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WORKSHOP ON OPTICAL FIBER COMMUNICATION
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APPLICATIONS OUTSIDE TELECOMMUNICATIONS - OPTICAL FIBER SENSORS

presented by

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These are preliminary lecture notes, intended only for distribution to participants.

APPLICATIONS OUTSIDE THE TELECOMMUNICATIONS

A. OPTICAL FIBER SENSORS

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1. General Considerations

This lesson is dedicated to applications of optical fibers which do not concern optical communications precisely optical fibers as sensors and optical fibers in medicine.

From the historical point of view, medicine has been the first field in which optical fibres have been applied. Special bundles of very thin fibres (5-10 μm diameter) have replaced the optical systems that were used in semirigid endoscopes, both for illumination and for imaging, achieving a significant size reduction and a greater flexibility which allowed their insertion in natural channels of the human body and otherwise inaccessible regions [1].

Subsequently, [2] as a by product of the high degree of quality reached in the o.f. for telecommunications (especially for what concerns attenuation) the optical fibres found a new field of application in medicine as a delivery system of laser radiation (also of high power) expecially in cavitational and endoscopic laser surgery, therapy and diagnosis.

Another relatively recent application of optical fibers now attracting an increasing interest is in the field of sensors which represent one of the most important aspects of instrumentations for different applications (military, industrial, biomedical automation, etc.) [3,4,5]

A sensor can be defined as a device capable of transforming a physical or chemical quantity into a modulated signal which can be directly detected.

Sensors form a vital and necessary part of any measurement and control system and there have been many predictions concerning the demand for such devices, which foresee the growth of the sensor market in the next 10 years. In all these studies the need for low cost, rugged and reliable sensors compatible with computer-based control systems is constantly stressed. While there is little disagreement concerning the need and extent of the future requirements for sensors, there is considerably less certainty concerning the technologies that will fulfil this need. This is perhaps understandable in that the requirements for one particular application will differ considerably from those for another.

Four main sensor technologies are considered to likely play a major role in the sensors of the future: namely those based upon resonator or variable frequency techniques, optics and optoelectronics, microelectronics or solid state techniques and integrated or "smart" systems (6)

The main interest in the field of optoelectronic sensors is concerned with optical fiber sensors. The increasing number of conferences and seminars along with the noticeable amount of publications demonstrate the research effort in this area.

The optical fiber technology now firmly established in telecommunications for data and voice transfer offers a good choice of

sources, detectors, connectors and the optical fibers themselves. Consequently it is not surprising that alternative applications could arise from the availability of such high technological achievements. In particular the measurement metodology developed for optical fiber sensors have taken advantage in principle from the existing optical fiber telecommunication circuitery, giving rise subsequently to particular measurement methods which besides making use of "ad hoc" components combine dielectric waveguide propagation, coherent and incoherent optical detection techniques with typical techniques of electronics and telecommunications.

An optical sensor is in principle consituted by at least one light source, the propagation medium, the light detector for receiving the signal modulated by the measurand and by electronics for converting the detected signal into a useful otuput.

In an optical fiber sensor the propagation medium is constituted by an optical fiber which can act as detector of the measurand or simply as light guide to and from the sensing element.

In the first case the sensor is defined as intrinsic as the quantity to be measured modulates directly the light transmitted along the fiber while in the second case the modulation occurs externally to the fiber and the sensor is denoted as extrinsic.

Optical fibers offer to sensors the same advantages they do to telecommunication systems, that is, low attenuation, and high information transfer capacity, lightweight and geometrical flexibility. Another important advantage with respect to conventional sensors is that the fibers are chemically inert, electrically passive and insulating thereby removing electromagnetic interference problems and numerous safety considerations for operation in hazardous areas. However it is to be noted that there are some effects which can disturb propagation and hence are accurately avoided in telecommunciations which on the contrary result useful for some parameter sensing (f.i. stressing, pressing, micropending, etc.)

Further optical fiber sensors are responsive to a large range of measurands, and present a sensitivity which can be higher with respect to that of the more conventional sensors (long optical interaction paths) while the response can be very rapid (do to large

measurement bandwidth). Finally such sensors can be easily integrated into an optical communciation system.

However it is to point out that o.f.s. present also some disadvantages: the most serious is probably the possibility of influence of more than one parameter at one time. In comparison with traditional sensors (electrical, hydromhic, etc.) which are engineerized since a long time and hence on the market at reasonable price, the o.f.s. may result for the time being expensive not for the fiber itself (but some time special fibers can be necessary) or for the main components but rather for the processing of the light signal which may be complex and sophisticated.

Development of optical fiber sensors started about the half of seventies even though some isolated demonstrations preceeded this date. Since then many laboratories have entered this field and many types of sensors have been proposed and realized passing from configurations making use of optical bulk components to more compact all fiber configurations. The initial impetus in sensor effort has been for defence and aerospace applications where the technical advantages are prevailing while in the industrial sphere fiber optic sensors must compete on both technical and cost grounds. High technology medicine is another area where there is a pronounced need for new types of sensors. Although the progress has been rapid only a few type of sensors have been engineered and made available on the market.

The working principle of an o.f.s. is based on the modification of any one of the various parameters which characterize a guided optical wave. The relevant parameters are amplitude frequency, phase, polarization state and velocity. The measurand may affect the parameter by means of a modification either of a material property or a waveguide property. The o.f.s. can be divided into two wide classes: coherent and incoherent sensors. The first ones imply the use of interferometric configurations (interferometric sensors) and monomode fibers. They result more complicate but offer order of magnitude increased intensity over existing technologies, and hence are investigated for sophisticated applications such as magnetic, acoustic vibrations, rotation sensing. The incoherent

sensors, by contrast, are simpler and compatible with multimode fiber technology. In view of the fact that extreme sensitivity is not required for most applications (velocity temperature, pressure, levels, flux, sensing, gas partial pressures, etc.) these devices may result competitive with the existing ones.

In the following sections the most significant applications of o.f.s. will be reviewed considering separately the two classes of coherent and incoherent sensors. Finally a section will be dedicated to biomedical sensors which constitute a particular category in view of their peculiar requirements.

2. *COHERENT SENSORS*

2.1 Introduction

Optical fiber coherent sensors are based on phase modulation technique. As well known, detection of optical phase change offers the possibility of measuring very small variations in physical parameters (easily as small as 10^{-4} radians and down to 10^{-8} radians) but must be performed interferometrically. This requires a stable reference, a coherent source and a stable output polarization state of the fiber in order to avoid alteration of the fringe contrast. All these requirements imply the use of lasers as source and of monomode fibers and relative technologies.

Fiber optic interferometric sensors (FOIS) are particularly suited for measuring a variety of physical parameters such as vibration, rotation angles, strain, pressure, current, temperature, acoustic pressure, with extreme sensitivity in hostile environment (power plants, explosive, chemical plants) or for military purposes. Besides the sensitivity which can be maximized by the possibility of optical path length increase (long fibers), under certain conditions they may achieve a large dynamic range and can be realized in very compact form.

However in spite of such advantages FOIS still present a number

of problems:

- sensitivity to several parameters in particular strain and temperature which can affect the measurement of small displacements. Further temperature and strain are not independent variables.
- difficulty to ensure source wavelength stability which in turn can cause a phase change.
- stability of reference arm which must be protected for all variables which can produce a phase change.
- phase recovery problems.

Efforts to overcome these problems add complexity of the system (7,8)

2.2 Interferometric sensors

The main forms of interferometers are four and include the Fabry-Perot, the Mach-Zehnder, the Michelson and the Sagnac interferometers.

A Fabry-Perot (fig.1) consists of two parallel partially trasmissive mirrors (reflectivity e.g. 95%) at a distance apart so to constitute a resonant cavity at a given wavelength. The light from a laser, injected into the cavity, is in part reflected and in part transmitted to the detector where it combines with the light which has been reflected back and forth successively between the mirrors. The intensity at the detector resulting from a vectorial summation of all contributions is a sharply peaked function of the distance between the mirrors reaching a maximum value when the distance is an integral number of half wavelength (resonance peak). Hence in the vicinity of its maxima the Fabry-Perot interferometer is an extremely sensitive length measuring device. Modulation of the Fabry-Perot device is by alteration of the distance or travel time between the reflecting mirrors which can be accomplished by temperature, pressure or strain. In the optical fiber version two mirrors can be applied at the ends of two sections of aligned fibers and used in transmission or a small length of fiber with the end faces suitably coated is joined to the fiber and used in back reflection (fig.2).

A temperature sensor in the form of a Fabry-Perot interferometer, recently proposed (9) consists of a fiber Fabry-Perot made of a short piece of singlemode fibre (26 mm long) with the terminal end faces polished and dielectrically coated; the light from a laser diode (AlGaAs) is transported along a monomode fiber to the fiber Fabry-Perot and back reflected along the same fiber through a directional coupler to the detecting system. The working principle is based on the compensation of the temperature change ΔT which would shift the Fabry-Perot output to the neighbouring order ($K \rightarrow K+1$) by a suitable wavelength change $\Delta\lambda$ so that the reflected signal is continuously kept at the reflection minimum of order K. The sensor which has been envisaged for continuous temperature monitoring in hyperthermia systems covers the temperature range 25-45°C. with a resolution better than 0.1°C.

Michelson and Mach-Zehnder interferometers have a two paths configuration: the mesured parameters alter the optical

path or transit time of the light on one arm, thus changing the phase relationship with respect to the reference path (fig.3,4).

In the Michelson interferometer the light from a laser source is splitted into two beams by a semitransparent mirror (at 45°) and reflected by two plane mirrors (one fixed and one connected with the transducer) and recombined through the beam splitter towards the photodiode which gives an amplitude modulated signal as a function of the phase difference between the two waves.

The Mach-Zehnder configuration makes use of two reflecting mirrors and two separate paths (signal and reference) so that no return to the source occurs which could give rise to source instability and noise. In both cases the described bulk configurations can be replaced with an optical fiber configuration where the mirrors (semitransparent or reflecting mirrors) are replaced by optical fiber couplers and the optical path runs along monomode fibers (fig.5,6). The phase shift between the reference and measuring signals gives rise to a sinusoidal amplitude function, with maximum sensitivity and linearity for quadrature relationship. The problem of mantaining such a situation can be technically solved by different detection technique (i.e. homodyne and heterodyne). Further in order to eliminate ambiguity caused by ripetitive sinusoidal output signal there is the necessity of constant reference to a standard input condition. Temperature, strain, acoustic pressure, (which in turn produces displacement or strain), magnetic and electric fields can be measured with these interferometers by direct application on the signal arm or by using appropriately coated fibers in such arm.

An all fiber Michelson interferometer configuration has been proposed for a temperature optical fiber sensors (10). The light from a laser (λ = 800 nm) is injected into a monomode fiber and through a directional coupler sent to two fibers constituting the reference and measurement arms of the interferometer. The fiber constituting the measurement arm is attached to a steel probe (3 cm long) having a large expansion coefficient with temperature. The end faces of the two fibers are mirrored so that the two beams propagating inside the two fibers are backreflected towards the coupler where interference occurs detectable by means of a photodetector. In order to reduce the effect of environmental induced perturbations the signal and reference fibers are closely coupled along their entire path (except for the probe). Measurements have been performed in the range 30-210 deg.C with a sensitivity of 0.1 deg.C and accuracy of $\pm$1°C.

However the Mach-Zehnder is the most widely used interferometric configuration. In particular a great amount of work has been carried out based on this technique at the NRL for developing acoustic sensors for hydrophone applications. Early efforts concentrated on single sensors and later developments are extending this work to beam forming arrays, multiplexing technique and inherent signal processing problems. Fig.7 shows the typical scheme of an hydrophone (4).

A laser is split so to illuminate a reference fiber while the sensing fiber is exposed to acoustic field which can cause changes in the diameter of the fiber core, fiber length or core/cladding refractive index. The dominant effect is the length which can be enhanced by wrapping the fiber on a suitable mandrel. In the reference arm a modulatind device (for instance a piezoelectric fiber stretcher) is inserted to give rise to the phase shift equal to that occurring in the sensing arm thus allowing the interferometer to work in quadrature condition (homodyne detection). To hold the interferometer at quadrature an error signal must be produced: this can be done by using both outputs of the interferometer to produce the error signal which is then applied to the modulating device as the correction signal. Typically phase difference of 10 ,10 radians between the two arms can be measured. Fig.8 shows the minimum detectable pressure for different fiber lengths.

Another typical example of Mach-Zehnder interferometer application (11) concerns an AC current sensor which makes use of two different approaches to transform the current to a phase shift detectable in the interferometric system:

- the IR^2 heating produced in the fiber coating heats the fiber;
- the magnetic field produced by the current acting on a magnetostrictive material bonded to the fiber (fig.9).

The current range investigated was 5÷2000 mA. The measurement of the phase shift produced by the heating or magnetostrictive effects was performed again by maintaining the interferometer at its maximum sensitivity by an electronic compensation system. At 10 KHz the sensitivity of the magnetostrictive current sensor was of $7 \cdot 10^{-9}$ A while for the heating sensor at 10 Hz was of $5 \cdot 10^{-6}$ A per meter of sensor.

Similar configurations (with magnetostrictive coatings) are applied to the measure of small magnetic fields (4,12).

Finally one of the most investigated interferometric sennsor is the gyroscope which is based on the Sagnac interferometer, whose bulk configuration is shown in fig.10. The laser output is split into two beams which are sent into two opposite directions around a closed path formed by a beam splitter and three mirrors. The two beams are then recombined at the photodetector: under ideal conditions the two opposite light paths should be identical and the beams recombine in phase. When the system rotates around an axis perpendicular to its plane the path of the light travelling with rotation results slightly longer than that travelling in the opposite direction and this results in a phase difference between the two beams. Consequently the Sagnac interferometer can be used as a rotation measuring device.

In the optical fiber configuration the laser light is split into two equal components launched in opposite s directions into the fiber loop (fig.11) of radius R and the whole assembly rotates at an angular velocity (radians/sec). Under simplifying hypothesis the phase shift between two opposite beams results:

$$\Delta\phi = \frac{8\pi\Omega N A}{\lambda \cdot c}$$

where: A is the area covered by one fiber loop

c the light velocity

N the number of loops

Consequently this interferometer can be used as a rotation measuring device in particular as a gyroscope which are instruments currently used in inertial navigational systems (13,14). Typically phase difference of microradians are obtained for a fiber length of 1 Km with R=10 cm and for rotation rate of 0.1°/hour. However design, stability and signal detection problems are still important problems to be solved and a lot of investigations are being carried out in different laboratories, in particular at NRL, MIT Stanford University, Thomson CSF, AEG Telefunken.

Before closing the chapter dedicated to coherent sensors, it is worthwhile to mention sensors again using monomode fibers but not based on phase detection. These are based on polarization modulation (which in turn result into an intensity modulation) and take advantage of the recent introduction of monomode fibers with special polarization characteristics such as "polarization maintaining", and "single polarization fibers". Such fibers can be used as intrinsic sensor as the birefringence changes with temperature, longitudinal strain but also when subjected to electrical and magnetic fields (4,8)

3. *INCOHERENT SENSORS*

This wide class of sensors, instead of using a phase modulation, is based on modulation by a measurand, of one of the other parameters, different from the phase, which characterize a guided optical wave, such as amplitude, polarization, wavelenght (or colour), velocity.

The modulation can acts upon the fiber itself or upon a photosensitive material connected to the fiber and used as transducer.

This sensors, therefore, utilize inchoerent sources and multimode fibers. For such reason their technology results simpler and cheaper. In general, however, they presents less sensitivity, even if comparable with that of conventional sensors.

Next part is dedicatet to a brief description of some inchoerent sensors.

3.1 Light-interruption sensors

The simplest sensors are the optical switches acting as go/no-go devices. These can be very useful as control or alarm elements for monitoring the integrity of offshore structures and gas pipelines, for detecting hazardous conditions (e.g. fire in its early stage), for monitoring the integrity of doors, windows, and walls, for replace numerous microswitches and valves in process plants and in aircrafts.

In a "fire-alarm" device the aligment between two fibers is made dependent on the external parameter owing to two bimetallic strips connected to the fibers. A similar device use an opaque shutter interrupting the light through the fibers (15).

Optical sensors allow also liquid level detection in hostile environments (16,17). They are paticularly useful in case of explosive liquids. The light from a source is led by an optical fiber to an optical prism whose angles are constructed such that if it is surrounded by air, most of the light is reflected back and carried to a detector. If howevwer the prism is immersed in the fluid to be measured then the light is transmitted into the fluid and no signal returns to the detector. In this way the probe acts as level switch. By using several of this switches placed at different levels, it is possible to obtain a pseudo-continuous measurement. The prism can be either an external piece connected to the fiber, or realized on the fiber itself (fig.12).

Several instrument manufactures have developed bar-code reading light-pens (18). In these sensors the variations in reflectance from the code modulate the light intensity. The fibre optic solution offers not only low weight, but also permits larger tolerance in pen-to-code angle and distance than do conventional pens incorporating active components directly within the pen housing.

3.2 *Flow meters*

Flow measurements are very important in several process control. When it is necessary to obtain high sensitivity or not to disturb the flow pattern with the sensor, laser Doppler techniques have no rival. Doppler systems are, however, extremely expensive. Cheaper devices for lower accurate measurements can be realized.

For example, some standard meters uses a float whose vertical position depends on the flow intensity. This position can be detected by introducing a row of sensing fibres.

Different flow meters consist of standard turbine meters where two optical fibers are introduced to detect the speed of the rotor. The light carried by an optical fiber is reflected back into a second fiber from the blade tips. The optical signal detected by an electronic unit, give a TTL compatible squarewave whose frequency is related to the flow rate (fig. 13).

3.3 *Position,pressure,displacement sensors*

Several process controls involve frequently the need of position, pressure or displacement measurements.

In the robotics, in particular, several sensors are located at the robot hands but in many applications it is inconvenient or undesiderable to have electrical elements into that hands. Fiber optic sensors can be a solution.

As an example we can describe two sensors developed at the Jet Propulsion Laboratory (19).

The first one is a proximity sensor which is based on the focusing of an infrared light led by a fiber onto the target. The intensity of the reflected light can be measured and it results function of the optical head-target distance.

The second sensor is a tactile sensor constituded by several sensitive cells. The top of each cell is made with rubber or other elastic material which is the contact area between the objects and the robot hand. The light conducted by a fiber optic pointed toward the elastic material from below, is reflected and received from a second fiber connected to a detector. When the elastic material is pressed by an object from above, this causes the light reflected back to the second fiber to change. The changing amount generates a signal function of pressure acting on the cell (fig. 14).

An incoherent sensor for measuring acoustic pressure can be realized simply by interposing two parallel gratings between two multimode fibres (4,10). An acoustically excited diaphragm causes a grating to move relative to the other grating. This modulates the light transmission trough the fibres.

All the devices above described are very simple and cheap, but, in general, they are not very accurate or realiable. Infact their major disadvantage is that the detected power will vary not only with the measurand, but also with light source variations and spurious bends in the fiber.

A commercial fiber-optic system for vibration measurements wich is insensitive to spurious changes in the attenuation make use of a membrane placed at the end of a fiber modulating the light reflected back into the same optical fiber (21). The variations in intensity of the returned light detected by an optoelectronic system, are used as a measure of the acceleration of the membrane. In order to correct the received signal for spurious changes, a reference signal must be provided. For this purpose the cantilever membrane is fabricated by using a double heterostructure of GaAs-AlGaAs which converts a fixed portion of the impinging light to light of different wavelenght (22). So, while the backreflected portion of light is indipendent on membrane position, the portion absorbed and re-emitted as photoluminescence result practically insensitive to it. By taking the ratio of the two signals it is possible to obtain an output signal proportional to the value of the acceleration (fig.15).

A different pressure sensor can be realized by using particular transparent materials (photoelastic materials i.e. araldite, polyurethane, etc.) which become birifringent when one axis is strained by a mechanical force (23).

In fact, while this materials are isotropic in unstressed case, applying a unaxial stress to them, they show a difference on the refractive index between the stress direction and directions ortogonal to it. This birefringence effect depends upon the amount of unaxial stress applied. Then, if a piece of photoelastic material subjected to an unaxial stress is illuminated by a circularly polarized light, an indication of the applied stress value arise from the examination of the output polarization state of the light passing through the

piece.

Based on this effect fiber optic pressure sensors can be realized.

In this sensors the light from an input fiber is collimated by a graded index rod lens (GRIN rod), passes through a polarizer with axis at $\pi/4$, a quarter wave plate, and then through the active birefringent element followed by an analyzer. This permits the separation between the $\pi/4$ components. After separation, both components are sent by using two optical fibers, to two different detectors connected to a processing system wich gives the indication of the applied stress.

3.4 Temperature sensors

Optical fibres are very usefull for temperature measurements in hostile or electrically noisy conditions. For this reason in earliest pyrometers optical fiber was acting only as radiation transducer from a furnace to a detector so keeping the electronics away from the heat.

A more accurate pyrometer is produced bu the American Accufiber Company (24). A blackbody cavity is formed on the tip of a short single crystal aluminum oxide (sapphire) fiber and the radiance emitted from the cavity in a narrow wavelength band is used to measure its temperature. The blackbody cavity can be created by sputtering a thin iridium film on the surface of the sapphire fiber and, in order to reduce the oxidation of the metallic film, it can be coated with a film of aluminum oxide (fig.16). An ordinary glass fiber (which may be several hundred meters long) connected to the high temperature sapphire fiber, led back the radiation to the electronics where the optical power at one or two specific wavelength bands (depending on the particular model) is used to compute the temperature. The device operates over the range 500-2000°C. with an accuracy of +-0.0025%. Its resolution is 1 part in 10^{-8} and its drift is less than 1 part in 10^{-8} per hour. This device is 20 times more accurate than the radiometric standard used by the U.S. National Bureu ofgf Standards. In fact has recently been adopted by the N.B.S. as temperature standard between the melting point of the aluminium and the melting point of platinum.

For lower temperatures measurements the swedish ASEA and the american Luxtron have developed two temperature sensors based on the photoluminescence of materials bonded on the tip of an optical fibre (21).

In the ASEA system light from a LED is transmitted via an optical fiber to a small semiconductor crystal. The light impinging on the crystal is absorbed and re-emitted at lower wavelength by photoluminescence (fig.17). This emission, whose spectrum is determined uniquely by the temperature of the sensor, is led back to the measuring equipement with the same optical fiber as the exciting light and is detected by a wavelength demultiplexing detector. The ratio between two different wavelength intensities gives the temperature measurement. The temperature range is 0-200°C., the resolution 0.1°C. and the accuracy 1°C. The time costant of the response is shorter than 5msec. Fiber lenghts up to 500m. can be used with a change in accuracy less than 1°C.

The Luxtron sensor uses ultraviolet light to stimulate rare earth phosphorous grains bonded at the end of the fibre (25,26). Otherwise its working is similar to the ASEA device. The range of operation is -50÷200°C.

A different temperature sensor can be realized by using the photoelastic effect (27). Sensors of this type can consist of a crystal of lithium tantalate (0.1 mm. tick) with a polarizing film cemented to one side and a dielectic mirror placed into the other side. Light from an LED is transmitted by an optical fiber to a polarizer and then to the crystal which changes the light state polarization as function of the temperature. When the light reflected back by the mirror returns to the polarizer, the change in the polarization state is converted into an intensity modulation proportional to the temperature.

3.5 Chemical sensors

Chemical sensing by optical fibers is one of the more interesting areas of optical fiber sensors, where classical spectrophotometric methods employed in chemical instrumentations can be extended to fibers. In fact the fiber can be used to conduct the light from a spectrometer to a separate optical cell or to improve or miniaturize the spectrometer itself.

The fiber can also allow interaction of the light with surrounding medium, more specifically the fiber can be terminated by an "optrode" (combination of optical and electrode in analogy with chemical electrode sensors), in general consisting of a reagent (in solid or liquid form) in a suitable membrane enclosure, through which it is exposed to the chemical being analyzed, by measuring changes in reflectance, adsorbance or luminescence.

Activity in optical chemical sensors is mainly in the research stage, but considerable interest is being shown by the chemical industry, where efficiency and safety of chemical processes rely on the extensive use of sensors to measure process variables. The number of different gas pollutants in the air (methane, ammonia vapours, ...), in water (oils) or the number of parameters in the human body (proteins, pH, partial pressure of O_2, CO_2 , etc.) are so high to require many specific and selective sensors.

While sensors of physical parameters (temperature, pressure, etc.) can be hermetically encapsulated, the chemical sensor cannot, because it must in general interfere with the measurand and hence results more critical. Sensor technology in general is multidisciplinary and this is particularly true for chemical sensors, simply because knowledge in physics, optics and electronics must be combined with knowledge in disciplines such as electrochemistry, biochemistry, etc.

We will now describe some examples of chemical sensors designed for measurements or controls in chemical plants.

A monitor for hydrocarbons in water employs un unclad optical fiber coated with an organophilic compound enabled to adsorb oleous hydrocarbon materials (28). The fiber is inserted into a stainless steel capillary containing the water to be tested. When a small quantity of hydrocarbon material, with an index of refraction greater than that of the optical fibre core material, is introduced into the water surrounding the fiber, the coating refractive index increases reducing the intensity of light arriving at the output end of the fiber. The degree to which the light intensity is reduced, measured by a suitable detector, is related to the quantity of contaminant.

A similar sensor for ammonia vapours uses as waveguide a small glass capillary coated with a thin film of an oxazine perchlorate dye (29). This dye, when exposed to ammonia vapour, rapidly changes colour from blue to red. This produce a waveguide attenuation which can be detected.

A different sensor based on the differential absorption technique has been developed for detection of explosive gases (e.g. methane) (30). Two optical wavelengts are used: one for which the gas has a large absorption coefficient, the other is chosen as reference at an adjacent wavelength where the absorption is weak. The two different wavelengths are emitted as time-multiplexed signals, from two LED's and coupled into a same fiber which conducts the light to the probe. Inside them one of two wavelengths is adsorbed by the methane, the other is used as reference. On return, both signals are detected by the same detector and a suitable electronics gives an output signal related to the concentration of gas.

3.6 *Multiple sensors*

In the present day several efforts are dedicate to the development of fiber optic systems for multiplexing or scanning several intensity sensors.

In fact it may be convenient to produce the multiplexing or the scanning dyrectly on the optical signal before the optical-electrical convertion.

Examples of multiplexing techniques are described in the literature (31,32).

Several sensors are placed at different distances along a multimode fiber (fig. 18). Just as with a radar system, a repetitively pulsed light source uses these path differences to create a difference in time between pulsed received back from the various sensors. A time division multiplexing detector system measures the individual sensor signals.

Simpler techniques utilize electromechanical devices based on rotary or tranlational motion. For example we can consider the sketch of fig.19 (33). The device is based on rotary motion, by means of a stepper motor, of one (or more) fiber scanning the position of 24 fibers. By using a graded-index rod lenses, the radial and axial tolerances are alleviated and the device become less sensitive to dust. Typical loss caused by misaligment is 0.3 dB and the acces time between two adjacent fibers is 60 msec.

4. SENSORS FOR BIOMEDICAL APPLICATIONS

Sensors of physiological parameters are of great interest for the medical world. An accurate description of the functions of physiological systems and organism is performed "in vivo" by means of direct observations of a number of fundamental variables. A new and better sensor results in a better diagnosis and consequently an optimal treatment of the illness.

For medical applications a distinction must be made between invasive (e.g. in the blood stream or in tissue) and non invasive (e.g. on the skin) sensors. Clearly there is preference for non invasive sensors, in view of patient safety and confort. However the necessity of more accurate and reliable values of the measured physiological parameters may require the use of invasive sensors, which in general are in the formm of catheters, provided with one or more sensors. Hence the miniaturization is essential for invasive sensors, while biocompatibility of materials is important especially when the catheter is placed in the blood stream,owing to emolysis or to plaque, aggregation and coagulation problems.

Fiber optic sensors are now attracting considerable interest especially for invasive measurements. In fact they well satisfy the flexibility and miniaturization requirements, can be easily inserted in catheters for multiple sensing or in hypodermic needles and may offer adequate accuracy and stability (34).

Another advantage with respect to more conventional sensors (electro-sensors) is once again the safety of the fiber optic device which do not involve electrical connectors to the body.

According to the type of variable to be measured, two wide classes of biomedical optical fiber sensors can be defined; biochemical sensors (for Oxygen saturation, pH, pO2, pCO2 measurements etc.) and physical sensors (for pressure, temperature, blood velocity and flow monitoring).

Biochemical sensors make in general use of an appropriate reagent fixed at a fiber end (optrode), which allows spectrophotometric or fluorimetric analysis. The optrode can be constituted by:

- a reagent immobilized on a polymer support and contained in a protection membrane through which the analyte diffuses and reacts with the indicator
- a reagent generally in liquid form enclosed in a membrane selective to the measurand
- the indicator can be adsorbed by the core of a bare terminal portion of the fiber.

4.1 Biochemical Sensors

One of the oldest fiber optic sensor (now commercially available), based on photometric measurements of the light carried by a bare end fiber, was performed in conjunction with blood oxygen saturation analysis (35,36).

Oxygen saturation refers to the amount of oxygen carried by the hemoglobin in red blood cells relative to the maximum

carrying capacity. The saturation level may be related to the effectiveness of cardiopulmonary system, compromised cardiac output or reduced oxygen carrying capacity of the blood. The measurement of oxygen saturation is based on the fact that fully oxygenated and fully reduced hemoglobin have very different optical reflectance when plotted versus wavelength (Fig. 20). The crossing between the two curves (where the anount of light reflected is independent of the amount of oxygen) is called "isosbestic point" and is used to normalize the signal measured in general near 650 nm, where there is useful difference between the two reflectance curves.

pH, pO2, pCO2 sensors are among the most recent ones to appear: their basic design consists of an indicator system fixed inside an appropriate permeable container at the fiber end (Fig.21).

The knowledge of pH in blood and tissues is desirable in a wide variety of chemical and biological studies such as respiration studies, including blood and tissue oxygen content and oxygen- hemoglobin dissociation curve. Peterson and al. (37) designed and developed a pH sensor based on old fashion dye indicator chemistry. An hydrophilic gel structure of polycrylamide microspheres covalently bound to the dye for providing a fixed concentration, containing also smaller microspheres for light scattering, is packed in an envelope of hydrogen ion permeable dyalisis tubing at the end of a pair of large NA plastic fibers (diam. 0.15 mm). The light injected into one fiber is sent to the sensor package, backreflected and scattred into the second fiber and then selected into two wavelengths by a cilinder filter wheel. Green light (λ = 560 nm) is absorbed by the base form of the dye as a function of the pH, while the red light is not absorbed thus giving a reference signal. The ratio R between green and red light is measured by the photo detection and signal processing system connected to the fibers.

Fluorescence is another optical phenomenon used for pH sensing. The simplest example is based on fluoresceinamine linked to cellulose. In this sensor an increase of pH converting the dye from its acid to basic form corresponds to an increase of fluorescence intensity (38,39).

Other optical pH sensors measure the ratio between the intensities measured at two fluorescence wavelengths.

Biochemical parameters such as pO_2, pCO_2 are equally important to be monitored for metabolic and respiratory problems. They are similar in construction to the pH sensor and based on the same principle of the reagent coupled to the fiber. pCO_2 can be derived from pH measurements. Recently Peterson (40) developed a pO_2 sensorbased on quenching of the fluorescence of a dye (on a polymeric support, in a porous polypropylene envelope) by oxygen. Fluorescence is excited through one fiber andobserved through the other. Filters are used to measure separately the green fluorescence of the dye and scattered blue excitation radiation which are then ratioed to compensate the source fluctuations. The sensor is 0.5 mm in diameter and provides a read out of the pO_2 over the range 0 to 150 torr with a precision of 1 torr.

A model of pH sensor based on colorimetric method is also

being developed at IROE by using as optrode a dye (bromotymole blue solution) contained in a H+ selective membrane cylinder.

4.2 *Pressure sensors*

Biomedical optical fiber pressure sensors are chiefly housed in a catheter tip and their working principle is practically mechanical, based on mirrors, moved by pressure-sensitive membranes that distorts and vary the distribution of light coupled into the sensing fibers.

Fiber optic pressure transducers are important for intracranial and cardiovascular pressure monitoring, in particular for arterial pressure wave recording of left ventricule, but also in urological neurology and urodynamics. Biomedical field needs the working range 0÷300 mmHg with a repeatibility major than 0.5 per cent.

A typical fiber optic pressure device (41) is based on a pressure- balancing system (Fig. 22): a pressure- sensitive watertight membrane, located in a side hole of the catheter tip, is attached to a cantilever mirror. If there is no pressure, the reflector plate is parallel to the cross section of the fiber optic bundle used to transmit the light to the mirror and to receive the pressure modulated signals. Any pressure on the membrane presses down the cantilever plate: the reflector changes its position with respect to the cross section of the fiber bundle and hence alters the amount of the backreflected light. The output voltage of a photodiode, used as the light detector, is thus proportional to the applied pressure.

Another typical fiber optic pressure device based on a bifurcated bundle with a pressure- sensitive membrane at the common end (42,43). The two legs of the bundle are connected to a light emitter and to a photodetector (Fig. 23). The pressure acting on the membrane displaces the membrane position from the bundle end and hence changes the amount of light coupled into the output fibers. As usual, the output voltage of the photodetector is proportional to the applied pressure.

Another mechanical optical fiber pressure transducer has been more recently designed (44), that relies on diaphragm curvature rather than on diaphragm displacement. The light is brought to the diaphragm surface by a circle of fibers and the reflected light from the diapragm is then distributed among collection fibers arranged concentrically with the illumination fibers. The diaphragm deflection, and hence the pressure, is derived from the ratio of the light received by the outside collection fibers to that from the inside collection fibers. Because of this ratioing procedure, this sensong technique automatically compensates intensity losses, resulting from source intensity fluctuations and fiber microbend losses.

4.3 *Blood velocity and flow*

Sensors for mesuring blood velocity and flow are highly requested in cardiovascular clinic physiopathology and their

use is also foreseen in transluminar coronary angioplasty and in quantification of coronary arterial stenoses. Velocity of flowing blood in vessels can be mesured by means of the fibre optic adaption of Laser Doppler method, based on the frequency Doppler shift of laser light, scattered by the moving red cells (erythrocytes, diameter about 7 μm) (45). In the most implemented version (46) (Fig. 24) a 50 μm core graded index fiber is inserted into a blood vessel at a fixed angle with the vessel axis. The Doppler shifted backscattered light is partially collected by the same fiber tip and backtransmitted to its entrance. The light signal has a Doppler shift frequency:

$$D_f = \frac{2nv\cos\theta}{\lambda}$$

where: n=1.33 is the refractive index of the blood

v blood velocity

The Doppler frequency is measured by observing on a spectrum analyzer the beats between the frequency shifted signal and the original reference signal, suitably biased by means of a Bragg cell to distinguish forward from reverse flow. The weak backscattered signal requires a very carefully designed detection system. The fiber tip is inserted into the blood vessel through the center of an hypodermic needle at 60° (optimum angle), with a plastic holder especially developed to allow heparin to be injected to prevent coagulation around fiber tip. A micromanipulator allows to move the fiber across the vessel for measurements at different sampling points, thus deriving flow profiles. Performance characteristic of this sensor are: velocity range 4cm/sec ÷ 10m/sec, measurement accuracy ± 5%, spatial resolution 100 μm, temporal resolution 8 msec. Preliminary experiments have been performed by using a blood flow simulator and subsequently in vivo tests in femoral and coronary arteries of mondrel dogs.

4.4 *Temperature sensors*

Optical fiber thermometers, owing to their electrical insulation and immunity from e.m. interference are particularly suited for controlled heating of biological tissues in microwave or R.F. hyperthermia for cancer treatment, where the use of conventional temperature sensors (thermocouple or thermistors) can perturb the incident electromagnetuc field and may also cause localized heating spots. There are also other particular fields of application of optical fiber thermometers, for instance to determine thermal distribution during photoradiation therapy of malignant tumors or in thermodilution techniqueee for blood flow measurements, where a known change in the heat content of the blood is induced at one point of the circulation and the resultant change in temperature detected at one point downstream.

Main measurements requirements are: resolution of 0.1 deg.C over a range of a few degrees (35-50°C.), with the possibility of simultaneous multiple locations. As a result, many wholly dielectric optical fiber temperature sensors have been developed, which in general involve a temperature

sensitive optical material, from which is formed the sensor, attached to a bundleee or a single optical fiber.

Some examples will be reported, limiting to those systems which are now well estabilished or to those which are under current research in different commercial and academic research laboratories.

A thermometer already described in the preceeding sections is on the market also in the medical version. It is produced by LUXTRON Co. and exhibits a working range from 0 to 80°C. with a sensitivity of 0.1°C.

Another thermometer based on temperature dependent photoluminescencee of a GaAs crystal, which again has been preceedingly described, is that produced by ASEA. Owing to its characteristics it can be used also in the biomedical area.

Two optical fiber thermometers, mainly aimed to biomedical applications, have been proposed and tested at IROE-CNR, Florence (47,48). The first one, is based on the light intensity modulation induced by a thermosensitive cladding applied on the distal end of the fiber (49,50). The more-up dated version, which makes usee of 200 μm silica-core plastic-clad fiber and has a miniaturized probe 1 cm long and 1 mm external diameter, has a sensitivity of 0.1 deg.C in the 35-50°C. interval (51). Fig. 25 shows the package of the optoelectronic system (860 nm LED, beam splitter anddetectors with electronic circuit) connected to the sensor and to the processing and display unit.

The second thermometer is based on the thermochromic properties of a Cobalt salt solution in iso-propyl alcohol used as temperature transducer (52,53). The optical spectrum of such solution results strongly modulated by temperature variations at certain wavelengths and temperature independent at other wavelengths (Fig. 26). By choosing two suitable wavelengths one obtains a sensing and a reference signals: their intensities ratio is a temperature function practically insensitive to fluctuations and transmission losses not strictly related to temperature variations. The device has been set up and tested in the laboratory: the source is constituted by two LEDs at λ = 660 nm (sensing signal) and λ= 840 nm (reference signal) respectively, which are used in time multiplexing; the probe is constituted by a thin glass capillary with mirrored bottom filled with the thermochromic solution and containing two optical fiber terminal portions: one for conducting the light to the transducer and the other to collect the backscattered light. Its overall dimensions are 1 cm length, 1.5 mm external diameter. The resolution is of 0.1 ødeg.C over temperature range 25-50°C.

5. *CONCLUSIONS*

The aim of this lesson was chiefly that of giving the basic concepts of an optical fibre sensor, outlining the problems related to the development of such sensors. We have also given a review of the most significant devices which have been developed or are under investigation, although we are well aware that the literature reported may be not complete.

Intrinsic sensors will be greatly accelerated by the development of special fibres and coatings which are capable of enhancing a single measurand and reducing the effects of other parameters. Extrinsic sensors on the other hand do not present such technical problems.

Aspects which are particulary important for the exploitation future of optical sensors are:

- reliable and cheaper components
- improved fibres and fibre coatings
- self-checking compensation techniques
- interfacing techniques with optical fibre hihways.

It is possible however, to predict that optical sensors will be an important technology of the future.

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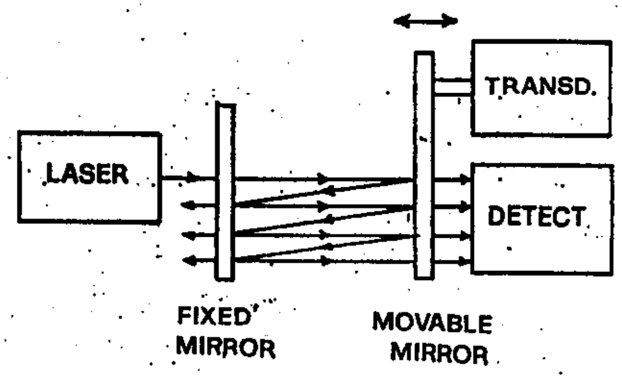


Fig.1

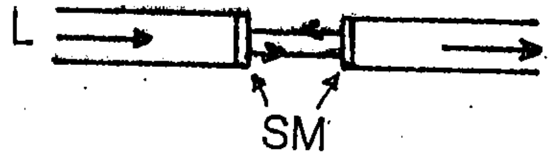
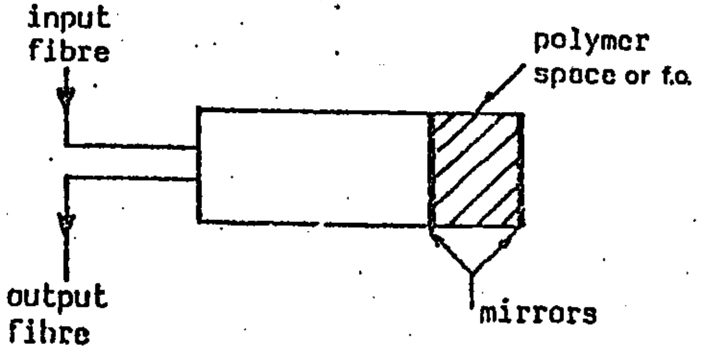


Fig. 2



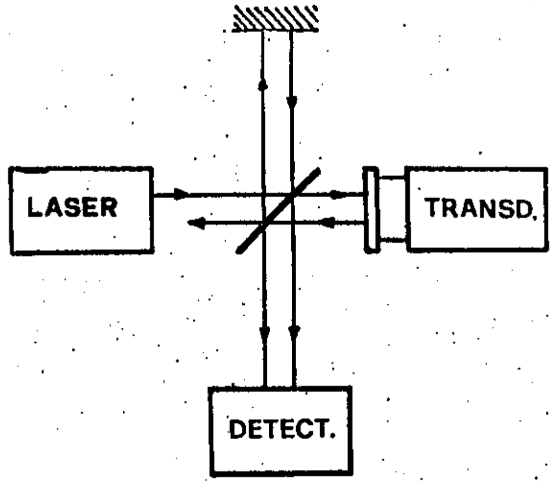


Fig.3

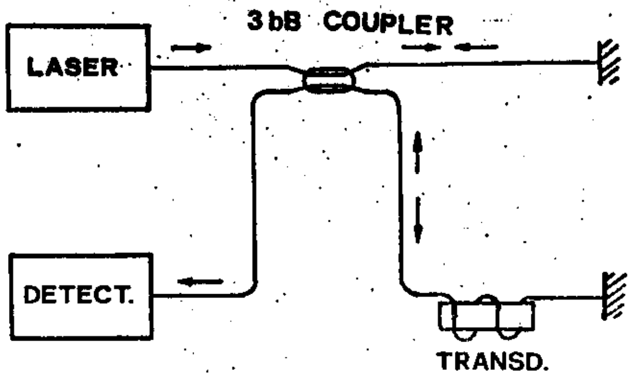


Fig.4

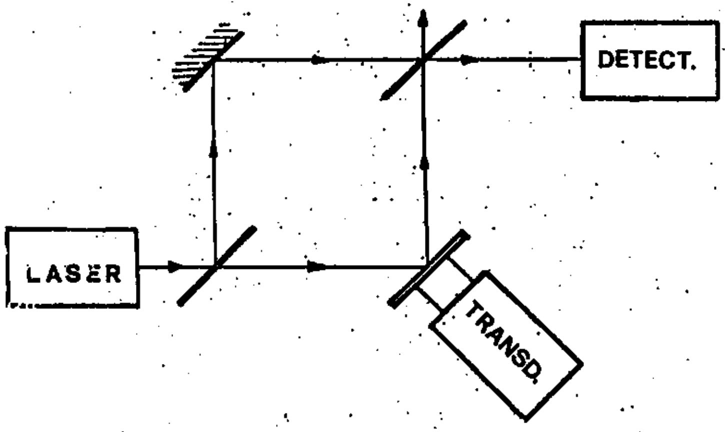


Fig. 5

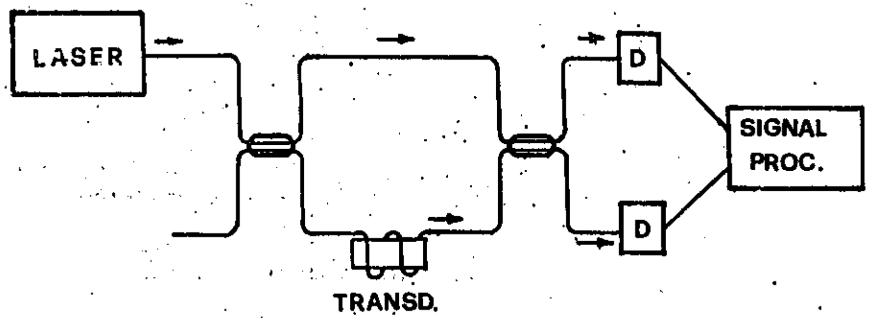


Fig. 6

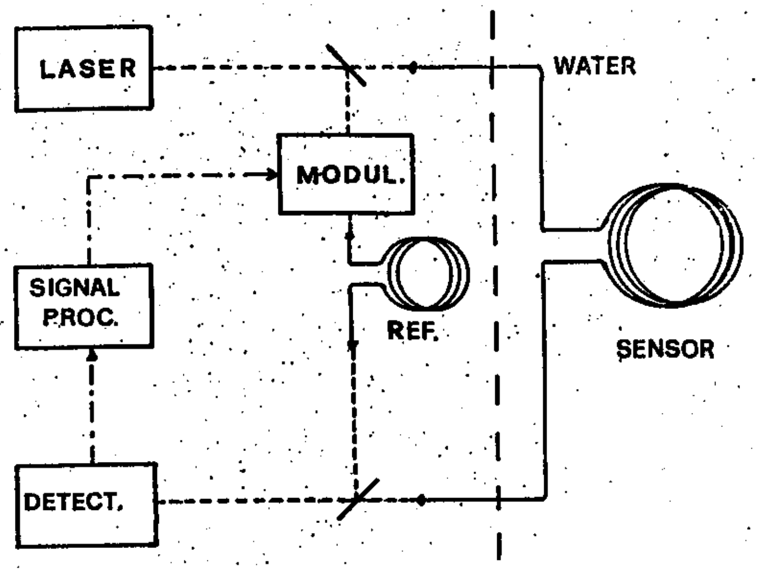


Fig.7

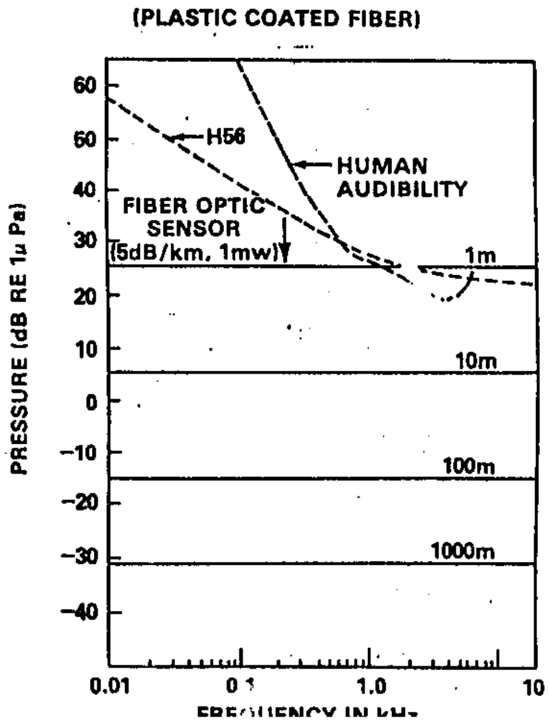


Fig. 8

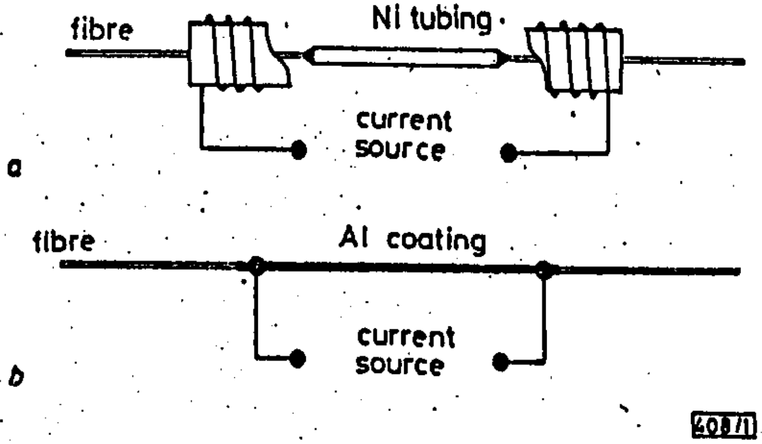


Fig. 9 *Schematic design of fibre-optic current sensor*
a Magnetostrictive sensor
b Heating sensor

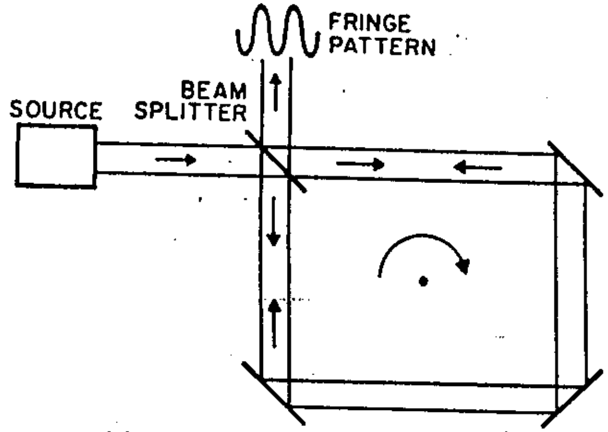


Fig. 10 Bulk-optic loop interferometer.

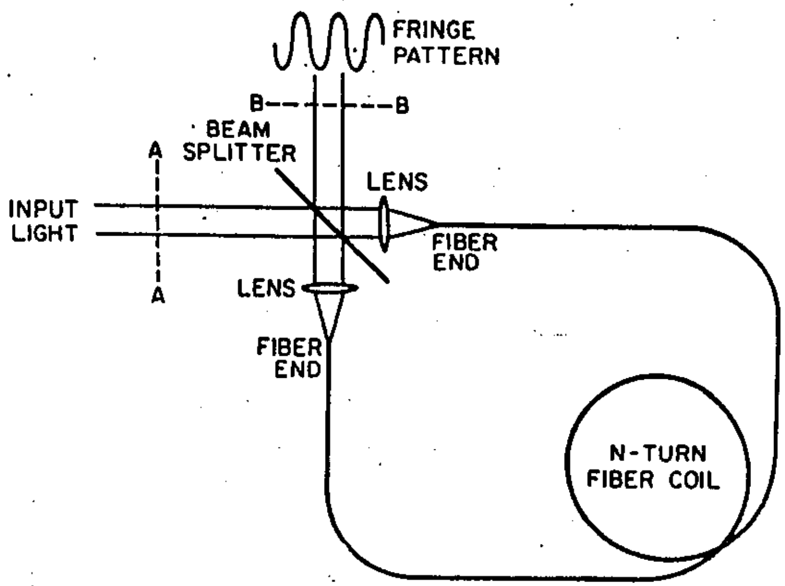


Fig. 11 Loop interferometer with fiber-optic coil.

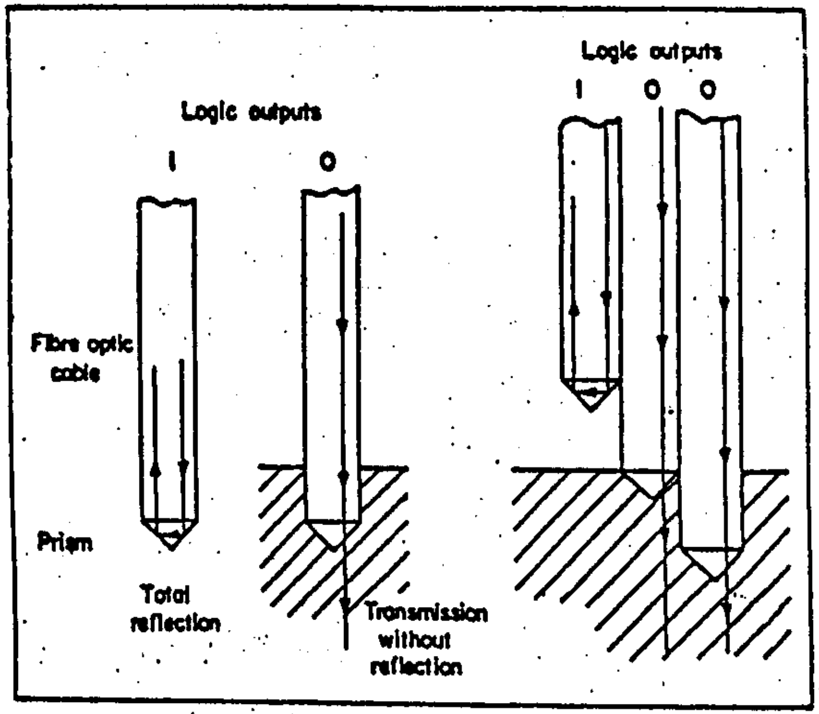

Logic outputs
1
0
Logic outputs
1
0
0
Fibre optic cable
Prism
Total reflection
Transmission without reflection

FIG. 12

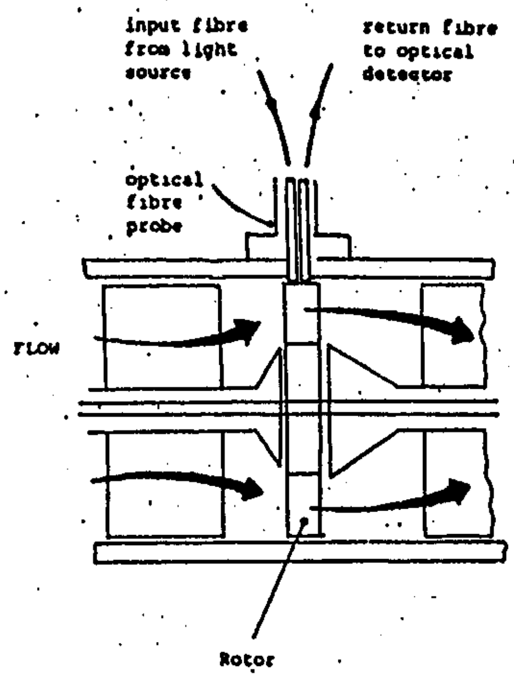

input fibre from light source
return fibre to optical detector
optical fibre probe
FLOW
Rotor

FIG. 13

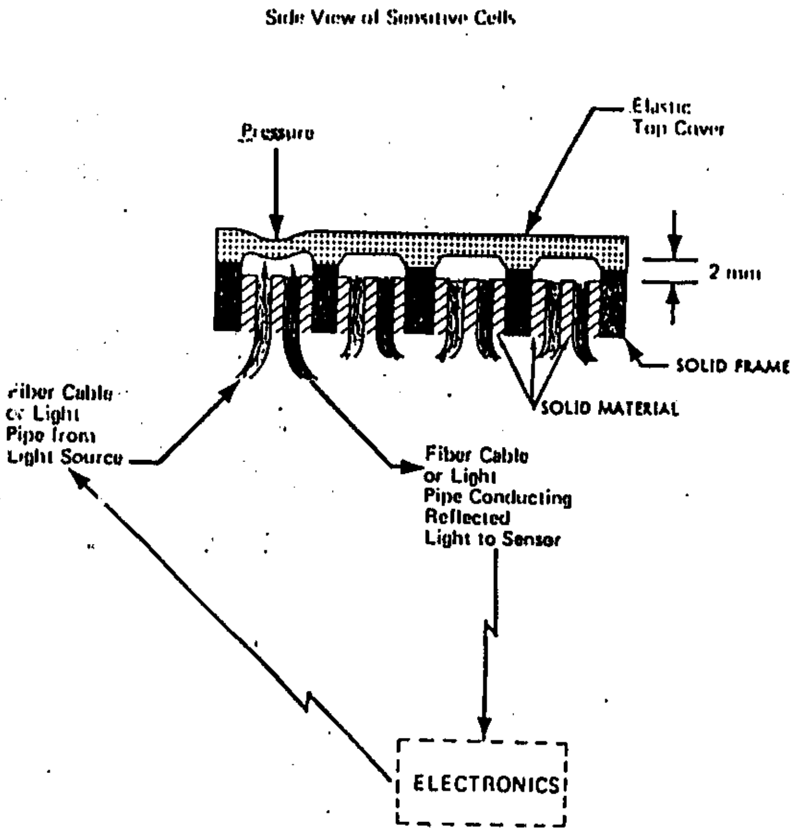

Side View of Sensitive Cells
Pressure
Elastic Top Cover
2 mm
SOLID FRAME
SOLID MATERIAL
Fiber Cable or Light Pipe from Light Source
Fiber Cable or Light Pipe Conducting Reflected Light to Sensor
ELECTRONICS

FIG. 14

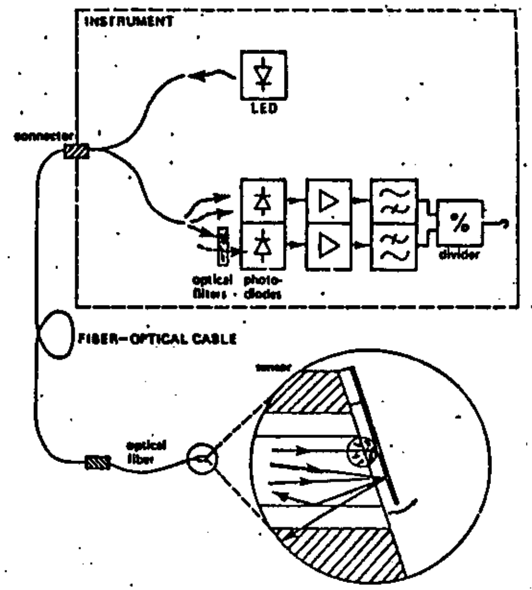

INSTRUMENT
LED
connector
optical filters
photo-diodes
divider
FIBER-OPTICAL CABLE
sensor
optical fiber

FIG. 15

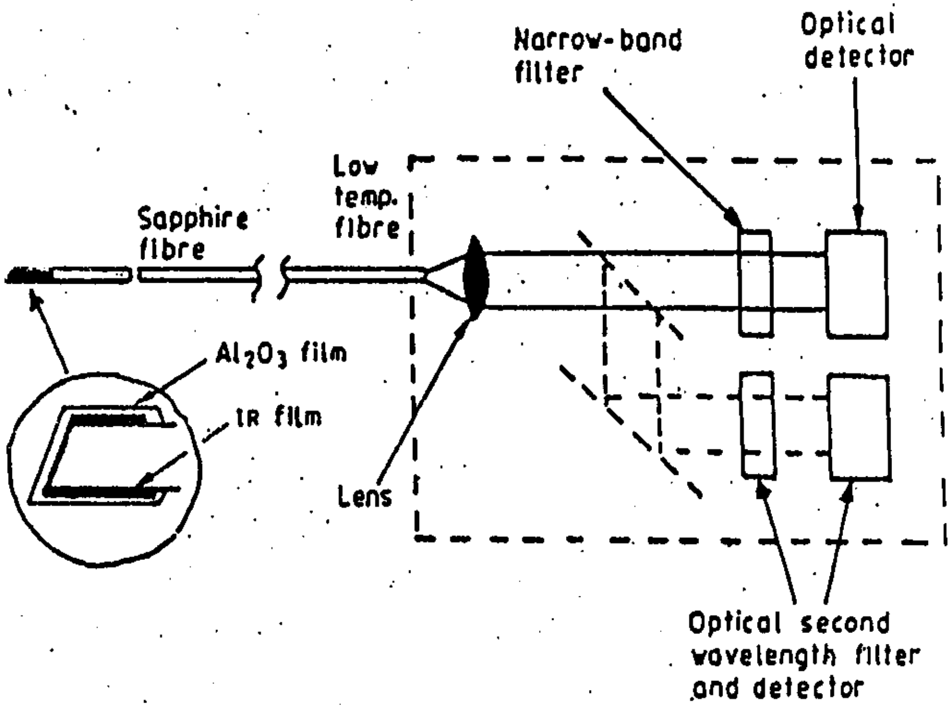
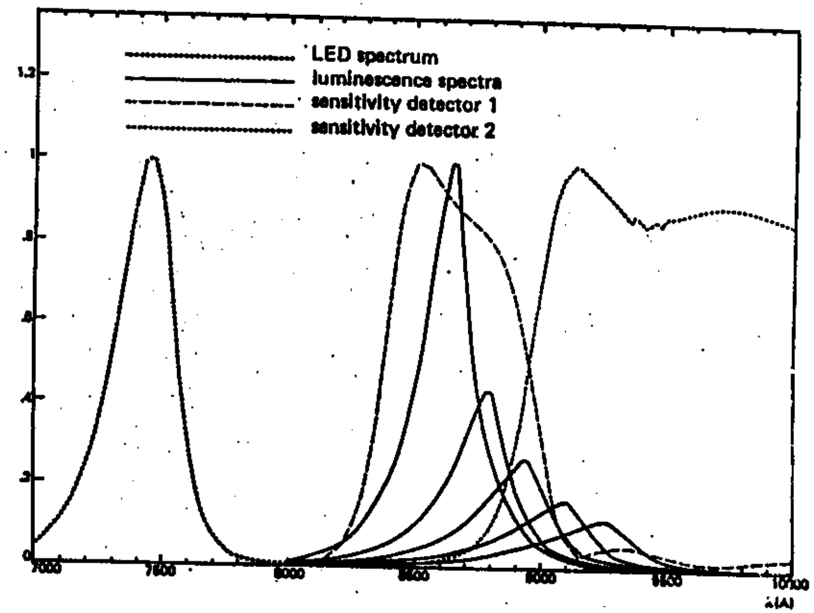
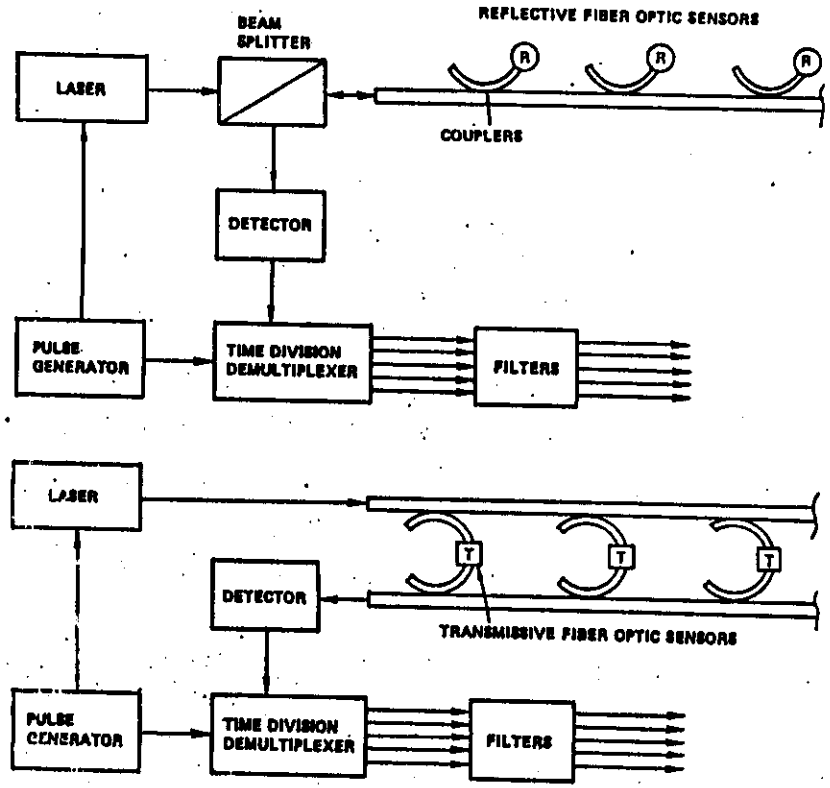


FIG. 16



The spectrum emitted from the LED is shown (dashed-point curve) together with the photoluminescence spectra emitted from the sensor crystal of different temperatures (full curves). Also shown are the spectral response curves of the two terminals of the demultiplexing detector (dashed curves)

FIG. 17



Passive optical multiplexing systems used with either transmissive or reflective sensors.

FIG. 18

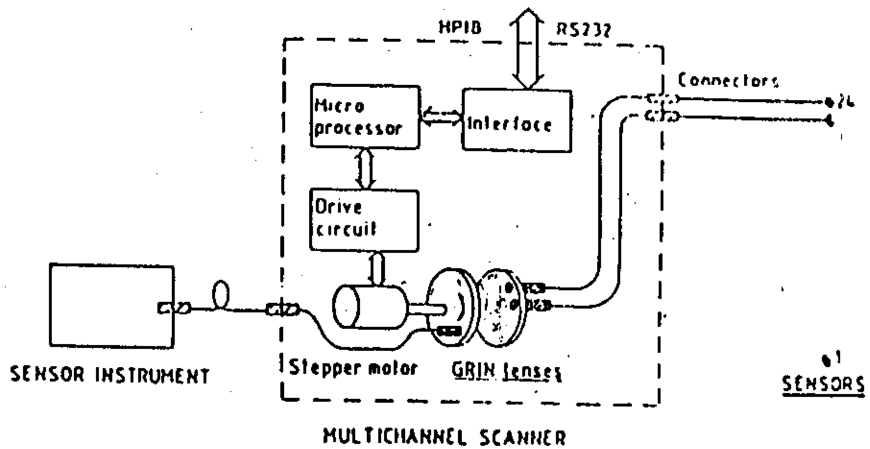


FIG. 19

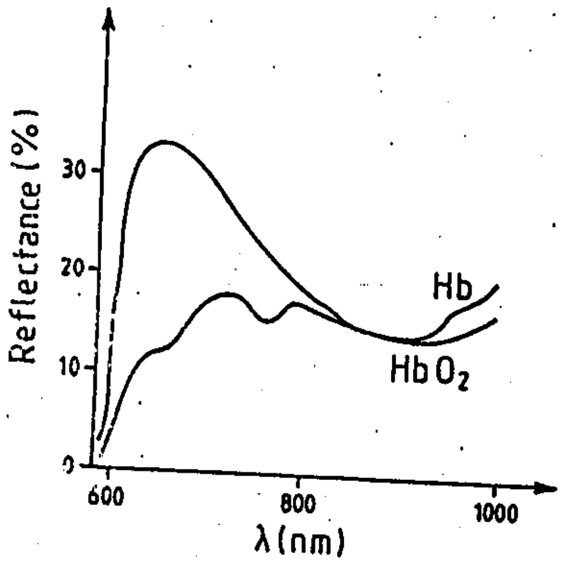


Fig. 20

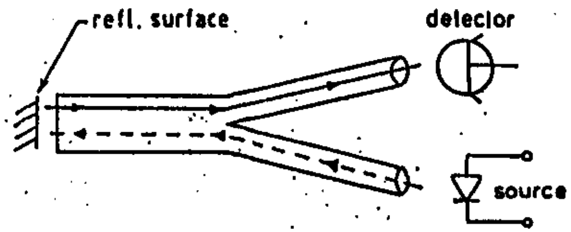
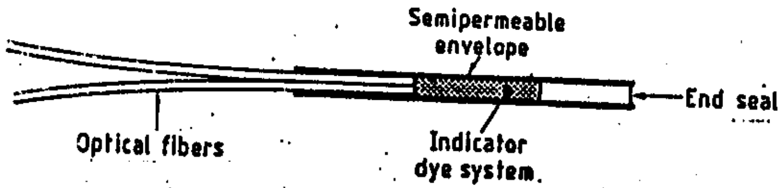


Fig. 23

Fig. 21



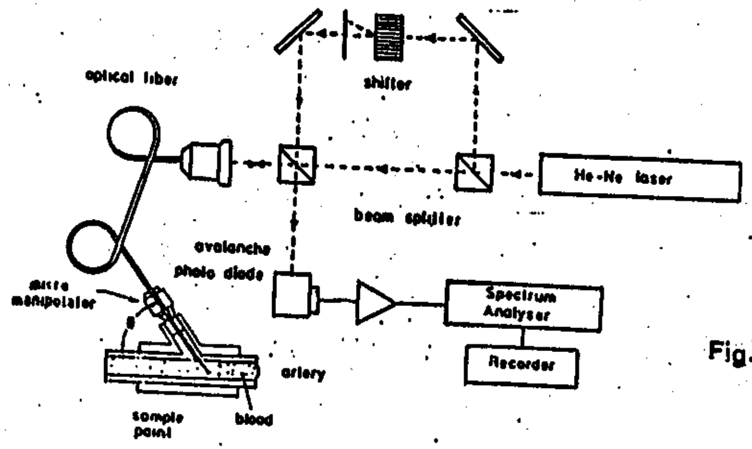


Fig. 24

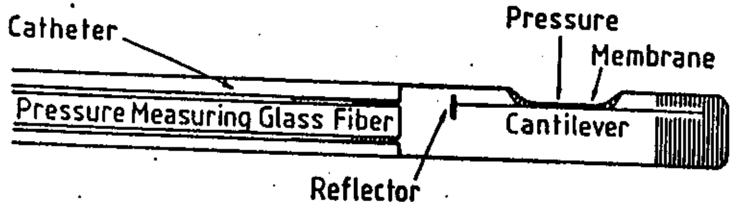


Fig. 22

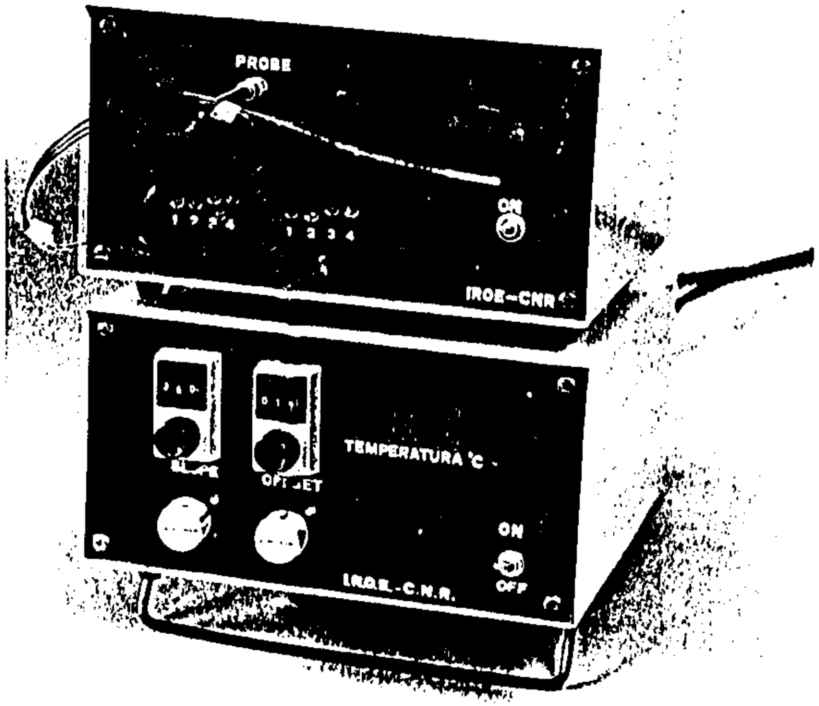

PROBE
ON
IROE-CNR
TEMPERATURA °C
OFFSET
ON
OFF
IROE-C.N.R.

FIG. 25

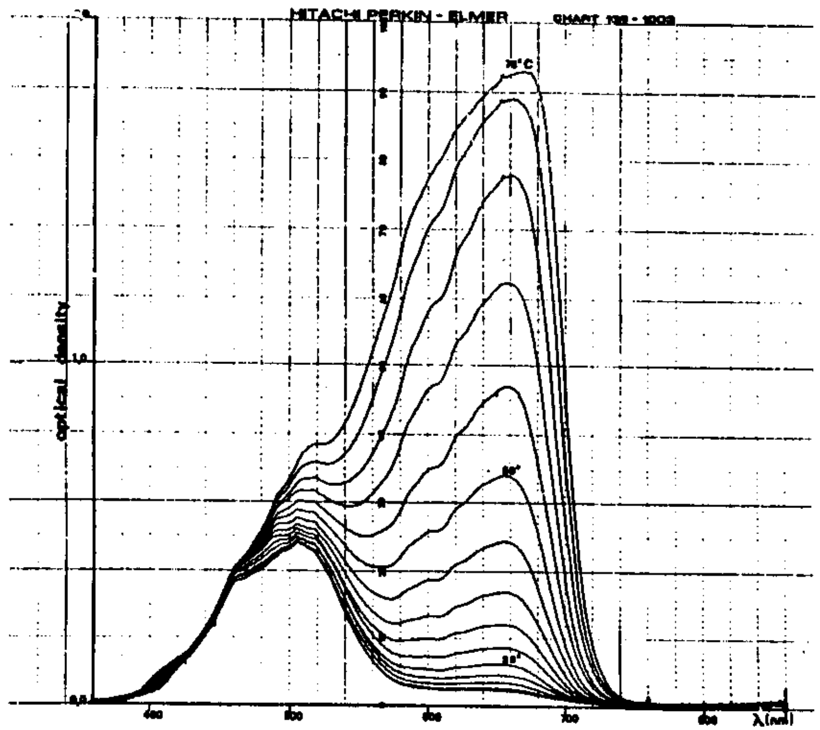

HITACHI PERKIN - ELMER
optical density
1.0
500
600
700
λ(nm)

FIG. 26