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Original Research

Optical Fiber Sensors for Biomedical Applications of Optical Fibers, Fiber Sensors, Impact of Light and Healthcare Industry Trends

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Abstract

The global recognition of optical fibers as medical sensors is now widespread. The most prominent characteristics are immunity to electromagnetic interference and compact size. Fiber optic sensors offer significant benefits in settings characterized by elevated temperatures, corrosive or explosive substances, intense electromagnetic fields (such as MRI), or ionizing radiation. The inherent galvanic isolation also provides advantages in terms of electrical safety, as mandated by IEC 60601. Implementing fiber optic sensor technology in practice, however, is not straightforward. Applications of Polymer Optical Fiber Sensors in Healthcare This section illustrates the healthcare applications of the sensor system, considering the current context, trends in healthcare, and advancements in POF sensing technology. The applications are categorized into five distinct groups, wherein the wearable robots (exoskeletons, prosthesis, and orthosis) are equipped with various techniques of POF sensors. Next, we go into the implementation of POF sensors in various healthcare devices. The gadgets in question are a software and a system designed to aid in walking by utilizing functional electrical stimulation (FES). These devices can be classified as either non-robotic, like the FES-assisted gait, or non-wearable, like the SWs. Subsequently, the text illustrates the applications of movement analysis, focusing on the utilization and discussion of numerous wearable sensors that employ POFs. Instrumented insoles and intelligent carpets are considered as a viable method to monitor plantar pressure during activities such as walking or other movements, providing an alternative strategy for assessing human activity. Lastly, the presentation focuses on the monitoring of physiological indicators utilizing POF sensors. Although numerous systems designed for this aim are not now wearable, it is crucial to examine their various uses and potential for advancement in order to develop wearable systems capable of assessing multiple physiological parameters. For reusable instruments, such as those commonly used in minimally invasive surgery, it is essential to ensure their durability and performance across multiple cleaning and sterilizing cycles. This necessitates meticulous consideration for numerous pragmatic aspects of the architecture of the sensor head. The forthcoming design considerations will be examined, exemplified by a force sensor devised for a haptic instrument.

Key words: Optical Fiber, Medical Applications, Sensors

Introduction:

The revelation that light may be transmitted through pliable glass fibers has greatly aided the development of numerous advanced medical devices. Endoscopes were a sensible and productive initial application [1]. However, fiber optics (FO) offer a wide range of possibilities that extend beyond what has been mentioned. The Fiber Bragg Gratings were initially developed as a strain monitoring sensor, but they have since been utilized to measure a diverse array of physical properties. Fiber interferometry allows for the precise measurement of nanometer-scale changes in hard-to-access areas. When implemented in a sensor, this has resulted in the development of compact pressure and temperature sensors. Fiber-optic spectroscopy allows for the visualization of individual cells within the human body. During endoscopic instrumentation, a fiber optic force sensor can be utilized to detect the clamping force during the process of electrosurgery. These are a few significant fiber optic techniques employed in medical applications. However, it is crucial to note that the provided overview is not exhaustive [2]. In order to develop an applied medical sensor, one must possess expertise in both sensor design and optical principles, as well as a thorough understanding of the specific medical application [3].

Medical applications:

One may observe a meteoric rise in the number of patents for fiber optic sensors used in medical applications over the past eight years by looking at the data. In both invasive and noninvasive applications, FO sensors are utilized. Because of their non-galvanic nature and their diminutive size, they can easily be inserted into human cavities. Additionally, they are not electrically conductive [4]. In addition to this, FO sensors are not affected by electromagnetic disturbances that can be caused by electrical equipment (such as electrosurgery, wireless communication, or MRI). The many applications of FO sensors can be categorized according to the numerous fields of application, such as in-vitro (for the examination of gases, body fluids, or tissue samples), for example. In-vivo, using non-invasive techniques (such as optrodes put on the skin), for example. In vivo, using invasive methods (such as catheters or other endoscopic instruments). In hostile situations where it is impractical to use electronics, such as an MRI scanner. It is anticipated that about 200 new patents are issued annually for the use of fiber optics in the analysis of blood and tissue. When compared to the number filed in the year 2000, it is clear that the number of patents requested each year has more than doubled [5]. This could be interpreted as a sign that a new generation of sensing medical tools is on the horizon. Measurement of the concentration of oxygen, partial pressure of carbon dioxide, and pH are examples of typical applications of invasive blood and tissue analysis.

Liquid crystal optical fiber sensor:

Common types of gaseous contaminants in the air include volatile organic compounds, sometimes known as VOCs. Organic synthesis utilizes a variety of basic materials, including acetone and tetrahydrofuran (THF), both of which are relatively important organic solvents. In addition to this, they are the primary chemical components that are present in the pharmaceutical waste liquid and are notoriously challenging to separate and recover at normal pressure [6]. For the purpose of dissolving drug molecules, the pharmaceutical industry makes use of a mixture of acetone and tetrahydrofuran. Separating and purifying this mixture [7] presents a number of challenges, one of which is the problem of solvent volatilization. For this reason, sensors that can monitor the quantity of volatile organic compound gases in chemical and pharmaceutical applications in real time are desirable. It has been suggested that some technologies, such as gas chromatography-mass spectrometry (GC-MS), resistive-based gas sensors, and ion mobility spectrometry could be utilized to detect volatile organic compound (VOC) gases [8].

Although these techniques offer a high sensitivity and accuracy for the detection of volatile organic compound (VOC) gas, they do have certain drawbacks, such as the need for expensive and enormous facilities, as well as complicated experimental preparations and difficulty in performing real-time VOC detection. Consequently, optical fiber sensors offer the advantages of low cost, fast reaction, and ultra-compactness in the process of detecting volatile organic compound gas [9].

Liquid crystals, often known as LCs, are pliable substances that may react speedily to various stimuli from the outside world. The effects of the surrounding environment and substances, such as biological cell detection [10] electric field polarization imaging and volatile gas detection , can have an effect on the properties of LC, causing such properties to alter. In addition, LC is temperature sensitive, which is why it is frequently employed in the construction of temperature sensors. Cholesteric liquid crystal, often known as CLC, is distinguished by its self-assembled spiral structure and its selective reflection capabilities.

The activity of chiral molecules [11] causes rod-shaped LC molecules to self-assemble into a helical structure. The distance along the helical axis reaches a pitch as the LC directors rotate two degrees counterclockwise. The variations in wavelength caused by the change in pitch are caused by the CLC selective reflection. It is only possible to do a qualitative analysis of the gas concentration using numerous CLC-based VOC gas sensors [12], which are based on reflecting color changes of CLC films. These gas sensors are not very effective when utilized in real situations, and their ability to detect volatile organic compounds (VOC) is also impacted by temperature. The optical fiber, which acts as a carrier for liquid crystal, is not only compact in size but also has the ability to monitor the gas concentration from a great distance. This has the potential to significantly lessen the negative effects on the human body.

Typical Medical applications of Optical fiber Temperature sensors:

The development of localized and controlled hyperthermia, also known as raised temperatures in the range of 42 - 45 °C or higher, for the purpose of treating cancer with electromagnetic energy, either the Radio frequency (RF), or Microwave frequency range, provides a challenging problem with regards to temperature measurement. Traditional temperature sensors, such as thermistors and thermocouples, feature metallic components and connecting wires. These components and cables produce disturbances in the incident electromagnet (EM) fields, which can lead to localized hot areas and unpredictable temperature readings owing to interference [13]. The utilization of temperature sensors that are based on fiber optics provides an efficient solution to this issue. These optical fiber devices make use of changes in the transmission characteristics of the optical fibers that are caused from the outside and give the benefits that are typical of optical fibers, such as flexibility, small size, and immunity to electromagnetic interference.

Pressure Sensors:

Utilizing fiber optic sensors allows for accurate measurement of both the pressure within the intracranial and intracardiac spaces. The gadget is based on a pressure balancing system, which allows for accurate measurement of intracranial pressure. In this situation, monitoring the static pressure will involve using a sensor that is based on the deflection of a cantilever mirror that is attached to a membrane [14]. Because of the deflection of the membrane, the light that is emitted from the central optical fiber is reflected in a manner that is not uniformly directed towards either of the two collecting fibers that are situated on either side of the control fiber.

The ratio of the light gathered by two separate fibers is measured, and then adequate feedback air pressure is provided to the interior of the probe through the pneumatic connecting tube. This balances the membrane to its null state and provides a readout of the pressure that is being used to balance it. This similar idea can also be employed for the monitoring of intravascular pressure, although the design will need to be modified slightly.

Photometric Sensors:

The operation of optical fiber photometric sensors is based on the light that is scattered or fluoresced back into the fiber after it has emitted from a fiber end. This allows for the measurement of the returning light as an indication of the optical absorption or fluorescence of the volume at the fiber tip. A photodetector is used to detect any deviations in the amount of light that is reflected back. These sensors keep an eye on how the amplitude and frequency of the reflected light change over time. Some examples of the photometric sensors' applications in medicine include the following: Measurement of amplitude is important to the operation of the oximeter [15], which derives its readings from this parameter. Because haemoglobin and Oxyhaemoglobin have distinct absorption spectra, this device is able to determine the extent to which oxygen is present in the blood. In the field of blood flow monitoring, a technique known as dye densitometry can also be classified as a photometric optical fiber sensor. During this procedure, a dye known as indocyanine green is injected into the blood, and the blood's concentration is determined by measuring the dye's level of absorption at a certain wavelength.

After that, the time fluctuation of the dye concentration is used in conjunction with dilution procedures to compute the cardiac output. When measuring blood flow with the Doppler frequency shift method [16], it is also possible to use a fiber-optic light guide to direct light from a laser onto the surface of the skin. We are able to obtain information regarding the blood flow thanks to the Doppler frequency shift.

Chemical Sensors:

The interaction of chemical species with light is the fundamental principle behind optical detection of chemical species. When light touches a substance, a number of interactions between the photons of electromagnetic radiation and the molecules of the substance can take place. These interactions can range from simple to complex. These interactions involve the transfer of energy and may result in the light being absorbed, transmitted, emitted, scattered [17], or reflected depending on the specific circumstances. The quantized character of this energy transfer results in the production of significant data regarding the make-up of the system, which is the fundamental principle behind the spectroscopic method of conducting chemical analysis.

Types of optical fiber sensors used in chemical measurement:

Chemical sensors are implemented here by interfacing a chemical transduction system with the optical fiber at the fiber's terminus. During operation, the interaction with the analyte causes a change in the optical characteristics of the reagent phase. This change is then probed and detected through the use of the fiber optic. Absorbance, reflectance, or luminescence are all possible choices for the optical quality that is measured. In this particular use of spectroscopy, the optical fiber serves merely as a light guide, transporting light from the source to the sampling area and then from the sample to the detector. The species that are being felt are affected by the light's presence.

Advantages of Optical Fiber Sensors as Applied in Medicine:

Because the sensors do not require any kind of electrical connection to the patient's body, the patient's safety is not compromised in any way. They are not electrical, thus there is no chance of electrical interference caused by them. Through the utilization of several probe detection wavelengths [18], a single sensor is capable of measuring more than one chemical species at the same time. In comparison to several other sensors, this one offers a significant cost savings. Fiber optics are characterized by a great degree of mechanical flexibility; this, in conjunction with their diminutive size, makes it possible to access parts of the body that would otherwise be inaccessible.

Polymer Optical Fiber Sensors in Healthcare:

Optical fiber sensors are an emerging sensor technology that possesses the inherent benefits of being lightweight, small, chemically stable, immune to electromagnetic fields, and capable of multiplexing. As a result of these benefits, optical fiber sensors are an inherently secure technology that may be applied in industrial, medical [19] and structural health monitoring settings. In addition, optical fiber sensors are utilized in the process of measuring a variety of characteristics, including angles, refractive indices temperatures, humidity, acceleration, pressure [10, breathing rates, and oxygen saturation. Optical fibers can also be embedded in textiles for use in sensing applications, Additionally, optical fibers can be used to create optical fiber-based textiles, also known as photonics textiles. Optical fibers can also be integrated onto composite laminates, metals through the welding process, concrete, and even in three-dimensional (3D)-printed structures [20]. Alongside the development of optical fiber sensors has come an accompanying rise in demand for medical technology, which is mainly attributable to a rising average age of the world's population.

Additionally, developments in electronics, the processing of materials, and the transmission of data have led to the creation of a new generation of robotic devices, wearable sensors [20], and cloud services for healthcare [21]. More stringent requirements are being placed on the performance of the sensors as novel healthcare devices and applications are being developed. This is because robust control strategies for wearable robots require a dependable sensor system. In addition, because the components are becoming increasingly miniaturized, the sensor system needs to be as adaptable and condensed as is humanly possible.

When it comes to invasive sensor systems, the requirements are considerably more stringent because the sensor system needs to fulfill all of the prerequisites listed above in addition to being biocompatible. As a result, the development of sensor systems is ongoing in order to keep up with the required performance of novel wearable systems and gadgets. Conventionally, sensor systems make use of electronic or electromechanical sensors. These types of sensors, however, can have a number of drawbacks, including sensitivity to misalignments, sensitivity to electromagnetic fields (which is undesirable when electric actuators are activated in wearable robots), lower compactness, the necessity of frequent calibration, and, in some cases, hysteresis and drift on the sensor response.

When it comes to soft wearable robotics, the drawbacks associated with electrical sensors are especially problematic. In this scenario, the composition of the robotic structure and actuators includes flexible materials in order to obtain lesser weight and higher compliance with the user. As a result, unique customized actuators and robots have been developed. There is also the option of designing a robot with geometries and actuators that are especially intended for a particular user in a process known as human-in-the-loop design. When taking into consideration the architectures of soft robots, the sensors are continually subjected to large stresses or deflections of the structure. This can prevent the application of the majority of traditional sensors [22], as only flexible electronic sensors would be able to function in such situations. Nevertheless, the production processes for such sensors are typically somewhat involved.

Viscoelasticity in Polymer Optical Fibers:

It is essential to recognize that the features of the POF material serve two distinct functions simultaneously. Sensors manufactured from polymer organic frameworks (POFs) have a lower Young's modulus and greater strain limits when contrasted with sensors made from silica fibers. Because of this, it is now possible to build sensors that have a far higher sensitivity and a greater dynamic range. On the other hand, polymers are instances of viscoelastic materials, meaning that they do not demonstrate a relation that is constant with stress or strain. In addition to this, viscoelastic materials have a hysteretic response between stress and strain, and it is possible that this phenomenon is the source of hysteresis and nonlinearities in POF sensors.

In addition, viscoelastic materials display a change in their Young's modulus in reaction to other parameters such as strain cycle frequency, temperature, and relative humidity [23]. This change can be attributed to the fact that viscoelastic materials are sensitive to these factors. In spite of the fact that all of these parameters are fixed, this is nonetheless the case. Therefore, it is necessary to understand and characterize the POF viscoelastic response in order to propose a compensation of the viscoelastic effects and obtain a more reliable measurement of any POF sensor that is based on direct stress or strain on the fiber (such as curvature sensor, strain sensor, and force sensor, sensors). This is necessary prior to their applications in healthcare devices and movement analysis.

Conclusions:

Fiber optics offer a unique combination of characteristics that can be extremely beneficial for a wide range of medical applications. Fibers are utilized for the transportation of sensor signals because of their immunity to electromagnetic interference (EMI), in addition to their employment in the transportation of an image or spectral information. In (endo) electro-surgery, electromagnetic interference (EMI) presents a significant challenge when attempting to implement small electronic sensors for the measurement of physiological and tactile data. The electromagnetic immunity requirements must be met, and even higher standards must be met, for MRI compatibility. FO sensors are not susceptible to this, and as a result, they provide for an interesting addition to galvanic sensors.

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