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Fiber optic sensing applications in the electric power industry☆

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Abstract

Fiber optic telecommunications is a well-established discipline which finds applications in all industrial areas for signaling and control. However, fiber optics for intrinsic sensing of fluid levels, gas presence, temperature, pressure, or rotation, is rapidly being applied to the medical, petrochemical, and marine professions. Not to be overlooked are several new fiber optic sensing techniques which are now capable of accurately measuring electric current, voltage levels, and even breaker status. By monitoring such parameters, the power industry can take full advantage of the benefits of fiber optics, especially in high electromagnetic field environments. This paper surveys those techniques and experiences with fiber optic sensing applicable to today's power industry.

Keywords: Fiber optic sensing

1. Introduction

Since the 1970s, optical transmission using fiber optics has enjoyed a steady technological evolution which has allowed it to mature into a unique science. Widespread acceptance of optical fibers occurred as the manufacturing technique improved and became cost effective. Likewise, the advent of energy-efficient material compounds and the ability to reliably produce smaller optical sources further refined the technology. Optical fiber transmission systems supporting voice and data communications are now routine and are firmly established as a technical alternative to copper cabling and radio frequency systems.

Capitalizing on the availability and progress of the optical fiber technology for telecommunications, a relatively new optical discipline has grown up which applies fiber optics to sensing applications. This technical spinoff is not simply the telemetry of electrical sensor data converted for optical transmission, but rather the use of inherent optical fiber properties or indirect fiber attachments to determine the status of a given sensed parameter or disturbance.

Fiber optic sensing technology today is capable of monitoring temperature, pressure, rotation, torque, gas concentrations, voltage, current, electric fields, magnetic fields, acoustic pressure, liquid presence/level, flame quality/presence, vibration, acceleration, nuclear radiation levels, pH concentrations, dissolved gas levels, humidity, flow rates, chemical concentrations, bacteria presence, specific gravity, corrosion, and mechanical stress. With such a comprehensive list, it is difficult to imagine any parameter which may not eventually be monitored with fiber optic sensing technology.

Fiber optic sensors offer a number of specialized advantages over customary electrical and electromechanical transducers. These advantages include increased sensitivity, operational dynamic range, geometric versatility since fiber sensors can be configured in somewhat arbitrary shapes, a common technical base from which various physical phenomena can be sensed, dielectric constructions so that they can be employed in explosive, high temperature, nuclear, corrosive, or other stressing environments, and the total elimination of electric power consumption and wiring requirements at the sensing point. In addition, optical fibers offer the same benefits to transducer applications as they do to telecommunications systems, namely, low signal attenuation, light weight, high information capacity, and the ability to operate in electrically noisy surroundings if

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necessary. Considering these attributes, it is certain that fiber optic sensing will become increasingly important in the role of instrumentation in the biomedical, industrial, and military arenas. Not to be overlooked is its direct application to the generation and monitoring of electric power.

2. Fiber optic sensor principles

Before sensors can be discussed for power applications, a brief review of basic fiber technology is required. Optical fibers are essentially solid transparent waveguides which operate at wavelengths on the order of 1 μm. A typical fiber consists of a cylindrical core of glass surrounded by a concentric cladding region whose material has a lower refractive index than the central core. Each optical fiber presents this core–cladding interface as a geometrical boundary which mathematically generates discrete solutions to Maxwell's electromagnetic equations. Based on the dimensions of the fiber and the material characteristics, the number of allowed solutions can range from one to thousands. Each of these discrete solutions is a possible mode for the waveguide. Thus, optical fibers can be identified as single-mode or multimode fibers, depending upon the particular boundary conditions in existence and the resulting number of modes. In multimode fibers, these modes can be intuitively understood by considering the internal reflection of the modes at the refractive material boundary. Relative to each other, certain modes will travel exactly a half wavelength difference, causing these particular modes to destructively interfere or cancel. This supports the mathematical field predictions of only discrete modes being allowed. Multimode fibers carry information by amplitude variations, and cannot support phase information as a result of the many propagating modes and travel time variations between these modes. It is exactly this variation in travel time (dispersion) which limits the bandwidth capacity of a multimode optical fiber.

Several fabrication techniques are employed in multimode fiber production and include step index, where the index of refraction is constant across the core region, and graded index, where the refractive index is altered in a decreasing pattern outward from the core center. This pattern is called a graded-index profile and offers the highest bandwidth capacity for a multimode fiber. Since the index of refraction is the ratio of the velocity of light in a vacuum to the velocity of light in the fiber media, graded-index fibers allow the higher order modes to vary in velocity along part of their path as they propagate across the index profile. This causes an individual mode's travel time to be nearly equal to that of any other mode propagating, thus reducing dispersion. This phenomenon further benefits graded-index fibers in that they are relatively immune to small microbending effects which are known to increase local attenuation at the bend site [1].

More complex is the single-mode fiber where only a unique solitary propagating mode is allowed. More often than not, comprehension of single-mode fibers requires a detailed mathematical treatment, which has been extensively documented in the literature [2, 3]. It is important to note that a single-mode fiber carries not only amplitude information as did the multimode fiber, but meaningful phase information because of the single propagating mode.

Other types of dispersion are predominant in the single-mode optical fiber, but they can be limited by narrowing the spectrum of the optical source employed. Single-mode fibers offer the greatest possible bandwidth for current state-of-the-art optical fiber technology and are bending insensitive to the highest degree possible.

The difference in the fiber operation suggests that there are two broad categories of fiber optic sensors— one that depends on the amplitude basis of multimode fibers and a second that relies on the phase basis of single-mode fibers.

2.1. Amplitude sensors

Amplitude sensors are those devices which transform a measurand's status or its change in status into a calibrated variation of optical intensity, amplitude, or power within an optical fiber. Usually this approach is reserved for use with multimode optical fibers and incoherent sources such as light emitting diodes, implying simplicity and therefore cost effectiveness. Many methods may be used to implement the mapping of the physical parameter into the amplitude changes of the optical signal within the fiber, including both intrinsic and extrinsic approaches. The intrinsic approach requires a change in the internal optical characteristics of the fiber to modulate the optical energy. Such techniques may include variations in the refractive index of the fiber, changes in the fiber's scattering coefficient, or optical attenuation (loss) as a function of the applied perturbation. Extrinsic techniques usually provide for some mechanism which externally acts upon the fiber itself, causing a change in the optical signal propagating in the fiber core. This mechanism can be an appliance which is attached to the optical fiber in a particular way. As a complete category, amplitude sensors can be built using gap transmission, reflection, mechanical deflection, fiber axis bending (microbending), absorption, fluorescence, phosphorescence, chemically reactive, bioactive, refractive, or spectrally resonant (wavelength selective) phenomena [4]. Based on the mechanism selected, the amplitude variation can be directly established as

$$\text{Amplitude Variation} = \frac{\mathrm{d}A}{\mathrm{d}X}$$

where A is the fiber signal amplitude and X is the excitation parameter to be measured.

It is possible to envision an indirect process for the mechanism which is

$$\text{Amplitude Variation} = \frac{\mathrm{d}A}{\mathrm{d}I} \times \frac{\mathrm{d}I}{\mathrm{d}X}$$

where I is some indirect variable capable of altering the fiber signal amplitude. For example, the amplitude of the signal may directly vary with the amount of bending applied to the fiber, I, but the mechanical bending is generated mechanically in proportion to the measurand X.

2.2. Phase sensors

Because optical wavelengths are extremely short, phase based fiber sensors are very precise and produce the most sensitive fiber optic transducers. Phase sensors produce a known variation in the optical phase of a fiber signal according to a particular measurand's present value or change in its value. This phase change is meaningless without a comparison with a known reference signal. As a result, coherent optical sources and single-mode sustaining fibers must be employed in phase transducer development and, furthermore, an alternative path must be established as a reference signal. These factors increase the cost of fiber optic phase sensors compared with the amplitude based transducers. A conventional phase sensor uses a coherent optical source which is split into two discrete paths. After travelling along these different paths the separate signals are eventually recombined. Most phase based sensors are therefore designed in the form of classical optical interferometers having one leg responsive to the measurand and another reference leg isolated from any measurand effects or perturbations. Such fiber based interferometers include Michelson, Mach–Zehnder, Fabry–Pérot, Sagnac, and Fizeau. Ironically, the signal recombination results in either constructive or destructive interference which is translated into an amplitude change proportional to the phase difference. The secret to fiber optic interferometric sensors is in the sensitization of the fiber sensing leg to the parameter of interest. This can be done by creating either a refractive index change within the fiber which alters the propagation velocity of the single mode, or a fiber length change (admittedly small) which will vary the constant-velocity travel time. There may also be some synergism between these approaches.

Mathematically, this idea can be expressed as

$$\text{Phase Shift} = XL\frac{\mathrm{d}n}{\mathrm{d}X} + Xn\frac{\mathrm{d}L}{\mathrm{d}X}$$

where L is the fiber interaction length and n is the optical index of refraction of the fiber.

Note that the phase shift can occur from an index change within a constant fiber length or a length change of a nonvarying refractive medium. In either case, it is imperative that the reference branch of the interferometer remains immune to measurand X in both length and refractive index sensitivity. With these fabrication criteria, interferometric sensors can be designed to sense physical phenomena as can the amplitude sensors, but with a sensitivity and accuracy several orders of magnitude greater. Other techniques such as polarization variation, now possible with the advent of single-mode polarization-preserving fibers, and evanescent wave variable coupling can further enhance options for single-mode sensing.

3. Sensor applications

Proponents of fiber sensing technology are always seeking markets and sponsors for their development work and operating devices. Electric power systems are important application arenas and proving grounds for this technology. There are obvious benefits, since the high electromagnetic interference associated with the electric power production is not capable of affecting a fiber optic sensor, unless the device is engineered specifically for that purpose. Electrical utilities and equipment manufacturers in Europe, the United States, and Japan are devoting significant research and development effects toward perfecting fiber optic high-voltage, magnetic field, and current sensors. In addition, fiber optic temperature, stress, rotation, and pressure sensors suit many other monitoring and control needs associated with the power industry, including the monitoring of combustion process or exhaust gas conditions in electric generating plants. Dielectric fiber optic temperature sensors can probe operating transformers and generators, watching for hot spots and the internal overheating conditions that precede catastrophic failure, while rotation sensors can monitor revolutions and torque on rotating turbine or generator shafts. Another possible application could be to measure the effect of wind force or ice loading on high-voltage transmission cables by employing a distributed fiber optic stress sensor system. This system could determine loading factors for different portions of the transmission line, in turn alerting the utility company to conditions where damage is likely. Fiber optic nuclear radiation sensors could monitor the levels of radioactive products within containment structures or other facilities at nuclear power plants.

The following sections contain information regarding various sensors directly applicable to the power production industry.

3.1. Torque sensors

Using multimode amplitude based sensing principles, a reflective fiber optic torquemeter has been designed, constructed, and proven. The primary advantage of such a device lies in its remote measurement capability. With no local electronic circuitry or electric power requirements at the sensing location, the sensor can be installed in high electromagnetic field environments without fear of interference. This opens the applications to variable-torque motors in addition to turbine or generator shafts. The concept was devised by the College of Engineering at the University of New Orleans with the development sponsored by Litton Industries. Several approaches can be taken to measure torque, the simplest being one which measures the timing difference between two axially separated optically reflective shaft marks. At zero (baseline) torque the timing is referenced by a microprocessor. As the torque increases, the shaft twist over the intermark length disturbs the initial timing difference, indicating a measure of the torque angle when the time shift value is compared with the zero-torque timing reference. The University of New Orleans' approach requires only a single optical probe by using a unique mechanical construction. A concentric sleeve of known length is placed around the shaft to be monitored and attached to the shaft by an internally machined 'land' and mechanical bands. Because the sleeve is freely movable, there is no torque applied through its length and therefore no angular displacement from end to end. However, once a torque is applied to the shaft, an angular displacement occurs between the free end of the mechanical sleeve and the part of the drive shaft located directly beneath it. This part of the drive shaft contains a concentric collar which raises the reflective mark to the level of the sleeve's reflectors. These reflectors are displaced relative to each other according to the amount of applied torque. The relative positions of these marks can be monitored by a single fiber optic bifurcated probe connected to an optical transceiver and microprocessor.

Mathematically, it can be shown that the relative angular displacement of the two reference cross sections is proportional to the time difference divided by the time of one revolution. A revolution can be timed by a reflective target pair, distinguishing its reflection from the sleeve target. This can be expressed as

$$\text{Angular Displacement} = \frac{K(t_2 - t_1)}{t_2 + t_1}$$

where K is the proportionality constant based on the shaft diameter, the axial length of the sleeve, the shaft construction, and the torsional modulus of the shaft material; t_1 is the time between the mark on the sleeve and the mark on the shaft, and t_2 the time between the mark on the shaft and the mark on the sleeve.

An additional benefit of this concept is that the angular velocity in revolutions per minute can be easily acquired since it is inversely proportional to the sum of t_1 and t_2. In some cases it is desirable to calculate torque prior to one revolution. This can be accomplished by placing multiple reflectors on both the sleeve and the shaft collar so that the microprocessor can compute torque based on the relative time difference between each collar–sleeve mirror pair. Furthermore, the power can be calculated since it is directly proportional to the product of the torque and revolutions per minute. Torsional vibrations due to oscillatory twisting of the shaft can be accounted for using finite impulse response (FIR) digital filtering algorithms resident in the processor. The ideal mounting of the fiber optic probe is near the bearing structures to minimize bending vibrations of the shaft.

Initially, a prototype demonstration system was constructed with a shaft diameter of only 1/2 inch (12.7 mm). Later, a 19-inch ($\approx$0.5 m) diameter fiber optic torsionmeter was fabricated and installed on a US Navy vessel in 1987 and remains operational at the time of this writing. The installed system is capable of measuring torque with a 10 Hz bandwidth and an accuracy of 1% [5]. The full-scale torque range for the Navy's system exceeds 1.5 million foot pounds (2.0 MN m).

3.2. Electric/magnetic field strength sensors

Optical fibers can also be used to measure and map the degree of electric field strength without seriously perturbing the electric field itself. Development work by NASA's Jet Propulsion Laboratory has resulted in a unique amplitude based multimode fiber approach to sensing the distribution of electric fields in a power substation or under high-voltage transmission lines [6].

The device is based on multimode intensity principles and is simple to fabricate. Incoherent light from a light emitting diode (LED) is launched into a 7 mm long length of fiber which is coated with a thin electrically conductive coating. A second identical fiber is placed parallel to the first and connected to a photodetector. The parallel fibers behave as an electroscope in that they bend away and separate from each other under the influence of an electric field. The device operates optimally when the electric field is perpendicular to the fiber pair's longitudinal axis. Specifically, one of the coated fibers intercepts the field's lines of force while the second fiber is blocked from the field by the presence of the other fiber. An unbalanced lateral force results on each fiber, the force being proportional to the square of the field strength and the diameter of the optical fiber.

The coupling between the LED excited fiber and the fiber connected to the photodetector depends on a lens assembly, mirror structure, or curved light guide. As the fibers separate, less light is coupled or reflected between the excited and receiving fibers. The light intensity at the photodetector varies as a predictable function dependent on the amount of mechanical motion which is directly related to the electroscopic movement.

By using a single-mode interferometer, a very sensitive device for detecting weak magnetic fields can be constructed [7]. The basic principle depends on the relative phase change between an optical signal passed though a magnetically isolated reference fiber and a signal coupled into a sensing fiber where longitudinal strain is induced by a magnetostrictive jacket which has been deposited by electroplating, evaporation, ion sputtering or thin-film methods [6]. Magnetostrictive materials include nickel and metallic glass composites. Other approaches documented include the wrapping of a single-mode optical fiber around a magnetostrictive mandrel rather than the fiber coating process and bonding a section of single-mode fiber to a bulk nickel 'stretcher'. In all cases, as the magnetic field strength increases, the resulting magnetostrictive force creates a mechanical strain on the single-mode sensing fiber which minutely alters the sensing fiber's length and refractive index. These changes cause an apparent optical phase shift between the sensing fiber signal and the magnetically isolated reference fiber's signal. The sensing fiber and the isolated fiber form two legs of a classical interferometer.

The literature describes several interferometric magnetic field sensors which have been built and evaluated [8]. Using a 0.85 μm optical source and a 1 m length of nickel-jacketed optical sensing fiber, a magnetic field strength of 1.8×10^{-7} Oe ($1 \text{ Oe} = 10^3/4\pi \text{ A m}^{-1}$) has been detected. A minimum detectable magnetic field of 5×10^{-9} Oe was measured using a 1 m long sensing fiber coated with an amorphous magnetostrictive material. Extrapolation indicates that the latter method could produce a device capable of measuring 5×10^{-12} Oe using a kilometer of optical fiber, or with only a centimeter of coated fiber a magnetic field as small as 5×10^{-7} Oe can be detected. Operation at power line frequencies of 60 Hz is well within the capabilities of such devices and measurements at frequencies up to tens of kilohertz have been demonstrated.

3.3. Current/voltage sensors

Several methods are available which can be used to measure electric current using fiber optic technology. One such device can be fabricated using an interferometric magnetic field sensor as previously described. The nickel-jacketed fiber is located in the center of a wire coil through which passes the monitored electric current [9]. The resulting magnetic field due to the current flow in the coil constricts the nickel-coated fiber resulting in an optical phase shift within the sensing fiber relative to an optical reference signal. For a given value of electric current, the amount of optical phase shift produced depends on the length of sensing fiber employed and the winding construction of the solenoid coil. Therefore, very sensitive fiber optic current sensors can be constructed. Documented laboratory results indicate detectable current values on the order of 30 nA per meter of sensing fiber.

The phenomenon of resistive heating can also be used to produce a fiber optic current sensor [9]. A small section of optical fiber is coated with aluminum about 2 μm thick. With a coating length of 10 cm the electric resistance is about 3 Ω. Passing electric current through the aluminum jacket creates an absorptive heat proportional to the square of the electric current value and the equivalent resistance of the aluminum jacket. This localized heating expands the fiber length and alters the optical index of refraction. When used as the sensing leg of an interferometer, a minimum detectable electric current of 13 μA per meter of sensing fiber has been reported.

Large values of electric current can also be sensed using the Faraday effect. Using this approach, electric currents ranging from a few to several thousand amperes have been measured. The Faraday effect is exhibited by a number of materials such as lead glass, flint glass, BGO (bismuth germanium oxide), BSO (bismuth silicone oxide) and YIG (yttrium iron garnet). When linearly polarized light propagates through a Faraday material in the same direction as a magnetic field which is applied to the material, the polarized light is observed to rotate its plane of polarization by an amount proportional to the strength of the magnetic field. The rotation of the plane of polarization is

$$\text{Angular Rotation} = VBl$$

where V is the Verdet constant for the particular material, B is the magnetic field flux parallel to propagation, and l is the propagation path length within the material.

A 'sandwich' can be created with a polarizer bonded to the Faraday material on the source side and one bonded to the exit side of the material. In this way, the optical source signal is polarized immediately prior to material entry and analyzed immediately after exit. The degree of polarization twist affects the amplitude of the light exiting the second polarizer. This implies that the Faraday based sensor can be implemented with multimode fibers on an intensity basis. Multimode optical fibers can certainly be used to bring randomly polarized light into the first polarizer and, after the analyzer has discriminated the degree of polarization rotation by amplitude coding, a multimode fiber can route the source power toward a photodetector. With today's polarization-preserving single-mode fibers, the Faraday sensor could also be constructed of these fibers and components as well.

Obviously, this device could be directly used as a magnetic field sensor, but by wrapping a current carrying coil around the Faraday material a magneto-optic current sensor can be realized. Conversely, the Faraday material could be fabricated as a ring which slips over the current carrying conductor. With careful selection of the proper material and thus the appropriate Verdet constant, electric current sensors have been fabricated which can measure currents ranging from only a few milliamperes to several thousand amperes [10].

A similar approach can be used to measure high potential values using electro-optic effects in certain crystals. This technique is also an alternative form of electric field sensor. Anisotropic materials offer different indices of refraction based on the direction in which light propagates through the material. Materials such as lithium niobate, lithium tantalate, potassium dihydrogen phosphate (KDP), and BGO are known for this characteristic. This effect can be enhanced by applying an electric field to the material. Linear variations of refractive index with the electric field are exhibited in Pockels material while a quadratic variation is dominant in Kerr media. Most fiber optic voltage sensors are dependent on the Pockels effect.

A voltage sensor can be realized by placing an electro-optic Pockels crystal between two crossed polarizers bonded to the material, similar to the 'sandwich' fabrication of the Faraday magnetic sensor. Incident light from a fiber is immediately linearly polarized by the first polarizer and launched into the Pockels cell. A measurand voltage is impressed across the material which alters the polarization components by the refractive index variation along the crystal's axes. The second polarizer analyzes the degree of resulting polarization rotation and provides an output amplitude proportional to the rotation. The characteristic equation for the Pockels operation is

$$\frac{S}{S_0} = \sin^2\left(\frac{\pi E}{2E_\pi}\right)$$

where S is the incident light intensity, S_o the output light intensity, E is the impressed voltage to be measured, and E_π the impressed voltage required for input polarized light to be rotated by 90° and depends on the material selected.

While the refractive index variations with applied voltage are linear the output result is clearly not. In fact, for very small values of applied E, the output intensity is proportional to E^2. The ease of operation of the device can be enhanced by placing a quarter-wave plate in between the first polarizer and the Pockels crystal which biases the device optically about the 50% intensity output point. The advent of polarization-preserving fibers also allows construction of this device with single-mode technology as well as the multimode fiber delivery.

Devices have been constructed which are capable of measuring from a few volts to several thousand depending upon the Pockels material selected [10].

While the use of these devices is straightforward, the optical current sensors can be configured into a novel system reported by the Japanese for fault detection and location along gas-insulated power transmission lines [11]. The principle of this method is to detect the phase difference of the fault currents measured at two adjacent fiber optic current sensors. Should any grounding fault occur between the two sensors, the output signals from the individual sensors will differ enough to toggle a comparator alarm. The system employs BSO Faraday sensors.

3.4. *Temperature*

There are many approaches which can be utilized for developing fiber optic based temperature sensors. Single-mode interferometric sensors can be constructed using fibers with thermally sensitive jackets which produce length and refractive index changes via induced thermal stress. Fiber claddings can be doped with materials which behave similarly or optical signals can be passed through thin films of materials such as vanadium oxide, the index of refraction of which changes with temperature. Multimode technology can also be used for temperature sensors with such amplitude devices depending on crystalline absorption variations, Fabry–Pérot cavity resonance shifts, fluorescent decay time changes, or mechanical reflectors and shutter actuations as functions of temperature. One of the most unique approaches for multimode temperature sensing is that of a distributed temperature sensor using Raman scattered light [12]. The term 'distributed' implies continuous monitoring of temperature conditions along the entire length of the optical fiber.

At high incidence powers, optical fibers demonstrate a very weak nonlinear scattering phenomenon known as Raman scattering. There are two components to Raman scattered light, namely, Stokes light which has a wavelength longer than that of the incident light and anti-Stokes light which is shorter in wavelength than the incident light. These Stokes terms are functions of temperature and by taking the ratio of anti-Stokes intensity to the Stokes intensity fiber loss variations due to mechanical bending and stress can be eliminated.

The literature describes such a distributed temperature sensor that can continually measure temperature along its length. The sensor was designed to enhance the efficiency and reliability of power plants by constant maintenance supervision and monitoring of temperature [13]. A single multimode fiber was connected to a 100 mW pulsed semiconductor laser source with a wavelength of 900 nm. An optical coupler launched the source energy into a 1 km long graded-index fiber. The returning Stokes radiation was separated by an interference filter into two channels with separate photodiodes, respectively responding to the Stokes and anti-Stokes signals. The output signals were processed by a microprocessor which computed the Stokes ratio as a function of time, and thus distance, along the fiber. The device had a distance resolution of about a meter and a temperature accuracy of ± 1 °C over a range of -20 to 100 °C. The fiber jacketing material used only for fiber protection was the limiting temperature range factor.

4. Conclusions

This paper has reviewed the optical technologies which are applicable to fiber optic sensing devices for power monitoring and generation, as they specifically relate to the electric power industry. Devices for measuring rotating machinery torque, electric and magnetic fields, electric currents and voltages, and distributed temperature are discussed and explained along with basic fiber technology.

Fiber optic sensing is one of the most rapidly expanding technology fields because it presents unique and often simple solutions to complicated measurement problems. This, along with fiber's inherent immunity to interference, its dielectric construction, light weight, and cost–benefit ratio, makes the technology an attractive choice for many instrumentation applications. However, the technologist must constantly remember that a fiber sensor or transducer is just a part of the total solution, since a system of reporting and alerting must accompany the device to be an adopted part of the industry.

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