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OPTICAL FIBER-BASED SENSORS AND THEIR RECENT APPLICATIONS IN SCIENCE AND ENGINEERING

SENSORES BASADOS EN FIBRA ÓPTICA Y SUS APLICACIONES RECIENTES EN LAS CIENCIAS E INGENIERÍA

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Abstract

This paper presents a review of fiber optic-based sensors and their main characteristics and classification. In the same way, the paper includes a series of applications of sensors based on fiber optics with Bragg gratings in different fields of study in research such as medicine, civil engineering, communications engineering, chemistry, and biochemistry, among others. Such sensors are developed taking advantage of certain characteristics of optical fibers, such as photosensitivity and the variation of the refractive index of their core. Applications of fiber optics in the detection of telecommunications signals are also discussed, particularly as a filter device through the usage of Bragg gratings. Due to its versatility, these optical devices have provided promising results and have become a leading technology in next generation DWDM systems, as well as in optical sensing networks.

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Resumen
Este artículo presenta una revisión de los sensores basados en fibra óptica y sus principales características y clasificación. Del mismo modo, el artículo incluye una serie de aplicaciones de sensores basados en fibra óptica con rejillas de Bragg en diferentes campos de estudio de la investigación como la medicina, la ingeniería civil, la ingeniería de comunicaciones, la química y la bioquímica, entre otros. Dichos sensores se desarrollan aprovechando ciertas características de las fibras ópticas, como la fotosensibilidad y la variación del índice de refracción de su núcleo. También se analizan las aplicaciones de la fibra óptica en la detección de señales de telecomunicaciones, en particular como dispositivo de filtrado mediante el uso de rejillas de Bragg. Debido a su versatilidad, estos dispositivos ópticos han proporcionado resultados prometedores y se han convertido en una tecnología líder en los sistemas DWDM de próxima generación, así como en las redes de detección óptica.

Key Words: Bragg Gratings, Optical Sensing, Optoelectronics, Optical Communications.

Palabras Clave: Rejillas de Bragg, Detección Óptica, Optoelectrónica, Comunicaciones Ópticas.

Introduction

Technological progress has directly influenced the development of communications technologies, which include different devices such as the telegraph, telephone, radio, data networks, as well as fiber optics, which provide multiple characteristics such as increased bandwidth, reduced losses, low latency, immunity to electromagnetic interference, improved network security, multiplexing capacity, among others (Ho et al., 2021; Kareem et al., 2021; Kersey et al., 1997). Such characteristics, as well as the different advances in optoelectronics and photonics, have allowed the expansion of the use of fiber optics as a transmission media, generating an increase in the implementation and development of optical communication networks, which are progressively replacing existing coaxial networks and ethernet networks (Bonk, 2021; Horvath et al., 2020; Waldman, 2019).

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Bragg gratings as a sensing instrument

In addition to the usage of fiber optics as a means of data transmission in communication networks, it can be used as a sensing instrument for different physical parameters such as temperature (B. Xu et al., 2021), pressure (Hong-kun et al., 2020), humidity (Zakaria et al., 2019), environment refractive index (Feng & Gu, 2019), among others, adding versatility to its functionalities and thus allowing it to be used for multiple applications in different fields of study.

That versatility is possible due to intrinsic characteristics of the optical fiber, such as photosensitivity, which is a nonlinear optical effect that affects the refractive index of the optical fiber core, once subjected to UV exposure (K. Hill et al., 2003), allowing the creation of periodic disturbances in the refractive index of the optical fiber core, also called Bragg gratings, which are the basis of multiple optical sensors, since they can filter the wavelengths of the incident light, while reacting to variations in the environment, depending on its configuration, (K. O. Hill et al., 1978).

The detection of the different parameters will depend on the configuration of the coupling mode of the grating structure which would depend on the angle of inclination and the period, so that the gratings can be classified according to their period as Short-Period Gratings (Fiber Bragg Gratings, FBGs), and Long-Period Gratings (LPGs), as shown in Figure 1 (Kashyap, 2010).

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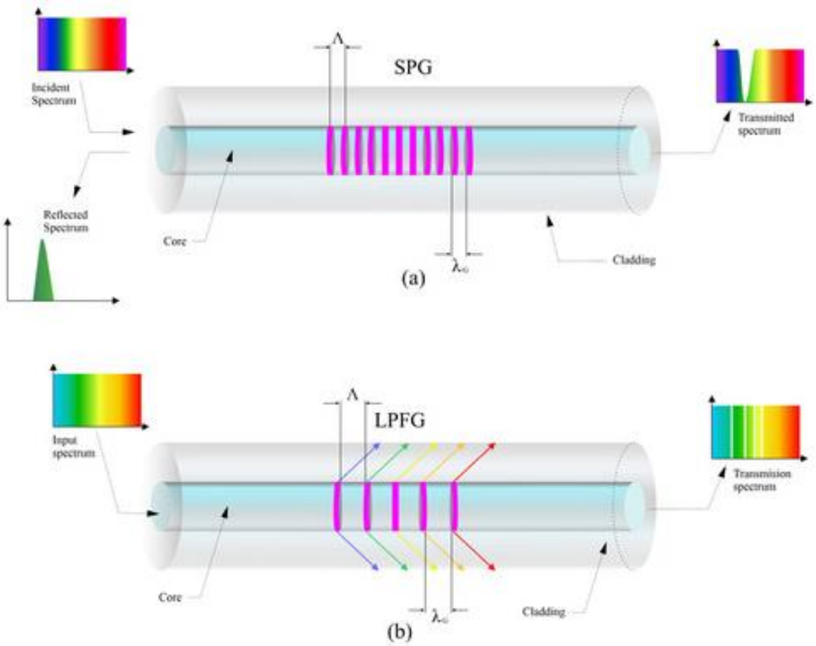

Fig.1 (a) Design structure of Short-Period Grating and (b) Long-Period Grating.

FBGs are formed by a periodic modulation of the refractive index of the fiber core due to high UV exposure, resulting in a strong resonance in the transmission spectrum, which response to parameters such as temperature (Duan et al., 2019), strain (Kim et al., 2020), pressure (Vorathin et al., 2020), among others. On the other hand, LPGs consist of multiple attenuation peaks due to the coupling of the core mode to the cladding modes in the forward direction, becoming a good candidate for the simultaneous measurement of parameters such as temperature, environment refractive index, relative humidity, among others (Hromadka et al., 2019; Pang et al., 2020; Zhou et al., 2020).

In addition to FBG and LPG, whose period is uniform, there are fibers with tilted gratings, whose gratings have an asymmetric structure. Such gratings could be classified according to the coupling mode as Tilted Fiber Bragg gratings (TFBGs), Radiation Tilted Fiber Gratings (RTFGs), and Excessively Tilted Fiber Gratings (Ex-TFGs), (Yuezhen et al., 2021). Tilted Fiber Bragg Gratings (TFBGs) are designed with a tilt angle of less than 23.1º in the period, during their manufacturing process.

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Figure 2. describes the diagram of phase-matching condition of different structures of gratings.

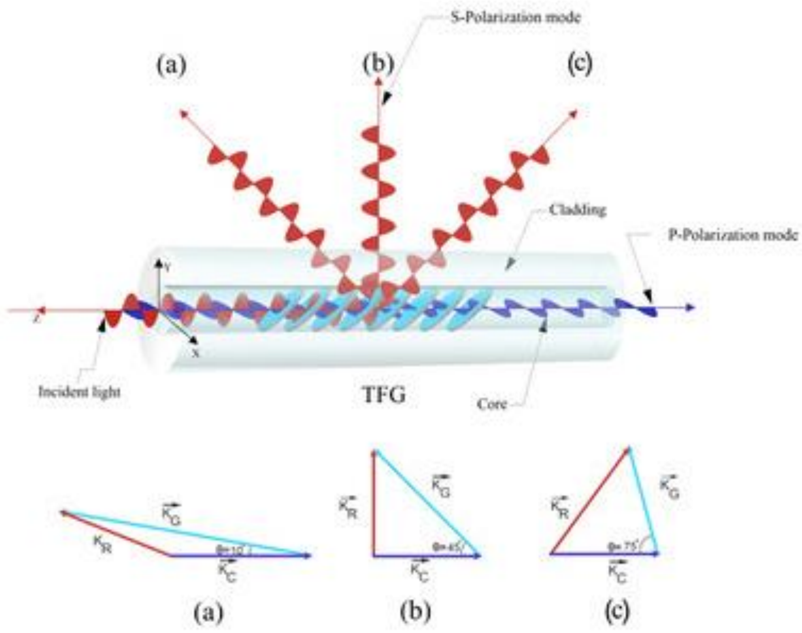

Fig 2. Diagram of the Phase Matching Condition of (a) TFBGs, (b) RTFGs and (c) Ex-TFG.

Also, its transmission light is coupled from the core mode (which propagates forward) to the cladding mode (which propagates backward), resulting in that, in addition to the primary resonance as in the FBG, they have a series of multiple resonances in the cladding mode (Albert et al., 2013), making them a good candidate for measuring parameters such as refractive index (Miao et al., 2009), Surface Plasmon Resonance (SPR) (Moreno et al., 2019), relative humidity (Yd et al., 2017), torsion (Sławomir et al., 2018), among others. On the other hand, the RTFGs have an inclination angle between 23.1º and 66.9º, which transmitted light is coupled from the core mode that propagates towards the radiation modes, allowing them to be widely used as optical polarizers (Yan et al., 2012), spectrometers (Qin et al., 2019) and polarimeters (Westbrook et al., 2000). Finally, the tilt angle of fibers with excessively tilted gratings (Ex-TFGs) exceeds 66.9º, and its transmission light is coupled from the forward propagating core mode to the forward propagating cladding modes, generating a unique polarization property, which allows them to be applied as magnetometers (Lu et al., 2019), refractive index sensors (Y. Xu et al., 2017), torsion sensors (Yan et al., 2011), transverse loading (Z. Sun et al., 2014), among others.

Conjointly, there are additional configurations, such as Chirped Fiber Bragg Gratings (CFBGs), produced by varying the refractive index modulation period, resulting in each portion of the grating reflecting a different section of the spectrum (Korganbayev et al., 2018; Tosi, 2018). Within the special configurations, we can also find Moire Gratings structures (MFBGs), whose grating was exposed twice by UV light with two phase masks (Min et al., 2018; T. Wang et al., 2017), thus offering a wide possibility of high-resolution optical sensors, which can be used depending on the requirements of each application (Werneck et al., 2013). All these grid configurations can be used to perform different types of measurements of physical parameters, such as those mentioned above, where we can add rotation measurements (Kisała et al., 2018), bending (Shao et al., 2010), protein detection, chemical, and biochemical analysis, among others, even simultaneously, depending on the configuration.

Applications of optical fiber-based sensors in Science and Engineering

Optical fiber-based sensors are increasingly used in different research areas such as optical communications, where applications such as the implementation of fiber optic sensor networks with SPON, and filter-based UWFBG networks (Chen et al., 2021) and multiplexers (C. Y. Li et al., 2021) and optical devices such as Bragg gratings, are used in communications applications as well as industrial applications (Q. Sun et al., 2019). In this sense, multiple applications have been developed in which fiber optic-based sensors are applied for the signals treatment in communication networks, as is the case of the one reported in (Ghosh & Priye, 2018), where Chirped Bragg gratings were used for suppression of Four-Wave Mixing (FWM) effects in a 22 x 10 Gbps Dense Wavelength Division Multiplexing

(DWDM) system. In the same way, fiber optic-based sensors have been reported for the signal filtering process in optical communications systems, by the use of filters such as the one reported in (Gao et al., 2021), where fiber Bragg gratings were used for the fabrication of high-performance Terahertz filters, or tunable microwave photonic filters, such as the one reported in (X. Li et al., 2021), in which linear chirped Bragg gratings were applied (Linear Chirped Fiber Bragg Grating, LCFBG).

In addition to its application in optical communications systems, fiber optic-based sensors have been used in different areas of medicine, such as physiological monitoring (Prata et al., 2021), minimally invasive surgical procedures (P. Wang et al., 2022), biomechanical analysis of fracture healing (Kalinowski et al., 2021), e-health (Domingues et al., 2021), development of photoacoustic tomography (Huda et al., 2022), becoming an essential tool for the development of novel techniques of sensing in the health area. Also, fiber-based plasmonic sensors provide different advantages over traditional plasmonic sensors, such as miniaturization, high sensitivity levels, and high resolutions, improving the sensing in several areas such as chemistry, biochemistry, and pharmaceutical sectors, where different applications have been reported. Such is the case of the optical fiber-based plasmonic sensor reported by (Moreno et al., 2020), presented in Figure 3, which obtains the surface plasmon resonance through a hybrid structure based on tilted fiber gratings, and which is used for hemoglobin detection. Similarly, in biochemical analysis, applications have been reported for hybridization (Pradhan & Vasimalla, 2022) and in-situ DNA detection (X. Li et al., 2022), with high levels of sensitivity.

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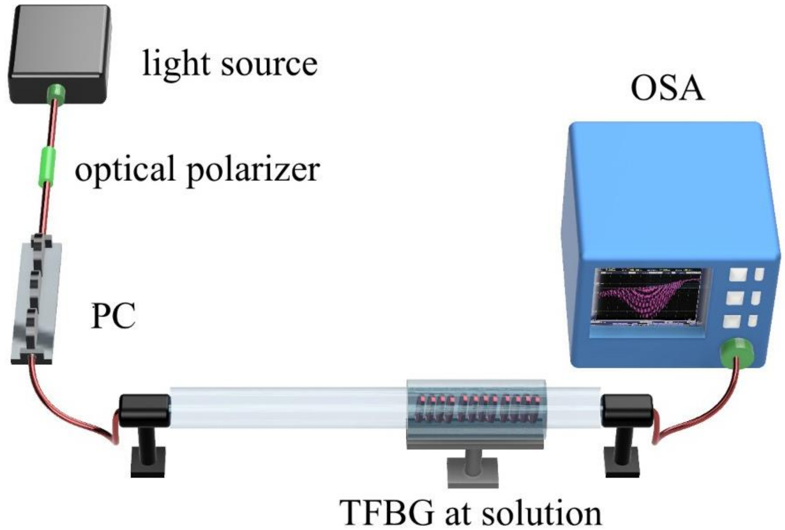

Fig 3. Optical Fiber-based Surface Plasmon Resonance Sensor reported by Moreno, et al.

Furthermore, fiber optic-based sensors are frequently used in civil engineering in different types of buildings such as bridges (Sliti & Boudriga, 2021), dams (Allil et al., 2021), buildings (di Palma et al., 2021), roads (Braunfelds et al., 2021), using different configurations, to obtain parameters such as strain, temperature, pressure, among others, and to determine the structural health of buildings, in order to avoid possible accidents caused by the collapse of structures. Similarly, these sensors are frequently used in train stations in applications both for the development of excavation work (Ye et al., 2013), as well as for operation monitoring systems (Yüksel et al., 2018) and traffic (Gautam et al., 2018), offering a miniaturized, robust, low-cost tool of great benefit for applications in these fields.

Likewise, the usage of optical fiber-based sensors is reflected in a significant way in the food industry, where multiple applications were reported, such as the use of LPGs for the detection of biogenic amines such as putrescine (frequently found in spoiled foods and fermented beverages) (Vasconcelos et al., 2020), as well as the detection and quantification of coloring agents such as sodium and copper chlorophyllin (used for the pigmentation of foods such as beverages and sweets), whose prolonged consumption prolonged at high concentrations is harmful to health (W. Li et al., 2021).

Similarly, in areas such as nautical engineering (Min et al., 2021), aeronautics (Bednarska et al., 2020; Ma & Chen, 2018), aerospace engineering (Pei et al., 2018), and automotive engineering (Falcetelli et al., 2022), fiber optic-based sensors have been used in applications taking advantage of their characteristics to operate in hostile environments, and of high sensitivity, with respect to electronic sensors.

In industrial engineering, fiber optic-based sensors are used in multiple systems, such as Supervisory Control and Data Acquisition (SCADA) systems (Nicola et al., 2018), supply chain monitoring, supply, condition monitoring of industrial induction motors (Bieler & Werneck, 2018), taking advantage of features such as miniaturization, low maintenance cost, robust design, and direct connection to AC power.

Furthermore, fiber optic-based sensors are present in the food industry (Leone, 2022) and the development of new devices (Garavito et al., 2021).

In earth sciences, fiber-optic-based sensors are also applied for purposes such as seismic monitoring and imaging of the seafloor using fiber-optic-based stress sensors (Jousset et al., 2018; Wentao et al., 2018), monitoring of groundwater pressure and temperature levels using Bragg gratings (Ho et al., 2021), development of geophones for geological exploration of oil (Ni et al., 2018), monitoring of the vertical deformation of the subsoil (Liu et al., 2021) among others.

Conclusion

The main objective in this paper is to highlight the applications of different types of fiber optic-based sensors, in fields such as science and engineering. Despite literature has shown important advances in R&D in this area, as well as recent applications in different fields, further research is required to keep improving several characteristics of the optical fiber-based sensing technology such as the sensitivity and miniaturization of novel devices. Furthermore, at some developing countries such as Panama, local industries often rely on electromagnetic based sensors which are prone to interference and require constant re-calibration, caused by extreme weather conditions, reason why the implementation of optical fiber-based sensing technology would be suitable for multiple applications in different fields such as agriculture, civil engineering, medical sector, chemical analysis, and so on.

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