1.3 μm) to resolve a temperature change of 0.1 °C or a strain change of 1 $\mu\varepsilon$. The response of the grating to strain can be improved through the use of specialized coatings. Polyimide coatings are commonly used as an efficient strain transducer for gratings embedded in composite materials. Because thermal effects in materials are usually very slow, it is relatively easy to measure dynamic strain (>1 Hz). However, in structural monitoring it can be necessary to distinguish between wavelength shifts due to static strain and those due to temperature. One technique is to use two collocated gratings whose response to strain and temperature is significantly different. In addition to strain and temperature measurement, grating sensors have also been used to measure flow, vibration, electromagnetic fields and chemical effects.

An example of quasi-distributed strain sensing, using a wavelength division multiplexed array of FBGs, is shown in Figure 14. Each FBG in the array has a unique Bragg wavelength. The return light from the FBG array is passed through a tunable narrowband Fabry–Perot filter. As the filter is tuned, the wavelengths returned by the individual FBGs can be analyzed and the strain present at each grating determined.

FBGs can be used as narrowband reflectors for creating fiber laser sensors, capable of measuring temperature, static strain, and very high-resolution dynamic strain. The basic form of an FBG laser sensor system shown in Figure 15 consists of a doped fiber section between two identical FBGs. The doped fiber is optically pumped to provide gain and thereby enable lasing to occur. Single-mode or multi-mode lasing is possible depending on the cavity length. In single-mode operation the FBG laser linewidth can be much smaller than the linewidth of diode lasers. This means that FBG laser sensors have greater sensitivities compared to passive FBG sensors.

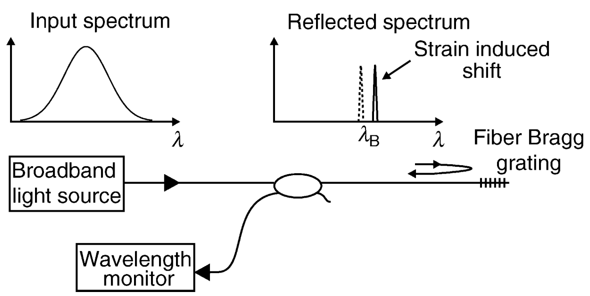

Figure 13 Basic reflective FBG sensor system.

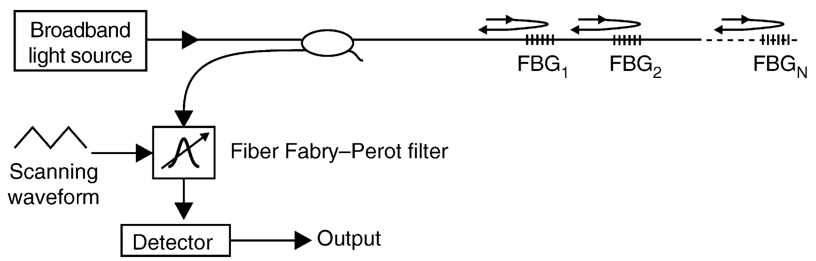

Figure 14 Quasi-distributed strain sensing using a wavelength division multiplexed array of FBGs.

When the cavity is subject to weak dynamic strain, the laser output is frequency modulated. This frequency modulation can be detected by using interferometric techniques. The main advantage of the FBG laser sensor over direct interferometry is that it is possible to obtain comparable strain sensitivities using a much shorter length of fiber.

Long-period fiber gratings (LPFGs) are attracting much interest for use in sensing applications. They are more sensitive to measurands than FBGs and easier to manufacture. A typical LPFG has a length of tens of mm with a grating period of 100s of μm. Its operation is different to an FBG in that coupling occurs between the forward propagating core mode and co-propagating cladding modes. The high attenuation of the cladding modes results in a series of minima occurring in the transmission spectrum of the fiber. This means that the spectral response is strongly influenced by the optical properties of the cladding and surrounding medium. This can be exploited for chemical sensing as shown in Figure 16, where a broadband source is used to interrogate an LPFG. The wavelength shifts of the output spectrum minima can be used to determine the concentration of particular chemicals in the substance surrounding the grating. The longest wavelength attenuation bands are the most sensitive to the refractive index of the substance surrounding the grating. This is because higher order cladding modes extend a greater distance into the external medium. LPFGs can also be used as strain, temperature, refractive index, bend, and load sensors.

Fiber Laser Doppler Velocimeter

Laser Doppler velocimetry (LDV) is a technique used for measuring velocity, especially of fluid flows. A fiber LDV system and associated scattering geometry is shown in Figure 17. In LDV two coherent laser beams intersect in a small measurement volume where they can interfere. The light reflected by a seed particle passing through the measurement volume is modulated at a frequency proportional to the spatial frequency (Doppler difference frequency Δf) of the interference fringes and the component of its velocity

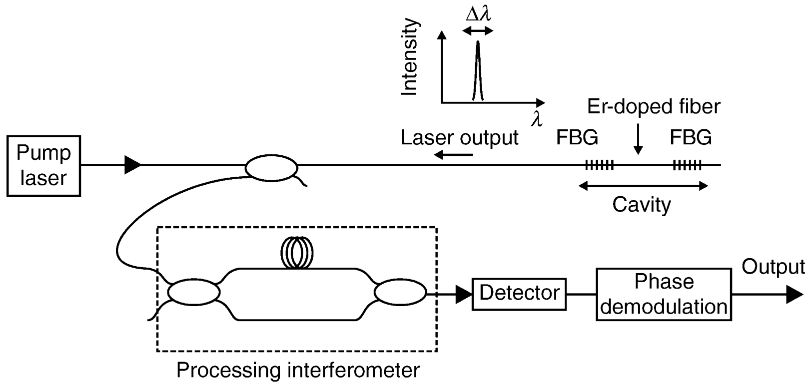

Figure 15 FBG laser sensor with interferometric detection.

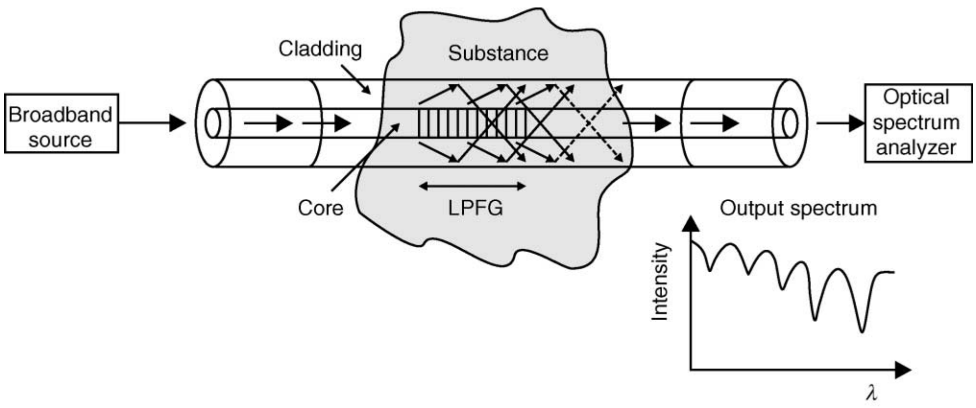

Figure 16 Detail of LPFG sensor.

normal to the interference fringes. Δf is given by

$$\Delta f = \frac{2nV \cos \beta}{\lambda_0} \sin(\theta/2) \qquad [6]$$

where n is the fluid refractive index, V the particle velocity and λ_0 the laser free-space wavelength. The output of the detector is processed to extract Δf and therefore $V \cos \beta$. Δf is independent of the scattered light direction so collection of the scattered light using a lens increases the system sensitivity. The form of eqn [6] indicates that the direction of flow cannot be ascertained. The simplest technique to resolve this ambiguity is to apply a frequency shift Δf_s to one of the input beams. This can be achieved by the use of a piezoelectric frequency shifter. The frequency shift causes a phase shift to appear between the two beams. The phase shift increases linearly with time. This results in a fringe pattern of spacing s, which moves with constant velocity $V_f = s\Delta f_s$. In this case the measured Δf will be less than or greater than Δf_s, depending on whether the particle is moving with or against the fringe motion. There will then be an unambiguous detectable range of velocities from zero to V_f.

Luminescence-Based Fiber Sensors

Luminescence-based fiber sensors are usually based on fluorescence or amplified spontaneous emission occurring in rare earth materials. They can be used in many applications such as chemical, humidity, and temperature sensing. It is possible to connect a fiber to luminescent material or to introduce luminescent dopants into the fiber. An example of the latter, used to detect chemical concentration is shown in Figure 18. A laser pulse causes the doped section of the fiber to luminesce at a longer wavelength than the

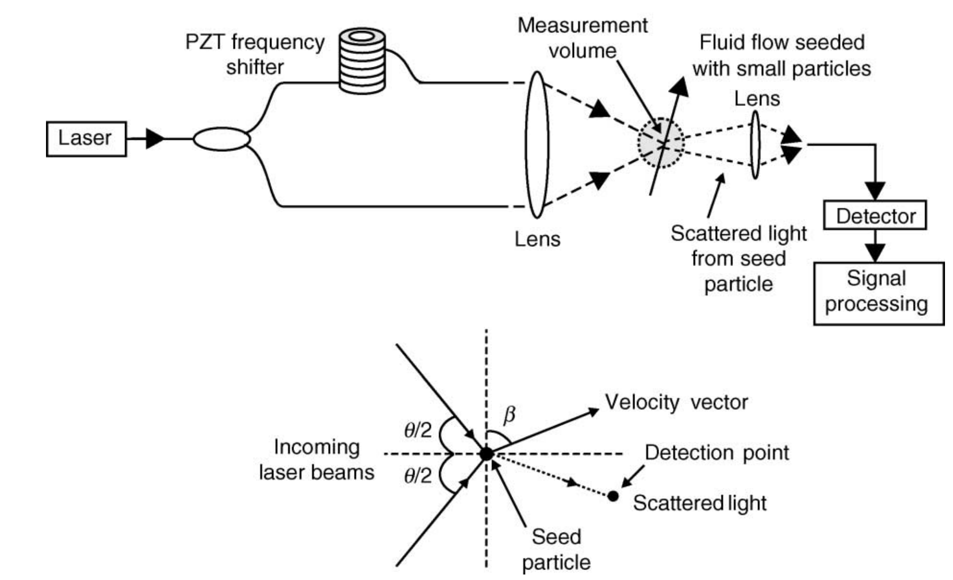

Figure 17 Fiber Doppler velocimeter and scattering geometry.

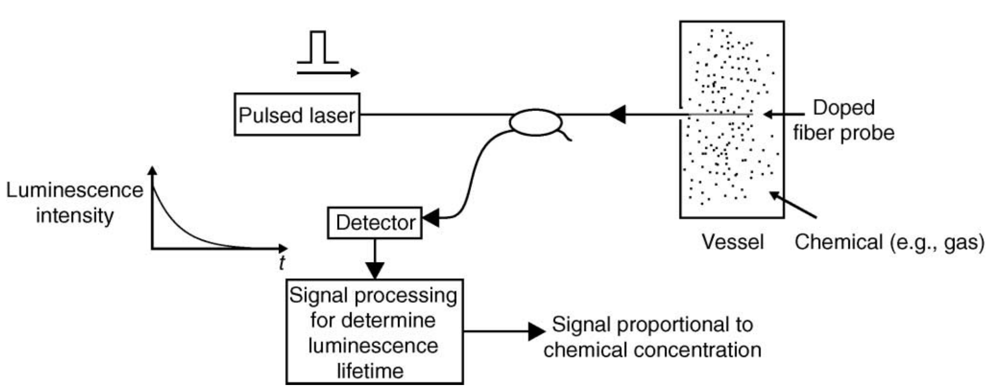

Figure 18 Chemical sensor based on fluorescence in doped optical fiber.

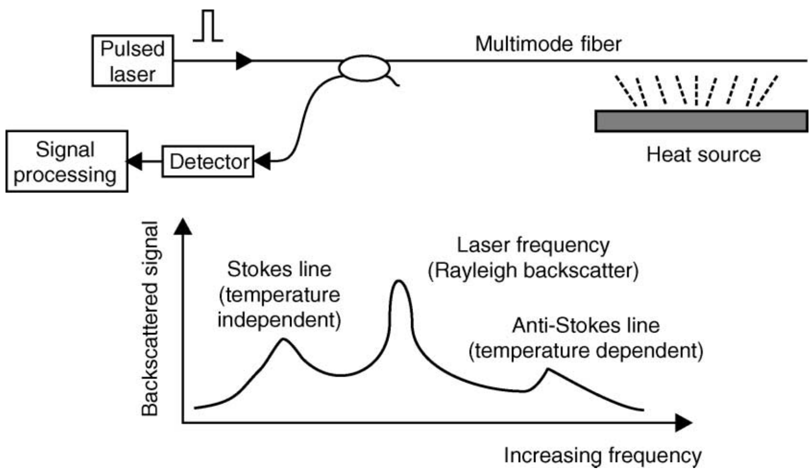

Figure 19 Anti-Stokes Raman thermometry system.

laser. The luminescence intensity *I(t)* at the detector has an exponential decay profile given by

$$I(t) = I_0 \exp\big(-(k_1 + k_2 C)t\big) \qquad [7]$$

where I_0 is the initial luminescence intensity, t time, k_1, k_2 constants, and C the chemical concentration. The luminescence time constant $1/(k_1 + k_2 C)$ can be determined by comparing the luminescence intensity at various times after excitation by the laser pulse, from which C can be determined. The use of time division multiplexing allows quasi-distributed measurement of chemical concentration. The use of plastic optical fiber for luminescence-based sensors is attracting much interest.

Distributed Fiber Sensing

We have seen that both point and quasi-distributed sensing are possible using fiber sensors. Distributed sensing can be achieved through the use of linear or nonlinear backscattering or forward scattering techniques. In linear backscattering systems, light backscattered from a pulse propagating in an optical fiber is time resolved and analyzed to obtain the spatial distribution of the measurand field, e.g., polarization optical time domain reflectometry analyzes the polarization state of backscattered light to determine the spatial distribution of electromagnetic fields. Nonlinear backscattering schemes use effects such as Raman or Brillouin scattering. An important example of the former is the anti-Stokes Raman thermometry system shown in Figure 19. A light pulse is transmitted down the sensing fiber. Spontaneous Raman scattering causes Stokes and anti-Stokes photons to be generated along the fiber. Some of these photons travel back along the fiber to a fast detector. The intensity of the Stokes line is temperature independent. The anti-Stokes line intensity is a function of temperature. The ratio of the two intensities provides a very accurate measurement of temperature. The measurement location is determined by timing of the laser pulse.

See also

Environmental Measurements: Laser Detection of Atmospheric Gases. **Fiber Gratings**. **Interferometry:** Overview; Phase Measurement Interferometry; White Light Interferometry. **Optical Materials:** Smart Optical Materials.

Further Reading

Culshaw B and Dakin JP (1988, 1989, 1997) *Optical Fiber Sensors*, vols. I, II, III. Norwood, MA: Artech House.

Grattan KTV and Meggitt BT (1994, 1997, 1999, 1999) *Optical Fiber Sensor Technology*, vols. I, II, III and IV. Boston, CA: Kluwer Academic.

Grattan KTV and Meggitt BT (2000) *Optical Fiber Sensor Technology*. Boston, MA: Kluwer Academic.

Kersey AD, Davis MA, Patrick HJ, *et al.* (1997) Fiber grating sensors. *Journal of Lightwave Technology* 15: 1442–1463.

Krohn DA (1999) *Fiber Optic Sensors: Fundamentals and Applications*, 3rd edn. Research Triangle Park, NC: Instrumentation Society of America.

Lopez-Higuera JM (2001) *Handbook of Optical Fiber Sensing Technology*. New York: Wiley.

Othonos A and Kalli K (1999) *Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing*. Norwood, MA: Artech House.

Udd E (1991) *Fiber Optic Sensors: An Introduction for Engineers and Scientists*. New York: Wiley.

Udd E (1995) *Fiber Optic Smart Structures*. New York: Wiley.

Yu FTS and Yin S (2002) *Fiber Optic Sensors*. New York: Marcel Dekker.