Applications & Development of Fibre Optic Sensors in Biomedical Engineering: A Comprehensive Study

Nudrat Sufiyan[1], Archana Yadav[2]

1. Under Graduate Student, Electronics & Instrumentation Engineering, Integral University, Lucknow
2. Assistant Professor, Electronics & Communication Engineering, Faculty Of Engineering, Integral University
Email id: nudratsufiyan@gmail.com, archanayadav.ay@gmail.com

ABSTRACT

This paper focuses on the advantages that optical fibre sensors offer to the biomedical field, recalls the basic working principle and applications. Optical techniques developed for sensing purposes proved to be essential in many application fields, ranging from medicine, industry, process control, to security, and also aerospace. The capabilities of these sensors are generally enhanced when a bulk-optical configuration is replaced by optical fibre technology. In the past few years, research programmes and also the market for fibre sensors have assumed a relevant role. This is undoubtedly due to the growing interest in optoelectronics, but also to the very satisfactory performance and reliability that optical fibre sensors are now able to provide.

INTRODUCTION

Over the demand of high quality in the medical field, the opportunities offered by optical fibres have always been advantageously exploited. In fact, the use of optical fibres in medicine goes back to the sixties, when fibre bundles were successfully pioneered in endoscopy[1], both for illumination and for imaging. Subsequently, cavitation laser surgery and therapy also benefited from fibres, which proved to be the most flexible, and a low-attenuation delivery system inside the ancillary channel of endoscopes, and inside the natural channels of the human body as well. More recently, and especially since 1980, a great deal of research in optical fibres has been dedicated to sensing, and again the medical field found good opportunities for developing very promising sensors.

In this article a fiber optic sensor technology is developed. Emphasis is placed on the problem of feature extraction to reduce all spectral responses to several features allowing simple classification of different perturbation from the human body for continues monitoring of human activity. The identification of specific signals was investigated in the following application settings: - interferometer fiber optic sensor responses, - modalmetric fiber optic sensor responses. The field of signal processing techniques for fiber optic systems is relatively unexplored; however work has been reported in determining optimal techniques for demodulation, denoising of perturbance and identification.

FIBER OPTIC SENSORS

A fiber optic sensor is a sensor that uses optical fiber either as the sensing element ("intrinsic sensors"), or as a means of relaying signals from a remote sensor to the electronics that process the signals ("extrinsic sensors"). Fibers have many uses in remote sensing. Depending on the application, fiber may be used because of its small size, or because no electrical power is needed at the remote location, or because many sensors can be multiplexed along the length of a fiber by using light wavelength shift for each sensor, or by sensing the time delay as light passes along the fiber through each sensor. Time delay can be determined using a device such as an optical time-domain reflectometer and wavelength shift can be calculated using an instrument implementing optical frequency domain reflectometry.

Fiber optic sensors are also immune to electromagnetic interference, and do not conduct electricity so they can be used in places where there is high voltage electricity or flammable material such as jet fuel. Fiber optic sensors can be designed to withstand high temperatures as well.

Optical fiber sensors for the detection of polluting substances in water, soil, and air, such as the biological sensors, optimized for medicine applications, have attracted noticeable interest because they are directly related to the quality of human life. They have been investigated as key elements of environmental monitoring systems, with the aim of preventing environmental catastrophes, and also as novel techniques for medical diagnosis. In particular, optical fiber sensor systems can avoid the collection of samples to be investigated in appositely equipped laboratories. They provide means of overcoming the drawbacks exhibited by ex-situ techniques which are invasive, time consuming and expensive. In fact, optical fiber chemical/biological sensors, enable pollution detection and/or medical diagnostic monitoring via an in-situ and slightly invasive technique. Optical spectroscopy of water, atmosphere, soil or biological samples, is commonly performed in chemical laboratories and is based on Laser Induced Fluorescence (LIF) or Raman effects [3]. LIF or Raman equipment is generally expensive due to both the utilized light sources (and related optical components) and to the sophisticated processing electronics. In order to develop low-cost pollution and bio-medical monitoring, a promising approach concerns the optimization of microstructure optical fibres (MOFs) for sensing. In fact, in recent years, a number of sensors made of suitable MOFs have been theoretically and experimentally investigated for the measurement of a large variety of physical and chemical parameters [4–6]. Both conventional fiber optic and MOF sensors can be based on fiber gratings, interferometers, scattering/reflecting, Faraday rotation, fiber-optic gyroscopes, fluorescence, and luminescence.

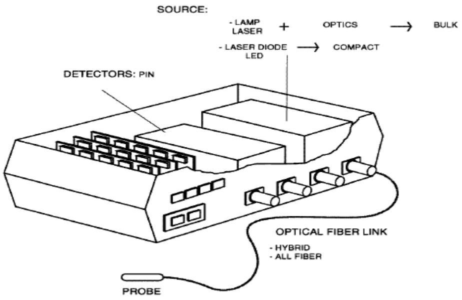


Figure 1. Sketch of the instrumentation of a fibre-optic sensor

The fibre optic sensor is well suited for this environment as it is functioning at temperatures too high for semiconductor sensors (Distributed Temperature Sensing). Another use of the optical fiber as a sensor is the optical gyroscope which is in use in the Boeing 767 and in some car models (for navigation purposes) and the use in Hydrogen microsensors. Fibers are widely used in illumination application optical fiber sensor systems are not available in a complete form, i.e., including both detecting and signal-processing electronics. However, their future is very promising because they exhibit well known advantages such as compactness, immunity to electromagnetic interference and to ionizing radiation (γ-ray, X-ray etc.), high sensitivity, large bandwidth, and minimum weight. These properties, make optical fiber sensors key photonic devices in radiative environments, like nuclear power plants, where the detection and evaluation of radiation levels and temperature changes are very important, especially in case of accidental constraints [1]. Optical fiber sensors have been developed to measure strain, temperature, pressure, current, voltage, gas, chemical contaminant, rotation, vibration, acceleration, bending, torsion, displacement, and biomolecules.

An optical fiber doped with certain rare-earth elements such as erbium can be used as the gain medium of a laser or optical amplifier. Rare-earth doped optical fibres can be used to provide signal amplification by splicing a short section of doped fibre into a regular (undoped) optical fiber line. The doped fiber is optically pumped with a second laser wavelength that is coupled into the line in addition to the signal wave. Both wavelengths of light are transmitted through the doped fiber, which transfers energy from the second pump wavelength to the signal wave. The process that causes the amplification is stimulated emission. Optical fibers doped with a wavelength shifter are used to collect scintillation light in physics experiments. Optical fiber can be used to supply a low level of power (around one watt) to electronics situated in a difficult electrical environment. Examples of this are electronics in high-powered antenna elements and measurement devices used in high voltage transmission equipment.

TYPES OF FIBER OPTIC SENSORS

Fiber optic stress sensors can be classified into two major categories: intension-metric and interfero-metric. An intension-metric sensor relies on variations of the radiant power transmitted through an optical fiber, whereas an interfero-metric sensor relies on measured induced phase change in light propagating through the optical fiber. External forces (such as compressive stress) can introduce small bends in an optical fiber which couples light out of the fiber, thereby varying the intensity of light transmitted through the fiber. A micro-bend sensor is a common intension-metric sensor. Two interfero-metric type sensors are Fabry-Perot and Bragg grating. The Fabry-Perot sensor consists of two mirrors placed in line with the optical fiber. Strain induced changes in the longitudinal mirror spacing produces a measurable phase change in the light frequency. Two samples of these

The Bragg grating sensor relies on the reflection of light from a region in the index of refraction of the optic fiber core. Longitudinal strain in the fiber changes the spacing of these periodic variations, thereby varying the wavelength of reflected light.

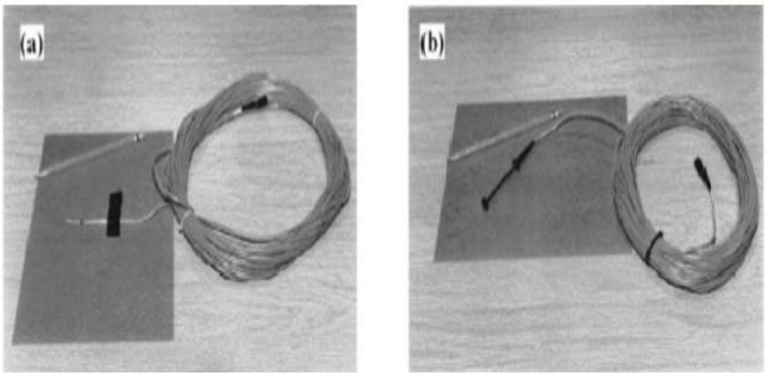


Figure 2. Two types of Fabry-perot fiber optic sensor.

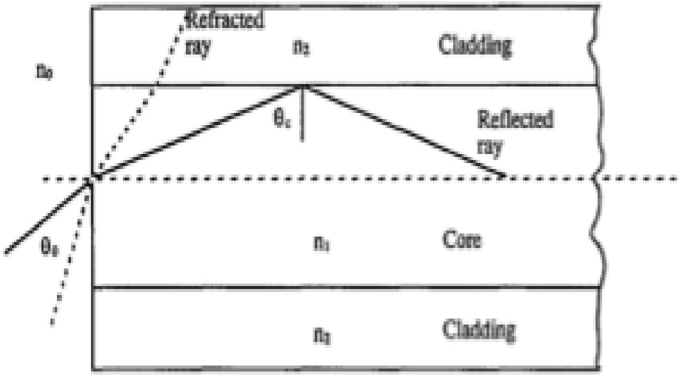


Figure 3. Basic geometry of optical fiber sensor

FIBER OPTIC BIOMEDICAL SENSOR

Optical fiber sensors comprise a light source, optical fiber, external transducer, andphotodetector. They sense by detecting the modulation of one or more of the properties of light that is guided inside the fiber—intensity, wavelength, or polarization, for instance. The modulation is produced in a direct and repeatable fashion by an external perturbation caused by the physical parameter to be measured. The measured of interest is inferred from changes detected in the light property. Fiber-optic sensors can be intrinsic or extrinsic (see Fig. 2). In an intrinsic sensor, the lightnever leaves the fiber and the parameter of interest affects a property of the light propagating through the fiber by acting directly on the fiber itself. In an extrinsic sensor, the perturbation acts on a transducer and the optical fiber simply transmits light to and from the sensing location. Many different fiber-optic sensing mechanisms have been demonstrating for industrial applications and some for biomedical applications among which are fiber Bragg gratings (FBG), Fabry-Perot cavities or external fiber Fabry-Perot interferometer (EFPI) sensors, evanescent wave, Sagnac interferometer, Mach-Zehnder interferometer, microbend, photoelastic, and others. By fur the most common, however, are based on EFPIs and FBGs. Spectroscopic sensors based on light absorption and fluorescence are also common. Biomedical FOS can be categorized into four main types: physical, imaging, chemical, and biological.

Physical sensors measure a variety of physiological parameters, like body temperature, blood pressure, and muscle displacement. Imaging sensors encompass both endoscopic devices for internal observation and imaging, as well as more advanced techniques such as optical coherence tomography (OCT) and photoacoustic imaging where internal scans and visualization can be made nonintrusively. Chemical sensors rely on fluorescence, spectroscopic, and indicator techniques to identify and measure the presence of particular chemical compounds and metabolic variables (such as pH, blood oxygen, or glucose level). They detect specific chemical species for diagnostic purposes, as well as monitor the body's chemical reactions and activity. Biological sensors tend to be more complex and rely on biologic recognition reactions—such as enzyme-substrate, antigen-antibody, or ligandreceptor—to identify and quantify specific biochemical molecules of interest.

In terms of sensor development, the basic imaging sensors are the most developed. Fiberoptic sensors for measurement of physical parameters are the next most prevalent, and the least developed area in terms of successful products is sensors for biochemical sensing, even though many FOS concepts have been demonstrated.

APPLICATIONS

(i) Endoscopic imaging - optics are well established, but the intrinsic physical characteristics of optical fibers also make them extremely attractive for biomedical sensing. Uncabled fibers (typically less than 250 μm diameter) can be inserted directly into hypodermic needles and catheters, so that their use can be both minimally invasive and highly localized—and fiber-optic sensors (FOS) made with them can perform remote multipoint and multiparameter sensing. Optical fibres are immune to electromagnetic interference (EMI), chemically inert, non-toxic, and intrinsically safe. Their use will not cause interference with the conventional electronics found in medical theatres. And, most importantly, the immunity of fibers to electromagnetic and radio frequency (RF) signals makes them ideal for real-time use during diagnostic imaging with MRI, CT, PET, or SPECT systems, as well as during thermal ablative treatments involving RF or microwave radiation.

(ii) Blood flow

Laser Doppler flowmetry is a powerful tool for vasomotion monitoring, and the use of optical fibres enhances the possibility of both invasive and contact measurements. The basic scheme of fibre-optical laser Doppler flowmetry is illustrated in figure 4. The light of a He–Ne laser is guided by an optical fibre probe to the tissue or vascular network being studied. The light is diffusely scattered and partially absorbed within the illuminated volume. Light hitting moving blood cells undergoes a slight Doppler shift. The blood flow rate is derived by the spectrum-analysis of the back-scattered signal, which presents a flow dependent Doppler-shifted frequency. Various types of probes have been developed, either using a single fibre for illumination and detection, or one fibre for illumination and two or three for detection [13]. An instrument that is widely used in the clinical practice is produced by the Swedish company Perimed (figure 4), which offers a wide selection of contact and endoscopic probes, with straight or angular tips, as well as with channels for liquid

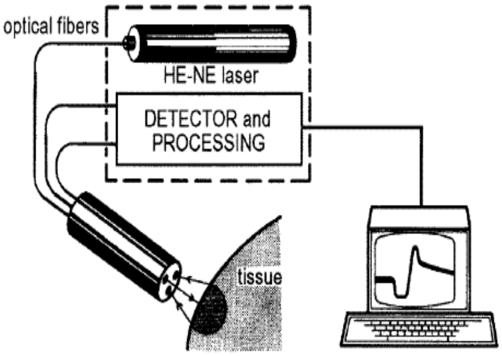


Figure 4. Basic scheme of fibre-optic laser Doppler flowmetry

(iii) Cataract onset

A major ophthalmological application of FOSs is the recognition of the onset of eye lens opacification, commonly known as cataracts. Since, in addition to ageing, cataracts can be caused by diseases such as hyperglycaemia or injury such as exposure to radiations, the early detection of a warning condition is essential in preventing and testing the new therapies that are now becoming available. As opposed to current clinical diagnostic methods, which only detect cataracts when they are nearly irreversible, fibre-optic monitoring makes detection possible at onset, in time for reversal. The eye lens is a water–protein system composed of water (≈ 65 weight percentage) and proteins (≈ 35 weight percentage). About 10% of the proteins, called the albuminoid fraction, are insoluble, while the remaining 90% of soluble proteins are divided into α, β, and γ crystallins. Cataract onset is attributed to crystallin aggregation and can be recognized by periodic measurement of the crystallin dimensions. A powerful and versatile tool for measuring particle size distribution in fluid systems is the Dynamic Light Scattering (DLS) technique. In this case, the Brownian motion of crystallins in the cytoplasm illuminated by a coherent light source produces temporal fluctuations in the scattered light. The measured intensity autocorrelation function shows an exponential decay, whose decay constant is related to the hydrodynamic radius of the scattering particles. Cataract onset is recognized by DLS measurement of the α-crystallin aggregation, since the α-crystallins are of greater molecular weight and size, and thus scatter.

more light than the β- and γ-crystallins. The non-invasive optical fibre probe is a stainless steel capillary (OD ≈ 5 mm) ending in a face plate which houses two monomode fibres sloped at a fixed angle with respect to the capillary axis (figure 5). One of the fibres is coupled to a He–Ne laser used for illuminating the scattering region inside the eye lens. The other collects the backward scattered light, which is measured by a photomultiplier and processed by a digital correlator. Intensity autocorrelation measurements show a nearly bimodal distribution of particle size, respectively corresponding to α-crystallins and their aggregation. The probe can be easily incorporated into conventional ophthalmological instruments such as an applanation tonometer mount [9-11].

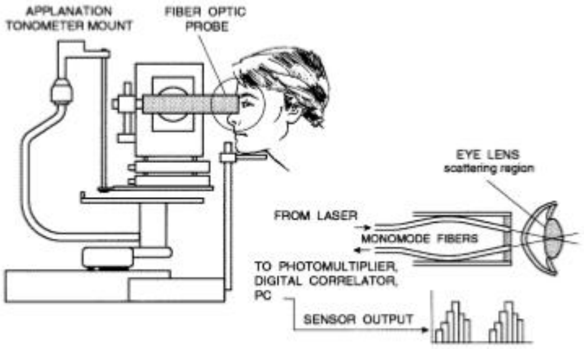


Figure 5. Assembly for cataract onset monitoring by optical fibres and Dynamic Light Scattering measurements.

In addition to allowing prompt, non-invasive monitoring of cataract onset, optical fibres also enhance the efficiency of the DLS technique. By providing a beam of small numerical aperture and dimensions, monomode fibres are able to produce an extremely small angle of coherence, and hence an optimal spatial coherence factor (≈ 0.9), which would be difficult to obtain with bulk optics systems [11].

(iv). Radiation dose

The success of radiotherapy is related to the on-line monitoring of the dose to which the tumour and the adjacent tissues are exposed. Conventional thermoluminescence dosimeters only provide off-line monitoring, since they determine the radiation exposure after completing irradiation. A short length of heavy metal-doped optical fibre coupled to a radiation resistant fibre is an optimal system for the continuous monitoring of radiation dosage in both invasive and non-invasive applications. The light propagating in the doped fibre section undergoes intensity attenuation in the presence of radiation, since the attenuation is nearly linear to the radiation dose. Differential attenuation measurement compensates for insensitivity due to cable and connector losses [12].

flushing [13]. Typical applications are in: (i) plastic and reconstructive surgery for monitoring flap quality; (ii) angiology for locating atherosclerosis and occlusions; (iii) dermatology for testing several types of skin irritancies such as psoriasis, or produced by topical drugs or cosmetics; (iv) pharmacology for detecting vasoactive drugs and dose response. Endoscopic and needle probes are used for invasive and deep measurements, for example in gastroenterology and in vascular surgery, respectively.

(v) Radiation ear thermometer

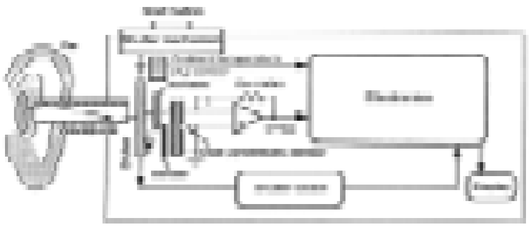


Figure 6. Radiation ear thermometer function.

This version is based on a pyroelectric sensor. Thermal radiation flux from the auditory canal is channelled by the optical waveguide toward the pyroelectric sensor. When pressing the start button, the shutter opens momentarily, exposing the sensor to thermal radiation and replacing the radiation coming from the shutter itself. An ambient temperature sensor element is behind the shutter. The radiation reaches the sensor where it is converted into electric current impulse due to the pyroelectric effect

(vi) Skin blood flow sensor

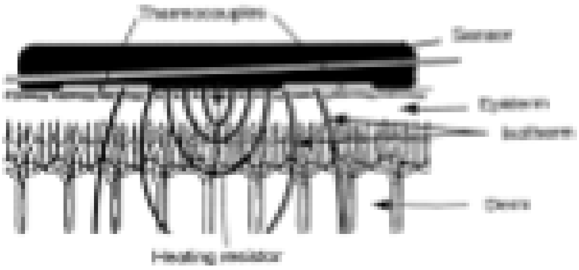
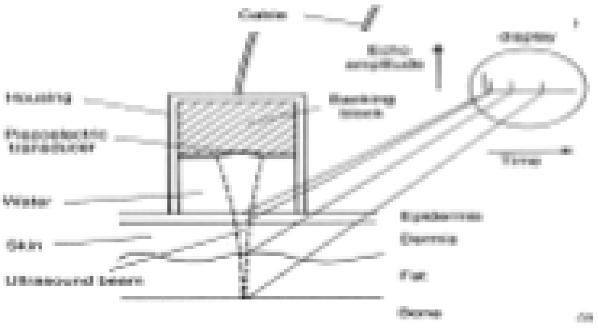


Figure7. A Thermal Conductivity Sensor for the Measurement of Skin Blood Flow

Skin blood flow (SBF) or skin perfusion is a complex phenomenon that occurs in capillaries. In perfused tissue, thermal conductivity depends not only on the thermal conductivity of the tissue materials, but also on the heat convection transferred by the blood flow in capillaries. Thus, thermal conductivity of the skin can vary within a wide range; its minimum value, 2.5 mW/cm°C

(vii) Sensor in ultrasound imaging



The first and simplest ultrasound imaging systems applied the A-mode (amplitude modulation) imaging illustrated in Figure.

LATEST PRODUCT DEVELOPMENTS AND FUTURE SCOPE

One of the early pioneers of fiber-optic biomedical sensors, Camino Labs (San Diego, CA), in 1984 introduced into the medical market an intracranial pressure (ICP) sensor that has since become one of the most commonly used ICP monitoring systems in the world. The device is based on an intensity modulating fiber-optic scheme relying on a miniature bellows as the transducer.

Other sensor pioneers are Lextron (Santa Clara, CA; now part of LumaSense) with its fluoroptic temperature sensor, and FISO (Quebec City, QC, Canada) which has positioned itself as a leading supplier of medical fiber-optic pressure and temperature sensors[13]. FISO's sensors are based on EFPI devices interrogated with white light interferometry. Among a new generation of companies are Opsens, Neoptix (both in Quebec City, QC, Canada), and Samba Sensors (Västra Frölunda, Sweden). By far, the most common medical FOS on the market are temperature and pressure monitors, but a handful of other diverse sensors an instruments does exist (see Table). As costs fall and new sensing techniques are developed, it's likely that the number and diversity of biomedical FOS will increase.

Figure 8. A fiber-optic intra-aortic force sensing catheter probe enables real-time monitoring of the force exerted against the heart wall by the catheter. (Courtesy of EndoSense)

REFERENCE

[1] Lee, B. Review of the present status of optical fiber sensors. Opt. Fiber Technol. 2003, 9, 57–79.

[2] Cordeiro, C.M.B.; Franco, M.A.R.; Chesini, G.; Barretto, E.C.S.; Lwin, R.; Cruz, C.H.B.; Large, M.C.J. Microstructured-core optical fibre for evanescent sensing applications. Opt. Express 2006, 14, 13056–13066

[3] B. Culshaw and J. Dakin, Eds, Optical Fiber Sensors: Systems and Applications, Vol. II, Artech House (1989)

[4]
A.G. Mignani and F. Baldini, "Biomedical sensors using optical fibres," Rep. Prog. Phys., 59, 1-28 (1996

[5] Gehrich J L, Lubbers D W, Opitz N, Hansmann D R, Miller W,Tusa K and Yafuso M 1986 Optical fluorescence and its application to an intravascular blood gas monitoring system IEEE Trans. Biomed. Eng. BE-33 117–32

[6] Walt D R and Bronk K S 1992 Spatially resolved photo-polymerized image-ready single fiber sensor for blood gas analysis Proc. SPIE Fiber Optic Medical and Fluorescent Sensors and Applications 1648 12–14

[7] Mordon S, Maunoury V, Devoisselle J M, Abbas Y and Coustaud D 1992 Study of normal/tumorous tissue fluorescence using a pH-dependent fluorescent probe in vivo Proc. SPIE Fiber Optic Medical and Fluorescent Sensors and Applications 1648 181–91

[8] Dhadwal H S, Ansari R R and Dell Vecchia M A 1993 Coherent fiber optic sensor for early detection of cataractogenesis in a human eye lens Opt. Eng. 32 233–7

[9] Ansari R R, Dhadwal H S, Cheung H M and Meyer W V 1993 Microemulsion characterization by the use of a noninvasive backscatter fiber optic probe Appl. Opt. 32 3822–7

[10] Hamano K, Kuwahara N, Chin B and Kubota K 1991 Dynamic light scattering measurement for a salt-induced cataract in the eye lens of a chicken Phys. Rev. A 43 1054–60

[11] Wickersheim K A and Sun M H 1987 Fiberoptic thermometry and its applications J. Microwave Power pp 85–94

[12] Takeo T and Hattori H 1991 Application of a fiber optic refractometer for monitoring skin condition Proc. SPIE Chemical, Biochemical, and Environmental Fiber Sensors III 1587 284–7

[13] E. Pinet and C. Hamel, "True challenges of disposable optical fiber sensors for clinical environment," Third European Workshop on Optical Fibre Sensors, EWOFS 2007, Naples, Italy.