Fiber Optic and Laser Sensors IV

Ramon P. De Paula, Eric Udd
Chairs/Editors

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Volume 718

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FIBER OPTIC AND LASER SENSORS IV

Volume 718

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Conference 718, *Fiber Optic and Laser Sensors IV*, was part of a nine-conference program on Fiber Optics held at SPIE's Fiber Optics, Optoelectronics and Laser Applications in Science and Engineering Symposium. The other conferences were

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Volume 718

INTRODUCTION

Fiber Optic and Laser Sensors IV was the fourth conference of a planned series that deals with advances in the state of the art of this technology area. The chairs and cochairs wish to extend our thanks to all of the speakers and authors who made this conference and publication possible.

The rapid growth of fiber optic sensor technology has been due to efforts by the telecommunication industry to develop suitable components, in combination with the realization that in many applications the advantages of this technology are compelling. In particular, these sensors have distinct advantages where electromagnetic interference, extreme shocks, vibrations, and temperatures are involved. Two major classes of fiber optic sensors have emerged: hybrid fiber optic sensors that have a fiber leading to and from a black box that impresses information on the light beam, usually in the form of intensity or polarization modulation, and the all-fiber-optic sensors that are primarily based on interferometric methods. In addition to efforts with fiber optic sensors, recent work has also focused on the means to multiplex these units into arrays suitable for beam forming and multisensing applications.

It is becoming apparent that this technology is rapidly evolving into what might be termed optical circuit design, and although it is in the very early stages of formation, the near-term and future impact of this breakthrough in technology is becoming increasingly clear and compelling.

This proceedings provides a series of tutorial papers that review the state of the art of this emerging technology in combination with papers that present the most recent results. It is our hope that the readers of this proceedings will share in the excitement and optimism that are so intertwined with this field.

Ramon P. De Paula
NASA—Jet Propulsion Laboratory
Eric Udd
McDonnell Douglas Astronautics Company

FIBER OPTIC AND LASER SENSORS IV

Volume 718

Contents

FIBER OPTIC AND LASER SENSORS IV

Volume 718

Session 1

Sensors Overview I

Chair
Joseph A. Bucaro
Naval Research Laboratory

Invited Paper

Intensity Modulated Fiber Optic Sensors Overview

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Abstract

Intensity modulated fiber optic sensors have the many distinct advantages associated with fiber optics that makes them suitable for several industrial and military applications. Although, the accuracy of the sensor is far less that for interferometric sensors, the accuracy is more than sufficient for most process control situations. The concepts for intensity modulated fiber optic sensors include: transmissive, reflective, microbending and intrinsic mechanisms. The paper describes the various concepts and applications.

Introduction

As industrial control requirements expand, more innovative sensors are urgently needed. *In fact, there are presently several sensing requirements going unmet because* adequate sensors are not available. Fiber optic sensors may go a long way towards meeting these needs due to their unique properties and distinct advantages. They have the potential to work over a wide temperature range. They are immune to radio frequency interference (RFI), electromagnetic interference (EMI) and toxic environments. They allow access into *normally inaccessible areas. System flexibility is enhanced by remote* sensing. Fiber optic sensors are in many instances passive and as a result, much more reliable than mechanical or electronic sensors. Systems can be designed with very high accuracies which can be easily interfaced with fiber optic data links back to control centers. Systems are now available to tie optical sensors into fiber optic data communication highways.

Most physical properties can be sensed fiber optically (1). Light intensity, displacement (position), temperature, pressure, rotation, sound, strain, magnetic field, electrostatic field, radiation, flow, liquid level and vibration are just some of the phenomena that can be sensed.

Historically, most fiber optic sensor applications have been for relatively simple absence or presence situations such as counting objects, tool break detection and rate counting. Technology has taken fiber optic sensors to the other extreme. Much research and development (2,3,4) has now been completed on ultra high accuracy military applications using interferometric techniques where accuracies of one thousandth of an angstrom have been achieved. Such high accuracies are required for gyroscopes and hydrophone sensors. A large number of both military and industrial applications will require analog physical property sensors more advanced than absence or presence sensors but considerably less complex than interferometers.

Sensor types

Intensity modulated sensors. Intensity modulatd sensors are advanced versions of the simple absence or presence sensors. While counters and switches use their digital capability for an on/off pulse, transmissive and reflective fiber optic sensors are analog in nature. Such sensors modulate the intensity of the light output for measurement. The intensity modulation can result from perturbations in the optical fiber or in transducers attached to the fiber. The light intensity can be monitored directly or ratiometrically.

Transmissive concept. The transmissive concept (5,6) is normally associated with the interruption of a light beam in a switch configuration. However, this approach can provide a good analog sensor. Figure 1(A) shows the probe configuration for axial displacement. Figure 1(C) gives a curve of output versus distance between the probes. The curve follows a $1/R^2$ law where R is distance. A more sensitive transmissive approach employs radial displayement as shown in Figure 1(B). The sensor shows no transmission if the probes are displaced a distance equal to one probe diameter. Approximately the first 20% of the displacement gives a linear output. The curve in Figure 1(C), showing the effects of radial displacement, is for probes with single fibers, 400 microns in diameter.

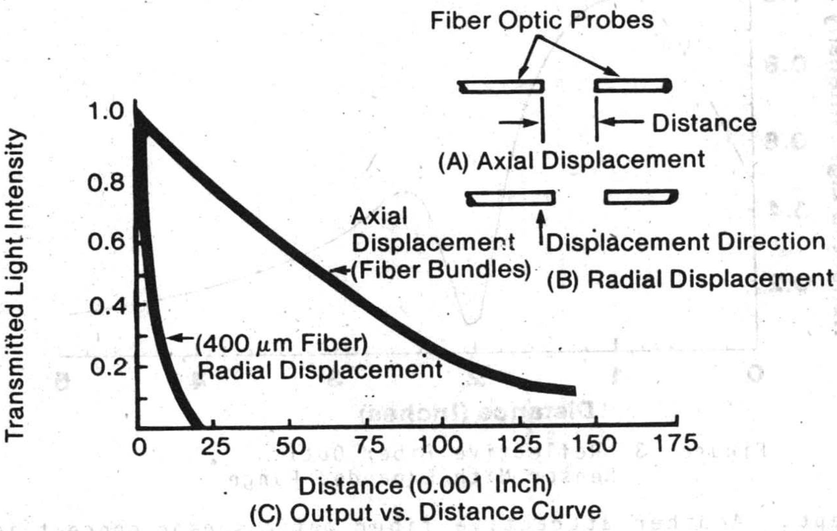


Figure 1 Transmissive Fiber Optic Sensor

Reflective concept. The reflective concept (7,8) is especially attractive for broad sensor use, due to accuracy, simplicity and potential low cost. The concept is shown in Figure 2(A). The sensor is comprised of two bundles of fibers or a pair of single fibers. One bundle of fibers transmits light to a reflecting target, the other bundle traps reflected light and transmits it to a detector. The intensity of the detected light depends on how far the reflecting target is from the fiber optic probe. Figure 2 (B) shows the detected light intensity versus distance from the target. The linear front slope allows a displacement to be measured with potential accuracy of one millionth of an inch. The accuracy depends on the probe configuration; a hemispherical probe has more dynamic range, but less sensitivity when compared to a random probe (Figure 2(C)). A fiber pair probe further expands the dynamic range. A single fiber used in conjunction with a beam splitter to separate the tansmitted and the received beams eliminates the front slope. Depending upon the fiber configuration, reflective probes can be tailored for a wide range of applications.

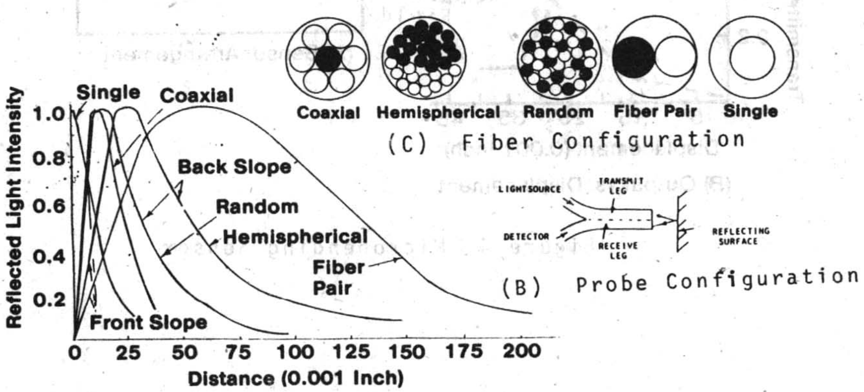


Figure 2 Reflective Fiber Optic Sensor Response Curve For Various Configurations

For applications that require a greater dynamic range than possible with any of the fiber configurations, a lens system can be added (9). Using a lens system in conjunction with a fiber optic probe, the dynamic range can be expanded from 0.2 inches to 5 or more inches as shown in Figure 3.

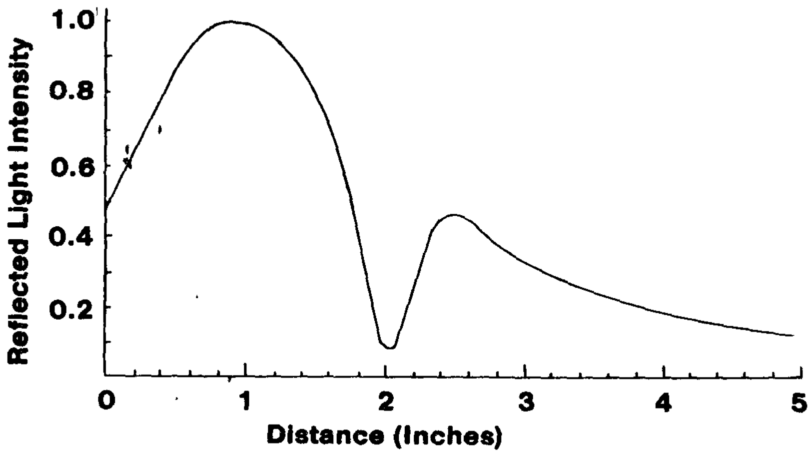


Figure. 3 Reflective Fiber Optic Sensor With Expanded Range

Microbending concept. Another attractive fiber optic sensor concept is that of microbending (4,10,11). If a fiber is bend, small amounts of light are lost through the wall of the fiber. If a transducer bends the fiber due to a change in some physical property, as shown in Figure 4(A), then the amount of received light is related to the value of this physical property. Figure 4(B) indicates that as pressure causes the transducer to squeeze together and bend the fiber, the amount of transmitted light decreases with displacement. Like reflective sensors, they are potentially low cost and accurate. It is also important to note that microbending sensors have a closed optical path and, therefore, are immune to dirty environments.

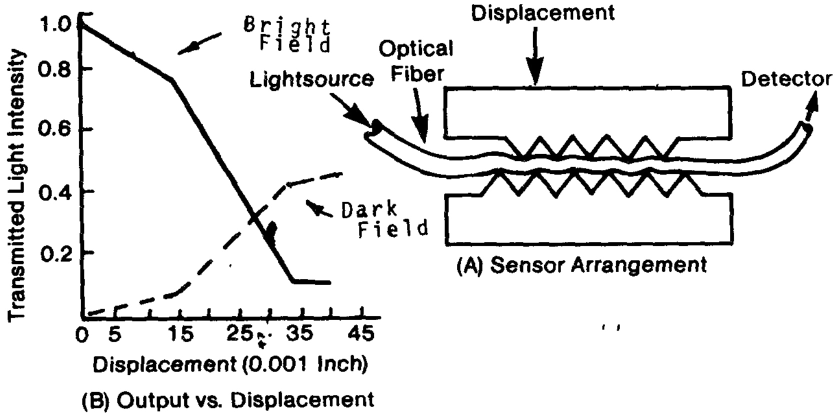


Figure 4 Microbending Sensor

In the response curve, the initial non-linear behavior is due to, at least in part, the rheological behavior of the polymeric protective coatings. The change in slope at high displacement values is due to light depletion. The linear central portion of the curve is the active sensing region. In general, as the number of bend points increase and/or the spacing between bend points decreases, the sensitivity increases.

The sensor described is referred to as a bright field microbending sensor; i.e., the intensity of the transmitted light is measured. It has been shown that dark field sensors are also quite useful. Dark field sensors measure the intensity of light lost through the fiber cladding upon bending. Since light collection is more difficult, the intensity curve is decreased by a scale factor as shown in figure 4B. The intensity curve is also reversed when compared to the bright field sensor.

Intrinsic concept. Intrinsic sensors change the intensity of the returning light from the sensor but unlike the transmissive, reflective and microbending concepts, no movement is required. Intrinsic sensors use the chemistry of the core glass (cladding glass or the plastic coatings) to achieve the sensing activity. The prime mechanisms are absorption, scattering, fluorescence, changes in refractive index or polarization.

For absorption, doping the core glass results in an absorption spectra[12] Generally, some peaks are temperature sensitive while others are not. The ratio of intensity at two specified wavelengths provides a temperature sensing function. A similar approach can be considered for scattering.

Fluorescence can be achieved by doping the glass with various additives. The sensor can function in two modes. A light source can be used to stimulate fluorescence, which is affected by temperature; or the fiber can be stimulated by outside radiation and the fluorescence detected which is a measure of the level of incident radiation.

Refractive index changes can vary the amount of received light by effectively changing the numerical aperture of the fiber. Many polymeric coating materials can be made to have index changes with temperature, thus providing a temperature sensor.

Lastly, doping the glass with various rare earth oxides can make the fiber sensitive to magnetic fields (13). Such fibers in the presence of magnetic fields rotate the polarized light beam in the fiber causing a partial extinction and a correlation of light intensity with magnetic field.

The intrinsic concept can be broadened to include intrinsic properties of a transducer attached to the fiber. Two basic concepts that fall into the category are fluorescence emission and black body radiation, both are being used for temperature measurement (16,17).

Applications

Digital switches and counters. Fayfield[5] gave a review of switch/counter applications, such as broken thread detection, register mark detection, and object detection in general. Transmissive and reflective sensors are primarily used. Figure 5 shows a fiber optic tachometer[14]. The device functions by transmitting light through the probe and reflecting off a rotating disk or shaft encoded with a reflective target. The detection rate is proportional to speed. Fiber optic limit switches are especially attractive due to their non contact nature which eliminates wear. As a general comment, fiber optic absence/presence sensors are more expensive than their photoelectric counterparts. The driving force for their use is almost always environmental difficulties. As the environmental problems become more severe, fiber optic sensors become more cost effective.

Fiber optic switches are expanding to physical property limit switches[15]. The target does not necessarily have to be an object located in space. If a target can be fabricated such that its position or state relative to the probe end is a function of some physical parameter to be sensed, then physical property sensors can be fabricated.

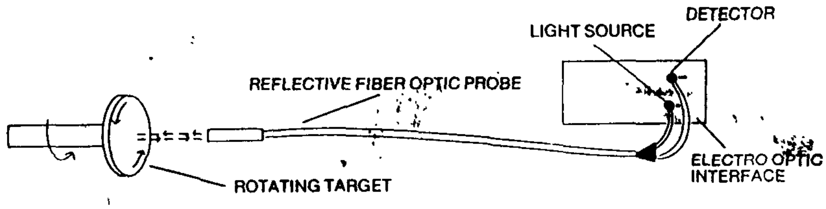


Figure 5 Fiber Optic Tachometer

Consider a reflective bimetal disc as one such target. As the surrounding area reaches its set point temperature, the disc deflects. The distance between the probe tip and the bimetallic element shown in Figure 6 changes correspondingly, affecting the amount of light reflected back to the probe which provides the basis for switching.

Pressure sensing via fiber optics is provided by a method analogous to the bimetal temperature disc. A flexible pressure sensitive diaphragm, with a reflective inner surface varies its distance from the fiber optic probe tip in response to a pressure input as shown in Figure 7. Using a snap diaphragm, a pressure set point is achieved.

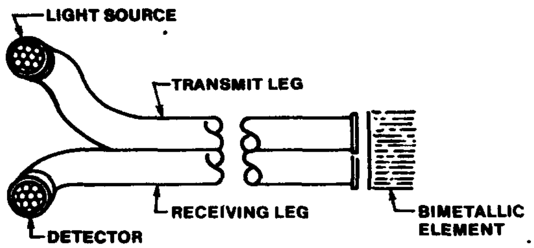


Figure 6 Fiber Optic Temperature Sensor

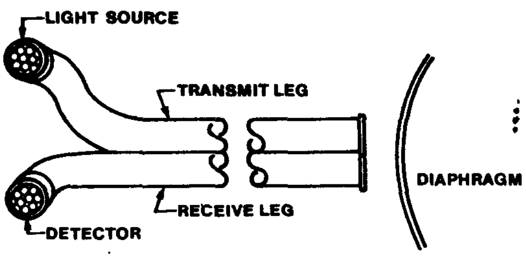


Figure 7 Fiber Optic Pressure Sensor

Another technique for utilization of fiber optic probes involves the use of a prism tip for liquid level sensing (15) (See Figure 8). Light traveling down one leg of the probe is totally internally reflected at the prism/air interface. Note that air (index of refraction=1) acts as a cladding material around the prism. As the prism contacts the surface of a liquid, light is stripped from the prism, resulting in a loss of energy at the detector. With the proper electronic circuitry, discrimination can be achieved between liquid types, such as gasoline and water. The discrimination occurs because the amount of light lost from the system is a function of the index of refraction of the liquid.

Displacement. Reflective, transmissive and microbending sensors are all suitable for displacement sensing applications (9). However, fiber optic reflective sensors are non-contact sensors and, as such have a broad application range. Much like inductive displacement proximity sensors, non-contact reflective fiber optic sensors provide excellent resolution and repeatability. Fiber optic sensors are not limited to metallic objects, but can be used with any material. Reflective fiber optic sensors have the potential of one microinch sensitivity. As the dynamic range of the sensor increases, however, the sensitivity decreases.

Used as a single point sensing system, they can be used for vibration monitoring, gauging parts, as well as measuring film thickness, shaft runout, eccentricity, axial motion and rotation, as shown in Figure 9. Fiber optic proximity sensors are affected by dirty environments which degrade the analog signal. This problem is minimized by working in the IR where light scattering is minimized; and by incorporating a posiive air pressure at the probe tip. In addition, variations in the light source intensity can decrease system accuracy. Electro-optic interfaces, which are compensated for lightsource variations, are available. The overall system effectiveness can often be enhanced by using a dual probe system with a common lightsource. The dual outputs can normalize lightsource variations as well as increase the output for a given movement, thereby increasing the accuracy. Dual probe sensors are positioned so that as the object comes closer to one probe, the output of that probe changes in a manner just inverse to that of the opposing probe. As the value of one goes down, the other goes up. The relationship holds true as long as both probes function either on the front slope or the back slope of the response curve. In addition to magnitude, such a configuration can provide directional information. Similar positioning effects can be achieved if one probe is working on the front slope while the other is working on the back slope. The advantage is that the sensing probes can be placed on one side of the object and no longer have to oppose one another as shown in Figure 10(15). Figure 11 illustrates applications such as measuring sheet thickness, concentricity, deviation or serve positioning, shaft diameter and alignment where dual probes are employed.

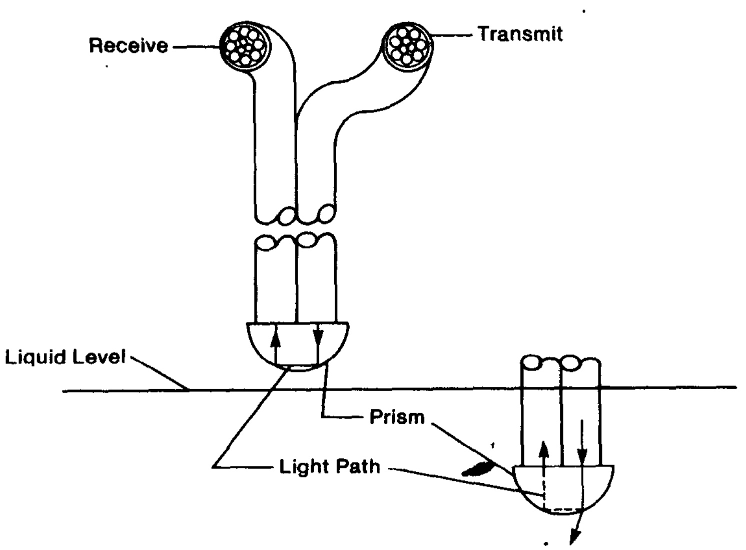


Figure 8 Fiber Optic Liquid Level Sensor

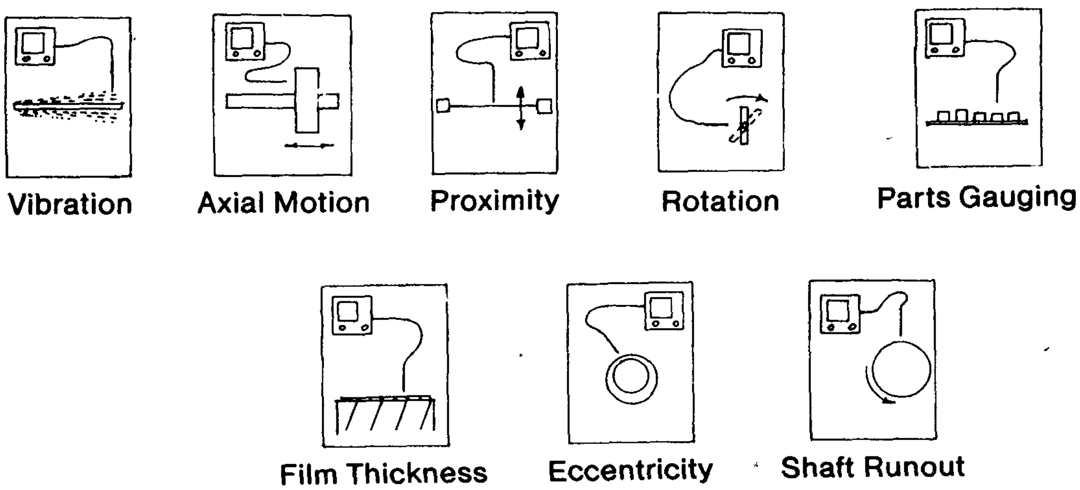
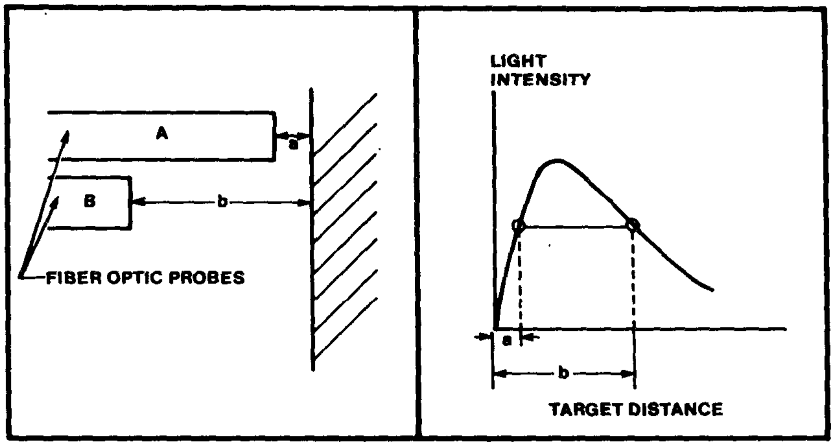


Figure 9 Displacement Sensor Applications



A. Probe position relative to object B. Probe position relative to sensor output

Figure 10 Dual Probe Fiber Optic Displacement Sensor

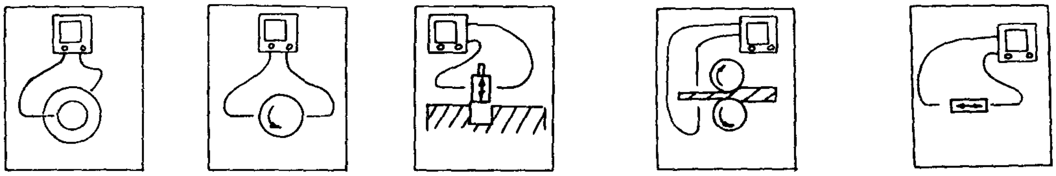


Figure 11 Typical Applications
Dual Probe

Physical properties. Temperature and pressure are two of the most important physical phenomena to be measured (14). A bimetallic element attached to the end of reflective fiber optic probe provides the basis for an analog temperature sensor, as shown in Figure 6. Unlike the temperature switch, the element for the sensor provides analog movement with temperature. With this type of configuration, a linear temperature response can be obtained from 0 to 200° C with an accuracy of +1° C as shown in Figure 12. Using a similar configuration, but replacing the temperature sensitive element with a diaphragm, produces a pressure sensor. The output versus pressure curve is shown in Figure 13. Sensors with a dynamic range of 0 to 500 psi and accuracies better than 1% have been developed.

Other techniques for measuring temperature have been devised (16,17). One approach uses a fiber optic probe on which the probe tip has a coating of rare earth phosphors. The phosphors emit fluorescent radiation when excited by UV light. The intensity of fluorescent radiation is a function of temperature which can be detected fiber optically.

As mentioned previously, intrinsic sensors can be used to measure temperature. Using the absorption approach, neodymium doped fibers have been used to sense temperature over a range of 25 to 900 °C(12).

Chemical analysis. Remote fiber fluorimetry (RFF) is a new technique for chemical analysis (18,19). Typically, a high intensity light beam is transmitted through the optical fiber to the sample material. When the target material is struck with the lightbeam, it emits a characteristic fluorescent emission, which is carried back along the same fiber used for transmitting the initial light. A computer aided detector is used in the analysis.

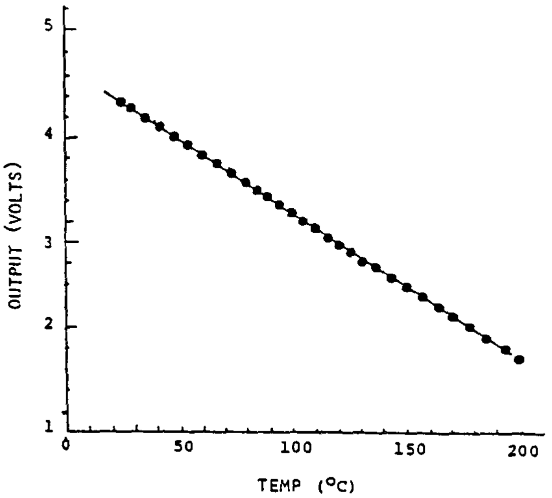


Figure 12 RESPONSE CURVE FOR FIBER OPTIC TEMPERATURE SENSOR

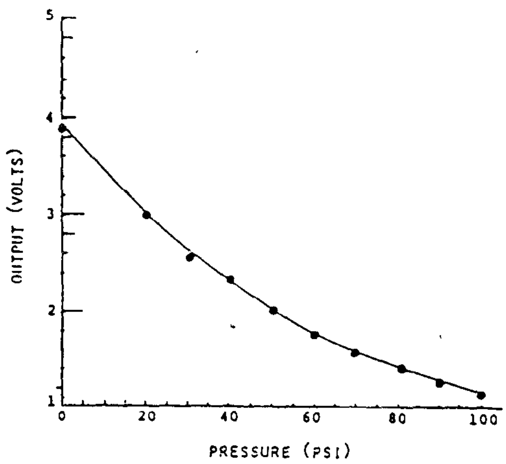


Figure 13 RESPONSE CURVE FOR A FIBER OPTIC PRESSURE SENSOR

A schematic representation of the system is shown in Figure 14. An important aspect of RFF is that it is possible to replace a number of in-line sensors (which includes process analysis capability) with a fiber optic probe for each sensing location which goes back to a common analysis processor, thereby providing significant cost saving.

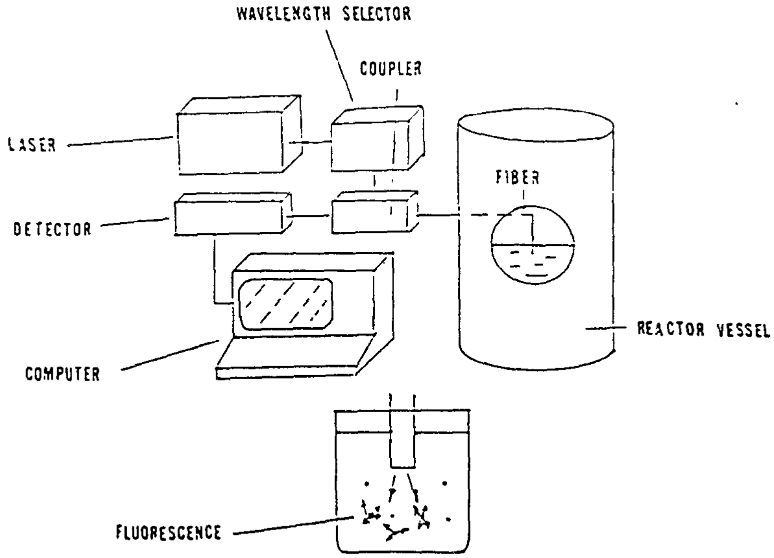


Figure 14 Remote Fiber Fluorimetry

Sensing/Communication System. As the requirements for factory and process automation increase, it will be necessary for several sensors to work together (20) and communicate over a common system. Figure 15 shows, schematically, a typical system configuration. The sensors, both analog and digital, interface to a node which performs an electro-optic conversion. It supplies digital sensing information which is multiplexed onto the fiber optic communications network. The information is then transmitted back to the host computer. The node is electrical and peforms two conversions, opto-electrical for digital conversion and electro-optical for digital transmission. Electro-optic components to achieve the sensor/communication system integration are now commercially available.

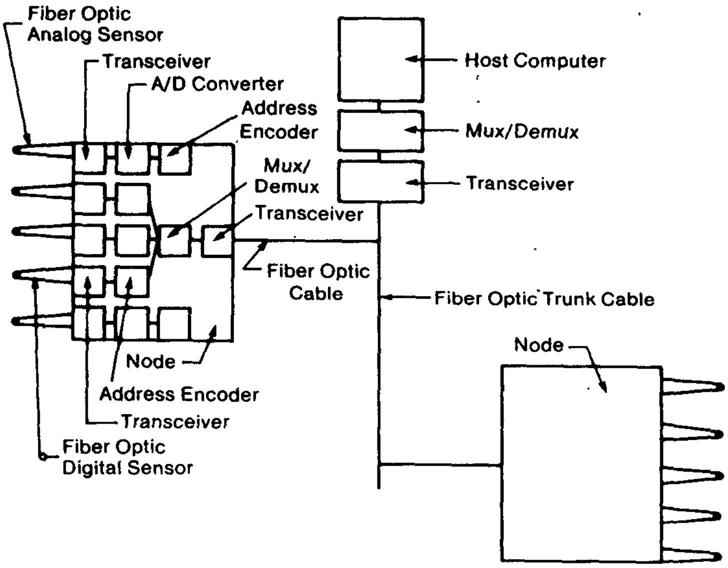


Figure 15 Fiber Optic Sensor Network

Summary. Fiber optic sensors can provide a series of functions from simple switches to the most advanced analog sensing requirements. A family of concepts are available for intensity modulated sensors which includes reflective, transmissive, microbending and intrinsic techniques.

As the technology advances, more of the sensing functions will be incorporated in the materials that comprise the fiber. As factory and process automation requirements expand, sensors will evolve into sensing systems, which, in turn, will be integrated into communications networks.

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