Toward Optical Sensors: Review and Applications

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Abstract. Recent advances in fiber optics (FOs) and the numerous advantages of light over electronic systems have boosted the utility and demand for optical sensors in various military, industry and social fields. Environmental and atmospheric monitoring, earth and space sciences, industrial chemical processing and biotechnology, law enforcement, digital imaging, scanning, and printing are exemplars of them. The ubiquity of photonic technologies could drive down prices which reduced the cost of optical fibers and lasers. Fiber optic sensors (FOSs) offer a wide spectrum of advantages over traditional sensing systems, such as small size and longer lifetime. Immunity to electromagnetic interference, amenability to multiplexing, and high sensitivity make FOs the sensor technology of choice in several fields, including the healthcare and aerospace sectors. FOSs show reliable and rigid sensing tasks over conventional electrical and electronic sensors. This paper presents an executive review of optical fiber sensors and the most beneficial applications.

1. Introduction
The field of fiber optics has undergone tremendous growth and advancement over the last 25 years. The fiber optic communication industry has literally revolutionized the telecommunication industry by providing higher performance, more reliable telecommunication links with ever decreasing bandwidth cost. This revolution is bringing about the benefits of high volume production to component users and a true information superhighway built of glass. Developments fiber optic sensor [1] technology has been a major user of technology associated with the optoelectronic and fiber optic communication industry. Since the past decades, various devices, including fiber optic gyroscopes; sensors of temperature, pressure, and vibration; and chemical probes has been under development of Fiber optic sensors (FOS) technology. FOS offer a number of advantages, such as increased sensitivity compared to existing techniques and geometric versatility, which permits into arbitrary shapes [2].

The ability of fiber optic sensors has been enhanced to substitute traditional sensors for acoustics, vibration, electric and magnetic field measurement, acceleration, rotation, temperature, pressure, linear and angular position, strain, humidity, viscosity, chemical measurements and a host of other sensor applications. They can be used in high voltage, high temperature, or corrosive environments due to its dielectric property; In addition, these sensors are compatible with communications systems and have the capacity to carry out remote sensing. Recently, investigation in the field has focused on the development of new materials with non-linear optical properties for important potential applications in photonics. Examples of these materials are the conjugated semiconducting polymers that combine optical properties with the electronic properties of semiconductors. In addition, these conducting polymers have photo luminescent and electroluminescent properties, making them attractive for applications in optoelectronics [3].
Fiber optic sensor technology in turn has often been driven by the development and subsequent mass production of components to support these industries. The inherent advantages of fiber optic sensors which include their ability to be lightweight, of very small size, passive, low attenuation, and low power, immunity to electromagnetic interference (EMI), high sensitivity, wide bandwidth and environmental ruggedness were heavily used to offset their major disadvantages of high cost and unfamiliarity to the end user [4][5].

2. Optical Fiber Sensors Advantages Over Traditional Sensors
The advances in research and development of FOS devices has extended their applications to various fields of technology, such as medical, chemical, and telecommunications industries. They have been developed to work on a wide variety of physical properties, like temperature, chemical changes, electric and magnetic fields, vibrations, strain, displacement (position), flow, pressure, rotation, radiation, liquid level, light intensity, and colour. For performance in harsh environments, FOS proves reliable and rigid sensing devices over conventional electrical and electronic sensors where they have difficulties [1][6][7]. Contrary, optical fiber sensors exhibit a number of advantages over other types of sensors; they are:

- Enable small sensor sizes
- Are non-electrical devices
- Offer sensitivity to multiple environmental parameters
- Require small cable sizes and weights
- Permit remote sensing
- Allow access into normally inaccessible areas
- Often do not require contact
- Immune to radio frequency interference (RFI) and electromagnetic interference (EMI)
- Do not contaminate their surroundings and are not subject to corrosion
- Provide high sensitivity, resolution and dynamic range
- Can be interfaced with data communication systems

3. Fiber Optic Sensor Principles
The general structure of an optical fiber sensor system is shown in Figure 1 which it composed of mainly of four components that are source, fiber optic, transducer and detector. Figure 2 depicts these component in more details, an optical source (Laser, LED, Laser diode etc), optical fiber (single or multimode), sensing or modulator element (which transducers the measure and to an optical signal), an optical detector and actuating circuitry (processing electronics, oscilloscope, optical spectrum analyzer etc). In the FOS devices, the optical parameters that can be modulated are the amplitude, phase, colour (spectral signal), and state of polarization [6][8]. The optical modulation methods of the sensors involve the following:
Intensity-modulated sensors: The variation of the light intensity that is proportional to the perturbing environment can be detected by sensors. The concepts associated with intensity modulation include transmission, reflection, and micro bending. For this, a reflective or transmissive target can be incorporated in the fiber. Other mechanisms that can be used independently or in conjunction with the three primary concepts include absorption, scattering, fluorescence, and polarization. Intensity modulated sensors normally require more light to function than phase modulated sensors; as a result, they employ large core multimode fibers or bundles of fibers.

Phase-modulated sensors: The phase of the light in a sensing fiber is compared to a reference fiber in a device known as an interferometer. These sensors employ a coherent laser light source and two single-mode fibers. The light is split and injected into the reference and sensing fibers. If the light in the sensing fiber is exposed to the perturbing environment, a phase shift occurs between them. The phase shift is detected by the interferometer. Phase modulated sensors are much more accurate than intensity-modulated sensors. The change in color is proportional to the changes in the absorption, transmission, reflection, or luminescence of the optical signal, whereas the polarization is related to the strain birefringence.

4. Intensity Based Fiber Optic Sensors
Fiber optic sensors are often loosely grouped into two basic classes according to the manner in which the optical fiber is used, sensor can be either an intrinsic one, if the modulation takes place directly in the fiber, or extrinsic, if the modulation is performed by some external transducer [4][6][7].

Intrinsic fiber optic sensor (IFOS): the intensity, phase, polarization, wavelength or transit time of light can be modulated. Sensors which modulate light intensity tend to use mainly multimode fibers, while only mono mode cables are used to modulate other parameters. An interesting feature of IFOSs is that they can provide distributed sensing over distances of up to 1 meter. In Intrinsic sensors, the variable of interest (physical perturbation) must modify the characteristics of the optical fiber to modify the properties of the light carried by the fiber, figure 3 (Intrinsic).
Intrinsic FOSs directly employs an optical fiber as the sensitive material, sensor head, and also as the medium to transport the optical signal with information of the perturbation environment to be measured. They operate through the direct modulation of the light guided into the optical fiber. The light does not leave the fiber, except at the detection end, the output, of the sensor. These sensors can use interferometric configurations, Fiber Bragg Grating (FBG), Long Period Fiber Grating (LPFG), or special fibers (doped fibers) designed to be sensitive to specific perturbations. Light intensity is the simplest parameter to manipulate in intrinsic sensors because only a simple source and detector are required.

Extrinsic fiber optic sensor (EFOS): the optical fiber is simply used to guide the light to and from a location at which an optical sensor head is located. The sensor head is external to the optical fiber and is usually based on miniature optical components, which are designed to modulate the properties of light in response to changes in the environment with respect to physical perturbations of interest figure 3 (Extrinsic). Thus, in this configuration, one fiber transmits optical energy to the sensor head. Then this light is appropriately modulated and is coupled back via a second fiber, which guides it to the optical detector. Extrinsic fiber optic sensors use a fiber optic cable, normally a multimode one, to transmit modulated light from a conventional sensor. A major feature of extrinsic sensors, which makes them so useful in such a large number of applications, is their ability to reach places which are otherwise inaccessible. For example, the insertion of fiber optic cables into the jet engines of aircraft to measure temperature by transmitting radiation into a radiation pyrometer located remotely from the engine. Fiber optic cable can be used in the same way to measure the internal temperature of electrical transformers, where the extreme electromagnetic fields present make other measurement techniques impossible. Extrinsic fiber optic sensors provide excellent protection of measurement signals against noise corruption. An executive comparison of fiber optic sensors classes are shown in table 1.

| Table 1. Comparison of the two types of optical sensors |
|--------------------------------------------------------|
| **Extrinsic**                                           | **Intrinsic**                                         |
| Applications                                           | Temperature, Rotation, Acceleration, Strain, Acoustic |
| Sensitivity                                           | More sensitive                                       |
| Multiplexed                                           | Easier                                               |
| Connection problems                                   | Ingress/ egress                                       |
| Cost                                                  | Less expensive                                        |
| Flexibility                                           | Easier to use                                         |

Intrinsic FOSs and Extrinsic devices.
5. Optical Sensor Types
Fiber optical sensors are sensors that can work in harsh environments where conventional electronic and electrical sensors have difficulties. They can sense various physical properties, such as pressure, position, strain, chemical changes, magnetic and electric fields, flow, vibration, light level, radiation and colour [3][6][9].

- Chemical sensors; remote spectroscopy, groundwater and soil contamination.
- Temperature sensors; largest commercially available sensors, range -40 °C to 1000 °C.
- Strain sensors; fiber Bragg gratings (FBG) technology, senses as little as 9 micro strain.
- Biomedical sensors; spectroscopic biomedical sensors, CO₂, O₂ and PH can be measured simultaneously, flow monitoring by laser dopplerimetry.
- Electrical and magnetic sensors; appealing inherent dielectric nature, less sensitive to electromagnetic interference, small size and safer, they are almost always hybrid.
- Rotation sensor; based on the sagnac effect, two types ring laser gyroscope (RLG) and fiber optic gyroscope (FOG).
- Pressure sensors; based on piezoresistive technique or movable diaphragm, high performance (polarization based sensors); operating pressure ranges from 0-70,000 torr.
- Displacement and position sensors; one of the first optoelectronic sensors to be developed, simple sensors rely on the change in retro reflectance due to a proximal mirror surface, also referred as liquid level sensors.

6. Optical Fiber Sensing Applications
For harsh environmental condition and sensing over long distances, Optical sensing is consider as the perfect solution for applications where conventional electrical sensors such as foil strain gages, thermocouples, and vibrating wires have proven ineffective or difficult to use due to those conditions. The features and benefits of fiber Bragg grating (FBG) optical sensing include the nonconductive, electrically passive, immune to electromagnetic interference (EMI), induced noise, sensor measurements over very long distances (10+ km), daisy chain multiple sensors on a single fiber. Large and lightweight structures can benefit from the distributed single fiber architecture to simplify installation and reduce weight [10]. The nonconductive and noncorrosive nature of the fiber benefits outdoor and industrial applications where hazardous gases and voltages might be present. Also, the immunity to EMI removes the need for expensive and often difficult signal conditioning required for measurements near noisy sources such as power transformers. FBG optical sensing can benefit many applications in areas such as energy, civil infrastructure, and transportation monitoring [6][10].

**Medical field:** Optical-chemical and biochemical sensing is being researched extensively all over the world, and these sensors are finding an increasing number of applications in industry, environmental monitoring, medicine, biomedicine, and chemical analysis [2]. The main physical phenomena exploited for optical chemical sensing are absorption and fluorescence, although chemical luminescence, Raman scattering, and Plasmon resonance have also been used. Health-care is unquestionably the application field which seems to have the most potential for future development [11][12]. Optical biosensors are finding ever-increasing applications in different branches of medicine for several reasons.

**Energy field:** FBG optical sensing has unique attributes that make it suitable for traditionally difficult applications. Monitoring structures that generate, produce, distribute, and convert electrical power introduces many challenges that can be addressed with FBG optical sensing. Whether it is a windmill requiring a lightweight solution or a hydroelectric turbine needing an EMI-resistant system, optical sensing has unique feature that match perfectly with these traditionally difficult applications. Partial discharge detection uses optical fiber sensors optical fiber sensors are being tested for use in detecting partial discharges in electrical transformers. Pinpointing such discharges is essential to preventing insulation breakdown and catastrophic failures. For example, monitoring the structural integrity of a wind turbine blade with electrical sensors would often result in noisy measurements because of long
copper lead wires. With optical sensing, accurate and noise-free strain measurements on wind turbine blades are possible with little added weight to the structure. Furthermore, the nonconductive and distributed nature of optical fibers lends well for many uses in oil and gas applications, including pipeline monitoring and downhole monitoring. Applications of energy FOS devices are wind turbine blade monitoring, pipeline monitoring, power line monitoring, offshore platform monitoring and downhole monitoring.

**Civil field:** Structural health monitoring systems based on electrical sensors often face significant environmental challenges. An electrical monitoring system would require the installation of countless wires, a lightning grounding system, periodic external calibration, and the potential maintenance of corroded and/or degrading sensors. With an optical sensing solution, these downfalls are all eliminated. The ability to daisy chain multiple sensors on a single fiber greatly reduces the weight and complexity of the system. Furthermore, optical fiber does not corrode or conduct like copper wire, which increases longevity and reduces the risk of damage due to lightning. These attributes, coupled with the fact that optical sensors and NI interrogators do not require calibration, drastically reduce the amount of maintenance required. Applications of civil FOS devices are large building monitoring, bridge and road monitoring, airport landing strip load monitoring and dam monitoring.

**Transportation field:** To ensure passenger safety, monitoring systems are increasingly deployed to ensure the proper operation of airplanes, railways, ships, and more. However, weight, size, and harsh environmental requirements can pose significant challenges to implementing an electrical monitoring system. FBG optical sensors alleviate these challenges by providing lightweight distributed sensor measurements that are immune to corrosion, high voltage, and EMI-induced noise. Also, because of the longevity and ease of installation of FBG optical sensors and lack of need for external calibration, these sensing systems can be deployed reliably for decades without needing any maintenance; this is especially beneficial for long-term railway and ship hull monitoring. The ability to have multiple sensors on a single, very thin fiber dramatically reduces the weight of the monitoring system, which is especially important in aerospace applications. Applications of transportation FOS devices are railway monitoring, fuel tank monitoring, airplane wing monitoring, and Ship hull monitoring.

7. Conclusions

Recently, the advances of technology and applications based on fiber optics are progressed very rapidly. As a physical medium, Optical fiber is subjected to various perturbation of at all times. Thus, it experiences size and shape changes and optical (refractive index, mode conversion) changes to a larger or lesser extent depending upon the nature and the magnitude of the perturbation. It is crucial for communication application to be reliable all times and to minimize various effects on transmitted signals. On the other hand in fiber optic sensing, the response to external influence is deliberately enhanced so that the resulting change in optical radiation can be used as a measure of the external perturbation. Since light is characterized by amplitude (intensity), phase, frequency and polarization, any one or more of these parameters may undergo a change. The fiber acts as a modulator in sensing phase, while in communication, the signal passing through a fiber is already modulated. It also works as a transducer that converts measurands into a corresponding change in the optical radiation. FOSs offer many advantages such as freedom from EMI, wide bandwidth, compactness, geometric versatility and economy. Indeed of dielectric construction, passive, and high sensitivity when compared to other types of sensors. Specially prepared fibers can withstand high temperature and other harsh environments. In telemetry and remote sensing applications it is possible to use a segment of the fiber as a sensor gauge while a long length of the same or another fiber can convey the sensed information to a remote station. Deployment of distributed and array sensors covering extensive structures and geographical locations is also feasible.
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