MR-Compatible Optical Fiber-Based Sensors for Medical Applications

Monalisha Hati, Assistant Professor

Department of Computer Science, Arka Jain University, Jamshedpur, Jharkhand, India

Email Id- monalisa.hati@arkajainuniversity.ac.in

ABSTRACT: Due to a rising need for applications in medicine, Magnetic Resonance (MR)—compatible sensors based on various methods have been developed during the past several decades. There are a number of technical options for creating MR-compatible sensors, but the one based on optical fibers has a number of advantages. The high elasticity and small size allow miniaturized fiber optic sensors (FOS) to be designed with metrological characteristics (e.g., accuracy, sensitivity, zero drift, and frequency response) suitable for most common medical applications; the immunity to electromagnetic interference and the lack of an electrical connection to the patient make FOS suitable for use in high electromagnetic fields. These two characteristics increased the potential function of FOS in medicine, making them particularly appealing for use in MRI. This article gives an overview of MR-compatible FOS, with an emphasis on the sensors used in medicine to measure physical characteristics (i.e., temperature, force, torque, strain, and position). The operating principles of the most promising FOS are examined in terms of their respective benefits and drawbacks, as well as their medical applications.

KEYWORDS: Fiber Optic Sensors, Fiber Bragg Grating, Interferometry, MR-Compatibility.

1. INTRODUCTION

Optical fibers were initially used in medicine to light interior organs during endoscopic operations. Over time, the same technology has been used to accomplish additional activities, such as laser treatments and the development of transducers for monitoring parameters of interest for therapeutic and diagnostic reasons. Despite the fact that Fiber Optic Sensors (FOS) have been around for forty years and have certain benefits over other established technologies, their market has only expanded significantly in the past decade, owing to improvements in essential optical components and lower prices [1]. FOS is now used to monitor a variety of chemical and physical characteristics with medicinal applications. Extrinsic sensors, in which the optical fiber acts as a channel for transmitting light whose properties (e.g., intensity, frequency, phase) are controlled by the measured; intrinsic sensors, in which the optical fiber is the sensing element by itself. The fundamental components of FOS (e.g., light source, photodetector) may be deployed distant from the sensing element in this second class of sensors, allowing tiny sensors and hybrid solutions to be developed [2].

FOS is attractive for a variety of applications that take place inside or near the magnetic resonance scanner, in addition to the well-established applications in industrial and medical fields. Immunity to electromagnetic interferences, combined with good metrological characteristics and small size, make FOS appealing for a variety of applications that take place inside or near the magnetic resonance scanner. Magnetic Resonance Imaging (MRI) has grown in significance in clinical imaging since its debut in the early 1970s, far beyond even the most optimistic researchers' expectations[3]. The growing number of exams based on this method, as well as the introduction of novel procedures in clinical practice that are conducted under MRI supervision, has prompted research into new sensors that may be used in this situation. FOS is one of the MR-compatible applications that may be used to enhance surgical operation results as well as to monitor patients. The temperature of patients undergoing MRI-guided hyperthermia procedures[4], the assessment of deflection and force on needles during MRI-guided procedures and the estimation of physiological parameters (e.g., heart rate and respiratory monitoring) are just a few examples of those applications.

There are a plethora of ways that these sensors may be used in research procedures. The ASTM standard F2503 addresses MR safety-related interactions with equipment used in the MR environment. "MR safe," "MR conditional," and "MR unsafe" are the three categories defined by the standard. "MR-safe" items pose no known dangers in all MR settings; "MR-conditional" items have been shown to pose no known hazards in a specific MR environment under certain usage circumstances; and "MR-unsafe" items are known to pose risks in all MR environments. Despite the fact that the ASTM subcommittee for the F04.15.11 MR Standards chose to drop the phrase "MR compatible," it is still widely used in medical and technical circles. It's critical to understand the difference between "MR-safety" and "MR-compatibility". The term "MR compatible" refers to a device that has been shown to be "MR safe" when used in a magnetic resonance imaging (MRI) setting, meaning it has not been shown to have a major impact on the quality of diagnostic information or its operations. In this context, fiber optic technology is especially well suited to the development of "MR-compatible" sensors, as its immunity to electromagnetic fields allows for: safety, picture quality preservation; and sensor functionality preservation. Furthermore, the substance utilized to manufacture the optical fibers does not disturb magnetic fields within the MR-scanner, which is an important element in maintaining the diagnostic information's quality.

1.1 MR-Compatible FBG-Based Sensor

- Working Principle:

MR-compatible sensors based on fiber Bragg grating (FBG) technology, developed with different possible designs, allow sensing of temperature variations and strain. The introduction of the FBG in the field of thermal and mechanical measurements started with the research of Hill et al., who used electromagnetic waves to locally modify the refractive index of the optical fiber core. About ten years later, the study of Meltz et al., promoted the diffusion of FBGs, providing the description of a more effective, holographic technique for grating formation. Thanks to the characteristics of photosensitivity technology and its inherent compatibility with optical fibers, FBGs were introduced in different fields not only related to telecommunications, but also to the design of FOS. Despite several valuable characteristics of the FBG sensors, their spread was delayed because of the high cost and the difficulties of the manufacturing, which have been overcome only during the 1990s. The last decade saw several research groups developing sensors based on FBG. The characteristics of these sensors, their fabrication process, and their applications in medicine have been already described in detail in different reviews [2].

The working principle of an FBG is based on radiation reflection caused by the Bragg grating: when a fiber optic, which houses an FBG, is interrogated with a polychromatic radiation, only a narrow range of wavelengths are reflected by the FBG[5]. The central wavelength of such range, called Bragg wavelength (λB) can be expressed as a function of the effective refraction index of the core (ηeff) and of the spatial period of the grating (Λ)[6]. Temperature and strain influence and eff, allowing sensors to be designed to monitor temperature and strain, as well as other physical parameters related to them (e.g., pressure, force, vibrations, and flow)[7]. For FBG-based transducers, specific solutions can be used to make them selectively sensitive to strain or temperature. A reference FBG is usually added to the main sensor to reduce the influence of unwanted effects and improve the measurement system's repeatability. Sensors with good metrological characteristics, such as good accuracy, large bandwidth, large dynamic range, and high strain and thermal sensitivity (typical values range from 0.64 pm/ to 1.2 pm/, and 6.8 pm/°C to 13 pm/°C, respectively) can be developed using FBG technology. Furthermore, because multiple gratings with different Bragg wavelengths can be written on a single fiber, this technology allows for multiplexing. On the other hand, in order to avoid a reduction in performance (e.g., resolution and accuracy), the measurement chain should use an expensive device to detect the wavelength of reflected radiation (i.e., an optical spectrum analyzer).

- Medical Applications:

Biocompatibility, broad bandwidth, and compact size are the key features that make FBG technology especially suited for medical applications. Furthermore, fiber optics' resilience to electromagnetic fields, as well as the little interference with electromagnetic fields utilized in. This technique is extremely appealing for creating "MR-compatible" sensors because of MRI. FBG-based sensors for temperature monitoring in MRI have been suggested by several research groups. Is critical for a variety of applications: Rao and colleagues, for example, produced a With a resolution of 0.2 °C and an accuracy of 0.8 °C, a measuring chain for cardiac output estimate has been developed . This technique is also used to monitor tissue temperature during an MRI-guided hyperthemic procedure treatments. Temperature is very important during hyperthermia, and it may be monitored. helpful in assisting the physician in adjusting heat exposure The metrological, on the other hand, Electromagnetic fields have an impact on the operation of widely used temperature sensors utilized to generate hyperthermia during the operation (e.g., artifacts caused by self-absorption of Thermocouples are a kind of thermocouple.

Webb and colleagues suggested a measurement to solve this issue. They use a device with five FBGs to take temperature readings during hyperthermia. In live rabbits, therapy of the kidneys and liver. In a similar vein, other organizations evaluated the viability of FBGs were used to measure temperature in hyperthermic swine pancreatic tissue. In a later research, the same scientists measured tissue in an effort to increase spatial resolution. To increase temperature, 12 tiny size FBGs (1 mm length) were used [8], and an ad hoc constructed To properly position the optical applicator and the MR-compatible polymethylmethacrylate (PMMA) mask Figure 1A shows the FBGs within the tissue. This technology has also been used to keep track of things. temperature during prostate cryosurgery and liver cryosurgery , where MRI compatibility was tested experimentally evaluated [9].

1.2 Intensity-based and interferometry-based fibre optic sensors that are MR compatible:

- Working Principle:

FOS for MRI applications may be developed using several operating concepts based on light intensity modulation. The measurand controls the intensity of light flowing through the fibre in this kind of sensor. The most frequently utilised configurations' operating principles may be divided into three groups.

- Intensity reflective FOS, in which a reflector (e.g., a mirror) is positioned at a known distance from the distal endpoints of two optical fibers. The light carried by the first fiber is reflected by the mirror and then carried into the second fiber. A photodetector is connected to the second fiber. The radiation in this arrangement is the photodetector's intensity is determined by the distance between the two fibers and the wavelength mirror. Because of the light intensity, this arrangement allows for indirect measurements. The photodetector's data is linked to the measured (for example, force, pressure, displacement, etc.). flowrate, which acts on the mirror directly. Puangmali et al. used a more complicated approach .setups with the goal of increasing sensor performance.

- Light coupling between two or more fibers is used in FOS. The distal tip of these sensors a light-transporting fiber is positioned in front of another or a collection of them. The with increasing distance, the strength of radiation linked to the receiving fiber(s) diminishes. Figure 3ac shows the distance between the tips. FOS with reflecting and light coupling topologies are susceptible to undesired drift. Fluctuations in the intensity of the input light or light lost owing to fiber bending to address some of these issues, Differential arrangements with two or more receiving fibers may be utilized to alleviate these issues. The outputs of two or more devices are combined in these arrangements. Drift has an effect on photodetectors in the same manner. As a result, proper processing of photodetectors' output allows for compensation or reduction of measurement errors caused by noise. Unfavorable shift.
- Macro bending FOS: their mechanism of operation is based on light modulation due to fiber bending. The quantity of radiation lost into the cladding when a light beam hits a fiber bend because higher-order modes strike the cladding beyond a critical angle, the area grows. The fiber core is leaking out. This method may be used to measure physical properties. Force, torque, and pressure are all factors that induce fiber bends. In most cases, a sequence of Small macro bends are used to enhance light leakage, with the goal of increase the sensitivity of the sensor The primary benefit of intensity modulated FOS is the low cost of the measurement chain: Unlike FBG sensors, they do not need the use of costly equipment to measure the data output of the transducer Finally, interferometric methods like as Sagnac, Fabry-Perot, and others may be used to create FOS methods. In In the first instance, the fiber serves as a conduit for radiation that has been modified by a sensing device positioned at the apex. The fiber itself represents the sensing element in the second, where interferences, occur, regulated by the measured. The Fabry-Perot interferometric configuration is the most popular interferometric configuration used to create FOS interferometry. Its sensing method makes use of two semi-reflective mirrors that partly transmit and partially reflect light reflects some of the light carried by the fiber. The electromagnetic waves, which are subjected to a variety of processes, Reflections interact with themselves in both productive and destructive ways, resulting in fringes. The The optical path, which is linked to the distance between the two points, determines the strength of these fringes mirrors. As a result, these FOS may be utilized as supplementary components to monitor parameters that alters the gap between the two mirrors (such as pressure, force, torqu).

- *Medical Applications*

In medicine, there are many instances of intensity-based FOS developed a simple intensity-based 2-axis force sensor in which force applied along two axes modifies the coupled light between one emitter and four receiving fibers used reflected light intensity modulation to create a three-axial force sensor. During MRI-guided cardiac ablation, the sensor gives force feedback created an MR-compatible intensity modulated FOS for measuring 3D forces during robotic MRI-guided operations. The sensor described in this paper operates on the basis of reflected intensity: the reflector is mounted on an elastic frame construction at a distance of h from the transmitting and receiving fiber optics. The distance h, which is controlled by the applied force, determines the coupled light between the two fibers. Based on the reflected intensity concept, a “MR-compatible” robotic system with a force/torque sensor and a position encoder [8]. Su and colleagues developed a force/torque sensor based on a spherical mirror and numerous optical fibers for prostate needle insertion in MRI-guided operations. A point source's light is reflected by the mirror and gathered by numerous optical fibers. When the axial distance between the light source and the mirror is reduced, the light intensity rises. Turkseven and Ueda developed intensity reflective FOS to give force feedback in robotic applications. For respiratory monitoring, a similar method was employed in [49]. The sensor detects variations in abdominal circumference caused by breathing movements: the intensity of reflected light is controlled by the distance between the mirror and the distal portion of the optical fiber as the belly moves. Macrobending is also utilized in widely used intensity-based fiber optic sensors, which are used in a variety of medical applications. A similar technique is utilized by Grillet et al., De Jonckheere et al., and Witt et al. to create two macrobending sensors implanted into textiles to detect respiratory abdomen movement. Macrobending sensors are recommended for big movement monitoring due to their poor sensitivity as compared to FBG sensors. For example, in respiratory monitoring, they are better for estimating abdomen movements, which are considerably more visible than thoracic excursions. Several publications have detailed the use of interferometry-based FOS for monitoring thermal and mechanical parameters of physiological relevance, but only a few have focused on MRI applications. Su et al., for example, constructed and evaluated a sensor for measuring needle insertion force during minimally invasive prostate surgery as well as evaluating its MRI compatibility in a 3 Tesla system, produced a FOS based on low-coherence signals. For vitreoretinal microsurgery, Fabry-Perot interferometry is used.

2. DISCUSSION

The advent of magnetic resonance imaging (MRI) is without a doubt the greatest significant milestone in biomedical research and treatment during the past two decades. Just to have an idea of its social and economic implications, the Organization for Economic Co-operation and Development (OECD) health statistics declare the presence of more than 20,000 MR scanners in the OECD countries , and the request for high field devices (7 Tesla or even more) is increasing worldwide. MRI has become a "can't do without tool" in medical disciplines such as cardiology, surgery, orthopedics, and neurology, owing to its capacity to examine and distinguish soft tissues [10]. Furthermore, MRI's great spatial resolution, along with its ability to acquire functional characteristics of the investigated tissue indirectly, make it essential for investigating organ functions and imaging-guided invasive treatment. In the aforementioned situation, the need for "MR-compatible" sensors that can monitor physical parameters within the scanner and offer real-time feedback on the patient's condition and/or the impact surgical operations have on tissue is rapidly increasing. We evaluated the most promising work concepts used to develop “MR-compatible” sensors using optical fiber technology in this article. Transducers created for measuring temperature, force, torque, strain, and position received specific attention, with an emphasis on their operating principles, benefits and disadvantages, and medical applications. We divided the “MR-compatible” sensors into three groups based on their operating principle, using a variety of categorization criteria. Sensors;

a. Intensity-based sensors
b. Interferometry-based sensors
c. Interferometry-based sensors
d. Interferometry-based sensors
e. Interferometry-based sensors

The usage of FBG sensors provides for improved sensitivity and resolution, as well as multipoint measurements, and they are unaffected by variations in input light intensity, despite the fact that they need an optical spectrum analyzer, which is a costly and large instrument. As a result, when high performance is critical to improving the operation outcome, FBG technology is suggested (e.g., needle deflection in microsurgery). The use of FOS in therapeutic practice is only being started. The adequate metrological characteristics for the majority of medical applications, the lack of an electrical connection with the patient, and the small diameter of fiber optics are significant advantages over conventional transducers that drive the market growth of this technology (for example, FISO Technologies Inc. and Camino Laboratories Inc. manufacture pressure and temperature sensors for medical applications). FOS is also an excellent option for meeting the increasing need for MR-compatible sensors because to its resilience to electromagnetic fields. Ad hoc developed FOS for medical applications has been commercially accessible in recent years; for example, Micronor Inc. and Opsense Inc. provide MR-compatible FOS for displacement, temperature, and pressure monitoring.

3. CONCLUSION

For two primary objectives, "MR-compatible" sensors based on FBG technology have been used. For starters, they provide real-time monitoring of critical parameters during therapeutic invasive operations, resulting in better procedure results. Examples of such applications include: tissue temperature assessment and control during hyperthermia or cryoablation done under MRI guidance; and monitoring of needle deflection and/or force used during MRI-guided treatments. Second, FBG has been used to track physiological characteristics that are of interest (e.g., respiration and heart rate). For comparable purposes, interferometric and intensity-based FOS have been used. Intensity-based FOS have several drawbacks, including undesired drift caused by variations in light intensity and bending losses; on the other hand, their measurement chain is simple and inexpensive. As a result, they are appropriate for a variety of medical applications that do not need precise metrology, such as respiration rate monitoring.

REFERENCES

[1] F. Taffoni, D. Formica, P. Saccomandi, G. Di Pino, and E. Schena, "Optical fiber-based MR-compatible sensors for medical applications: An overview," *Sensors (Switzerland)*. 2013, doi: 10.3390/s131014105.

[2] F. Parent, M. Gerard, R. Kashyap, and S. Kadoury, "UV exposed optical fibers with frequency domain reflectometry for device tracking in intra-arterial procedures," 2017, doi: 10.1007/978-3-319-66185-8_67.

[3] L. Mescia and F. Prudenzano, "Advances on optical fiber sensors," *Fibers*. 2014, doi: 10.3390/fib2010001.

[4] J. P. Carmo and J. E. Ribeiro, "Optical Fibers on Medical Instrumentation," *Int. J. Biomed. Clin. Eng.*, 2014, doi: 10.4018/ijbce.2013070103.

[5] C. Elosua *et al.*, "Micro and nanostructured materials for the development of optical fibre sensors," *Sensors (Switzerland)*. 2017, doi: 10.3390/s17102312.

[6] T. Cheng *et al.*, "Mid-infrared supercontinuum generation spanning 20 to 151 μm in a chalcogenide step-index fiber," *Opt. Lett.*, 2016, doi: 10.1364/ol.41.002117.

[7] F. Baldini and A. G. Mignani, "Optical-fiber medical sensors," *MRS Bull.*, 2002, doi: 10.1557/mrs2002.123.

[8] K. Kong, C. Kendall, N. Stone, and I. Notingher, "Raman spectroscopy for medical diagnostics - From in-vitro biofluid assays to in-vivo cancer detection," *Advanced Drug Delivery Reviews*. 2015, doi: 10.1016/j.addr.2015.03.009.

[9] K. Prokopczuk, T. Poczesny, P. Sobotka, and A. W. Domański, "Extrinsic optical fiber sensor for medical audiometric applications," *Acta Phys. Pol. A*, 2012, doi: 10.12693/APhysPolA.122.957.

[10] Y.-L. Park *et al.*, "MRI-Compatible Haptics: Feasibility of using optical fiber Bragg grating strain-sensors to detect deflection of needles in an MRI environment," *Int. Soc. Magn. Reson. Med. ISMRM 16th Annu. Sci. Meet.*, 2008.