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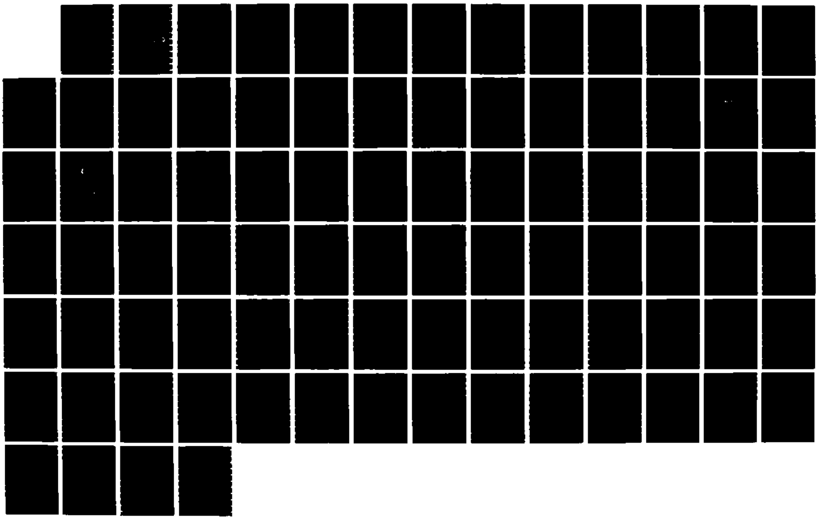

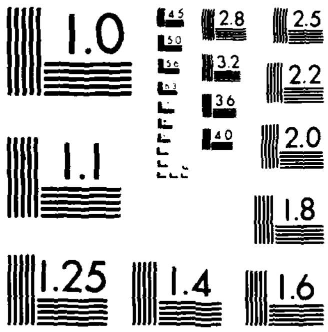

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ABSTRACT

An analysis of the current state-of-the-art of intensity-modulated fiber-optic sensors is performed. The dominant types of intensity-modulated fiber sensors are outlined. The principles of operation are detailed and a description of the performance potentials and limitations are described. Trends in development and application areas are depicted.

5

FIBER-OPTICS -- A SENSING DEVICE

BY

BOOKER HOWELL TYRONE, JR., B.S.E.E.

CAPTAIN, US AIR FORCE

82 pages

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN ENGINEERING

THE UNIVERSITY OF TEXAS AT AUSTIN

August 1986

FIBER-OPTICS — A SENSING DEVICE

APPROVED:

Carter F. Womack

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June 24, 1986

ABSTRACT

An analysis of the current state-of-the-art of intensity-modulated fiber-optic sensors is performed. The dominant types of intensity-modulated fiber sensors are outlined. The principles of operation are detailed and a description of the performance potentials and limitations are described. Trends in development and application areas are depicted.

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1. INTRODUCTION

Fiber-optic sensor technology is rapidly establishing itself as an accurate, sensitive, and robust means for measuring physical variables in industrial, avionic, medical, and military applications [1]. Since 1977 the realization that optical fibers could be used for sensors and sensing systems has increased exponentially; yet the technology is still in its infancy. The initial impetus has been for defense and aerospace applications. More recently, the unrelenting pressure to reduce cost, improve accuracy and reliability, and replace inadequate or unsatisfactory traditional methods in the industrial sphere has fostered the entrance of many research laboratories and universities into the fiber-optic sensor field. Rapid progress has been made toward development of sensing devices that exploit the technical improvements of the relatively mature point-to-point fiber-optic data communications, namely, low signal attenuation, flexibility, and high information transfer capacity [2].

Fiber-optic sensors are dielectric devices that demonstrate acute sensitivity, inertness to hazardous or extreme environments, immunity from radio-frequency or electromagnetic interference, geometric versatility, and simplicity [3]. They can detect physical perturbations in sound, displacement, temperature, pressure, magnetic fields, electric fields, rotation rate, strain, liquid level, and flow. The light weight, small size, and lack of moving parts make fiber-optic sensors a major goal for aerospace and military use [4]. These sensors require a light source (incandescent or laser), an optical interface, one or more optical fibers, an optical modulation mechanism, a photodetector, and signal processing equipment. Depending on the type of sensor, the optical fiber and other optical components may be single-mode or multimode [5].

There are two distinct types of optical sensors, extrinsic and intrinsic. Most fiber-optic sensors implemented to date have been extrinsic systems, employing optical fibers to convey light but using external phenomena such as reflection from a target or attenuation in an absorbing medium for the actual measurement. Intrinsic sensors derive measurement information directly from interactions between the fibers and the phenomena of interest (e.g., physical effects such as strain or pressure) by producing an interference pattern of optical fringes and detecting any path length changes [6]. A further distinction can be made according to the modulation mechanism employed. Phase, intensity, color (wavelength), and polarization are the optical parameters that can be modulated; therefore, modulation mechanisms of each type are being investigated [7]. Table 1 [8] lists the optical properties and associated variables.

Three international conferences on optical fiber sensors (London, 1983; Stuttgart, 1984; San Diego, 1985) [9], the establishment of the Optical Sensors Collaborative Association [10], and the recent barrage of publications in this area are indications that the fiber-optic revolution is moving beyond communications. Instruments using optical fibers to form the basis of ever more complex instrumentation systems are already on the market; government and industrial labs are researching the use of fiber sensors for detecting submarines, monitoring high-tension power lines, and even replacing the metal strings on electric guitars [11]. Of immediate

Table 1. Principles of Fiber-optic Sensors (after [8]).

Variables	Light properties	Principles	Fibers
Current Magneticfield	Polarization	Farady effect	M , S
	Phase	Interference (magneto-strictive effect)	S
Voltage Electricfield	Polarization	Pockels effect	M
	Phase	Interference (electro-strictive effect)	S
Temperature	Intensity	Shutter Absorption (semiconductor) Reflection (liquid crystal)	M
		Photoluminescence (phospher, semiconductor)	
	Intensity Spectrum	Black body radiation	M
	Polarization	Birefringence	M
Rotation rate	Phase	Sagnac effect	S
Velocity	Frequency	Doppler effect	M , S
Pressure Vibration Acceleration	Intensity	Microbending loss	M
		Shutter Reflection	
	Polarization	Elasto-optic effect	M
	Phase	Interference (elasto-optic effect)	S
	Frequency	Doppler effect	M , S
Level	Intensity	Reflection	M
Gas	Intensity Spectrum	Absorption	M
Radiant rays	Intensity	Color center	M

Fibers, M : Multimode fiber , S : Singlemode fiber concern are problems with detection processes, packaging, optimized fiber coating, and noise sources. Although many projects will inevitably fall short of expectations, the development of optical fiber sensors will embrace a new and exciting chapter in measurement technology.

The purpose of this thesis is to analyze the current state-of-the-art of intensity-modulated fiber-optic sensors. Due to the enormous quantity of research literature being published and the wide variety of ideas on optical fiber sensors, a comprehensive treatment of each variation is beyond the scope of this paper. Instead, the dominant types of intensity-modulated sensors are presented. The technology is explained in terms of theory and applications, the development of the support technology is assessed, and remarks on the future direction of optical fiber sensors are given.

2. INTENSITY-MODULATED SENSORS

Intensity modulation is an attractive mechanism for sensing light in optical fibers since all forms of optical modulation must be converted to an intensity variation for photo-detection. With intensity sensors the physical perturbation modulates the intensity of light propagating in the fiber or through optical elements connected by fibers. The light beam is either detected upon transmission or upon reflection in the interaction region. Figure 1 shows the general form of an intensity-modulated sensor and indicates the most often used intensity modulation mechanisms [12].

The principal advantages of intensity sensors are simplicity of design, adequate sensitivity for most applications, reduced susceptibility to environmental effects, compatibility with present-day multimode fiber technology, and the ability to measure ac or dc signals. Intensity-modulated sensors employ relatively simple optics (LED light sources rather than lasers) of which many produce no noise in excess of quantum shot noise. This results in systems having extremely large dynamic range. These sensors can incorporate time multiplexing

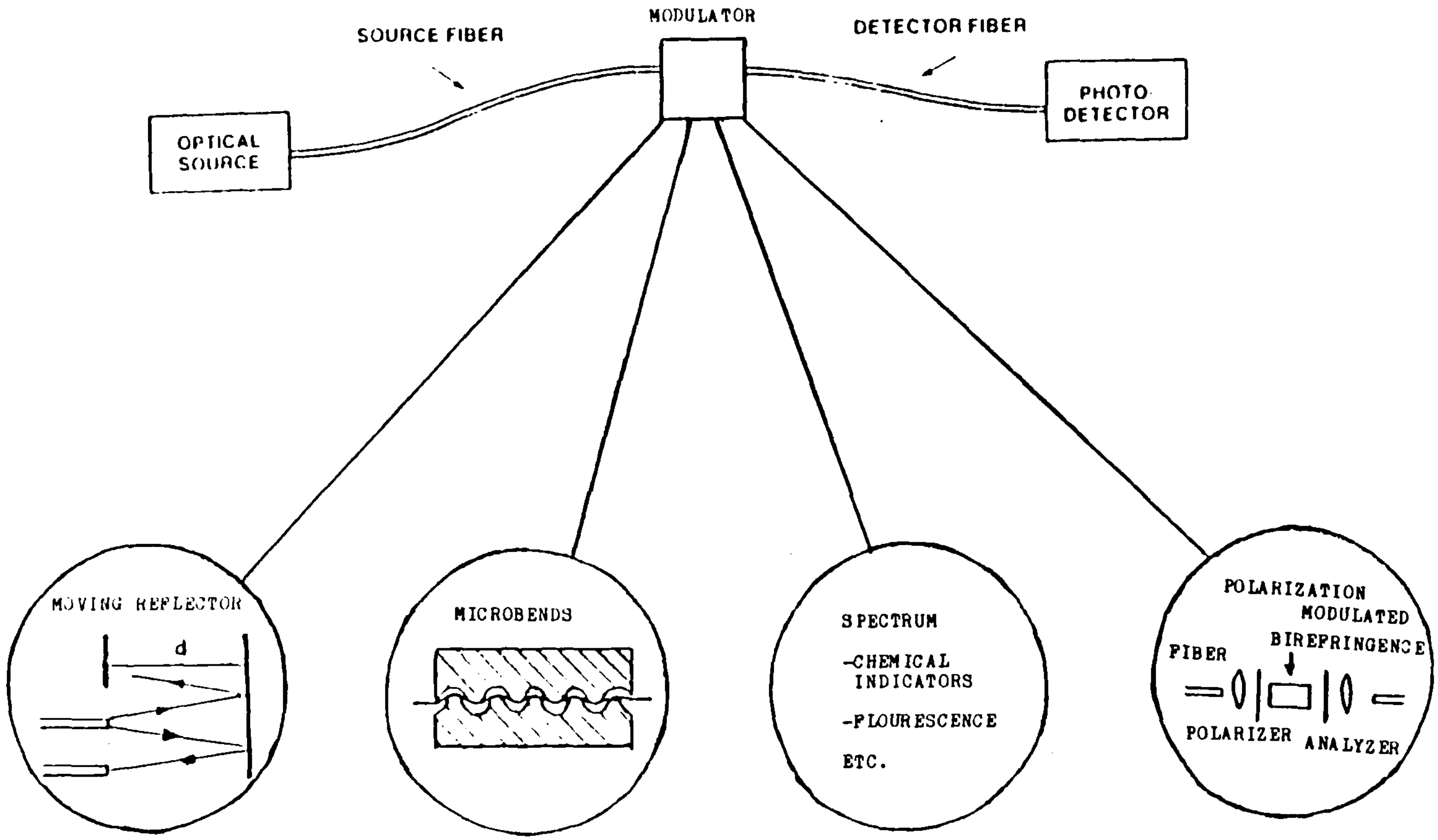


Figure 1. General Intensity-Modulated Sensor Configuration and Mechanism.

techniques without dispatching external electric power to the sensor location.

While intensity sensors are attractive in their inherent simplicity, they are prone to errors due to critical mechanical alignment, variations in signal amplitude along forward and return fiber paths, fluctuations in the optical power levels launched at the receiver, and long term instability of photodetector sensitivity. Mechanical couplings are necessary between source and fiber and detector because most intensity modulation mechanisms require a break in the optical path. Some form of referencing is required to allow for coupler and source introduced anomalies [13].

To date, the best sensitivities that can be attained with intensity-modulated devices, in terms of minimum detectable displacements of mechanical-motion detectors, lie in the range of 10^{-10} to 10^{-7} m (meter), as compared with the lower limit of 10^{-14}m achievable with interferometric type sensors [14]. This diminished sensitivity has been adequate in the majority of sensor applications but shows extreme promise for acoustic applications in shallow water where ambient sea noise is relatively high and only simple multiplexing is required. Table 2 [15] provides a comparison of the detection thresholds of the intensity sensors.

Table 2. Summary of Intensity Sensor Performance (after [2]).

	Sensor Type	Measured Detection Threshold dB re 1μPa	Advantages	Disadvantages
1.	Evanescent	83 (17)	Multimode Fiber	Critical mechanical alignment, light not confined
2.	Reflective		Potentially attractive as a simple surface proximity sensor. Can use a single fibre to sensing point.	Calibration of non-digital systems. Can also be problems with cross-talk limiting dynamic range if single fibre used.
3.	FTIR	60 (20)	Multimode fiber	Critical mechanical alignment. Light not confined.
4.	NTIR	110 (Projected)	Point probe. Large bandwidth	Single mode fiber Critical mechanical alignment. Low sensitivity.
5.	Wavelength		More absolute sensors. Potentially many applications.	High detection sensitivity required. More complex sensing system.
6.	Microbend	60 (34)	Multimode fiber, Light confined to fiber	Critical mechanical alignment
7.	Polarization	35 (2)	Light confined in fiber	Single mode fiber
8.	Photoelastic	48 (41)	Multimode fiber	Sensitivity to temperature and pressure ambients.
9.	Schlieren	50 (43)	Multimode fiber	Light not confined
10.	Moving Fiber	80 (49)		Single mode fiber. Critical mechanical alignment. Light not confined

2.1 Evanescent Sensors

In the evanescent-field or coupled-waveguide [16-18] sensors, an evanescent field couples light energy from one fiber core to the other as a directional coupler and penetrates into the cladding or lower index material when total internal reflection (TIR) occurs. The TIR sensors are considered in Section 2.2. As illustrated in Figure 2, a pair of single or multimode fibers is placed in close proximity with each fiber's cladding either partially or completely removed to enhance light coupling. When the transduction element is acted upon by a measurand, light is coupled between the fibers. This coupling is the result of minute perturbations in the separation distance d, in the interaction length L, or in the refractive index n_2. A further enhancement can occur if the fiber is situated in a fluid or flexible elastomer of identical refractive index as that of the cladding.

Sheem and Cole [16] demonstrated that the single-mode fiber optical power divider can be used as an acoustic sensor through evanescent field overlap. A modulation index of $9 \times 10^{-15}/\mu Pa$ (micropascal) was calculated for this device and $7 \times 10^{-17}/\mu Pa$ was measured. The

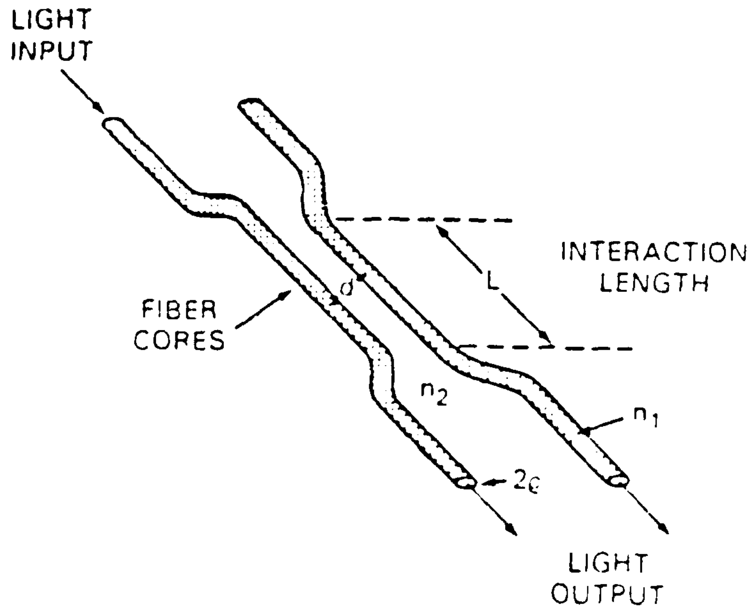


Figure 2. An Evanescent-Field or Coupled-Waveguide Intensity-Modulated Sensor (after [2]).

several orders of magnitude difference is speculatively attributable to a flexing motion not accounted for in the transduction coefficient for the rate of change with pressure of the core separation. A minimum detectable acoustic pressure of 52 dB relative to 1 μPa was measured for a shot-noise-limited device of 1 mW optical power [16].

Carome and Koo [17] employed two plastic-clad multimode fibers and a LED source to fabricate an optical waveguide coupler-type acoustic sensor [17]. At the center of each 3 m long fiber, a 10 cm (centimeter) section of fiber was stripped of cladding, and these sections were twisted together. This linear twisted pair was then mounted under adjustable tension, along the 15 cm diameter of a Plexiglas hoop to form the transduction element of an acoustic sensor. Acoustic sensitivities of 83 and 72 dB relative to 1 μPa were measured for the coupled fiber and directly fed fiber, respectively. Higher sensitivities obtained using a Helium-Neon (He-Ne) laser source seemed to result from phase modulation rather than intensity modulation processes.

J. D. Beasley [18], also, successfully demonstrated an acoustic sensor [18] using evanescent coupling between optical fibers. The sensor has a detector shot-noise-limited sensitivity at a sound pressure of approximately 50 dB relative to 1 μPa. The bandwidth of the sensor is dc to 8000 Hz.

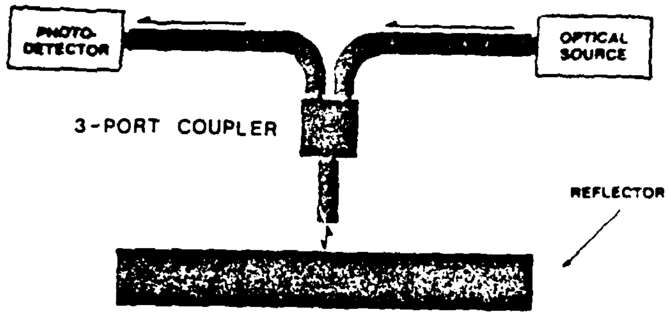
In these demonstrations, acoustic fields were employed as the perturbation source, but almost any condition can be converted into a motion; thus, this mechanism can be used to construct thermometers, accelerometers, strain sensors, or pressure sensors. The main disadvantage of such sensors is the inevitable loss of light which occurs, because it usually necessitates the use of more sensitive receivers.

2.2 Reflection Sensors

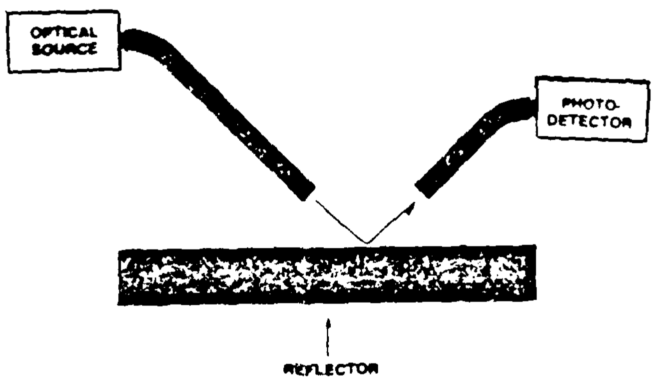
A type of very simple but effective intensity sensor is based on the reflection of light from one fiber into another or back into the same fiber from a mirror-like surface. These reflection sensors [19-24] are gaining rapid acceptance in the industrial sector. Their applications include automated manufacturing component identification, proximity and motion sensing, and surface finish inspections [19]. In addition, the military has employed them as hydrophones [20] for underwater acoustic detection, and researchers are investigating their potential to measure temperature [21] and pressure [22-23].

Two basic configurations of surface reflection sensors are shown in Figure 3. Each operates on the principle that light from the optical source will emerge from one or more source fibers, propagate through the medium separating the fiber end from the reflecting surface, reflect from that surface, and propagate back toward the output fiber. A portion of the reflected light re-enters the source fiber (single fiber case) or enters the output fiber (two-fiber case) where it is guided to a light detector. The quantity of light captured from the reflecting surface is a function of the distance between the fiber end and the surface. Depending on the sensor application, a variable angle can be introduced in the two-fiber sensors that will also effect the fraction of light coupled to the output fiber.

Lewis et al. [19] reported the construction of industrial application sensors capable of measuring the proximity to a reflective surface, determining spatial relationships to weld joints, gauging the size and shape of holes in workpieces, and judging the surface finish on a machined workpiece. With modifications the proximity



(a) One-Fiber Reflective Sensor



(b) Two-Fiber Reflective Sensor

Figure 3. Surface Reflection Intensity-Modulated Sensors (after [19]).

sensor can be adapted to measure temperature utilizing the thermal expansion of metal.

OPTECH [24] developed a pressure gauge of single fiber configuration and a reflective diaphragm that moves with pressure. It demonstrated nonlinearity of less than 1% between 100 and 400 μm. The range of the pressure gauge is related directly to the designed range of the diaphragm (e.g., 0 to 1 psi or 0 to 1000 psi, etc.) [24].

Two reflection sensors which combine evanescent-field coupling with Fresnel reflections are the FTIR (frustrated-total-internal-reflection) sensor [20-21] and the NTIR (near-total-internal-reflection) sensor [23]. An internal reflection sensor [20-21, 23] uses the evanescent wave which penetrates into the reflection or transmission surfaces at an optical interface as a source for extreme sensitivity to movement. The Fresnel intensity reflection coefficients [24] at the interface are given by:

$$R_1 = \left(\frac{\cos\theta - (n^2 - \sin^2\theta)^{1/2}}{\cos\theta + (n^2 - \sin^2\theta)^{1/2}}\right)^2$$

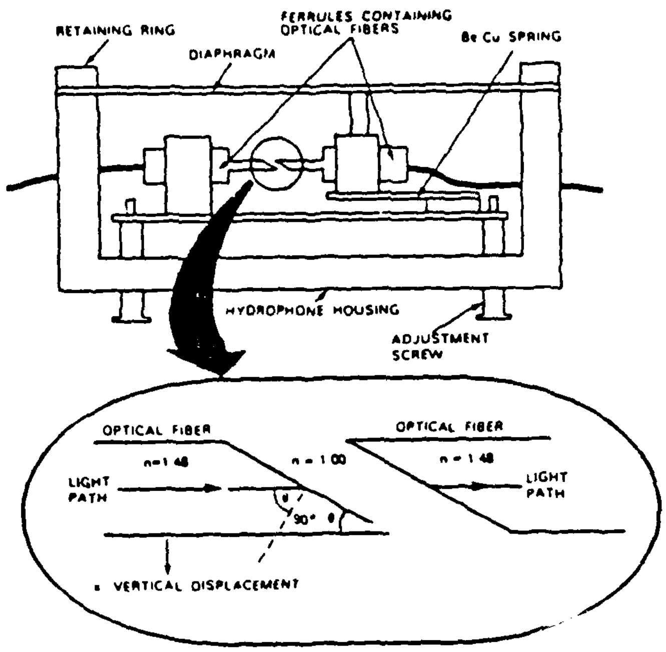
$$R_{11} = \left(\frac{n^2\cos\theta - (n^2 - \sin^2\theta)^{1/2}}{\cos\theta + (n^2 - \sin^2\theta)^{1/2}}\right)^2$$

for the perpendicular, R_1, and parallel, R_{11}, polarization directions.

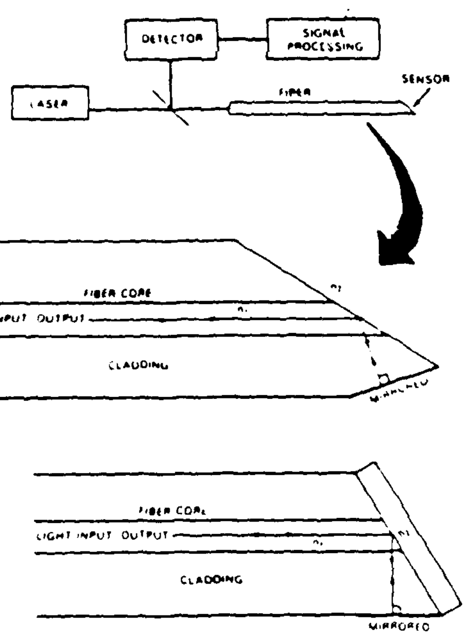
$$n = n_2/n_1$$

where n_2 is the external medium refractive index and n_1 is the refractive index of the fiber core. θ is the incidence angle. The derivative of the coefficient equations gives the rate of change of reflected power as a function of the external refractive index n_2.

Efforts are being made to exploit point sensors which depend on the principle of TIR to measure variables such as displacement, temperature, pressure, etc. One such multimode sensor, the FTIR sensor [20-21] is shown in Figure 4a. This sensor consists of two optical fibers separated by an air gap of prescribed thickness and unity index. The ends of the fiber adjacent to the air gap are polished at an angle to the fiber axis large enough to cause total internal reflection for all modes propagating in the fiber. Provided the distance between the fiber ends is sufficiently small, a huge portion of the light energy is coupled from one core to the other. The transmitted light from the output fiber will be intensity modulated when the air gap thickness is varied by the desired measurand. One fiber end is held stationary



(a)



(b)

Figure 4. (a) Frustrated-Total-Internal-Reflection Mode Sensor (after [20]).
(b) Near-Total-Internal-Reflection Sensor (after [23]).

while the measurand vertically displaces the other, thereby modulating the air gap thickness.

Spillman and McMahon [20] constructed and tested a multimode optical fiber hydrophone utilizing FTIR. Achieving significantly improved results over any fiber-optic hydrophones previously reported, they stated that the FTIR hydrophone could be implemented with present fiber-optic technology. The minimum detectable pressure threshold of 60 dB relative to 1 μPa was measured over a bandwidth of 100 Hz to 10 KHz. Stringent mechanical tolerances and confinement of light within the fiber were noted as disadvantages of this approach.

Palmer et al. [21] have proposed a FTIR temperature sensor which uses the differential thermal expansion and contraction of a stainless steel base to modulate the air gap thickness. The air gap can be adjusted between nearly 100 percent and 0 percent transmission, providing a wide temperature range. Problems with this approach include stability of the resin glue over varying temperatures and non-linearity between temperature and light intensity as reflecting evanescent waves vary exponentially with distance.

A single-mode NTIR sensor [23] is one of several point sensors in which the propagating light in the optical fiber is used to measure the external variable at the single point. The NTIR or critical angle probe proposed by Phillips [23] is shown in Figure 4b. The sensing end of the fiber requires two reflecting surfaces whenever the critical angle, defined by $\theta_c = \sin^{-1}(n_2/n_1)$, is not near 45°. The second surface allows the reflected beam to return through the fiber.

When the light is injected into the left end of the fiber core, it travels to the right end where part is transmitted into the medium and part is reflected back through the fiber. A beam splitter directs the reflected portion to the photodetector. Variations in the index n_2 caused by the force field of interest modulates the intensity of the reflected beam. Difficulties with the practical implementation of such a probe arise because single mode fiber must be utilized and the orientation of the reflecting surface relative to the interface and fiber core is critical.

2.3 Wavelength Sensors

Closely related to the optical reflection devices described in the previous section is a family of sensors whose optical fibers are terminated by a material sensitive to spectral-dependent variations of absorption, emission, and refractive index. These wavelength (color) sensors [25-30] are becoming increasingly important for biomedical and industrial process applications. Generally configured as color probes, these sensors are employed in chemical, black body radiation, and phosphorescence and luminescence analysis. Interference filters whose transmission characteristics are a function of an external physical parameter also are incorporated in color modulation.

Since optical fiber sensors which rely on wavelength or color modulated effects can inherently overcome the need for intensity referencing, some researchers categorize these sensors separately from intensity-modulated devices. The sensors described here rely on ratiometric measurement of the color intensity and, therefore, will be considered intensity-modulated sensors.

Figure 5 shows the basic configuration of the wavelength sensor. Visible or ultraviolet light from the optical source is guided via the fiber to the monitoring region where wavelength modulation occurs. Visible or infrared light is then returned by a second fiber to an analyzer for ratiometric measurements of the optical intensities at a minimum of two different frequencies. Typically, one wavelength is used for measurement and another is used to normalize for tranmission line losses. In contrast to sensors previously described, the optical fiber of the color sensors simply serves as a passive light guide.

Numerous color sensors have been extensively investigated by M. Hutley [25]. They use diffraction gratings and zone plate tranduction elements, shown in Figure 6, to provide a relatively simple means of measuring angular and linear displacement. As the grating rotates in response to a change in some parameter, the output wavelength changes, and as the zone plate moves back and forth, the image of the input fiber on the end of the output fiber is formed at different wavelengths [25].

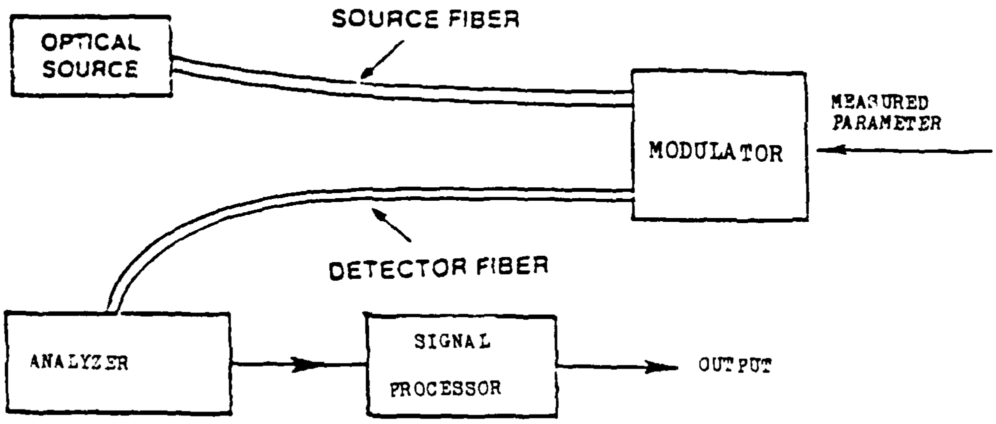


Figure 5. Wavelength Intensity-Modulated Sensor Basic Configuration.

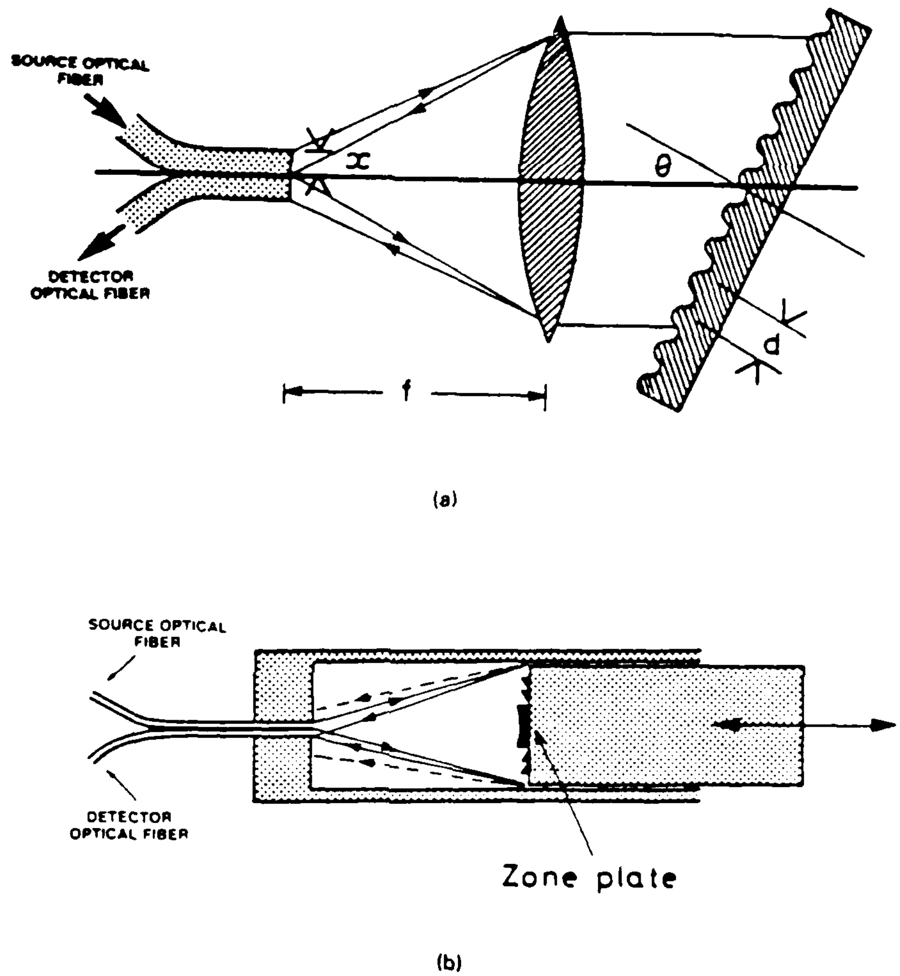


Figure 6. Two Wavelength Transducer Elements (after [25,26]).
(a) A Grating Monochromator.
(b) A Reflecting Zone Plate.

The application of a zone plate linear transducer to pressure measurement was reported by J. D. Place [26]. The pressure sensor utilized a zone plate with a series of concentric circular grooves as a spherical concave mirror. When the distance between the optical fiber and the zone plate equals the effective radius of curvature, which is inversely proportional to wavelength, the incident light is focused back onto the output fiber. As the zone plate translates relative to the fibers, the transmitted wavelength is modulated [26]. The zone plate transducer demonstrated a resolution of 6.5 μm or 0.65% of the displacement range attainable using a LED light source.

These wavelength sensors have biomedical applications [27-28] as physical sensors for pressure, temperature, blood velocity, and blood flow monitoring and as chemical sensors for oxygen saturation, PH, PO_2, and PCO_2 measurement. Also of considerable interest is their application for invasive (e.g., in the blood stream or in tissue) measurement. Biochemical sensors use reversible reagents located at the fiber end that allow spectrophotometric or fluorometric analysis. Physical sensors use transduction elements located at the fiber end that modulate the light signal according to desired variables.

Brenci, et al. [29] proposed an experimental fiber-optic temperature sensor [29]. The tranduction element consists of a thermochromic solution of a Cobalt salt that varies its optical absorption spectrum with temperature. A sensing and a reference signal are generated by different absorptions at two different wavelengths. A resolution better than 0.1°C with a maximum rise time of approximately two seconds was achieved. Stability to an accuracy of ± 0.4°C (24 hours) and ± 0.2°C (4 hours) was exhibited.

In industrial processing, the steel manufacturers of Japan employ fiber-optic pyrometers [30] developed from commercially available components as hot metal detectors. The intensity or spectrum of the light signal from the black body radiation is used to measure a temperature range from 600°C to 1200°C. Mitsubishi Electric in conjunction with Japan National Railway has measured hot spots of a transformer operating at 30 kilovolts (KV). Their sensor was based on the optical absorption property of a GaAs semiconductor chip [30].

Wavelength sensors in which the optical fiber serves merely to transmit information to and from the sensor have proven economically attractive to the electric power generation and medical areas. This is due to the large number of optical phenomena that can be used to measure an even greater variety of physical parameters. However, limitations of this sensing technique include the instability of the optical source spectral properties, thermal variations of the analyzer (e.g., spectrometer), relatively short transmission range, and the necessary use of high loss fibers.

2.4 *Microbend Sensors*

Microbend modulation is one of the most sensitive and one of the most often used intensity-modulated sensing techniques. This technique is applicable for monitoring strain [31-32], sound [33-34], displacement [35], velocity [32], or acceleration [32]. The microbend fiber-optic sensors [31-35] operate on the principle of intensity modulation of core modes produced by a periodic axial deformation of the fiber.

A multimode fiber is placed between two corrugated plates as shown in Figure 7a. When the force field of interest vibrates one of the plates against the other,

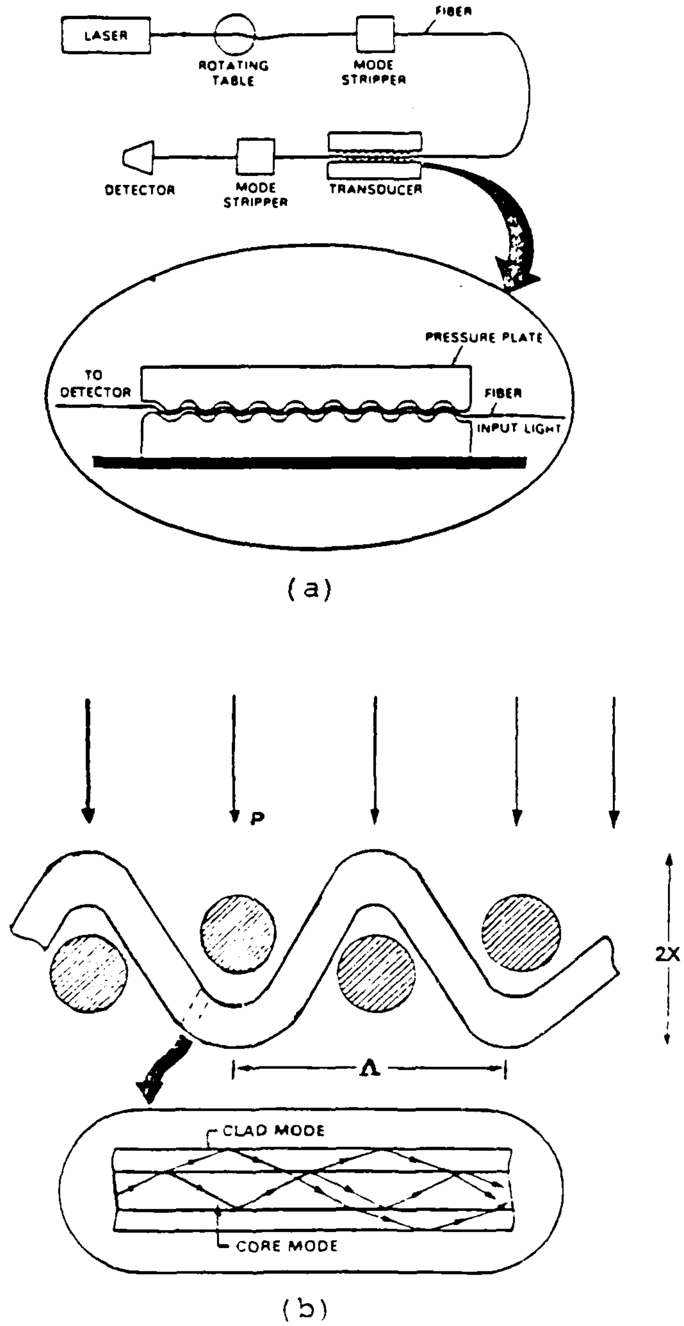


Figure 7. (a) Microbend Intensity-Modulated Sensor (after [2]).
(b) Microbend transduction mechanism illustrating pressure induced mode coupling (after [34]).

small bends are introduced in the fiber. Light rays propagating through the fiber at an angle less than critical will have their angle of incidence increased at the core-cladding interface and will radiate into the cladding as illustrated in Figure 7b. The changes in beam intensity provide a measure of the displacement of force applied. If the distance between adjacent teeth, defined as the spatial frequency of the deformer, has the correct periodicity, the microbend effect will be considerably enhanced.

Asawa et al. [31] constructed a microbend strain sensor of optical fiber to detect bending and vibrations of large mechanical structures. Optical time domain reflectometry was used in conjunction with these high sensitivity strain gauges for detecting strains at several structural points simultaneously. Structural bend radii of larger than 5 Km were measured.

Typically, microbend devices have sensitivities of a few decibels per micrometer of displacement and ranges of 100 μm. Marvin and Ives [32] have been investigating a strain sensor developed for a much larger range and correspondingly lower sensitivity. The extended range of this device is achieved through replacement of the corrugated plates by a roller chain-like deformer. A constant curvature bend rather than a sinusoidal bend is imposed on the fiber. The wide range of sensitivity adjustment and the linear calibration curves vary as a function of the number of roller links, the radius of the bearings, the pitch of the chain, and the diameter of the fiber.

OPTECH [36] has fabricated a microbend optical fiber accelerometer mounted on a calibrated piezoelectric transducer stack. The minimum detectable acceleration in a 1 Hz band over the frequency range of 5 Hz to 800 Hz was 15 μg and the dynamic range corresponding to 1% linearity was 100 dB. Linear operation is anticipated over the range from 15 μg to 1.5 g.

Fields [33] and Lagakos et al. [34-35] have demonstrated microbend acoustic sensors [33-34] and a microbend displacement sensor [35]. Except for the acoustic device of Lagakos et al. [34], the microbend sensors suffered because of complicated mechanical design, critical deformer alignment, limited bandwidth, and acceleration effects.

2.5 Polarization Sensors

Polarization is vital to a variety of optical fiber sensors, especially devices developed to monitor current [37] and voltage [38] in electric power systems. As a modulation mechanism, polarization is a somewhat ambiguous technique. It will be considered here as an intensity modulation mechanism, yet it could equally well be thought of as a totally separate modulation mechanism. This ambiguity arises because all forms of optical modulation must be translated to an intensity variation for detection which creates an unclear distinction between intensity-modulated sensors and sensors employing other modulation schemes.

In the polarization sensor [37-38] of Figure 3, two modes having identical propagation constants but orthogonal polarizations travel along the single-mode fiber. A phase difference directly proportional to a polarization rotation of the beam propagating through the fiber is induced between these two polarization states. The rotation angle is then converted into an intensity modulation by the appropriate polarization analyzer.

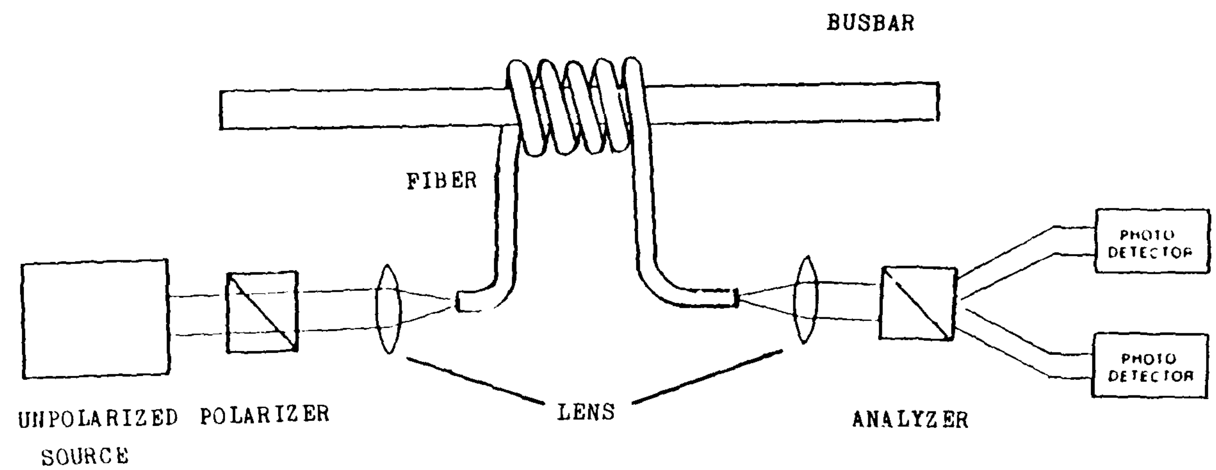


Figure 8. Polarization Intensity-Modulated Sensor.

A. J. Rogers [37] tested an optical fiber current sensor that rotated the polarization plane of the linearly polarized light by the current generated magnetic field in a busbar. Over a 15 month period, he reported measurements of currents from 10 A to 14 KA with an accuracy of ± 2%, and less than 1% non-linearity.

Matsushita Electric and Hitachi [38] of Japan have each developed optical fiber current sensor constructed from ferromagnetic materials and Mitsubishi [38] has developed a current sensor in which a thin film polarizer and analyzer are directly fabricated at the ends of the Faraday cell. Each of the sensors described above employs the Faraday rotation.

Sumitomo Electric and Mitsubishi Electric [28] developed optical voltage sensors based on the electro-optic Pockels effect. When an external electric field is applied to the Pockels cell, the refractive indices of the optical principal axis are changed by the electric-field-induced birefringence. The linearly polarized light is converted into the elliptically polarized light, and the intensity-modulated light is obtained by a quarter-wave-plate and an analyzer [38].

These voltage and current optical sensors can be used to measure temperature, pressure, strain and other power system parameters. They display advantages such as freedom from saturation effects, large bandwidth, and compatibility with interference-immune communications links. Sensitivity to vibration and temperature is a primary disadvantage.

A polarization device which interposes photo-elastic material between two fiber ends has been proposed for industrial temperature and pressure measurements. In the photoelastic sensor [39-42] of Figure 9, graded-index rods are used to collimate the light supplied to the sensor through an input optical fiber and refocus the collimated light before injecting it into the output fiber. Within the sensor, the collimated light is circularly polarized and passed through the photoelastic material. This material exhibits a degree of linear birefringence related to the asymmetrical stress distribution in the core caused by the measurand. Intensity modulation results when the proper polarization analyzer is used. The sensitivity of this modulation mechanism can be significantly enhanced through shaping the cross-sectional area of the photoelastic material. Also, by

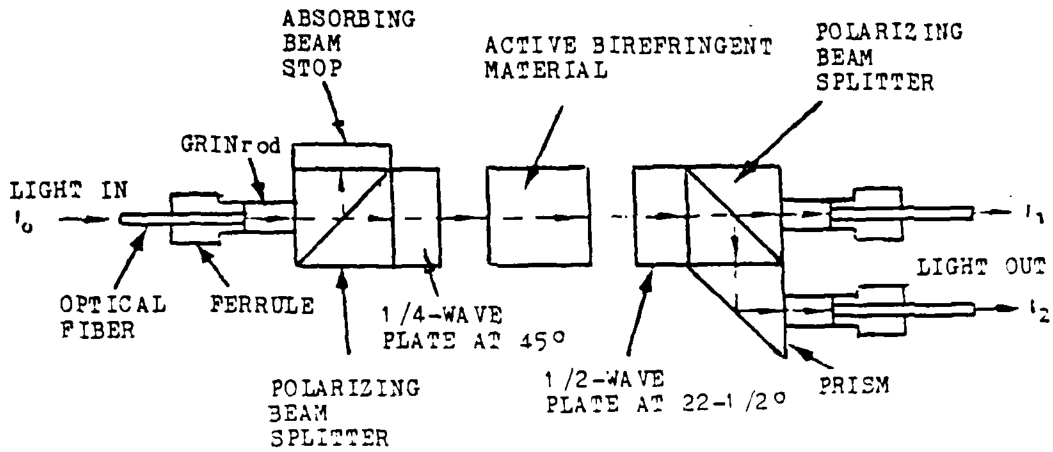


Figure 9. Photoelastic Intensity-Modulated Sensor (after [41]).

using a combination of intensity changes and fringe counting, extended dynamic range and increased accuracy can be achieved.

W. B. Spillman [39] reported the test results of a photoelastic pressure sensor that used a prism of quartz glass as the active birefringent element. The device detected pressures as small as 95 Pa, had a dynamic range of 86 dB, and displayed hysteresis less than 1%.

Tai, Kyuma, and Nunoshita [40] of Mitsubishi Electric Corporation, Japan constructed a fiber optic acceleration sensor based on the photoelastic effect of transparent isotropic materials such as epoxy resin, diallylphthalate polymer, or $LiNbO_3$ single crystal. A weight is attached to the upper surface of a sensing rectangular rod of the photoelastic material and, in response to vibrational acceleration, causes a stress-induced birefringence in the sensing rod. The output light is intensity-modulated proportionately to the acceleration. This device has accurately measured acceleration from 10^{-3} to 30 g over a frequency range of dc to 3 KHz.

Spillman and McMahon [41] designed a photoelastic fiber optic hydrophone using Thiokol Solithane Urethane

113 as the birefringent element. This photoelastic material was bonded to two thin rubber diaphragms on the top and bottom of an air-filled hydrophone housing. A differential approach which examines the difference signal over the sum signal is employed to reduce the amplitude noise (e.g., optical source noise). This multimode device measured a minimum detectable pressure of 48 dB relative to 1 μPa at 500 Hz and demonstrated potential for even lower pressure measurements provided less sensitive photoelastic material is used.

Sensitivity to temperature and pressure ambients, a common problem of all photoelastic sensors, must be significantly reduced and some form of static pressure relief must be designed before the idea could be deemed generally useful. McMahon, Soref, and Sheppard [42] have reported a minimum threshold measurement of 41 dB relative to 1 μPa after modifying the above-mentioned hydrophone and experimenting with photoelastic materials.

2.6 Schlieren Effect Sensors

A pair of fine absorptive grating strips inserted on the opposing ends of multimode fibers or alternating totally reflective and transmissive strips inserted into a gap between two fibers describe a schlieren effect [43-44] or movable grating [45-47] sensor. Figure 10 shows the configuration used by Spillman and McMahon [43] in their fiber-optic hydrophone. Graded-index lenses are used to collimate light from the input fiber and to refocus the collimated light into the output fiber. The opposed grating members are connected to diaphragms attached on opposite sides of the transduction element. When the force field of interest displaces the gratings in the direction perpendicular to the rulings, modulation of the transmitted light results. The two identical bar gratings have opaque and transparent stripes of equal width. 100% modulation of the transmitted light occurs when the relative displacement of the gratings is one-half the linewidths; therefore, the device sensitivity is a function of the spatial frequency or density of the line gratings.

Detection thresholds on the order of 50 dB relative to 1 Pa and static displacements as small as 2.5×10^{-3} Å have been measured [43]. The Knudson sea noise levels were detected by the schlieren hydrophone for frequencies up to 1 KHz, and a dynamic range of 125 dB was demonstrated [44]. Hydrophone prototypes built by

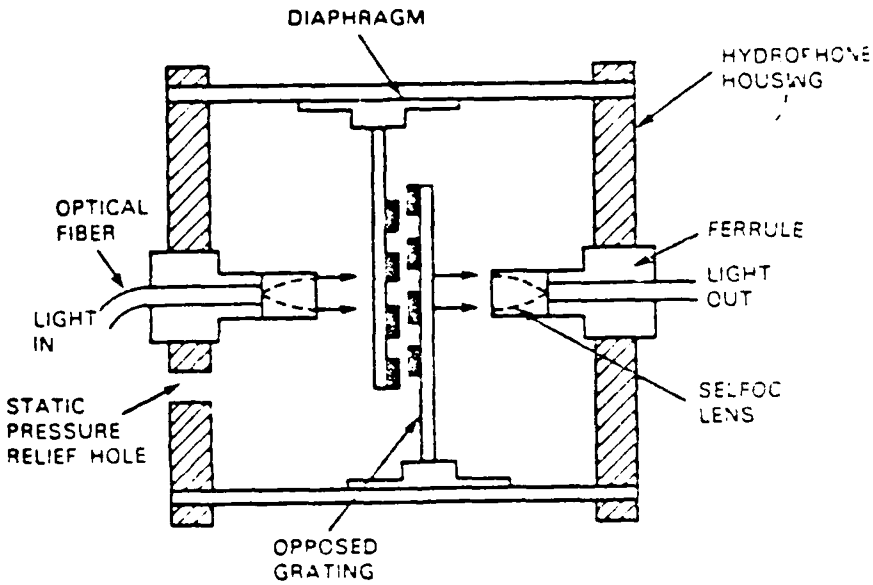


Figure 10. Schlieren Effect or Movable Grating Intensity-Modulated Sensor (after [43]).

Tiejten [45] demonstrated dynamic ranges as high as 160 dB.

An industrial prototype pressure sensor using displacement of a holographic grating was developed by Jones and Spooncer [46]. A holographic notch filter with narrow-band reject characteristics is used to form the bars of one grating. The center wavelength of the filter is modulated by displacement of the holographic grating relative to the fixed grating. The wavelength outside the notch profile passes through the grating unmodulated and its transmittance is used to normalize the signal intensity. Referencing is achieved by measuring the ratio of the output intensity of the modulated signal to the output intensity of the unmodulated signal. The pressure sensor performance over a design range of 0-7.5 kPa shows resolution of the order of 0.1% of span, non-linearity and hysteresis of less than ± 1% of span, and repeatability of at least ± 2% of span over a 10 dB variation in light level. Jones and Spooncer [47] also reported an alternate method of intensity referencing using two color photographic film grating.

2.7 Moving Fiber Sensors

The final sensors to be discussed utilize relative fiber motion between a fixed fiber and a fiber either free or connected to a diaphragm to modulate the transmitted light intensity. These sensors are appropriately titled moving fiber sensors [48-49]. Two applications of these sensors are acoustic microphone [48] and hydrophone [49].

Researchers at Sperry [48] have developed a multimode fiber-optic microphone. In it one end of a fiber cable is fixed and the other movable end is connected to the diaphragm of the microphone. The motion of the diaphragm displaces the movable end relative to the fixed end causing the light intensity traveling from the input fiber to the output fiber to vary. A transverse displacement of 10^{-2} cm for a multimode fiber with a core diameter of 100 micrometers results in 100% modulation. The minimum detectable movement of the microphone is 2×10^{-10} cm and the dynamic range is 110 dB. The limiting factor on the sensitivity of the acoustic microphone is the required displacement by a distance equal to the diameter of the fiber core to get total modulation of the transmitted light.

Spillman and Gravel [49] fabricated a moving fiber hydrophone [49] in which the end surfaces of two single-mode fibers are parallel, coaxial, and separated by 2-3 μm. A diagram of this sensor is illustrated in Figure 11. The physical parameter to be measured moves a free fiber with respect to a fixed fiber and thereby modulates the intensity of the transmitted light. This device has exhibited a detection threshold of approximately 80 dB relative to 1 μPa. Factors limiting the appeal of this sensor are its employment of single-mode fibers, its need for critical mechanical alignment, and its non-confinement of light to the fiber.

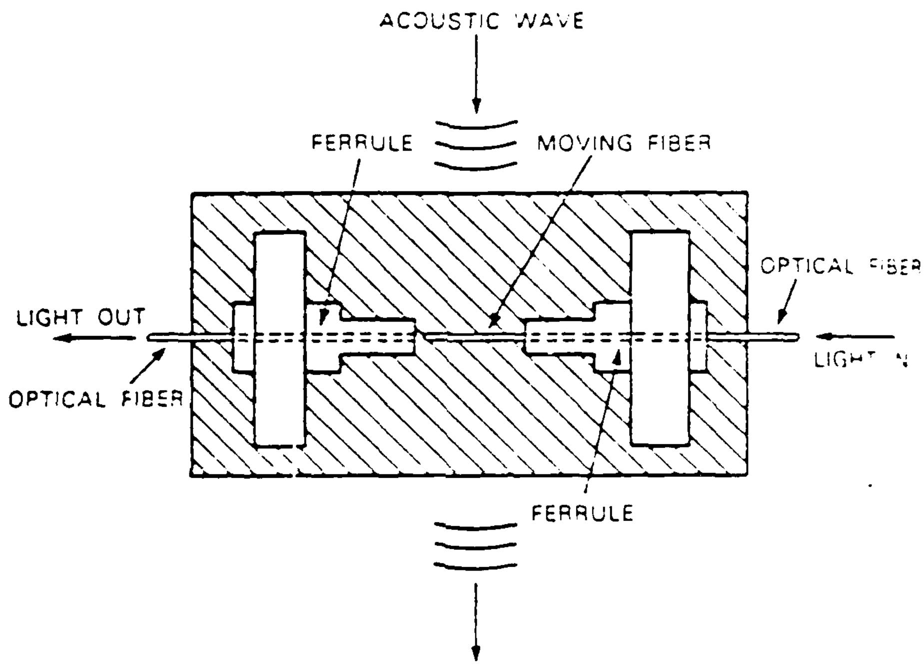


Figure 11. Moving Fiber Intensity-Modulated Sensor (after [49]).

3. SUPPORT TECHNOLOGY

Remarkable advances in measurement technology made over the past 30 years is being eclipsed by the rapid evolution of fiber-optics, principally for telecommunications systems which offer tremendous commercial opportunities. Conventional copper conductors are being superseded by optical cables carrying telephone service across land and sea, with data and video at rates soon to exceed 1 Gb/S [50]. The increasingly sophisticated telecommunications industry has spawned some novel uses of fibers in the areas of non-communication applications. These unconventional applications exploit not only properties of importance to transmission but also those regarded as a nuisance. For instance, a hydrophone designer considers microphony, inherent in an optical fiber, an asset while a transmission engineer regards it as a liability [51].

One major spin-off technology, fiber-optic sensors, has advantageously utilized many of the components and materials evolved for telecommunciations systems and it is probably realistic to operate under the premise that fiber sensor technology will continue to exploit the telecommunications arena for available components from which sensor and signal processing systems can be assembled. Therefore, it seems appropriate to examine components related to fiber-optic transmission systems -- optical fibers, sources, detectors, and couplers.

3.1 Optical Fibers

Since predominantly all of the experimental and commercial fiber sensors to date employ telecommunication-grade fibers, knowledge of three important parameters of communications optical fibers is essential to understanding the development of sensor fibers. These parameters are [52]:

a). numerical aperture -- a measure of the coupling efficiency between the fiber and the light source

b). dispersion -- the distortion of a signal during propagation

c). attenuation -- the power that a signal loses during propagation

The numerical aperture limits the optical power transmitted in a fiber as a function of the distance. The number of connectors and method of optical coupling from fiber to fiber and from source to fiber depend entirely on matching the size and numerical aperture of the fiber core to that of the light source.

Dispersion, the broadening of a sharp light pulse as it propagates along an optical fiber, determines the information-carrying capacity of a fiber. The two sources of dispersion are intermodal -- interaction between different modes of propagation within the fiber and intramodal -- interaction within each mode of propagation. Intermodal dispersion occurs in single-mode fibers having two orthogonal polarization modes and in multimode fibers. It results from the modes traveling at different velocities and causes the light to emerge from the fiber distributed in time. A reduction in intermodal dispersion can be effectuated by decreasing the numerical aperture, decreasing core diameter, or employing graded-index fiber. However, a reduction in numerical aperture reduces coupling efficiency, and a reduction of the core diameter decreases the number of modes propagating in the fiber.

Intramodal dispersion is significant in single-mode fibers but negligible in multimode fibers when compared to intermodal dispersion. Intramodal dispersion results from variations of the index of refraction with the wavelength of the signal (material dispersion) and from the dependence of the group velocity in each mode on wavelength (waveguide dispersion). Waveguide dispersion can have a cancelling effect on material dispersion at wavelengths of 1.3 to 1.4 μm.

The attenuation of a signal in an optical fiber is caused primarily by Rayleigh scattering due to minute inhomogeneities in the core material, material absorption due to impurities (metallic or hydroxl ions) in the fiber, and microbend losses. Modes that are neither refracted or totally guided and variations in core diameter are other sources of signal attenuation, yet losses due to these sources are negligible in commercial fibers.

Understanding the above-mentioned parameters and their effects on optical fibers has enabled manufacturers to reduce by many orders of magnitude the loss characteristics of fibers over the past 17 years. Presently, manufacturers are moving from the 0.85 μm wavelength region toward the 1.3 and 1.5 μm region with ambitions of developing fibers in the 2.0 to 10 μm range. The incentive for this move is lower signal dispersion and attenuation. The impediments to longwave transmission are increased modal noise, smaller launched power, and reduced receiver sensitivity [53].

The fibers utilized most often in optical sensors have been large-diameter cored multimode optical fibers.

This is attributable to the availability of inexpensive, consonant sources (LEDs) and the facility of coupling and launching light in the fiber. Graded-index multimode fibers, as previously noted, reduce intermodal dispersion. This property has prompted the emergence of graded-index (GRIN) rods. When placed at the end of optical fibers, the GRIN rods collimate the light over short distances. For optical switching between fibers, GRIN rods can be used as movable focusing elements [54].

Lower losses which provided the initial impetus for operation in the 1.3 μm and 1.5 μm regions are providing a choice between multimode fiber and singlemode fiber for high bit rate systems. Typically, multimode links are bandwidth limited, while single mode links are attenuation limited. Attenuation at wavelengths beyond 1 m is substantially less than attenuation at 0.85 μm for both fiber types; therefore, single mode fiber can equal or improve upon multimode fiber loss with higher bandwidth potential. Unfortunately, smaller core diameters create special requirements for launching and detecting in single mode fibers, and the cost of single mode components is prohibitive when compared to multimode components.

3.2 Optical Sources

Solid-state optical sources (the semiconductor injection lasers and LEDs) are universally used as light sources in communication systems based on optical fiber transmission lines. No other optical sources can achieve the high bit rates required with as little drive and high output power [55]. Lasers have proven themselves ideal for applications requiring long distance transmission with large modulation bandwidths, where their high power and fast response time are unmatched. For short and medium range, narrowband systems operating at modest modulation rates, the incoherent LED is usually selected because it offers inherent simplicity of construction and operation. LEDs also have extended trouble-free operational life at a lower cost per unit than lasers [56].

The low loss window and zero chromatic dispersion at 1.3 μm wavelength in optical fibers have made the use of LEDs as sources a practical solution in multimode telecommunications systems. Two basic LED types have emerged: the surface emitter (SLED) and the edge emitter (ELED). The microlensed SLED has become an established device in commercial systems operating at 34 Mb/s over repeater distances of up to 10.5 Km [57]. However, the drive for higher data rates (140 Mb/s) and longer repeater distances requires narrower spectral linewidths and higher coupled power than can be achieved with SLEDs, thus providing the impetus for the development of the ELED as a higher output power device. The stimulated emission in the plane of the junction (that contributes to radiance saturation in SLEDs) can enhance both coupled power and switching speed in the ELED structure. The linewidth of this device is inherently narrower due to self absorption [58]. The ELED in terms of its construction, processing, and assembly makes it complementary to the laser. It can take advantage of the high reliability processing and packaging developments carried out for the laser [59].

A semiconductor laser is merely a LED to which a cavity has been added to provide feedback. The principal ingredient of these optical devices is GaAs because, in combination with a number of other material solid solutions (e.g., InP, AlAs, AlSb), it provides a range of energy gaps and close lattice-matching. To meet the requirement of silica fiber with considerably lower loss and dispersion at 1.3 and 1.5 μm, optical sources have been developed based on GaInAsP semiconductor alloys. This is a binary-to-quarternary III-V lattice-matched device. Semiconductor diode lasers are very versatile, high power (up to tens of milliwatts) sources of optical energy.

Besides semiconductor diode devices, solid-state neodymium (Nd) lasers represent attractive sources for optical-fiber transmission systems because they have emission wavelengths in the 1.05 to 1.35 μm region. The spectral linewidths of Nd lasers are very narrow and homogeneously broadened, permitting single frequency, single-mode operation that leads to maximization of the transmission bandwidth of a fiber. Nd lasers can be pumped by long-lived AlGaAs LEDs and are particularly useful for high capacity, long-haul applications requiring reliability, modal purity, and narrow spectral linewidth [60].

3.3 Optical Detector

In most optical communication systems, the optical power is converted to electrical current by two principal types of photodetectors, the positive-intrinsic-negative (PIN) photodiode and the avalanche (APD) photodiode.

These detectors convert photons to electrons by the identical process of creating electron-hole pairs through incident photon absorption. While PIN diodes have unity gain, the APDs create additional electron-hole pairs through collision which increases its current and provides a gain larger than unity.

At 0.85 μm inexpensive and efficient silicon detectors are commercially available; however, as a result of the recent trend toward low loss optical fiber operating above 1.0 μm, research is aimed at developing detectors suitable for these longer wavelengths. Silicon ceases to function beyond 1.0 μm. Germanium can be used at the longer wavelengths, but it exhibits high dark currents and degraded noise figure. Investigation of alternative detection materials such as alloys of indium, gallium, arsenic, and phosphorus are being conducted. Thus far the advantageous carrier ionization rate of silicon has not been exhibited by any of the alternative materials.

APDs have greater sensitivity than PIN diodes and are more desirable for optical detectors. Because they are silicon-based, APDs are not yet commercially available for the 1.0 to 1.6 μm wavelength spectral region. They also suffer from the requirement for much higher voltages to provide gain. Thus some of the inherent advantages of fiber-optics, namely, small size and low power requirement must be sacrificed in favor of the enhanced sensitivity of APDs.

PIN diodes are attractive due to their fast response, high efficiency, low capacitance, and low dark current. The silicon PIN diodes are the most commonly used photodetectors for short-haul communications applications. PIN diodes of the III-V alloy materials are currently being fabricated at Standard Telecommunication Laboratories, Electrik Lorenz, and ITT Electro-Optical Products Division for wavelengths beyond 1.0 μm. Indium gallium arsenide has been used to make a PIN detector suitable for 1.3 and 1.5 μm applications.

Although considerable progress has been made in optical detector technology, there is still a great deal of research needed to improve APDs, find new materials, and allow operation at longer wavelengths [61].

3.4 Optical Connectors and Couplers

The realization of high performance optical connectors and couplers is essential to meet the increasing demand that fiber-optic components fulfill the user's handling, environmental, and economic requirements. In particular, military and industrial users require demountable connectors with very high reliability to work at the extremes of environmental conditions. The connectors must be capable of being disconnected frequently with minimum regard for their care yet yield repeatable optical performance [62]. Permanent fiber joints which are indistinguishable from uniform lengths of fiber must be economically feasible.

Optical fiber cable joints take two basic forms: connectors and couplers. These are described as follows [63]:

-- A connector provides an in-line joint between two fibers or between a fiber and an end device. The joint is generally demountable but can be permanent.

-- A coupler provides two or more paths for the transmission signal by linking two or more fibers. A form of the coupler that permanently joins two fibers or fiber bundles is known as a splice.

In making a joint, the realization and maintenance of an accurate optical alignment of the fibers to be joined are crucial factors. The smaller the fiber core, the more difficult it is to maintain the rigid tolerances required for successful joints. For this reason, an abundance of inexpensive large-core (> 100 microns) connectors are widely available while smaller-core ($\leq$ 50 microns) connectors are expensive and require skilled assembly.

Two types of demountable connectors are possible. In a butt ferrule connector [64], prepared fiber ends are aligned and butted together in accurately machined housings. In an expanded beam connector [65], lenses are used to collimate light into a beam several millimeters in diameter across an air gap. The butt ferrule connector has the better performance under optimum conditions but is susceptible to contamination. Any ingress of dirt or sand onto the unprotected fiber ends during mating of the connector will cause deterioration in optical performance. The expanded beam connector, however, offers reliable, repeatable operation in more stringent environments with only slightly higher loss. Its operational advantages make it more suitable for field use. Variations of the expanded beam connector have contributed to the development of the optical rotary joint or slip ring [66].

In applications that require lower losses than those of demountable connectors (typically between 0.5

and 3 dB for 50 μm fiber core) and where joints need not be demountable, splices are more appealing than connectors. Splices exhibit lower loss and greater mechanical tolerance of environmental variations. They fall into two categories, those in which the fibers are held in alignment by some mechanical means, and those in which the fibers are melted together. Fusion splices, the latter type, display lower losses than mechanical splices and are the most widely used technique presently. Field-usable fusion splicers are becoming available with varying degrees of sophistication, however they have not proven practicable in a military environment. As a result mechanical splices are often used on multimode fibers.

Low-loss couplers which allow multiplexing of several sensors onto a single source and detector or the combination of a source and detector onto a single fiber down lead to a sensor are difficult to produce because they must be demountable and reproducible, yet meet the same tolerances as splices. Therefore, coupler designs are focusing on techniques for reproducible, accurate alignment and for minimal reflections at fiber interfaces. Fusion and index-matching techniques are employed such that evanescent coupling can occur [67].

New developments in coupling and connector technology are aimed at achieving a high degree of alignment and at finding methods and tools that can be handled by relatively unskilled personnel. Numerous types of optical connectors are already commercially available; however, the emphasis on devices that can withstand severe environmental conditions without degradation of the optical performance must be a design criteria of the second generation connectors now being introduced.

4. FUTURE TRENDS

The applications of optical sensing and signal processing techniques have been restricted to those areas where their advantages of safety in a hazardous environment and immunity from electromagnetic interference are important and cost is not a major consideration. Now, however, recent advances in the available optical and materials technology have spurred a growing interest in optical sensors, particularly with regard to their enormous potential for industrial and process control applications. By 1990, systems designers will have the option of building sensors and signal processing systems from elegant monomode fiber systems and integrated optics provided the rapid rate of expansion continues in the component technologies.

Since development of optical fiber sensors began in earnest in 1977, the optical sensor technology has been dominated by the particular needs of the military. This dominance has resulted from the reluctance of the private sector to invest large sums of money into developing a new, unproven technology. Instead, the government has borne the initial expense for research. Now that the basic research and development has been accomplished, the private sector is poised to commercialize a broad range of the applications. By 1993, the commercial sector is predicted to have outgrown the military sector [68].

An objective assessment of the true potential of the fiber-optic sensor technology must begin with the assertion that traditional sensing techniques satisfy the majority of the requirements which may be realized optically. Therefore, the first practical applications of optical sensor technology are the substitutions for the more well established technology. Fiber-optic sensors must demonstrate a clearly identifiable advantage or be more cost-effective than their conventional counterparts before they will displace the traditional devices. For example, there is interest in oil contamination sensors to be located in the pump room of supertankers where, for safety reasons, no electrical systems (i.e., no conventional transducers) are allowed [69]. Also, optical sensors to monitor material and thermal conditions inside nuclear reactors are being considered for use in positions inaccessible to conventional sensors [70].

While the substitution of fiber-optic sensors for conventional sensors will dominate the growth market for the next few years, the truly volatile market will emerge through the creation of new applications resulting from the fiber-optic sensor technology. The extent to which this market will flourish largely depends on the limits to which the technology is stimulated, the cleverness of inventors and suppliers, and the desires of the consumer.

The alternative applications of the fiber gyroscope, primarily a substitute for existing military mechanical and ring-laser gyroscopes, exemplifies how a sensor market can expand through new applications. Genuine interest is being displayed for the engineering application of fiber-optic gyroscopes to automobile navigation and robotics. Ultimately, each of these spin-offs could surpass the military gyroscope market [71].

The sensor technology which has primarily developed hospital equipment such as the endoscope for "in vivo" observations and measurements of numerous fundamental variables will venture in the new direction of "throw-away" devices for rapid measurement (e.g., pH, antibody-antigen, immobilization, etc.) near the patient [72]. Instruments designed for use in the doctor's office rather than a hospital environment will prove cost effective and efficient. Commercial spin-offs might include fiber-optic thermometers or "in-home" blood pressure monitors. A fiber-optic thermometer could offer the same accuracy as current glass/mercury thermometers without the hazards of mercury and glass.

The industrial area has demonstrated the greatest reluctance to convert from traditional sensing methods to fiber-optics. Cost-effectiveness is cited as the largest deterrent. However, the expansion of industrial control requirements is creating new sensing requirements -- a number of which would be impractical or impossible to meet with traditional sensors. Fiber-optic sensors capable of meeting these requirements are gaining footholes in the industry. For example [73],

-- Optical fiber temperature sensors can detect hot spots in electrical equipment such as transformers and motors without electromagnetic interference.

-- Optical fiber sensors can indicate exposure to radiation as dosimeters.

-- Optical fiber strain sensors can monitor structural anomalies and loading of bridge supports and roadbeds.

As the applications to optical fiber communications systems increase, so will industrial applications. The cost of fiber optic cable and related components will plummet with the advent of more vendors, and more practitioners will be enticed to adopt fiber sensors. The general attitude among industry will gradually change as the experience base grows, as products become more widely available and less expensive, as reliability is improved, and as support tools become more common [74]. Already, devices to monitor environmentally-sensitive goods for leakage, breakage, or spoilage are emerging; fiber-optic proximity sensors are used in automated factories to measure displacement, film thickness, and part dimensions; and intruder detection systems represent a potential substitution market.

Before this century is over, fiber-optic data highways will become common. We can expect to see optical fiber sensors used more extensively for digital switching and counting. The utilities industry will expand their use of both remote optical and pure fiber sensors where electromagnetic fields disrupt electronic instruments. Nuclear power plants will incorporate optical sensors for detection and recording of radiation. Oil exploration will provide the impetus to develop optical cable and sensors to withstand 250°C, 20,000 PSI, and extremely corrosive environments [75]. Risk will be reduced in the petrochemical, mining, and transportation industries by the non-electrical property of optical fiber sensors.

Research is presently driven by the telecommunications industry, but numerous components and material dedicated to sensor applications are emerging. The constraints on sensor performance imposed by the use of telecommunciation-based fiber technology are prompting researchers to contemplate a wide range of new material and fiber structures selectively sensitive to common variables. Continued development of fiber-optics will increase economic viability and technical feasibility of optical sensor technology; however, widespread use will depend on whether the perceived potential for fiber-optic sensors is great enough to make them commercially attractive.

5. CONCLUSION

Early workers in the telecommunications field sought ways to minimize the perplexing problems attributable to the high sensitivity of low-loss optical fibers to external perturbations (e.g., microbend loss, modal noise, etc.). Another group of workers considered means to exploit the exceptional sensitivity of the fibers to develop sensors. The outgrowth has been a very large activity worldwide in the development of optical-based devices that sense a wide variety of measurands.

In this thesis, the current state-of-the-art of intensity-modulated (non-interferometric) fiber-optic sensors has briefly been reviewed. Only the dominant classes of these sensors were presented because the enormous variety of novel approaches is too extensive to give adequate treatment to each variation. The principles of intensity sensors are well documented. From scientific journals to engineering magazines, the literature is filled with the latest laboratory results, product releases, and tutorials for sensor users.

The intensity sensors utilizing multimode fiber are furthest along in development. They have been demonstrated for sensing acceleration, acoustic pressure, displacement, liquid level, magnetic and electric fields, strain, temperature, and torque. Some are commercially available. They offer cheap, easily constructed sensors suitable for harsh environmental deployment. Adequate sensitivities are readily achieved and packaging techniques have been demonstrated or seem to be available for many of these sensors. Many problems remain in several of the sensor types; however, efforts are being devoted to remedy these problems and solutions are being found.

Major technology advancements have been made over the past decade, especially over the past five years, both in component capability and in performance of the final assemblies. These performance advances will continue over the next decade, while component cost and system fabrication cost continue to drop.

LIST OF ABBREVIATIONS

AlSb - Aluminum-Antimony

AlAs - Aluminum-Arsenide

A - amperes

Å - angstrom

C - centigrade

cm - centimeter

dB - decibel

FTIR - frustrated-total-internal-reflection

GaAs - Gallium-Arsenide

GaInAsP - Gallium-Indium-Arsenide-Phosphorus

Gb/S - gigabits per second

g - gravity

He-Ne - Helium-Neon

Hz - Hertz

InP - Indium-Phosphorus

KA - kilo-amperes

KHz - kilo-hertz

Km - kilometers

KV - kilo-volts

LED - light-emitting diode

$LiNbO_3$ - Lithium-Niobate

Mb/S - megabits per second

m - meter

μ - micron

mW - milli-watt

NTIR - near-total-internal-reflection

Nd - Neodymium

Pa - Pascal

PIN - positive-intrinsic-negative

PSI - pounds per square inch

re - relative

TIR - total internal reflection

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