

Overview of Fiber Optic Sensors

Over the past twenty years two major product revolutions have taken place due to the growth of the optoelectronics and fiber optic communications industries. The optoelectronics industry has brought about such products as compact disc players, laser printers, bar code scanners and laser pointers. The fiber optic communication industry has literally revolutionized the telecommunication industry by providing higher performance, more reliable telecommunication links with ever decreasing bandwidth cost. This revolution is bringing about the benefits of high volume production to component users and a true information superhighway built of glass.

In parallel with these developments fiber optic sensor [1-6] technology has been a major user of technology associated with the optoelectronic and fiber optic communication industry. Many of the components associated with these industries were often developed for fiber optic sensor applications. Fiber optic sensor technology in turn has often been driven by the development and subsequent mass production of components to support these industries. As component prices have fallen and quality improvements have been made, the ability of fiber optic sensors to displace traditional sensors for rotation, acceleration, electric and magnetic field measurement, temperature, pressure, acoustics, vibration, linear and angular position, strain, humidity, viscosity, chemical measurements and a host of other sensor applications, has been enhanced. In the early days of fiber optic sensor technology most commercially successful fiber optic sensors were squarely targeted at markets where existing sensor technology was marginal or in many cases nonexistent. The inherent advantages of fiber optic sensors which include their ability to be lightweight, of very small size, passive, low power, resistant to electromagnetic interference, high sensitivity, wide bandwidth and environmental ruggedness were heavily used to offset their major disadvantages of high cost and unfamiliarity to the end user.

The situation is changing. Laser diodes that cost \$3000 in 1979 with lifetimes measured in hours now sell for a few dollars in small quantities, have reliability of tens of thousands of hours and are used widely in compact disc players, laser printers, laser pointers and bar code readers. Single mode optical fiber that cost \$20/m in 1979 now costs less than \$0.10/m with vastly improved optical and mechanical properties. Integrated optical devices that were not available in usable form at that time are now commonly used to support production models of fiber optic gyros. Also, they could drop dramatically in price in the future while offering ever more sophisticated optical circuits. As these trends continue, the opportunities for fiber optic sensor designers to produce competitive products will increase and the technology can be expected to assume an ever more prominent position in the sensor marketplace. In the following sections the basic types of fiber optic sensors that are being developed will be briefly reviewed followed by a discussion of how these sensors are and will be applied.

Basic Concepts and Intensity Based Fiber Optic Sensors

Fiber optic sensors are often loosely grouped into two basic classes referred to as extrinsic or hybrid fiber optic sensors, and intrinsic or all fiber sensors. Figure 1 illustrates the case of an extrinsic or hybrid fiber optic sensor.

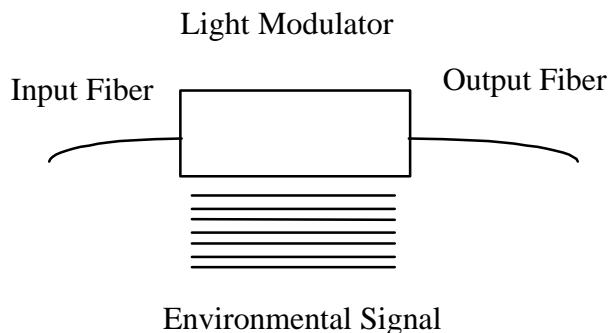


Figure 1. Extrinsic fiber optic sensors consist of optical fibers that lead up to and out of a "black box" that modulates the light beam passing through it in response to an environmental effect.

In this case an optical fiber leads up to a "black box" which impresses information onto the light beam in response to an environmental effect. The information could be impressed in terms of intensity, phase, frequency, polarization, spectral content or other methods. An optical fiber then carries the light with the environmentally impressed information back to an optical and/or electronic processor. In some cases the input optical fiber also acts as the output fiber. The intrinsic or all fiber sensor shown in Figure 2 uses an optical fiber to carry the light beam and the environmental effect impresses information onto the light beam while it is in the fiber. Each of these classes of fibers in turn has many subclasses with, in some cases sub subclasses (1) that consist of large numbers of fiber sensors.

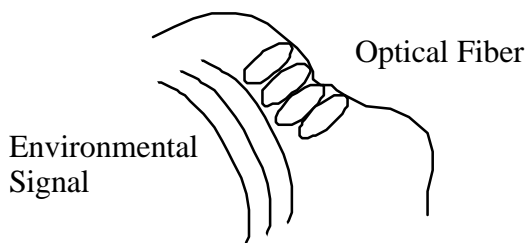


Figure 2. Intrinsic fiber optic sensors rely on the light beam propagating through the optical fiber being modulated by the environmental effect either directly or through environmentally induced optical path length changes in the fiber itself.

In some respects the simplest type of fiber optic sensor is the hybrid type that is based on intensity modulation [7-8]. Figure 3 shows a simple closure or vibration sensor that consist of two optical fibers that are held in close proximity to each other. Light is injected into one of the optical fibers and when it exits the light expands into a cone of

light whose angle depends on the difference between the index of refraction of the core and cladding of the optical fiber. The amount of light captured by the second optical fiber depends on its acceptance angle and the distance d between the optical fibers. When the distance d is modulated, it in turn results in an intensity modulation of the light captured.

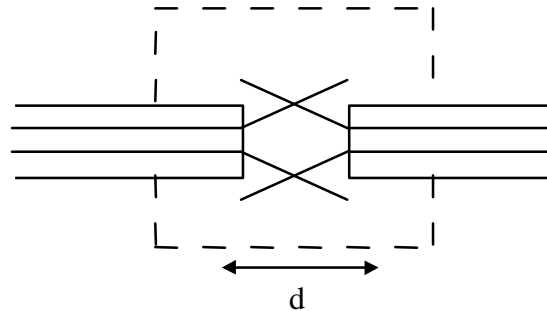


Figure 3. Closure and vibration fiber optic sensors based on numerical aperture can be used to support door closure indicators and measure levels of vibration in machinery.

A variation on this type of sensor is shown in Figure 4. Here a mirror is used that is flexibly mounted to respond to an external effect such as pressure. As the mirror position shifts the effective separation between the optical fibers shift with a resultant intensity modulation. These types of sensors are useful for such applications as door closures where a reflective strip, in combination with an optical fiber acting to input and catch the output reflected light, can be used.

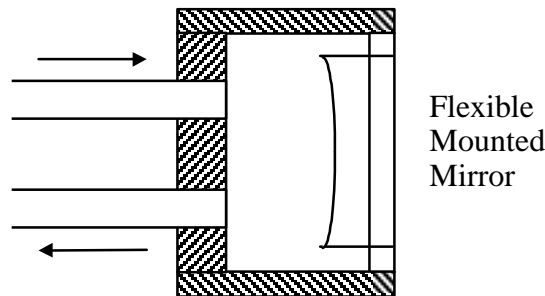


Figure 4. Numerical aperture fiber sensor based on a flexible mirror can be used to measure small vibrations and displacements.

By arranging two optical fibers in line, a simple translation sensor can be configured as in Figure 5. The output from the two detectors can be proportioned to determine the translational position of the input fiber.

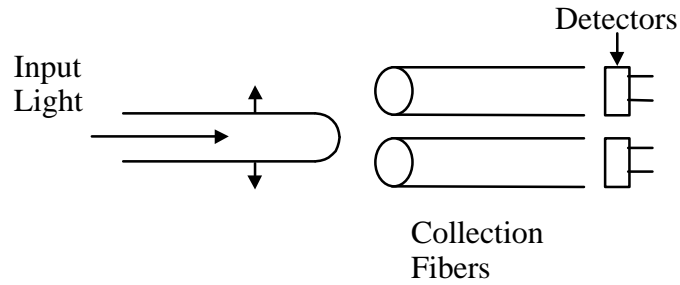


Figure 5. Fiber optic translation sensor based on numerical aperture uses the ratio of the output on the detectors to determine the position of the input fiber.

Several companies have developed rotary and linear fiber optic position sensors to support applications such as fly-by-light [9]. These sensors attempt to eliminate electromagnetic interference susceptibility to improve safety, and to reduce shielding needs to reduce weight. Figure 6 shows a rotary position sensor [10] that consists of a code plate with variable reflectance patches placed so that each position has a unique code. A series of optical fibers are used to determine the presence or absence of a patch.

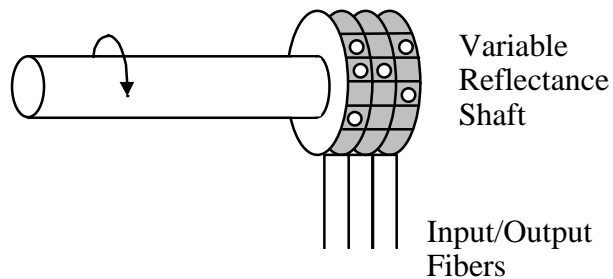


Figure 6. Fiber optic rotary position sensor based on reflectance used to measure rotational position of the shaft via the amount of light reflected from dark and light patches.

An example of a linear position sensor using wavelength division multiplexing [11] is illustrated by Figure 7. Here a broadband light source which might be a light emitting diode is used to couple light into the system. A single optical fiber is used to carry the light beam up to a wavelength division multiplexing (WDM) element that splits the light into separate fibers that are used to interrogate the encoder card and determine linear position. The boxes on the card of Figure 7 represent highly reflective patches while the rest of the card has low reflectance. The reflected signals are then recombined and separated out by a second wavelength division multiplexing element so that each interrogating fiber signal is read out by a separate detector.

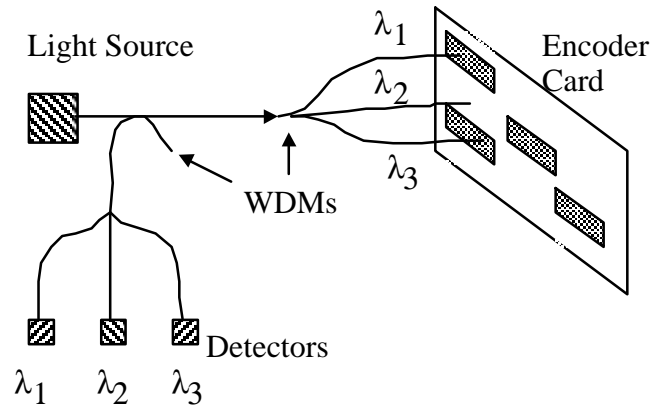


Figure 7. Linear position sensor using wavelength division multiplexing decodes position by measuring the presence or absence of reflective patch at each fiber position as the card slides by via independent wavelength separated detectors.

A second common method of interrogating a position sensor using a single optical fiber is to use time division multiplexing methods [12]. In Figure 8 a light source is pulsed. The light pulse then propagates down the optical fiber and is split into multiple interrogating fibers. Each of these fibers is arranged so that they have delay lines that separate the return signal from the encoder plate by a time that is longer than the pulse duration. When the returned signals are recombined onto the detector the net result is an encoded signal burst corresponding to the position of the encoded card.

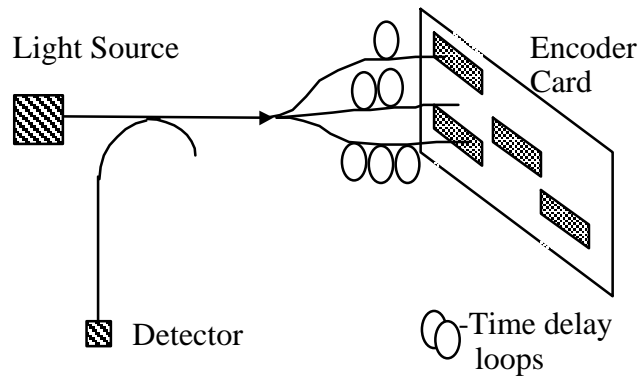


Figure 8. Linear position sensor using time division multiplexing measure decodes card position via a digital stream of on's and off's dictated by the presence or absence of a reflective patch.

These sensors have been used to support tests on military and commercial aircraft that have demonstrated performance comparable to conventional electrical position sensors used for rudder, flap and throttle position [9]. The principal advantages of the fiber position sensors are immunity to electromagnetic interference and overall weight savings.

Another class of intensity based fiber optic sensors is based on the principle of total internal reflection. In the case of the sensor in Figure 9, light propagates down the fiber core and hits the angled end of the fiber. If the medium into which the angled end of the

fiber is placed has a low enough index of refraction then virtually all the light is reflected when it hits the mirrored surface and returns via the fiber. If however the index of refraction of the medium starts to approach that of the glass some of the light propagates out of the optical fiber and is lost resulting in an intensity modulation.

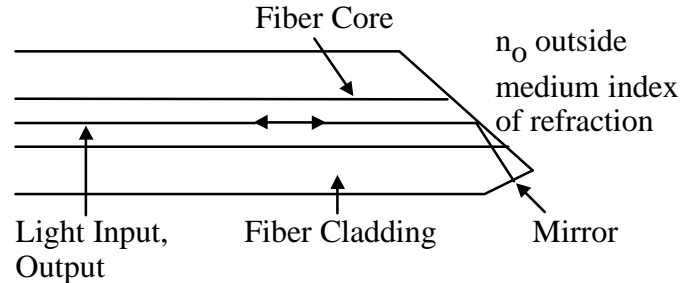


Figure 9. Fiber sensor using critical angle properties of a fiber for pressure/index of refraction measurement via measurements of the light reflected back into the fiber.

This type of sensor can be used for low resolution measurement of pressure or index of refraction changes in a liquid or gel with one to ten percent accuracy. Variations on this method have also been used to measure liquid level [13] as shown by the probe configuration of Figure 10. When the liquid level hits the reflecting prism the light leaks into the liquid greatly attenuating the signal.

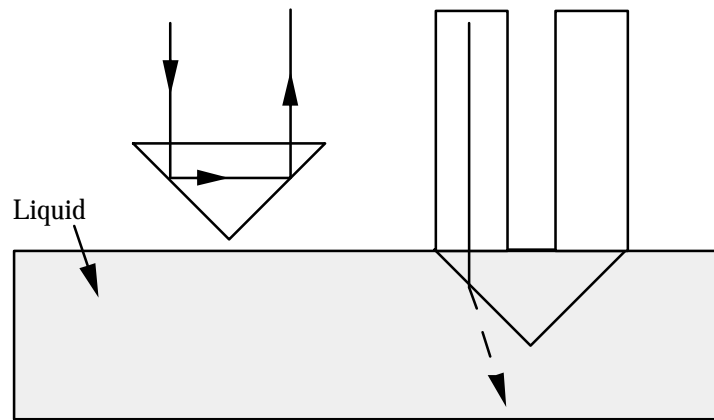


Figure 10. Liquid level sensor based on total internal reflection detects the presence or absence of liquid by the presence or absence of a return light signal.

Confinement of a propagating light beam to the region of the fiber cores and power transfer from two closely placed fiber cores can be used to produce a series of fiber sensors based on evanescence [14-16]. Figure 11 illustrates two fiber cores that have been placed in close proximity to one another. For single mode optical fiber [17] this distance is on the order of 10 to 20 microns.

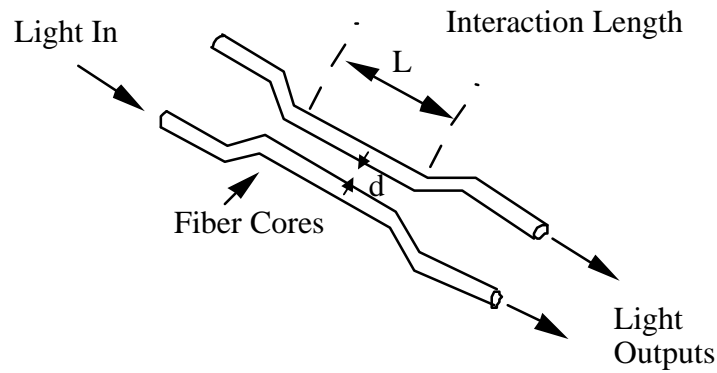


Figure 11. Evanescence based fiber optic sensors rely on the cross coupling of light between two closely spaced fiber optic cores. Variations in this distance due to temperature, pressure or strain offer environmental sensing capabilities.

When single mode fiber is used there is considerable leakage of the propagating light beam mode beyond the core region into the cladding or medium around it. If a second fiber core is placed nearby this evanescent tail will tend to cross couple to the adjacent fiber core. The amount of cross coupling depends on a number of parameters including the wavelength of light, the relative index of refraction of the medium in which the fiber cores are placed, the distance between the cores and the interaction length. This type of fiber sensor can be used for the measurement of wavelength, spectral filtering, index of refraction and environmental effects acting on the medium surrounding the cores (temperature, pressure and strain). The difficulty with this sensor that is common to many fiber sensors is optimizing the design so that only the desired parameters are sensed.

Another way that light may be lost from an optical fiber is when the bend radius of the fiber exceeds the critical angle necessary to confine the light to the core area and there is leakage into the cladding. Microbending of the fiber locally can cause this to result with resultant intensity modulation of light propagating through an optical fiber. A series of microbend based fiber sensors have been built to sense vibration, pressure and other environmental effects [18-20]. Figure 12 shows a typical layout of this type of device consisting of a light source, a section of optical fiber positioned in a microbend transducer designed to intensity modulate light in response to an environmental effect and a detector. In some cases the microbend transducer can be implemented by using special fiber cabling or optical fiber that is simply optimized to be sensitive to microbending loss.

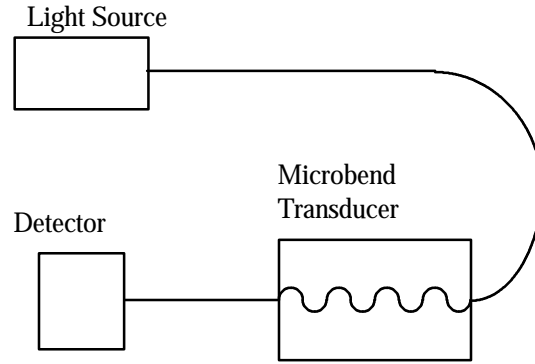


Figure 12. Microbend fiber sensors are configured so that an environmental effect results in an increase or decrease in loss through the transducer due to light loss resulting from small bends in the fiber.

One last example of an intensity based sensor is the grating based device [21] shown in Figure 13. Here an input optical light beam is collimated by a lens and passes through a dual grating system. One of the gratings is fixed while the other moves. With acceleration the relative position of the gratings changes resulting in an intensity modulated signal on the output optical fiber.

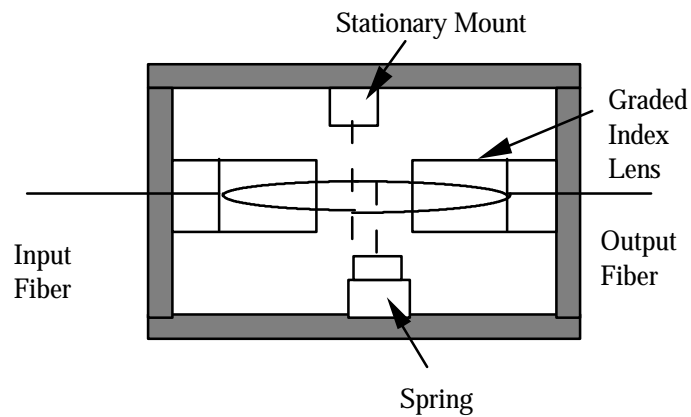


Figure 13. Grating based fiber intensity sensors measure vibration or acceleration via a highly sensitive shutter effect.

One of the limitations of this type of device is that as the gratings move from a totally transparent to a totally opaque position the relative sensitivity of the sensor changes as can be seen from Figure 14. For optimum sensitivity the gratings should be in the half open half closed position. Increasing sensitivity means finer and finer grating spacings which in turn limit dynamic range.

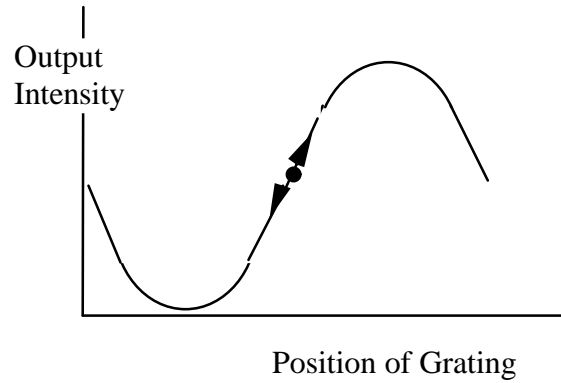


Figure 14. Dynamic range limitations of the grating based sensor of Figure 13 are due to smaller grating spacing increasing sensitivity at the expense of range.

To increase sensitivity without limiting dynamic range, use multiple part gratings that are offset by 90 degrees as shown in Figure 15. If two outputs are spaced in this manner the resulting outputs are in quadrature as shown in Figure 16.

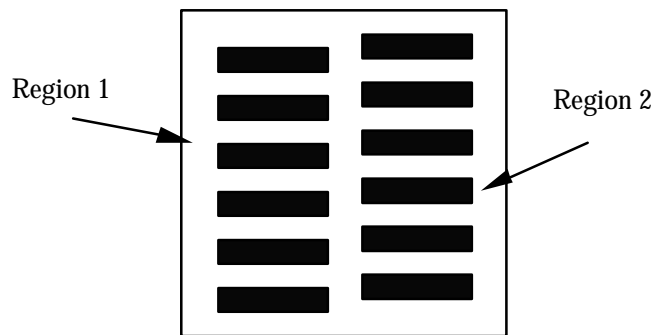


Figure 15. Dual grating mask with regions 90 degrees out of phase to support quadrature detection which allows grating based sensors to track through multiple lines.

When one output is at optimal sensitivity the other is at its lowest sensitivity and vice versa. By using both outputs for tracking, one can scan through multiple grating lines enhancing dynamic range and avoiding signal fade out associated with positions of minimal sensitivity.

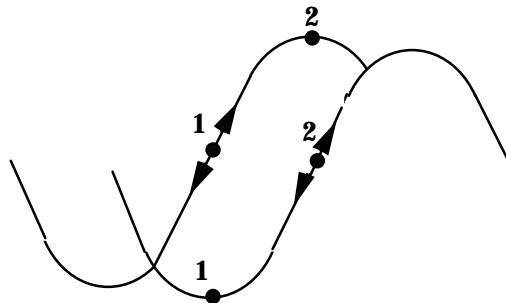


Figure 16. Diagram illustrating quadrature detection method that allows one area of maximum sensitivity while the other reaches a minimum and vice versa, allowing uniform sensitivity over a wide dynamic range.

Intensity based fiber optic sensors have a series of limitations imposed by variable losses in the system that are not related to the environmental effect to be measured. Potential error sources include variable losses due to connectors and splices, microbending loss, macrobending loss, and mechanical creep and misalignment of light sources and detectors. To circumvent these problems many of the successful higher performance intensity based fiber sensors employ dual wavelengths. One of the wavelengths is used to calibrate out all of the errors due to undesired intensity variations by bypassing the sensing region. An alternative approach is to use fiber optic sensors that are inherently resistant to errors induced by intensity variations. In the next section a series of spectrally based fiber sensors that have this characteristic are discussed.

Spectrally Based Fiber Optic Sensors

Spectrally based fiber optic sensors depend on a light beam being modulated in wavelength by an environmental effect. Examples of these types of fiber sensors include those based on blackbody radiation, absorption, fluorescence, etalons and dispersive gratings.

One of the simplest of these types of sensors is the blackbody sensor of Figure 17. A blackbody cavity is placed at the end of an optical fiber. When the cavity rises in temperature it starts to glow and act as a light source.

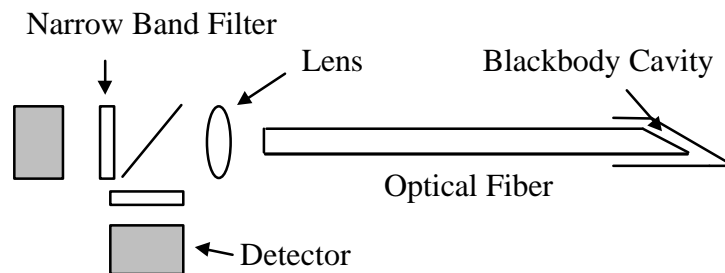


Figure 17. Blackbody fiber optic sensors allow the measurement of temperature at a hot spot and are most effective at temperatures of higher than 300 degrees C.

Detectors in combination with narrow band filters are then used to determine the profile of the blackbody curve and in turn the temperature as in Figure 18. This type of sensor has been successfully commercialized and has been used to measure temperature to within a few degrees C under intense RF fields. The performance and accuracy of this sensor is better at higher temperatures and falls off at temperatures on the order of 200 degrees C because of low signal to noise ratios. Care must be taken to insure that the hottest spot is the blackbody cavity and not on the optical fiber lead itself as this can corrupt the integrity of the signal.

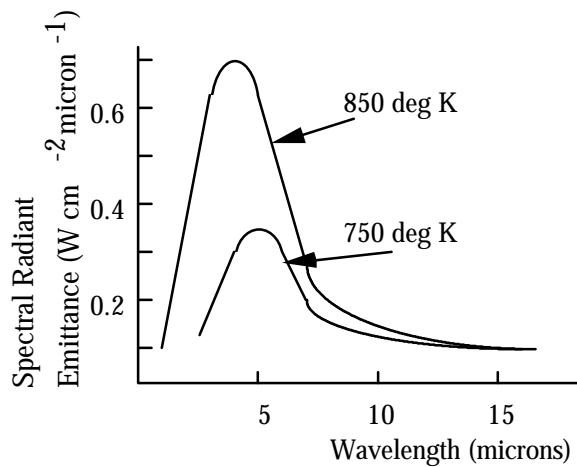


Figure 18. Blackbody radiation curves provide unique signatures for each temperature.

Another type of spectrally based temperature sensor is shown in Figure 19 and is based on absorption [22]. In this case a Gallium Arsenide (GaAs) sensor probe is used in combination with a broadband light source and input/output optical fibers. The absorption profile of the probe is temperature dependent and may be used to determine temperature.

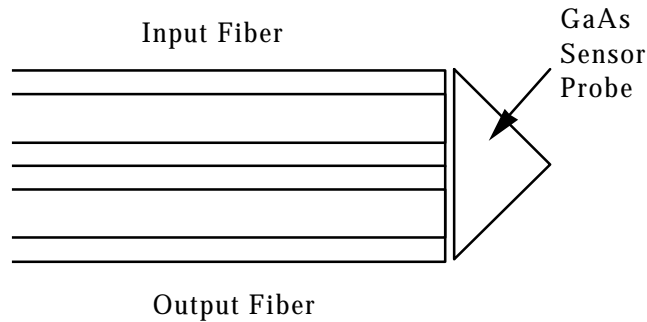


Figure 19. Fiber optic sensor based on variable absorption of materials such as GaAs allow the measurement of temperature and pressure.

Fluorescent based fiber sensors [23-24] are being widely used for medical applications, chemical sensing and can also be used for physical parameter measurements such as temperature, viscosity and humidity. There are a number of configurations for these sensors and Figure 20 illustrates two of the most common ones. In the case of the end tip sensor, light propagates down the fiber to a probe of fluorescent material. The resultant fluorescent signal is captured by the same fiber and directed back to an output demodulator. The light sources can be pulsed and probes have been made that depend on the time rate of decay of the light pulse.

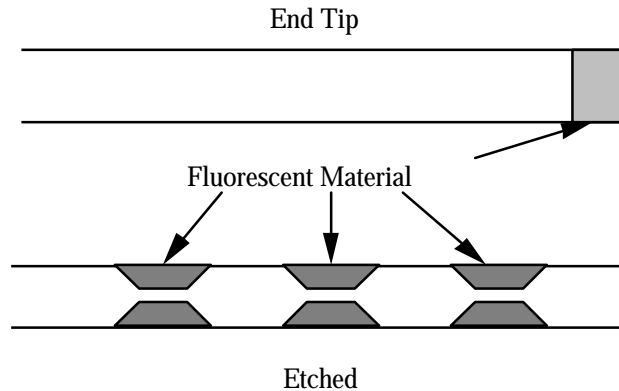


Figure 20. Fluorescent fiber optic sensor probe configurations can be used to support the measurement of physical parameters as well as the presence or absence of chemical species. These probes may be configured to be single ended or multipoint by using side etch techniques and attaching the fluorescent material to the fiber.

In the continuous mode, parameters such as viscosity, water vapor content and degree of cure in carbon fiber reinforced epoxy and thermoplastic composite materials can be monitored.

An alternative is to use the evanescent properties of the fiber and etch regions of the cladding away and refill them with fluorescent material. By sending a light pulse down the fiber and looking at the resulting fluorescence, a series of sensing regions may be time division multiplexed.

It is also possible to introduce fluorescent dopants into the optical fiber itself. This approach would cause the entire optically activated fiber to fluoresce. By using time division multiplexing, various regions of the fiber could be used to make a distributed measurement along the fiber length.

In many cases users of fiber sensors would like to have the fiber optic analog of conventional electronic sensors. An example is the electrical strain gauge that is used widely by structural engineers. Fiber grating sensors [25-28] can be configured to have gauge lengths from 1 mm to approximately 1 cm, with sensitivity comparable to conventional strain gauges.

This sensor is fabricated by "writing" a fiber grating onto the core of a Germanium doped optical fiber. This can be done in a number of ways. One method, which is illustrated by Figure 21, uses two short wavelength laser beams that are angled to form an interference pattern through the side of the optical fiber. The interference pattern consists of bright and dark bands that represent local changes in the index of refraction in the core region of the fiber. Exposure time for making these gratings varies from minutes to hours, depending on the dopant concentration in the fiber, the wavelengths used, the optical power level and the imaging optics.

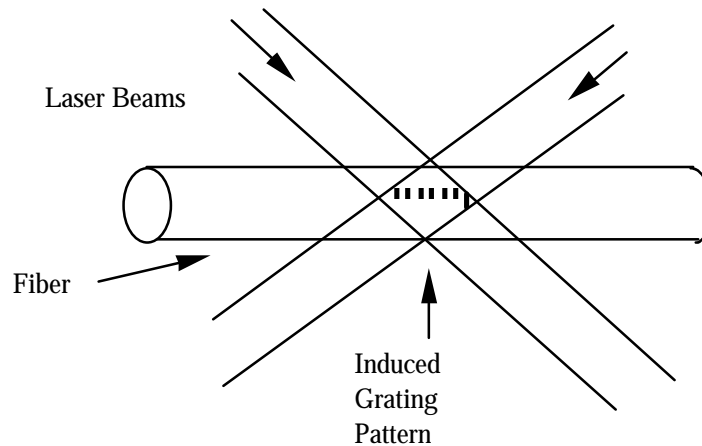


Figure 21. Fabrication of a fiber grating sensor can be accomplished by imaging to short wavelength laser beams through the side of the optical fiber to form an interference pattern. The bright and dark fringes which are imaged on the core of the optical fiber induce an index of refraction variation resulting in a grating along the fiber core.

Other methods that have been used include the use of phase masks, and interference patterns induced by short high-energy laser pulses. The short duration pulses have the potential to be used to write fiber gratings into the fiber as it is being drawn.

Substantial efforts are being made by laboratories around the world to improve the manufacturability of fiber gratings as they have the potential to be used to support optical communication as well as sensing technology.

Once the fiber grating has been fabricated the next major issue is how to extract information. When used as a strain sensor the fiber grating is typically attached to, or embedded in, a structure. As the fiber grating is expanded or compressed, the grating period expands or contracts, changing the gratings spectral response.

For a grating operating at 1300 nm the change in wavelength is about 10^{-3} nm per microstrain. This type of resolution requires the use of spectral demodulation techniques that are much better than those associated with conventional spectrometers. Several demodulation methods have been suggested using fiber gratings, etalons and interferometers [29-30]. Figure 22 illustrates a system that uses a reference fiber grating. The action of the reference fiber grating is to act as a modulator filter. By using similar gratings for the reference and signal gratings and adjusting the reference grating to line up with the active grating, an accurate closed loop demodulation system may be implemented.

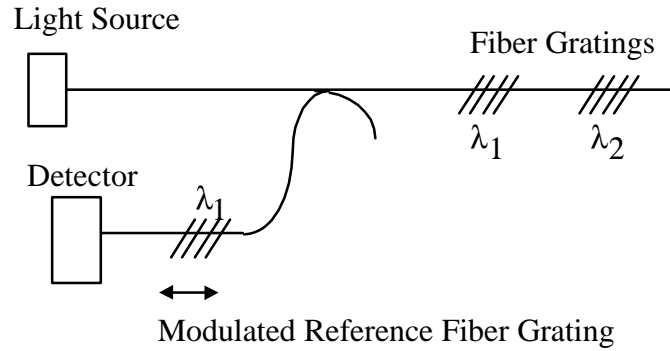


Figure 22. Fiber grating demodulation systems require very high resolution spectral measurements. One way to accomplish this is to beat the spectrum of light reflected by the fiber grating against the light transmission characteristics of a reference grating.

An alternative demodulation system would use fiber etalons such as those shown in Figure 23. One fiber can be mounted on a piezoelectric and the other moved relative to a second fiber end. The spacing of the fiber ends as well as their reflectivity in turn determines the spectral filtering action of the fiber etalon that is illustrated by Figure 24.

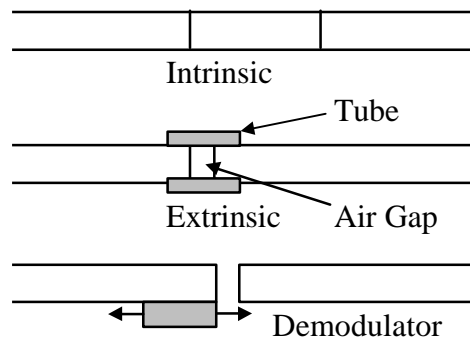


Figure 23. Intrinsic fiber etalons are formed by in line reflective mirrors that can be embedded into the optical fiber. Extrinsic fiber etalons are formed by two mirrored fiber ends in a capillary tube. A fiber etalon based spectral filter or demodulator is formed by two reflective fiber ends that have a variable spacing.

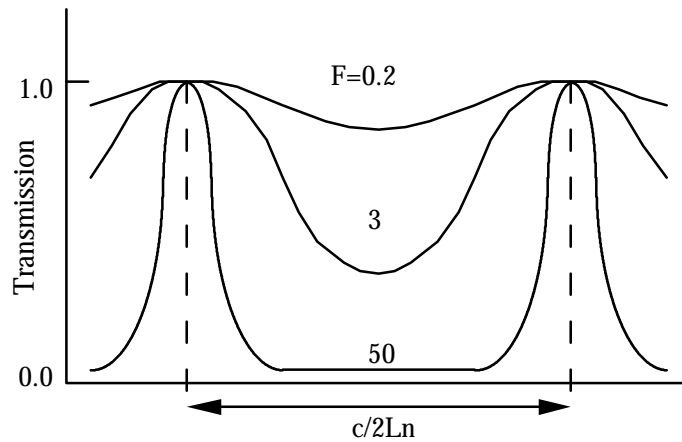


Figure 24. Diagram illustrating the transmission characteristics of a fiber etalon as a function of finesse, which increases with mirror reflectivity.

The fiber etalons in Figure 23 can also be used as sensors [31-33] for measuring strain as the distance between mirrors in the fiber determines their transmission characteristics. The mirrors can be fabricated directly into the fiber by cleaving the fiber, coating the end with titanium dioxide, and then resplicing. An alternative approach is to cleave the fiber ends and insert them into a capillary tube with an air gap. Both of these approaches are being investigated for applications where multiple, in line fiber sensors are required.

For many applications a single point sensor is adequate. In these situations an etalon can be fabricated independently and attached to the end of the fiber. Figure 25 shows a series of etalons that have been configured to measure pressure, temperature and refractive index respectively.

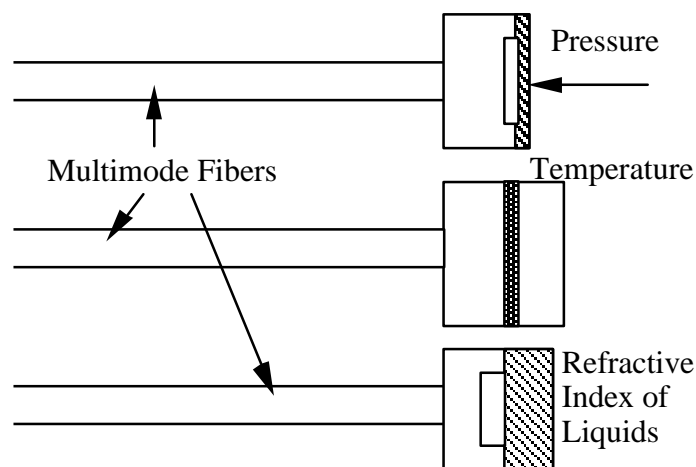


Figure 25. Hybrid etalon based fiber optic sensors often consist of micromachined cavities that are placed on the end of optical fibers and can be configured so that sensitivity to one environmental effect is optimized.

In the case of pressure the diaphragm has been designed to deflect. Pressure ranges of 15 to 2000 psi can be accommodated by changing the diaphragm thickness with accuracy of about 0.1 percent full scale [34]. For temperature the etalon has been formed by silicon/silicon dioxide interfaces. Temperature ranges of 70 to 500 degree K can be selected and for a range of about 100 degree K a resolution of about 0.1 degree K is achievable [34]. For refractive index of liquids a hole has been formed to allow the flow of the liquid to be measured without the diaphragm deflecting. These devices have been commercialized and are sold with instrument packages [34].

Interferometric Fiber Optic Sensors

One of the areas of greatest interest has been in the development of high performance interferometric fiber optic sensors. Substantial efforts have been undertaken on Sagnac interferometers, ring resonators, Mach-Zehnder and Michelson interferometers as well as dual mode, polarimetric, grating and etalon based interferometers. In this section, the Sagnac, Mach-Zehnder, and Michelson interferometers are briefly reviewed.

The Sagnac Interferometer

The Sagnac interferometer has been principally used to measure rotation [35-38] and is a replacement for ring laser gyros and mechanical gyros. It may also be employed to measure time varying effects such as acoustics, vibration and slowly varying phenomenon such as strain. By using multiple interferometer configurations it is possible to employ the Sagnac interferometer as a distributed sensor capable of measuring the amplitude and location of a disturbance.

The single most important application of fiber optic sensors in terms of commercial value is the fiber optic gyro. It was recognized very early that the fiber optic gyro offered the prospect of an all solid-state inertial sensor with no moving parts, unprecedented reliability, and had the prospect of being very low cost.

The potential of the fiber optic gyro is being realized as several manufacturers worldwide are producing them in large quantities to support automobile navigation systems, pointing and tracking of satellite antennas, inertial measurement systems for commuter aircraft and missiles, and as the backup guidance system for the Boeing 777. They are also being baselined for such future programs as the Comanche helicopter and are being developed to support long duration space flights.

Other applications where fiber optic gyros are being used include mining operations, tunneling, attitude control for a radio controlled helicopter, cleaning robots, antenna pointing and tracking, and guidance for unmanned trucks and carriers.

Two types of fiber optic gyros are being developed. The first type is an open loop fiber optic gyro with a dynamic range on the order of 1000 to 5000 (dynamic range is unitless), with scale factor accuracy of about 0.5 percent (this accuracy number includes non-linearity and hysteresis effects) and sensitivities that vary from less than 0.01 deg/hr to 100 deg/hr and higher [38]. These fiber gyros are generally used for low cost applications where dynamic range and linearity are not the crucial issues. The second type is the closed loop fiber optic gyro that may have a dynamic range of 10^6 and scale factor linearity of 10 ppm or better [38]. These types of fiber optic gyros are primarily targeted at medium to high accuracy navigation applications that have high turning rates and require high linearity and large dynamic ranges.

The basic open loop fiber optic gyro is illustrated by Figure 26. A broadband light source such as a light emitting diode is used to couple light into an input/output fiber coupler. The input light beam passes through a polarizer that is used to insure the reciprocity of the counterpropagating light beams through the fiber coil. The second central coupler splits the two light beams into the fiber optic coil where they pass through a modulator that is used to generate a time varying output signal indicative of rotation. The modulator is offset from the center of the coil to impress a relative phase difference between the counterpropagating light beams. After passing through the fiber coil the two light beams recombine and pass back through the polarizer and are directed onto the output detector.

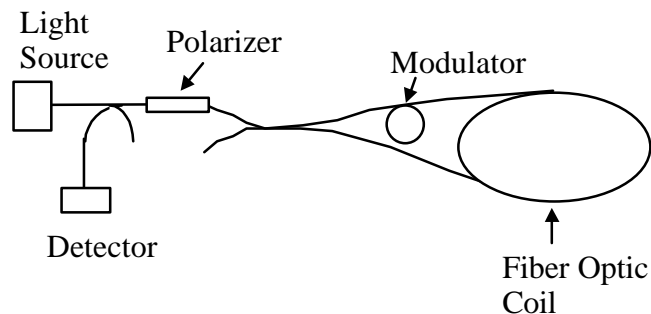


Figure 26. Open loop fiber optic gyro is the simplest and lowest cost rotation sensor. They are widely used in commercial applications where their dynamic range and linearity limitations are not constraining.

When the fiber gyro is rotated in a clockwise direction the entire coil is displaced slightly increasing the time it takes light to traverse the fiber optic coil. (Remember that the speed of light is invariant with respect to the frame of reference, thus coil rotation increases path length when viewed from outside the fiber.) Thus the clockwise propagating light beam has to go through a slightly longer optical pathlength than the counterclockwise beam which is moving in a direction opposite to the motion of the fiber coil. The net phase difference between the two beams is proportional to the rotation rate.

By including a phase modulator loop offset from the fiber coil a time difference in the arrival of the two light beams is introduced, and an optimized demodulation signal can be realized. This is shown on the right side in Figure 27. In the absence of the loop the two

light beams traverse the same optical path and are in phase with each other and is shown on the left-hand curve of Figure 27.

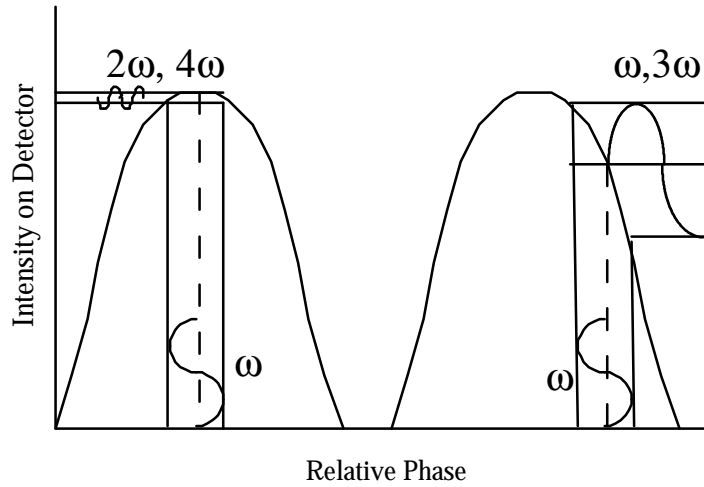


Figure 27. An open loop fiber optic gyro has predominantly even order harmonics in the absence of rotation. Upon rotation, the open loop fiber optic gyro has odd harmonic output whose amplitude indicates the magnitude of the rotation rate and phase indicates direction.

The result is that the first or a higher order odd harmonic can be used as a rotation rate output and improved dynamic range and linearity is realized.

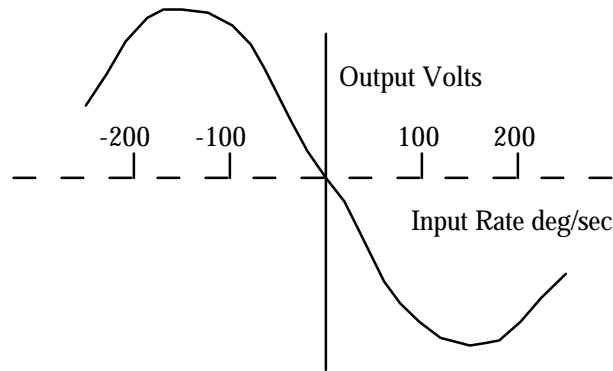


Figure 28. A typical open loop fiber optic gyro output obtained by measuring one of the odd harmonic output components amplitude and phase, results in a sinusoidal output that has a region of good linearity centered about the zero rotation point.

Further improvements in dynamic range and linearity can be realized by using a "closed loop" configuration where the phase shift induced by rotation is compensated by an equal and opposite artificially imposed phase shift. One way to accomplish this is to introduce a frequency shifter into the loop as is shown in Figure 29.

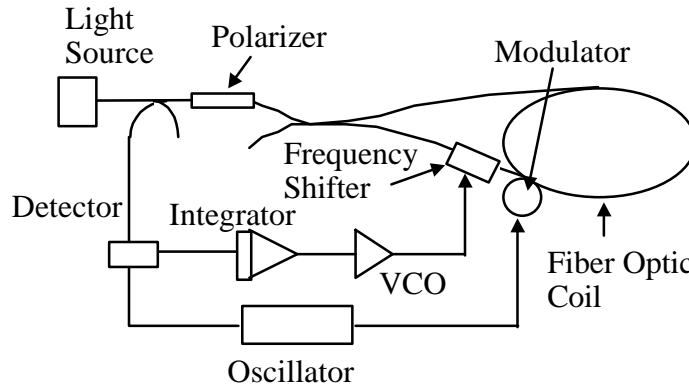


Figure 29. Closed loop fiber optic gyros use an artificially induced nonreciprocal phase between counterpropagating light beams to counterbalance rotationally induced phase shifts. These fiber gyros have the wide dynamic range and high linearity needed to support stringent navigation requirements.

The relative frequency difference of the light beams propagating in the fiber loop can be controlled resulting in a net phase difference that is proportional to the length of the fiber coil and the frequency shift. In figure 29, this is done by using a modulator in the fiber optic coil to generate a phase shift at a rate ω . When the coil is rotated, a first harmonic signal at ω is induced with phase that depends on rotation rate in a manner similar to that described above with respect to open loop fiber gyros. By using rotationally induced first harmonic as an error signal, the frequency shift can be adjusted by using a synchronous demodulator behind the detector to integrate the first harmonic signal into a corresponding voltage. This voltage is applied to a voltage controlled oscillator whose output frequency is applied to the frequency shifter in the loop so that the phase relationship between the counterpropagating light beams is locked to a single value.

It is possible to use the Sagnac interferometer for other sensing and measurement tasks. Examples include: slowly varying measurements of strain with 100 micron resolution over distances of about 1 km [39], spectroscopic measurements of wavelength to about 2 nm [40] and optical fiber characterization such as thermal expansion to accuracies of about 10 ppm [40]. In each of these applications frequency shifters are used in the Sagnac loop to obtain controllable frequency offsets between the counterpropagating light beams.

Another class of fiber optic sensors, based on the Sagnac interferometer, can be used to measure rapidly varying environmental signals such as sound [41-42]. Figure 30 illustrates two interconnected Sagnac loops [42] that can be used as a distributed acoustic sensor. The WDM (wavelength division multiplexer) in the figure is a device which either couples two wavelengths (λ_1 and λ_2 in this case) together, or separates them.

The sensitivity of this Sagnac acoustic sensor depends on the location of the signal. If the signal is in the center of the loop the amplification is zero as both counterpropagating light beams arrive at the center of the loop at the same time. As the signal moves away from

the center the output increases. When two Sagnac loops are superposed as in Figure 30, the two outputs may be summed to give an indication of the amplitude of the signal and ratioed to determine position.

Several other combinations of interferometers have been tried for position and amplitude determinations and the first reported success consisted of a combination of the Mach-Zehnder and Sagnac interferometer [41].

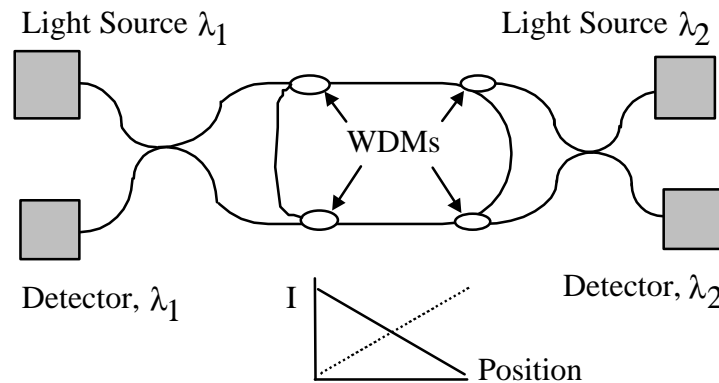


Figure 30. Distributed fiber optic acoustic sensor based on interlaced Sagnac loops allows the detection of the location and the measurement of the amplitude along a length of optical fiber that may be many kilometers long.

The Mach-Zehnder and Michelson Interferometers

One of the great advantages of all fiber interferometers, such as Mach-Zehnder and Michelson interferometers [43] in particular, is that they have extremely flexible geometry's and high sensitivity that allow the possibility of a wide variety of high performance elements and arrays as shown in Figure 31.

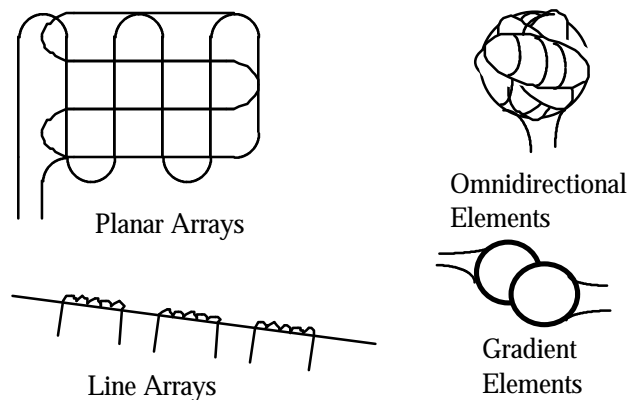


Figure 31. Flexible geometry's of interferometric fiber optic sensors' transducers are one of the features of fiber sensors that are attractive to designers configuring special purpose sensors.

Figure 32 shows the basic elements of a Mach-Zehnder interferometer, which are a light source/coupler module, a transducer and a homodyne demodulator. The light source module usually consists of a long coherence length isolated laser diode, a beam splitter to produce two light beams and a means of coupling the beams to the two legs of the transducer. The transducer is configured to sense an environmental effect by isolating one light beam from the environmental effect and using the action of the environmental effect on the transducer is to induce an optical path length difference between the two light beams. Typically a homodyne demodulator is used to detect the difference in optical path length (various heterodyne schemes have also been used). [43].

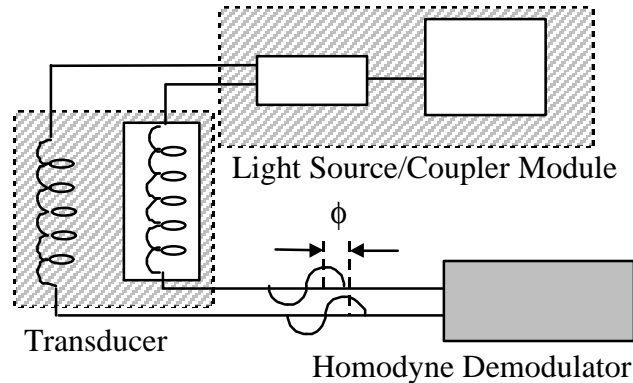


Figure 32. The basic elements of the fiber optic Mach-Zehnder interferometer are a light source module to split a light beam into two paths, a transducer used to cause an environmentally dependent differential optical path length between the two light beams, and a demodulator that measures the resulting path length difference between the two light beams.

One of the basic issues with the Mach-Zehnder interferometer is that the sensitivity will vary as a function of the relative phase of the light beams in the two legs of the interferometer, as shown in Figure 33. One way to solve the signal fading problem is to introduce a piezoelectric fiber stretcher into one of the legs and adjust the relative path length of the two legs for optimum sensitivity. Another approach has the same quadrature solution as the grating based fiber sensors discussed earlier.

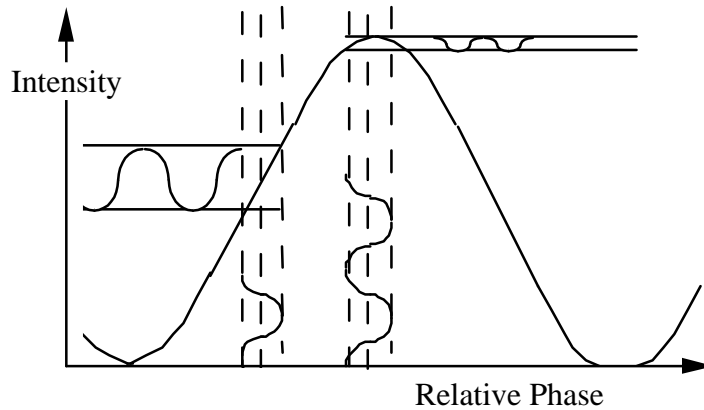


Figure 33. In the absence of compensating demodulation methods the sensitivity of the Mach-Zehnder varies with the relative phase between the two light beams. It falls to low levels when the light beams are completely in or out of phase.

Figure 34 illustrates a homodyne demodulator. The demodulator consists of two parallel optical fibers that feed the light beams from the transducer into a graded index (GRIN) lens. The output from the graded index lens is an interference pattern that “rolls” with the relative phase of the two input light beams. If a split detector is used with a photomask arranged so that the opaque and transparent line pairs on the mask in front of the split detector match the interference pattern periodicity and are 90 degrees out of phase on the detector faces, sine and cosine outputs result.

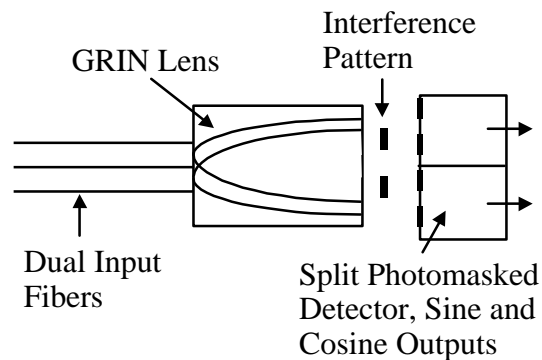


Figure 34. Quadrature demodulation avoids signal fading problems. The method shown here expands the two beams into an interference pattern that is imaged onto a split detector.

These outputs may be processed using quadrature demodulation electronics as shown in Figure 35. The result is a direct measure of the phase difference.

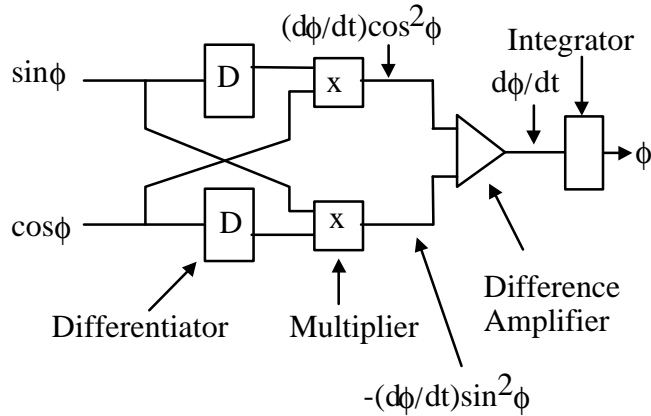


Figure 35. Quadrature demodulation electronics take the sinusoidal outputs from the split detector and convert them via cross multiplication and differentiation into an output that can be integrated to form the direct phase difference.

Further improvements on these techniques have been made; notably the phase generated carrier approach shown in Figure 36. A laser diode is current modulated resulting in the output frequency of the laser diode being frequency modulated as well. If a Mach-Zehnder interferometer is arranged so that its reference and signal leg differ in length by an amount (L_1-L_2) then the net phase difference between the two light beams is $2\pi F(L_1-L_2)n/c$, where n is the index of refraction of the optical fiber and c is the speed of light in vacuum. If the current modulation is at a rate ω then relative phase differences are modulated at this rate and the output on the detector will be odd and even harmonics of it. The signals riding on the carrier harmonics of ω and 2ω are in quadrature with respect to each other and can be processed using electronics similar to those of Figure 35.

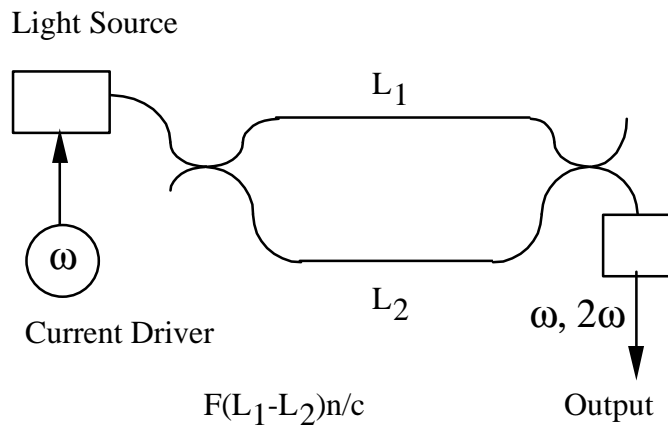


Figure 36. The phase generated carrier technique allows quadrature detection via monitoring even and odd harmonics induced by a sinusoidally frequency modulated light source used in combination with a

length offset Mach-Zehnder interferometer to generate a modulated phase output whose first and second harmonics correspond to sine and cosine outputs.

The Michelson interferometer shown in Figure 37 is in many respects similar to the Mach-Zehnder. The major difference is that mirrors have been put on the ends of the interferometer legs. This results in very high levels of back reflection into the light source greatly degrading the performance of early systems. By using improved diode pumped YAG (Yttrium Aluminum Garnet) ring lasers as light sources these problems have been largely overcome. In combination with the recent introduction of phase conjugate mirrors to eliminate polarization fading, the Michelson is becoming an alternative for systems that can tolerate the relatively high present cost of these components.

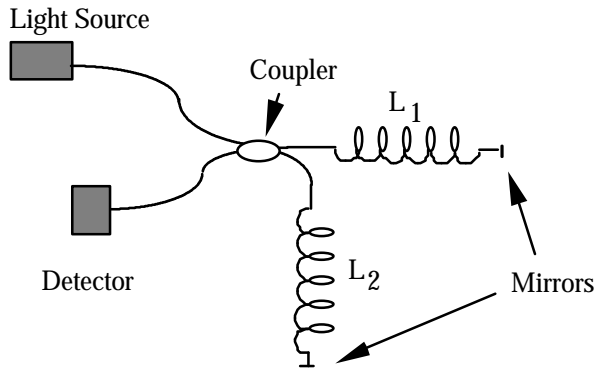


Figure 37. The fiber optic Michelson interferometer consists of two mirrored fiber ends and can utilize many of the demodulation methods and techniques associated with the Mach-Zehnder.

In order to implement an effective Mach-Zehnder or Michelson based fiber sensor it is necessary to construct an appropriate transducer. This can involve a fiber coating that could be optimized for acoustic, electric or magnetic field response. In Figure 38 a two part coating is illustrated that consists of a primary and secondary layer. These layers are designed for optimal response to pressure waves and for minimal acoustic mismatches between the medium in which the pressure waves propagate and the optical fiber.

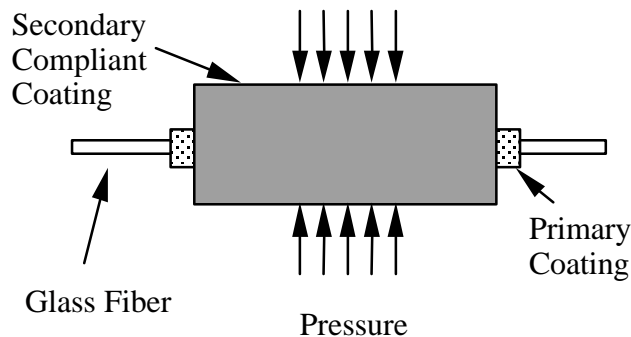


Figure 38. Coatings can be used to optimize the sensitivity of fiber sensors. An example would be to use soft and hard coatings over an optical fiber to minimize the acoustic mismatch between acoustic pressure waves in water and the glass optical fiber.

These coated fibers are often used in combination with compliant mandrills or strips of material as in Figure 39 that act to amplify the environmentally induced optical path length difference.

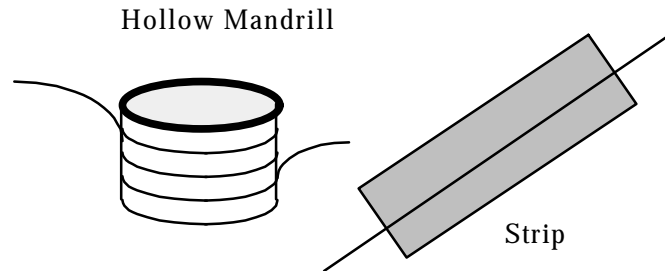


Figure 39. Optical fiber bonded to hollow mandrills and strips of environmentally sensitive material are common methods used to mechanically amplify environmental signals for detection by fiber sensors.

In many cases the mechanical details of the transducer design are critical to good performance such as the seismic/vibration sensor of Figure 40. Generally the Mach-Zehnder and Michelson interferometers can be configured with sensitivities that are better than 10^{-6} radians per square root Hertz. For optical receivers, the noise level decreases as a function of frequency. This phenomenon results in specifications in radians per square root Hertz. As an example, a sensitivity of 10^{-6} radians per square root Hertz at 1 Hertz means a sensitivity of 10^{-6} radians while at 100 Hertz, the sensitivity is 10^{-7} radians. As an example, a sensitivity of 10^{-6} radian per square root Hertz means that for a 1 meter long transducer, less than 1/6 micron of length change can be resolved at 1 Hertz bandwidths. [44]. The best performance for these sensors is usually achieved at higher frequencies because of problems associated with the sensors also picking up environmental signals due to temperature fluctuations, vibrations and acoustics that limit useful low frequency sensitivity.

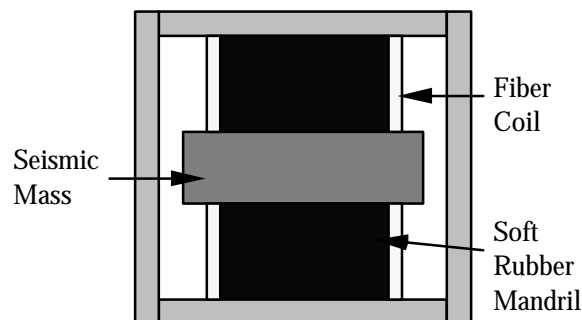


Figure 40. Differential methods are used to amplify environmental signals. In this case a seismic/vibration sensor consists of a mass placed between two fiber coils and encased in a fixed housing.

Multiplexing and Distributed Sensing

Many of the intrinsic and extrinsic sensors may be multiplexed [45] offering the possibility of large numbers of sensors being supported by a single fiber optic line. The techniques that are most commonly employed are time, frequency, wavelength, coherence, polarization and spatial multiplexing.

Time division multiplexing employs a pulsed light source launching light into an optical fiber and analyzing the time delay to discriminate between sensors. This technique is commonly employed to support distributed sensors where measurements of strain, temperature or other parameters are collected. Figure 41 illustrates a time division multiplexed system that uses microbend sensitive areas on pipe joints.

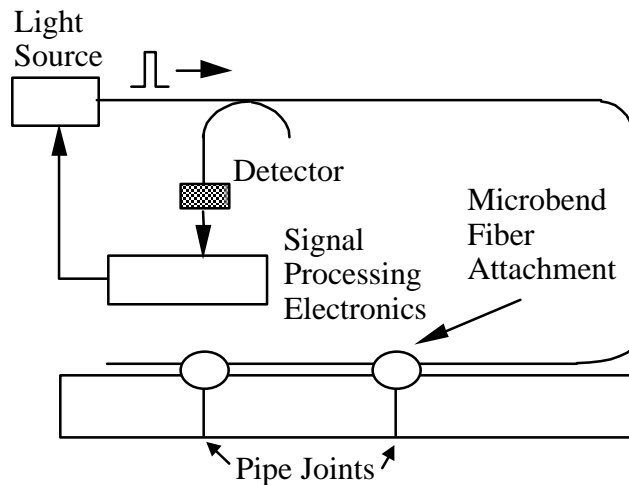


Figure 41. Time division multiplexing methods can be used in combination with microbend sensitive optical fiber to locate the position of stress along a pipeline.

As the pipe joints are stressed microbending loss increases and the time delay associated with these losses allows the location of faulty joints.

The entire length of the fiber can be made microbend sensitive and Rayleigh scattering loss used to support a distributed sensor that will predominantly measure strain. Other types of scattering from optical pulses propagating down optical fiber have been used to support distributed sensing, notably Raman scattering for temperature sensors has been made into a commercial product by York Technology and Hitachi. These units can resolve temperature changes of about 1 degree C with spatial resolution of 1 meter for a 1 km sensor using an integration time of about 5 minutes. Brillouin scattering has been used in laboratory experiments to support both strain and temperature measurements.

A frequency division multiplexed system is shown in Figure 42. In this example a laser diode is frequency chirped by driving it with a sawtooth current drive. Successive Mach-Zehnder interferometers are offset with incremental lengths $(L-L_1)$, $(L-L_2)$, and $(L-L_3)$ which differ sufficiently that the resultant carrier frequency of each sensor $(dF/dt)(L-L_n)$ is

easily separable from the other sensors via electronic filtering of the output of the detector.

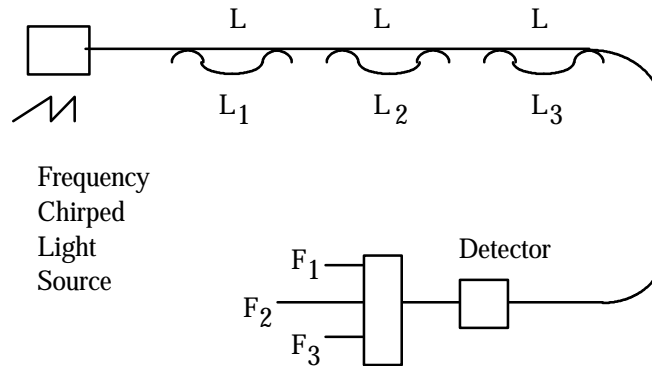


Figure 42. Frequency division multiplexing can be used to tag a series of fiber sensors, as in this case the Mach-Zehnder interferometers are shown with a carrier frequency on which the output signal ride.

Wavelength division multiplexing is one of the best methods of multiplexing as it uses optical power very efficiently. It also has the advantage of being easily integrated into other multiplexing systems allowing the possibility of large numbers of sensors being supported in a single fiber line. Figure 43 illustrates a system where a broadband light source, such as a light emitting diode, is coupled into a series of fiber sensors that reflect signals over wavelength bands that are subsets of the light source spectrum. A dispersive element, such as a grating or prism, is used to separate out the signals from the sensors onto separate detectors.

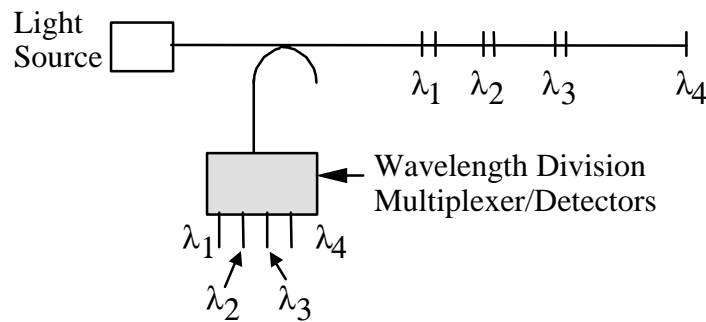


Figure 43. Wavelength division multiplexing are often very energy efficient. A series of fiber sensors are multiplexed by being arranged to reflect in a particular spectral band that is split via a dispersive element onto separate detectors.

Light sources can have widely varying coherence lengths depending on their spectrum. By using light sources that have coherence lengths that are short compared to offsets between the reference and signal legs in Mach-Zehnder interferometers and between successive sensors, a coherence multiplexed system similar to Figure 44 may be set up. The signal is extracted by putting a rebalancing interferometer in front of each detector so that the

sensor signals may be processed. Coherence multiplexing is not as commonly used as time, frequency and wavelength division multiplexing because of optical power budgets and the additional complexities in setting up the optics properly. It is still a potentially powerful technique and may become more widely used as optical component performance and availability continue to improve, especially in the area of integrated optic chips where control of optical pathlength differences is relatively straightforward.

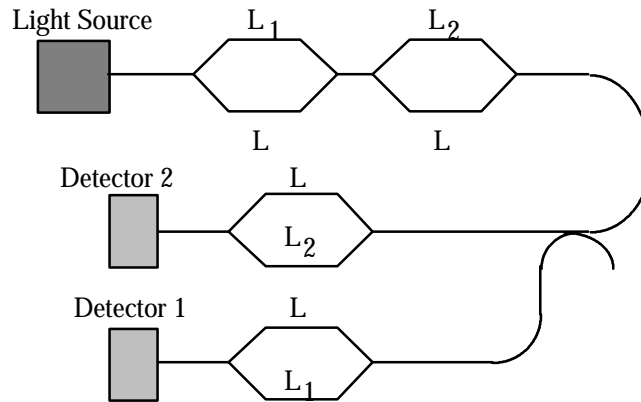


Figure 44. A low coherence light source is used to multiplex two Mach-Zehnder interferometers by using offset lengths and counterbalancing interferometers.

One of the least commonly used techniques is polarization multiplexing. In this case the idea is to launch light with particular polarization states and extract each state. A possible application is shown in Figure 45 where light is launched with two orthogonal polarization modes; preserving fiber and evanescent sensors have been set up along each of the axes. A polarizing beamsplitter is used to separate out the two signals. There is a recent interest in using polarization preserving fiber in combination with time domain techniques to form polarization based distributed fiber sensors. This has potential to offer multiple sensing parameters along a single fiber line.

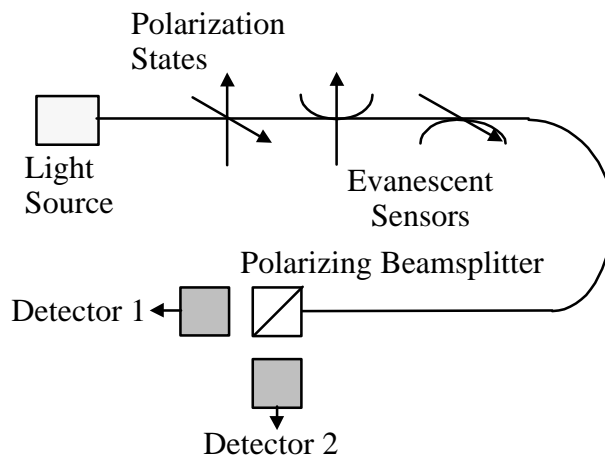


Figure 45. Polarization multiplexing is used to support two fiber sensors that access the cross polarization states of polarization preserving optical fiber.

Finally, it is possible to use spatial techniques to generate large sensor arrays using relatively few input and output optical fibers. Figure 46 shows a 2 by 2 array of sensors where two light sources are amplitude modulated at different frequencies. Two sensors are driven at one frequency and two more at the second. The signals from the sensors are put onto two output fibers each carrying a sensor signal from two sensors at different frequencies.

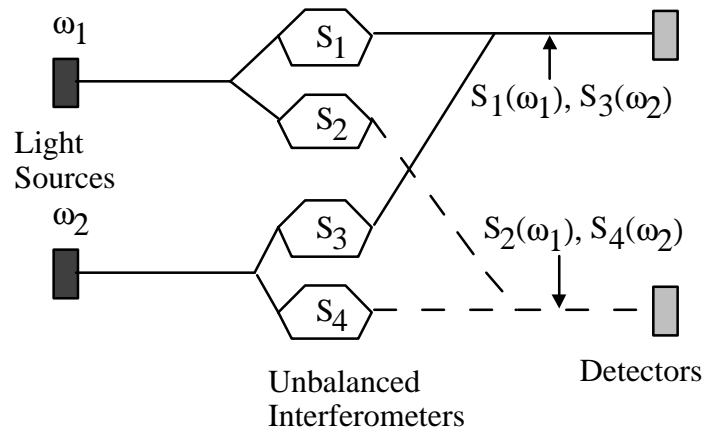


Figure 46. Spatial multiplexing of four fiber optic sensors may be accomplished by operating two light sources with different carrier frequencies and cross coupling the sensor outputs onto two output fibers.

This sort of multiplexing is easily extended to ‘m’ input fibers and ‘n’ output fibers to form ‘m’ by ‘n’ arrays of sensors as in Figure 47.

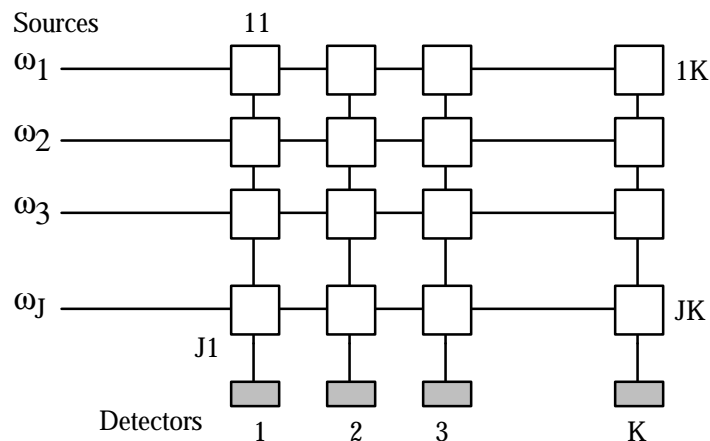


Figure 47. Extensions of spatial multiplexing the JK sensors can be accomplished by operating J light sources at J different frequencies and cross coupling to K output fibers.

All of these multiplexing techniques can be used in combination with one another to form extremely large arrays.

Applications

Fiber optic sensors are being developed and used in two major ways. The first is as a direct replacement for existing sensors where the fiber sensor offers significantly improved performance, reliability, safety and/or cost advantages to the end user. The second area is the development and deployment of fiber optic sensors in new market areas.

For the case of direct replacement, the inherent value of the fiber sensor, to the customer, has to be sufficiently high to displace older technology. Because this often involves replacing technology the customer is familiar with, the improvements must be substantial.

The most obvious example of a fiber optic sensor succeeding in this arena is the fiber optic gyro, which is displacing both mechanical and ring laser gyros for medium accuracy devices. As this technology matures it can be expected that the fiber gyro will dominate large segments of this market.

Significant development efforts are underway in the United States in the area of fly-by-light [9] where conventional electronic sensor technology are targeted to be replaced by equivalent fiber optic sensor technology that offers sensors with relative immunity to electromagnetic interference, significant weight savings and safety improvements.

In manufacturing, fiber sensors are being developed to support process control. Oftentimes the selling points for these sensors are improvements in environmental ruggedness and safety, especially in areas where electrical discharges could be hazardous.

One other area where fiber optic sensors are being mass-produced is the field of medicine, [46-49] where they are being used to measure blood gas parameters and dosage levels. Because these sensors are completely passive they pose no electrical shock threat to the patient and their inherent safety has lead to a relatively rapid introduction.

The automotive industry, construction industry and other traditional users of sensors remain relatively untouched by fiber sensors, mainly because of cost considerations. This can be expected to change as the improvements in optoelectronics and fiber optic communications continue to expand along with the continuing emergence of new fiber optic sensors.

New market areas present opportunities where equivalent sensors do not exist. New sensors, once developed, will most likely have a large impact in these areas. A prime example of this is in the area of fiber optic smart structures [50-53]. Fiber optic sensors are being embedded into or attached to materials (1) during the manufacturing process to enhance process control systems, (2) to augment nondestructive evaluation once parts have been made, (3) to form health and damage assessment systems once parts have been assembled into structures and (4) to enhance control systems. A basic fiber optic smart structure system is shown in Figure 48.

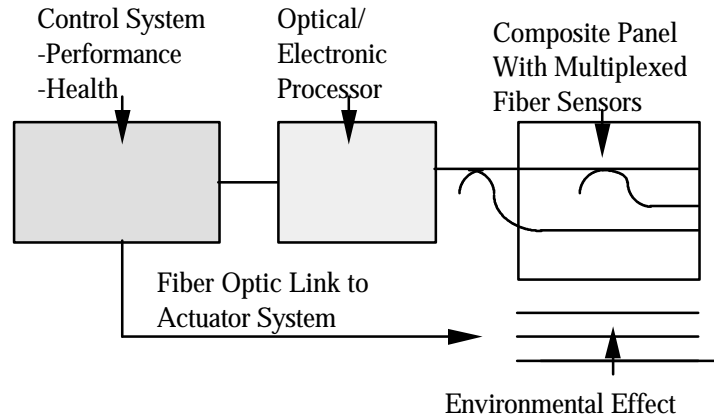


Figure 48. Fiber optic smart structure systems consist of optical fiber sensors embedded or attached to parts sensing environmental effects that are multiplexed and directed down. The effects are then sent through an optical fiber to an optical/electronic signal processor that in turn feeds the information to a control system that may or may not act on the information via a fiber link to an actuator.

Fiber optic sensors can be embedded in a panel and multiplexed to minimize the number of leads. The signals from the panel are fed back to an optical/electronic processor for decoding. The information is formatted and transmitted to a control system which could be augmenting performance or assessing health. The control system would then act, via a fiber optic link, to modify the structure in response to the environmental effect.

Figure 49 shows how the system might be used in manufacturing. Here fiber sensors are attached to a part to be processed in an autoclave. Sensors could be used to monitor internal temperature, strain, and degree of cure. These measurements could be used to control the autoclaving process, improving yield and the quality of the parts.

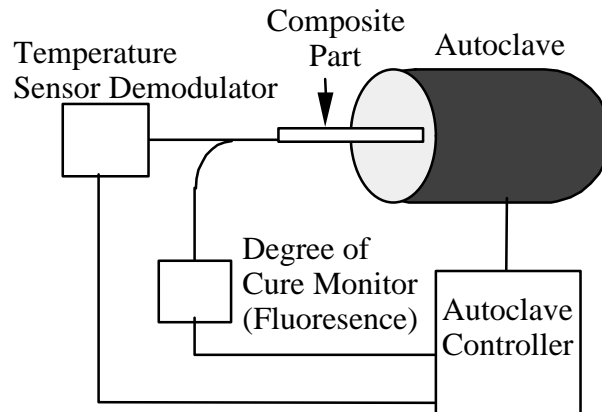


Figure 49. Smart manufacturing systems offer the prospect of monitoring key parameters of parts as they are being made, which increases yield and lowers overall costs.

Interesting areas for health and damage assessment systems are on large structures such as buildings, bridges, dams, aircraft and spacecraft. In order to support these types of structures it will be necessary to have very large numbers of sensors that are rapidly

reconfigurable and redundant. It will also be absolutely necessary to demonstrate the value and cost effectiveness of these systems to the end users.

One approach to this problem is to use fiber sensors that have the potential to be manufactured cheaply in very large quantities while offering superior performance characteristics. Two candidates that are under investigation are the fiber gratings and etalons described in the prior sections. Both offer the advantages of spectrally based sensors and have the prospect of rapid in line manufacture. In the case of the fiber grating, the early demonstration of fiber being written into it as it is being pulled has been especially impressive.

These fiber sensors could be folded into the wavelength and time division multiplexed modular architecture shown in Figure 50. Here sensors are multiplexed along fiber strings and an optical switch is used to support the many strings. Potentially the fiber strings could have tens or hundreds of sensors and the optical switches could support a like number of strings. To avoid overloading the system, the output from the sensors could be slowly scanned to determine status in a continuously updated manner.

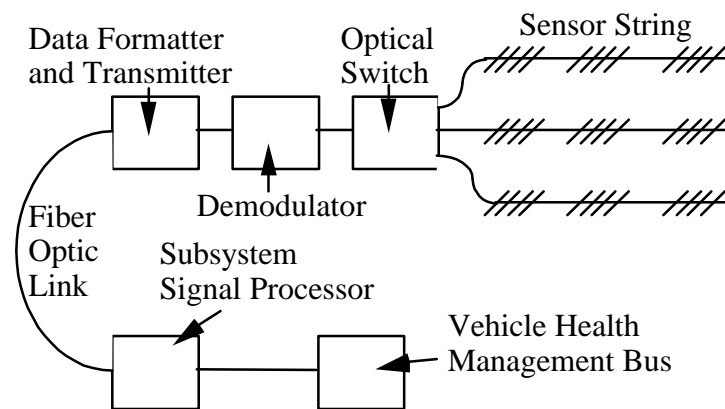


Figure 50. A modular architecture for a large smart structure system would consist of strings of fiber sensors accessible via an optical switch and demodulator system that could select key sensors in each string. The information would then be formatted and transmitted after conditioning to a vehicle health management bus.

When an event occurred that required a more detailed assessment the appropriate strings and the sensors in them could be monitored in a high performance mode. The information from these sensors would then be formatted and transmitted via a fiber optic link to a subsystem signal processor before introduction onto a health management bus. In the case of avionics the system architecture might look like Figure 51. The information from the health management bus could be processed and distributed to the pilot or more likely, could reduce his direct workload leaving more time for the necessary control functions.

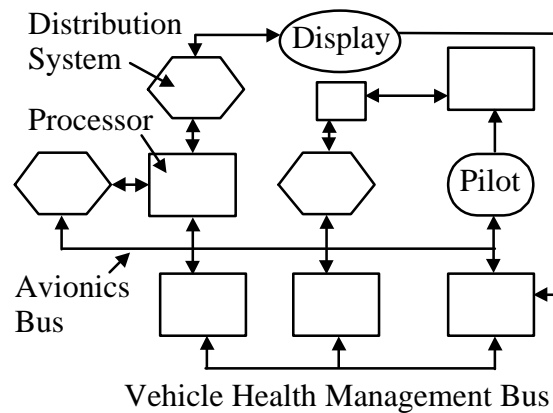


Figure 51. A typical vehicle health management bus for an avionics system would be the interface point for the fiber optic smart structure modules of Figure 50.

As fiber to the curb and fiber to the home moves closer to reality there is the prospect of merging fiber optic sensor and communication systems into very large systems capable of monitoring the status of buildings, bridges, highways and factories over widely dispersed areas. Functions such as fire, police, maintenance scheduling and emergency response to earthquakes, hurricanes and tornadoes could be readily integrated into very wide area networks of sensors as in Figure 52.

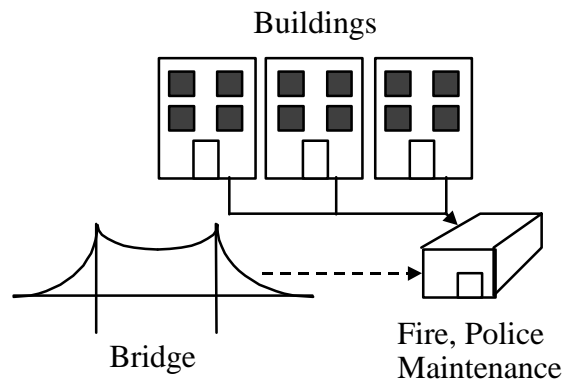


Figure 52. Fiber optic sensor networks to monitor the status of widely dispersed assets as buildings, bridges and dams could be used to augment fire, police and maintenance services.

It is also possible to use fiber optic sensors in combination with fiber optic communication links to monitor stress build up in critical fault locations and dome build up of volcanoes. These widely dispersed fiber networks may offer the first real means of gathering information necessary to form prediction models for these natural hazards.

Acknowledgment

Figures 1 through 52 are drawn from the Fiber Optic Sensor Workbook Copyright Eric Udd/Blue Road Research and used with permission.

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