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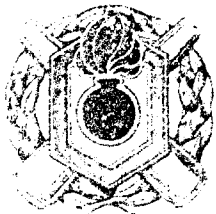
FIBER OPTIC SENSORS FOR THE MILITARY

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Nanette M. Shoenfelt

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INTRODUCTION

Fiber optics have traditionally been used for communication systems. These fibers are convenient to use because they are not susceptible to electromagnetic interference. Now fibers are being used in more fields. Sensors are a new application for fiber optics. They can be used to sense temperature, chemicals, and position. What makes optical fibers attractive for sensing, is that different wavelengths of light can be used for different sensing applications. The military are now starting to use fiber optic sensors for the guidance and control of munitions.

DISCUSSION

Fiber Optics

Fiber optics are being used to transmit light in thin glass rods without any interference from external electric fields. They also have the advantage of increased sensitivity, larger bandwidths and data rates, and greater geometric versatility than conventional electronic systems.

An optical fiber consists of a central part called the core. This is surrounded by a material with a lower refractive index, called the cladding. Due to this refractive index change, light waves can be confined to the core and transmitted by total internal reflections at the core-cladding interface. Since the diameter of this glass fiber is only 100 to 200 microns, it can break very easily; therefore, it must be coated with a polymer to keep the fiber mechanically strong, and not subjected to chemical degradation. The optical fiber is most widely known for communication transmission due to its low loss, high bandwidth, small size, and flexibility.

There are two important factors in the light guiding theory: the refractive index, n , and the angle of incidence, θ . When there is an interface between two media, two things can happen, refraction and reflection. In refraction, light waves hit the interface at an angle of incidence. This light is bent to the angle of refraction into the other medium. This angle is dependent on the indexes of refraction for the two substances and is shown in the equation

$$\frac{\cos\theta_1}{\cos\theta_2} = \frac{n_2}{n_1}$$

If n_1 is smaller than n_2 , then there is refraction. However, if n_1 is greater than n_2 , then there is no refraction. On the other hand, reflection occurs when the light waves hit the interface at the angle of incidence. In this case, however, the light does not go into the second material, it is bounced off the interface at that same angle of incidence. This will always occur no matter what n_1 and n_2 are; although, there is a critical angle equal to

the arccosine of the quotient of n_2 divided by n_1 . At this angle there is total reflection (fig. 1). This is very important in fiber optics. Ideally, it is desired that the light remains in the core and does not get refracted into the cladding. This is called total internal reflection and is accomplished by having the index of refraction of the core larger than that of the cladding. The light is launched into the fiber within the acceptance cone, which is established by the critical angle (fig. 2) Normally, the core has a uniform refractive index which is called step-index fiber. Conversely, if the index of refraction is not uniform, it is called graded-index optical fiber. This is much more difficult to understand and will not be covered.

Although fiber optics technology is mainly used for communications, it is now being used for sensors. There are many kinds of physical sensors that can measure temperature, pressure, and position. There are also chemical sensors that measure concentrations. Fiber optic sensors can give real time, instantaneous results. In general, a fiber optic sensor uses a light source, for example, a laser. This light is launched into the glass fiber where a light detector received the output of the fiber to measure a change in the desired parameter. There are basically two types of fiber optic sensors: the intensity modulated or amplitude modulated, and the phase modulated sensors. The intensity modulated sensors are used to measure attenuation or loss in the intensity of the light, the scattering of light, and grating plates. Phase modulated sensors are used to measure interferometric, resonant, or polarimetric parameters. This sensor is more sensitive but also more bulky. In addition, it requires high quality semiconductor lasers.

Microbend Sensor

The first type of intensity modulated sensor is a microbend sensor. As an optical fiber bends, there is a loss of intensity of the light being transmitted through the glass. As the fiber continues to bend, there is a greater loss (fig. 3). These microbend sensors can be used for tactile sensing in robots. They can also be used for vibration monitoring, G-force strain sensing, and high temperature pressure sensing.

Reflection-Displacement Sensor

A very important type of intensity modulated system is the reflection-displacement sensor (fig. 4) which is important for seekers in guided missile technology. Light is emitted from the fiber and reflected off of the object being sought back to the fiber. The intensity of the light is proportional to the distance at which the object is located. There are windows in the atmospheric spectrum from 3 to 5 micrometers and from 8 to 14 micrometers. This is in the infrared region of the electromagnetic spectrum; making infrared light advantageous for sensing. These wavelengths of light are good for remote temperature measurements. In this way, a tank or other mechanical object that is radiating heat will be detected with the infrared sensor. Usually, coherent bundles of optical fibers are used. Half of the fibers are used to transmit light from the light source,

while the other half are used for the reflected signal. The problem with using infrared light is the typical telecommunication optical fibers that are made of silica do not transmit these wavelengths very easily because of excessive attenuation. Therefore, different glasses must be used. Chalcogenides and halides are being used for the transmission of infrared light. Other types of glass that prove very useful are the fluorides. These glasses can transmit infrared and visible light, therefore giving two types of imaging. Many seeker systems are now using this bi-chromatic approach.

Many seekers use what is called proportional navigation. In two-point or homing guidance, the projectile is launched toward the target. There is a great deal of error in this method because the grain of the angular error of the tracking increases as $1/r$, where r is the instantaneous range between the missile and the target. The lateral displacement of the projectile off the tracker axis appears to increase as it approaches the target. Therefore, a method of seeking is needed; however, it is much more expensive. These seeker systems are based on a line-of-sight system in which the missile keeps a particular spot on the target in its line-of-sight. There are two kinds of systems: the semiactive and the active. A human operator is needed for the semiactive system. The person keeps the optical center line on the target. Usually a laser beam is shot onto the target, the missile senses the light reflected back, and can track the object accordingly. On the other hand, it is not always feasible to have a human shining a light on the object. Therefore, an active system, called the beam riding system, can be used. These sensors, comprised as a bundle of fibers, work to keep the object in the center of the sensing area. As the object moves out of the center of the sensing area, the intensity of the light in other fibers is greater. Accordingly, the missile moves to center the light. In this case, the infrared light is necessary to track the heat emitting target. The distance to the target is also measured by the intensity of light reflected back. This intensity is inversely proportional to the range.

Chemical Sensor

Another type of intensity modulated sensor is used to find concentrations of chemical substances. Most fiber optic chemical sensors use an optical electrode called an optrode. The optrode is at the end of the fiber in the sensing medium. It consists of a semipermeable membrane with a reactive substance inside. When the chemical being tested passes through the membrane, it can then react with the substance inside the optrode. This reaction usually causes a color change or fluorescence which is measured through the optical fiber (fig. 5). However, there are problems with this technique. There is a length of time for the chemical being tested to diffuse across the semipermeable membrane, and there is a time for the reaction to occur. These two times combine to give the response time for the sensor. Since the time for the light to travel through the optical fiber is very short compared to the diffusion and reaction

times, it can be neglected. If the response time is too large, the advantage of using fiber optics to get real time measurements is lost. Since the diffusion time is usually much greater than the reaction time, the response time could be significantly reduced if the diffusion were eliminated. If the reactive substance could be covalently bound to the fiber, the response time could be optimal.

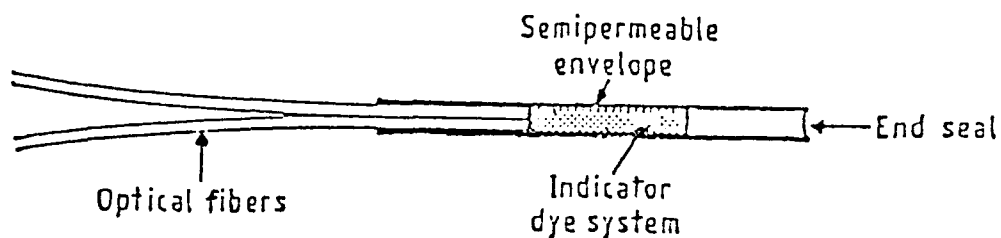


Figure 5. Chemical optrode sensor

Normally, in an optical fiber, not all of the light is reflected back into the core at the core-cladding interface. There is some light lost into the cladding, but very little light is lost out of the fiber. It would be advantageous if the light that escaped from the core could interact with the surrounding medium and be reflected back into the core to be measured. This is called evanescent sensing (fig. 6). If there is no cladding on the fiber, the coating could be removed from a small section of unclad fiber, and this area could be used for evanescent sensing. The small area without the coating, the active area, must be treated so that a chemical specific to the test substance, for example an enzyme, can be bound to the surface of the glass. This is accomplished by a method called silanization, and then enzyme immobilization. Silanization is a procedure for placing a silane on the glass. The silane binds to the silica, on the glass, leaving R-groups for binding the enzyme. For example, the silane could be gamma-aminopropyltriethoxysilane and the R-group is an amine. The enzyme is then bound at the site of the amine. With the enzyme immobilized, the optical fiber is ready for evanescent sensing of the chemical concentrations. This is accomplished by transmitting a light through the fiber and measuring the changes at the receiving end. A change in concentration of the chemical can be detected in one of two ways. Some chemicals exhibit a blue shift in that there is a shift in wavelength of the absorption peak. This shift is proportional to the change in concentration. The more common method is Beer's Law which is similar in that there is a change in the spectra as the concentration of the solution changes. In this case, the wavelength of the absorption peak remains the same, but the absorption level changes. Therefore, the absorbance is proportional to the concentration.

The sensitivity of these sensors can also be increased by making the sensing part of the fiber porous. This will increase the surface area of the sensing area. These chemical sensors can be used to measure many different kinds of chemical concentrations depending on the enzyme immobilized on the fiber. They can also make good humidity sensors.

Similar to these intensity modulated chemical sensors are the fluorescence sensors. Rather than a change in attenuation at the excitation wavelength, there is a change in attenuation at a different wavelength. A certain wavelength is transmitted through the fiber to the sensing area. The reaction of the test substance and the testing substance causes a different wavelength of light to be emitted or fluoresced (fig. 7). The intensity of the light detected is proportional to the concentration of the chemical. Again, it depends on the chemical being tested as to which method is used.

Interferometer Sensor

The most common type of phase modulated sensor is the interferometer. In these systems, there are two fibers. One of the fibers is squeezed while the other is not. The fiber being squeezed will elongate. A change of 0.0001 nanometers can be detected. This squeeze is due to pressure, magnetic field, electric field, or temperature. The optical fibers must be coated with a reactive substance. To sense pressure, the fiber is coated with an elastomer, like polystyrene or nylon. A magnetic sensor uses a magnetostrictive chemical, like nickel alloy. Electric fields are sensed with a piezoelectric or copolymer. Temperature is sensed with a conductive, thermally expansive substance, for example nickel or aluminum.

The first type of interferometer is the Mach-Zehnder (fig. 8). In this type of system, there is a reference arm and a sensor arm with two 3dB couplers between them. The reference arm is not subjected to the testing substance, while the sensor arm is exposed to the effects of the perturbation. The source, which is normally a narrow line laser diode is first split through a coupler. These light waves pass through both arms of the interferometer and are recombined at the second coupler. A phase shift as small as one microradian of the light source can be measured. This correlates to a 0.001 angstrom change in fiber length.

The second type of interferometer is the Michelson interferometer (fig. 9). This arrangement is very similar to the Mach-Zehnder; however, it requires less optical fiber. In this assembly, there are also two arms, but they use half as much fiber, and there is also only one coupler. In the Michelson interferometer the ends of the fiber are mirrored so the signal is reflected and sent back through the system. There is a significant problem

with this. Due to this reflection, there is great noise in the unit and there can be constructive or destructive interference from this reflected wave. It is also very difficult to mirror the ends of the fiber. Special equipment is needed to cleave and polish the ends so that they are completely flat. Next, the ends must be silverized. This is very difficult to achieve, and the reduced cost for using less fiber is lost when mirrorizing the ends of the fibers.

The third type is the Sagnac fiber optic interferometer (fig. 10). This sensor is only sensitive to changes in rotation. It consists of a fiber optic coil, two 3dB couplers, and a polarizer. The light that is split at the coupler is directed in opposite directions around the coil and is detected when it comes together. A change in phase is measured when the beams do not arrive at the same point at the same time. The length of the loop does not matter since the light is directed both ways through the same loop. However, the path length must be long for better precision.

The fourth type of interferometer is the resonator (fig. 11). This unit requires less fiber than the Sagnac system and uses one coupler and a coil. The light enters the fiber coupler and is split into the detector and the loop. The light leaves the loop and is coupled into the detector as well as back into the loop. The detector measures changes in amplitude. This kind of interferometer can sense any physical effect that can change the optical length of the fiber which, in turn, changes the state of interference between the two light beams entering the coupler. However, there are problems with this type of sensor. Unlike the Sagnac sensor, the resonator path length must be controlled, and it needs a highly coherent light source in addition to a very low loss coupler. There is a good amount of backscattering and interference at the coupler, making it difficult to control the stability.

Gyroscope

A fiber-optic gyroscope uses the Sagnac interferometer to measure rotation. In this system, light is injected into both ends of a fiber coil and then detected together. If the system is rotating, one path becomes elongated while the other is shortened. The change in phase, which is proportional to the rotation rate, is measured. Usually fiber-optic gyroscopes use 0.83 micron sources.

Velocimeter

Another important type of sensor is the laser Doppler velocimeter. A square wave reference beam is transmitted onto a moving object. The Doppler shifted light, which is scattered by the object, is detected. This measured change in frequency is proportional to the velocity.

CONCLUSIONS

Fiber optics is an emerging field for sensing. They can be used for measuring many parameters, such as distance, rotation, chemical concentration, velocity, and pressure in real time. They are very important for use in guided missiles. There are advantages to using optical fibers in that they are not susceptible to magnetic and electric fields. They bend easily and have large bandwidths. Fiber optics show great promise in the field of sensor technology.

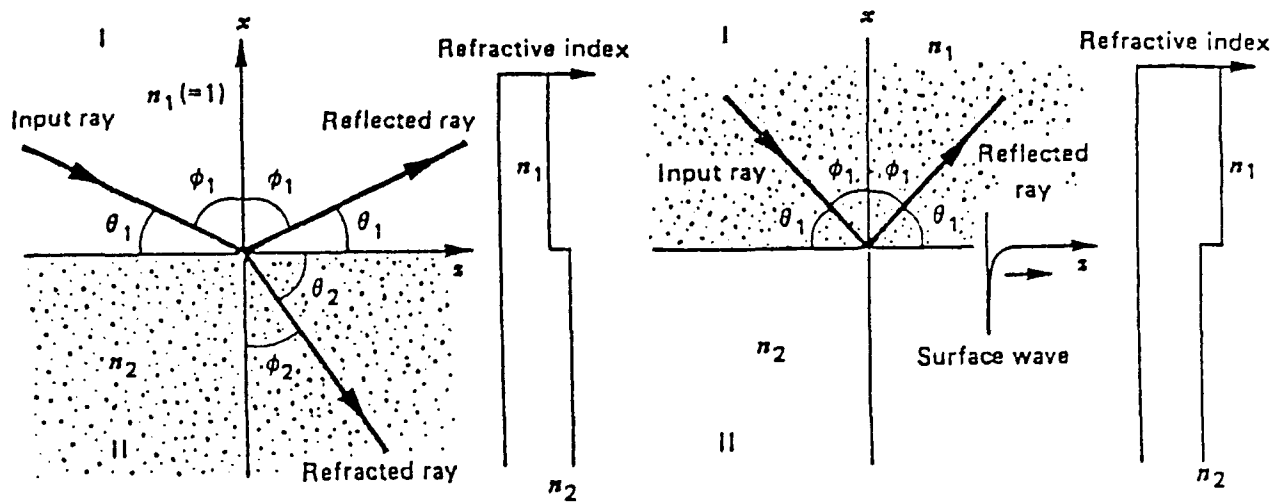


Figure 1. Reflection and refraction of a light ray

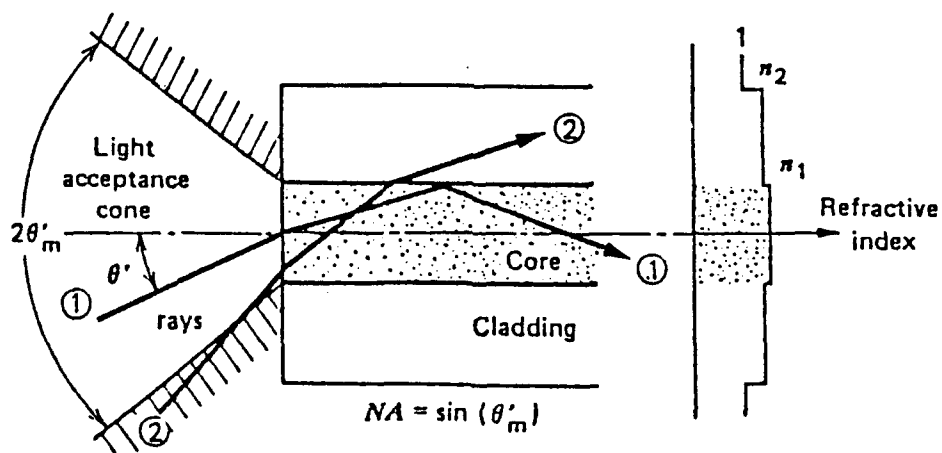


Figure 2. Light transmission in fiber (A section through a step-index fiber showing ray transmission and the light acceptance cone)

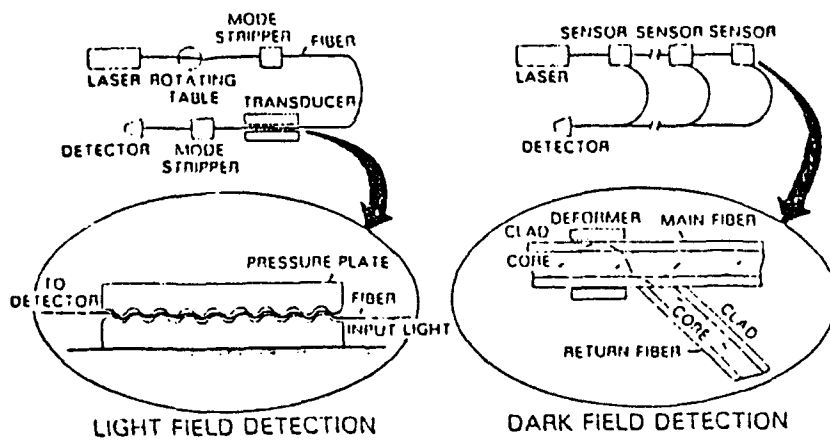


Figure 3. Fiber optic microbend sensors

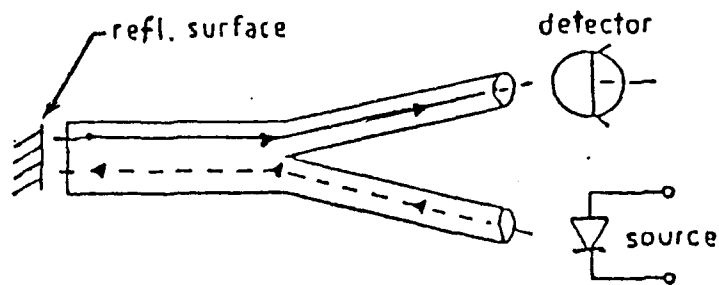
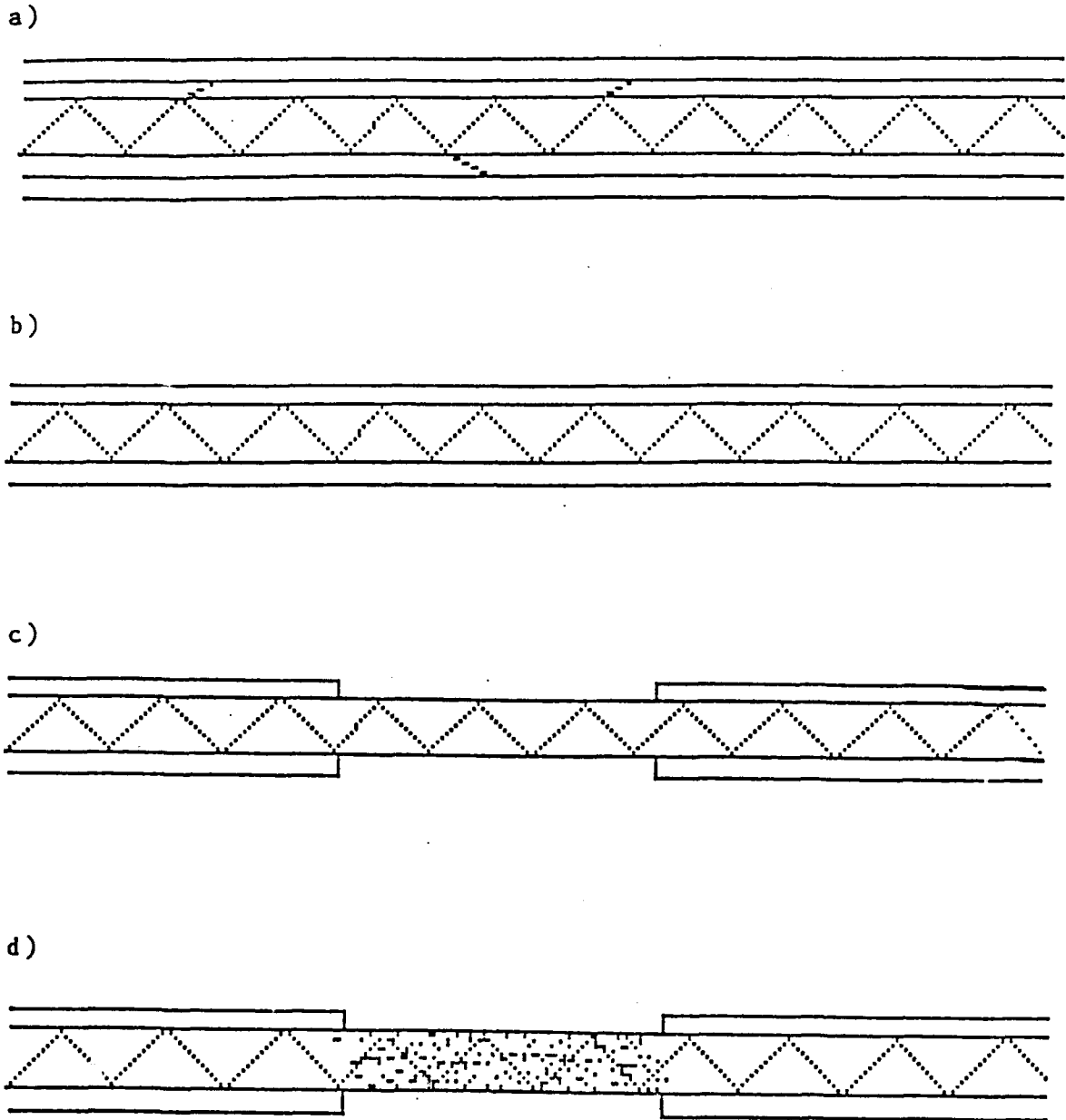


Figure 4. Reflection-displacement sensor



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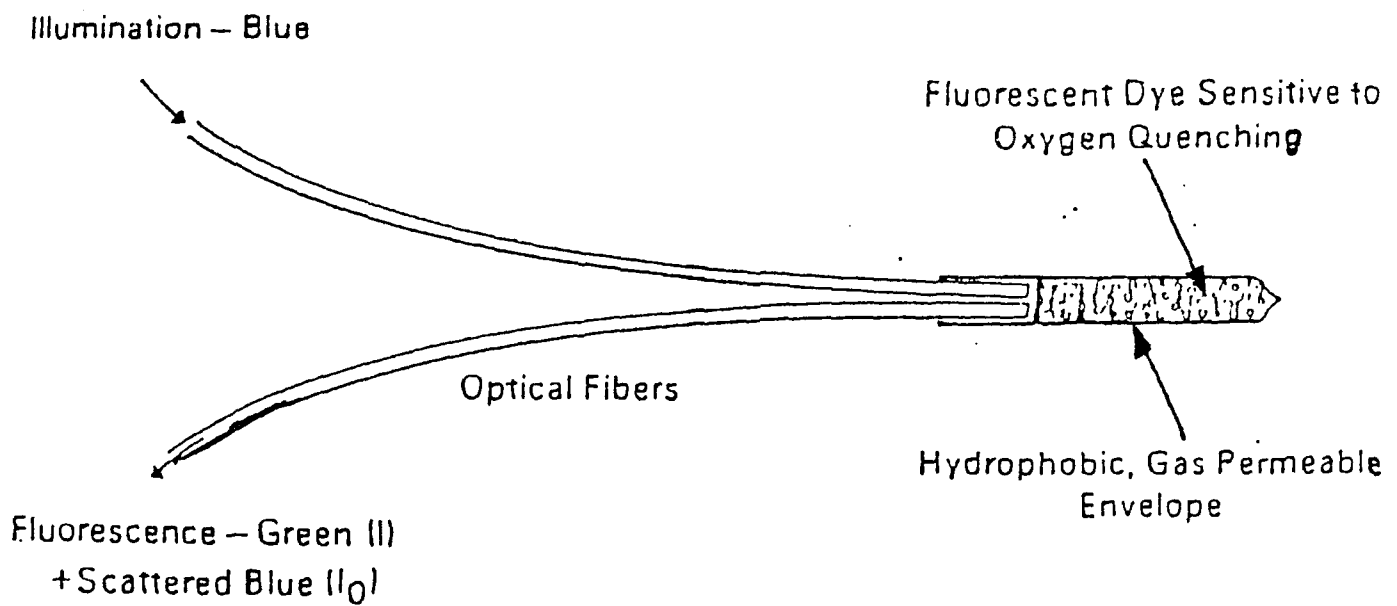
a) The normal optical fiber consists of a central core surrounded by a cladding, then a protective coating. The light is transmitted through the core, although a small amount of light escapes to the cladding.

b) The unclad fiber lacks the cladding layer.

c) The evanescent sensor is an unclad fiber with part of the coating removed. This allows for the light to come in contact with the sensing medium.

d) The porous fiber is an evanescent fiber, but the sensing area contains pores to allow more surface area for light-medium contact.

Figure 6. Types of optical fibers



NOTE: One color of light is transmitted through the fiber. When the testing substance reacts with the chemical inside the optrode, a different color is emitted and sent through the return fiber.

Figure 7. Fluorescence sensor

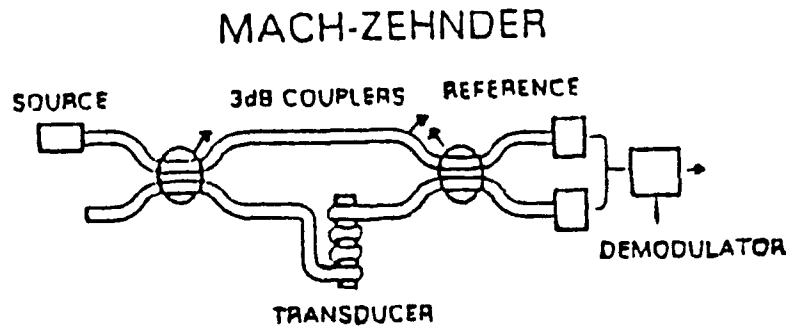


Figure 8. Mach-Zehnder interferometer

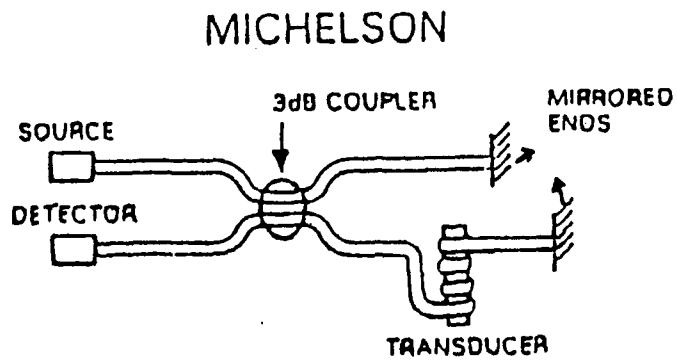


Figure 9. Michelson interferometer

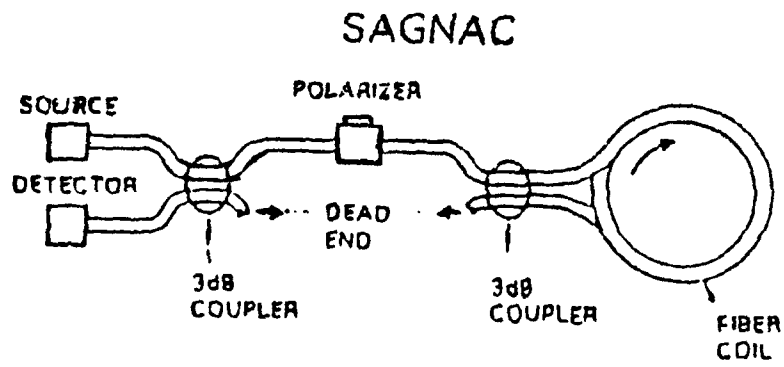


Figure 10. Sagnac interferometer

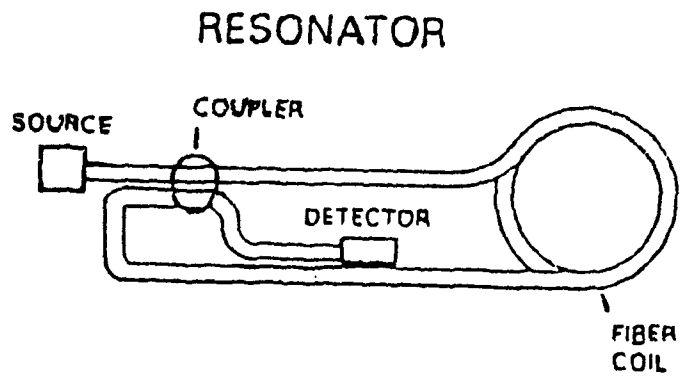


Figure 11. Resonator interferometer

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