# Advances in All-Optical Sensors for Biomedical Monitoring

*(Invited Paper)*

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***Abstract*— Advancements in optical technology have led to the development of a number of different sensor systems suitable for use in the biomedical industry, such as cardiovascular system monitors, lung/bladder pressure sensors and radiation dosimeters. Recent efforts in the Optical Fibre Sensors Research Centre at the University of Limerick have seen the application of all-optical sensors to these areas. This paper gives an overview to these activities and highlights the unique advantages optical sensors bring to this arena.**

## I. INTRODUCTION

The inherent properties of optical technology afford sensors, based on such technology, a number of advantages over conventional sensing techniques, such as semiconductor and electrochemical sensors. Recent advancement in optical sensing technology has led to the development of a number of novel sensors with applications specific to the biomedical industry. Non-invasive monitoring techniques are made possible by the penetrating characteristics of an optical signal, whereby the attenuation of light travelling through a patient's tissue, for example their finger or ear, can provide much information about the patient's well-being. Such non-invasive techniques are important for allowing continuous, real-time monitoring of the patient and reducing the risk of infection brought about by invasive procedures. Where invasive procedures are inevitable, for example in monitoring lung cavity and bladder pressures, optical fibres can provide a significant advantage over other sensing technologies by being small, light-weight and biocompatible. Additionally, the immunity of optical fibres to electromagnetic interferences makes optical fibres suitable for monitoring harsh environments, such as areas of high radiation. Optical fibres are shown to be capable of monitoring a wide range of ionizing radiation doses, indicating their suitability for monitoring both high dose gamma radiation in sterilization process of medical supplies and low dose x-ray used in radiation therapy.

This paper presents a number of different optical sensors developed by the Optical Fibre Sensors Research Centre at the University of Limerick, Ireland, that are suitable for use in biomedical applications.

## II. OPTICAL SYSTEM FOR NON-INVASIVE HAEMODYNAMIC MONITORING

The penetrating properties of light allow for non-invasive sensing technology, such as those used for monitoring haemoglobin levels and oxygen saturation. Non-invasive and continuous accurate monitoring of a patient's cardiovascular system can help to ensure the early detection of potential abnormalities and trigger a prompt haemodynamic assessment. A newly developed optical system is able to measure the standard pulse oximeter parameters: SpO2, HR and perfusion index (PI), in addition to other valuable parameters such as the total haemoglobin concentration, stroke volume variations (SVV) and pulse dicrotic transit time (PDTT), giving a more detailed overview of the patient's cardiovascular system [1].

The optical transmission of light in the red and near infrared region differs considerably between blood containing oxygenated haemoglobin (HbO2) or reduced haemoglobin (HHb). This forms the basis of the measurement technique, allowing for the differentiation between a number of different parameters in monitoring a patient's cardiovascular system.

The optical system is integrated into a finger clip, similar to that used in standard pulse-oxymetry measurements, shown in figure 1. Three LEDs are used and installed on the upper part of the finger clip. Two of the LEDs emit light in the wavelength range from 600nm to 1000nm, the so-called therapeutic window region, in which the blood absorption is dominated by the haemoglobin derivatives. The third LED emits light at 1300nm, where absorption of water is dominant. The light source intensity is controlled by time multiplexing the LED sources. An Indium Gallium Arsenide/Indium-Phosphor photodiode, with a spectral range of 400nm-1700nm, is used to detect the transmission of the optical signals [1].

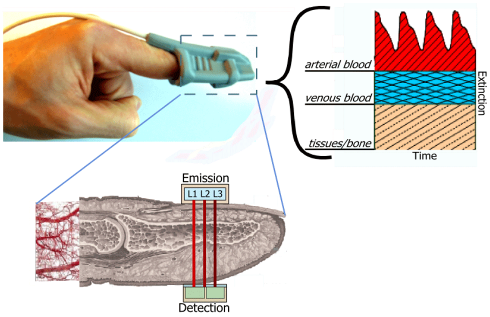

Figure 1. Human fingertip and measuring principle of the pulseoximetry based upon transmission/ reflection of the light on the sensor site.

A calibration curve was obtained by comparing 45 male and female blood probes using an invasive haemoglobin tester HemoCue[R] with the non-invasive results obtained using the

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optical sensor outlined above. A follow-up study monitored the haemoglobin levels of eleven male and nine female test persons. The test subjects' haemoglobin levels were non-invasively measured over time, for approximately 3 minutes, and an average obtained. This value was then compared with the invasive probe measured using the HemoCue. The result of the measurement is show in figure 2 [1].

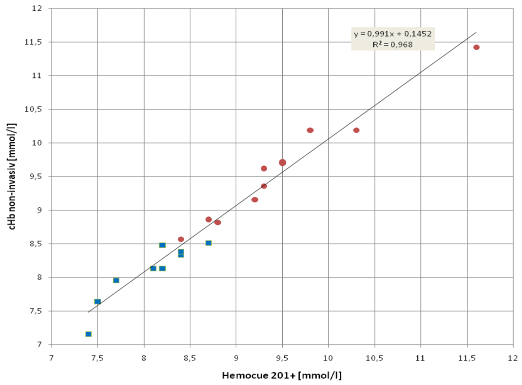

Figure 2. Comparison of non-invasive haemoglobin method vs. invasive Hemocue

Over the complete sample range, from 7mmol/l to 11.5mmol/l, a uniform distribution inside the confidence interval of 95% can be observed. The accuracy of these measurements indicates the suitability of this sensor system for a clinical application. Further results of this developed sensor, including monitoring Heart Beat Volume (HBV) and a complete analysis of photoplethysmograph- (PPG-) pulses as clinical diagnostic parameters in dialysis and ICU patients, is reported by Timm et al [1].

## III. OPTICAL FIBRE PRESSURE SENSOR FOR MONITORING LUNG AND BLADDER PRESSURE

The small, lightweight properties of optical fibre sensors, together with their remote monitoring capabilities, make them ideal for in-situ monitoring, for example monitoring lung and bladder pressures. An all-silica based pressure sensor has been developed, consisting of a silica glass diaphragm, a 133/220µm inner/outer diameter silica glass capillary and a Single Mode (SM) fibre [2]. The bio-compatible nature of silica makes this sensor highly suitable for in-situ patient monitoring.

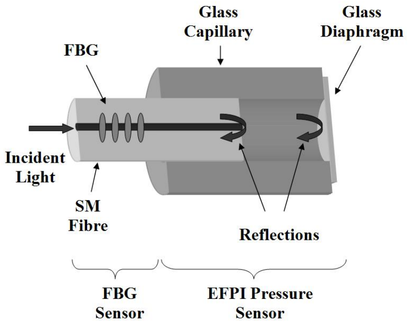

Figure 3. Concept of FBG/EFPI hybrid sensor

The novel technique is based on a fibre optic pressure and temperature hybrid sensor, and a tuneable laser source. The fibre optic hybrid sensor, shown in figure 3, consists of a miniature diaphragm based all-silica Extrinsic Fabry-Perot Interferometric (EFPI) Fibre Optic Pressure Sensor (FOPS) which additionally incorporates a Fibre Bragg Grating (FBG) temperature sensor.

Results, shown in figure 4 and figure 5, indicate the sensors response to temperature and pressure [2]. The FBG is not sensitive to pressure changes and so only the EFPI response to pressure, which exhibits a linear characteristic, is demonstrated. However, it is clear from figure 5 that the EFPI is also sensitive to temperature. To ensure accurate pressure reading this temperature sensitivity must be compensated for. The sensor's integrated FBG also shows linear temperature sensitivity, which can thus be used to ensure the sensor's pressure measurements are independent of temperature. Further results on the development of this all-silica pressure sensor are reported by Bremer et al [2, 3].

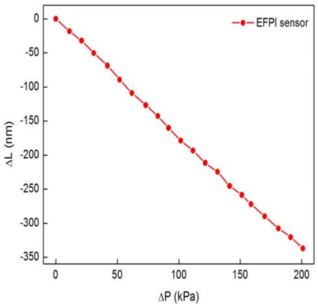

Figure 4. Pressure response of FBG/EFPI hybrid sensor

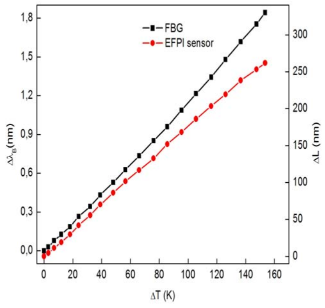

Figure 5. Temperature response of FBG/EFPI hybrid sensor

## IV. OPTICAL FIBRE RADIATION DOSIMETRY FOR BIOMEDICAL APPLICATIONS

Of particular importance to biomedical monitoring is the advancement of optical fibre technology in sensor development. In addition to the typical advantages of optical sensors, optical fibres also allow for remote sensing, whereby the sensor can be placed several hundred metres from the control electronics. This means that they can be employed in harsh environments, such as a radiation facility, to be monitored online, in real-time, from a control room. The ability to monitor ionising radiation doses is of particular importance within the medical industry, both for radiotherapy, in beam characterisation and patient dose verification, and also for the sterilisation of medical products. Radiation dosimetry, using plastic optical fibres, is shown to be effective in monitoring a wide range of ionising radiation doses suitable for use in both low dose radiotherapy applications and for monitoring high doses within the sterilisation industry.

### *A. Radiation dosimetry for high-dose monitoring of the sterilisation of biomedical products*

The ability of ionising radiation to kill pathogenic micro-organisms is the basis on which the sterilisation of medical products depends and is used for sterilising a wide variety of products such as hypodermic needles, blood handling equipment, surgical gloves and utensils, catheters. The exact dose of gamma radiation used in the sterilisation of medical products varies for different countries but is usually between 25 kGy and 35 kGy [4].

The sensing technique is based on the same principle used in the commercially employed dosimetry systems of dyed PMMA slabs. The ionising radiation causes attenuation in the optical signal that is directly related to the radiation dose received, known as the Radiation-Induced Attenuation (RIA). By monitoring the transmission through the optical fibre during irradiation the RIA, and thus the radiation dose, can be determined.

Radiation measurements were performed at the Isotron gamma radiation facility in County Mayo, Ireland. A 7m length of PMMA based optical fibre was placed in the irradiation chamber, where it was irradiated by the $^{60}$Co source, at a dose rate of 25kGy/hr. Two 50m length of fibre, allowed for remote monitoring of the optical signal though the irradiated fibre online and in real-time. The PMMA based plastic optical fibres (POF) used were supplied by Fibre Data and consisted of a 1mm PMMA core, fluorinated PMMA cladding and polyethylene jacket, ($n_{core}$ ~ 1.49, attenuation ~ 0.15 dB/m), terminated with SMA connectors [5].

The optical signal is monitored in the visible region between 500nm and 700nm, where transmission through PMMA POF is greatest. The sensitivity of the PMMA fibre to ionising radiation is directly related to the wavelength and thus by selecting the correct wavelength the fibre can be used to monitor over a wide dose range, selecting 525nm for low doses with high sensitivity and selecting 650nm for high doses with lower sensitivity, as outlined in figure 6. This work is further reported by O'Keeffe et al [5, 6].

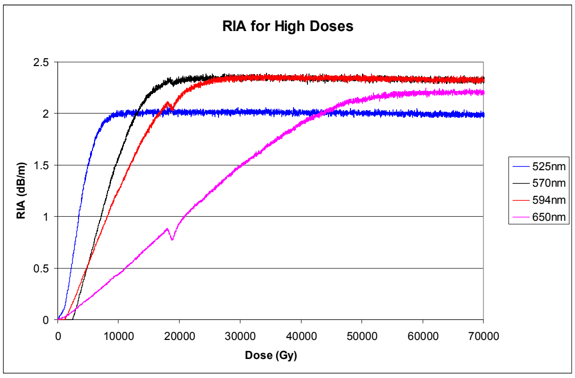

Figure 6. RIA for high doses of gamma radiation.

### B. *Radiation dosimetry for low-dose radiotherapy applications*

Using the same technique outlined above for monitoring high doses of gamma radiation, initial tests were carried out at the MD Anderson Cancer Centre in Orlando, Florida, to determine the sensitivity of PMMA optical fibres at low radiation doses [7]. It was concluded that although a measurable attenuation was observed in the PMMA fibres, the sensitivity is insufficient for low dose applications, such as radiotherapy, where the total dose received during a radiotherapy session is typically 2Gy. By coating the fibres with a radiation sensitive scintillation material it is possible to improve the sensitivity of the PMMA optical fibre sensor. The optical fibres are coated with a phosphor scintillation material that fluoresces when subjected to ionising radiation. The emitted fluorescent light travels along the optical fibre to the spectrometer where the intensity of the peak wavelength can be monitored [8].

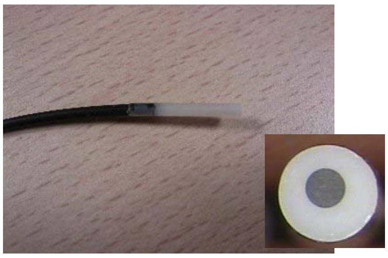

Figure 7. PMMA optical fibre sensor with a cross section view insert revealing uniform coating of phosphor and epxoy mix over the fibre cable.

## V. CONCLUSIONS

This paper presents a number of different optical sensors suitable for use within the biomedical field. It is clear that optical technology offers many advantages to the biomedical industry by providing non- and minimally- invasive patient monitoring solutions. Such solutions are important for allowing continuous real-time monitoring of parameters in a safe and non-intrusive manner, increasing patient's comfort and reducing their risk to infection. Optical fibres offer additional advantages by allowing for remote monitoring, either internal to the patient, e.g. lung cavity and bladder, or in areas of harsh environments, e.g. areas of high ionizing radiation.

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