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OPTICAL FIBER SENSORS

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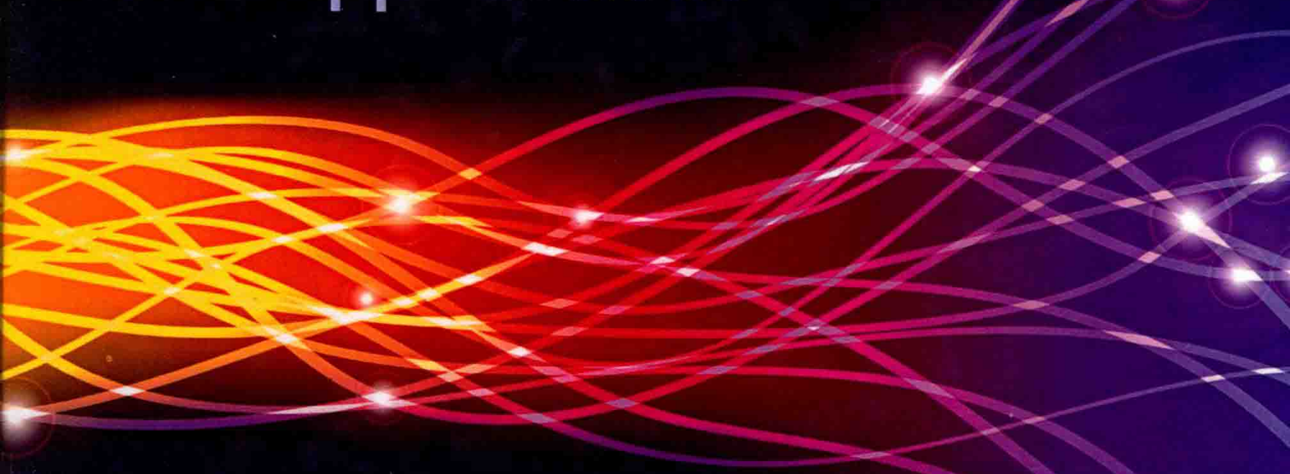

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Preface

In the past several decades since the invention of the laser in 1960 and the development of modern low-loss optical fibers in 1966, optical fiber technology has made a transition from the experimental stage to practical applications. The main focus of the development of optical fiber has always been on telecommunications, but the early 1970s saw some of the first experiments on low-loss optical fibers being used for sensor purposes. The field of optical fiber sensing has continued to progress and has developed enormously since that time. Magnetic, pressure, temperature, acceleration, displacement, fluid level, current, and strain optical fiber sensors were among the first types extensively investigated and explored for sensing and measurement. Compared with other types of sensors, optical fiber sensors exhibit a number of advantages, such as immunity to electromagnetic interference, applicability in high-voltage or explosive environments, a very wide operating temperature range, multiplexing capabilities, and chemical passivity. This book describes the fundamentals of optical fiber sensors, the latest developments in the field, and the practical applications of the optical fiber sensing technology.

This book covers wide aspects of different sensing mechanisms using optical fibers and also demonstrates their use in application areas. Chapters based on new and emerging areas such as photonic crystal fiber sensors, micro-/nanofiber sensing, liquid crystal photonics, acousto-optic effects in fiber and its sensing applications, and fiber laser–based sensing and other well-established areas such as surface plasmon resonance sensors, interferometric fiber sensors, polymer fiber sensors, Bragg gratings in polymer and silica fibers, and distributed fiber sensors are also included in this book. On the application side of optical fiber sensors, humidity sensing applications, smart structure applications, and medical applications are also covered. A future outlook on the fiber sensing research area is also presented to provide the reader with an understanding of its potential.

This book is a collective effort of a number of authors who contributed different chapters in their areas of expertise. With such a wide variety of topics covered in detail, we are hoping that the reader will find this book stimulating to read and will discover the sensing potential of optical fibers and devices. This book is intended to be a comprehensive introduction with a strong practical focus suitable for undergraduate and graduate students as well as a convenient reference for scientists and engineers working in the field.

Editors

Dr. Ginu Rajan is vice-chancellor's research fellow/lecturer at the University of New South Wales, Sydney, Australia. He earned his BSc in physics from the University of Kerala and MSc in applied physics from Mahatma Gandhi University, Kerala, India, in 2000 and 2002, respectively. He worked as a researcher at the Indian Institute of Astrophysics during the period of 2003–2005. He subsequently undertook research in the area of optical fiber sensors, following which he earned a PhD from Dublin Institute of Technology (DIT), Ireland, in 2008.

During 2009–2012, Dr. Rajan worked as a project manager/research associate at the Photonics Research Centre of DIT in collaboration with the Warsaw University of Technology, Poland. He also was a lecturer at DIT during this period. He has published more than 100 journal articles, conference papers, and book chapters. He also holds a patent. Dr. Rajan is currently a reviewer for many scientific journals and also an international reviewer for funding applications of the Portugal Science Foundation and Australian Research Council. His research and teaching interests include optical fiber sensors and their applications in biomedical engineering, fiber Bragg grating (FBG) interrogation systems, photonic crystal fiber sensors, polymer fiber sensors, smart structures, and physics of photonic devices. He can be reached at ginu.rajan@unsw.edu.au or ginurajan@gmail.com.

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In his career, Dr. Iniewski held numerous faculty and management positions at the University of Toronto, the University of Alberta, SFU, and PMC-Sierra Inc. He has published more than 100 research papers in international journals and conferences. He holds 18 international patents granted in the United States, Canada, France, Germany, and Japan. He is a frequent invited speaker and has consulted for multiple organizations internationally. He has written and edited several books for IEEE Press, Wiley, CRC Press, McGraw-Hill, Artech House, and Springer. His personal goal is to contribute to healthy living and sustainability through innovative engineering solutions. He can be reached at kris.iniewski@gmail.com.

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Contents

1 Introduction to Optical Fiber Sensors

Ginu Rajan

CONTENTS

1.1 INTRODUCTION

Sensing has become a key enabling technology in many areas, from entertainment technology to health, transport, and many industrial technologies. In many such advanced applications where miniaturization, sensitivity, and remote measurement are vital, optical fiber–based sensing techniques can provide novel solutions. As a result of this, optical fiber sensing (OFS) technology is developed as a powerful and rich technology that is currently being implemented in a wide variety of applications [1,2].

Research works on OFS are started in the 1960s, but it is the development of modern low-loss optical fibers that has made a transition from the experimental stage to practical applications. Some of the first sensing experiments using low-loss optical fibers [3–6] were demonstrated during the early 1970s. The field of OFS has continued to progress and developed enormously since that time. For instance, distributed fiber-optic sensors have now been installed in bridges and dams to monitor the performance and structural damage of these facilities. Optical fiber sensors are used to monitor the conditions within oil wells and pipelines, railways, wings of airplanes, and wind turbines. Decades of research led to the development of accurate optical fiber measuring instruments, including gyroscopes, hydrophones, temperature probes, and chemical monitors. As the OFS field is complementary to optical communication, it has availed the benefit of advancements on optical fibers and optoelectronic instrumentation. Due to the rapid development of optical fiber communication systems, the cost of optical fiber sensor systems has also significantly reduced due to the commercially viable key components such as light sources and photo detectors.

It is anticipated that research on OFS technology still continues to grow, and the technology will become widespread. Several new types of fiber sensors are progressively emerging, and some of the fiber sensing technologies are in a mature state and has been commercially produced and used in different applications. As light wave technology is becoming the new enabling technology behind many advanced high-end applications, optical fiber sensors can play an integral part of those developments.

The aim of this chapter is to introduce the basic principles of OFS and to provide a brief overview of some of the different types of fiber sensors developed all through the years and also to form the base for the rest of the chapters in this book.

1.2 OPTICAL FIBER SENSORS

For a given process or operation, a system needs to perform a given function that requires qualifying and/or quantifying the condition of one or multiple parameters. Therefore, these parameters are to be measured and processed so that the system can carry out its function. To facilitate the process, a sensor can be used, which is a device that provides these information by measuring any physical/chemical/biological measurand of interest (pressure, temperature, stress, pH, etc.) and converting it into an alternative form of energy (e.g., electrical or optical signal) that can be subsequently processed, transmitted, and correlated to the measurand of interest.

As an optical fiber alternative of traditional sensors, *optical fiber sensors* can be defined as a means through which physical, chemical, and biological measurands interact with light guided through an optical fiber or the light is guided to an interaction region by an optical fiber, to produce a modulated optical signal with information related to the measurement parameter. The basic concept of a fiber-optic sensing system is demonstrated in Figure 1.1, where the fiber (guided light) interacts with an external parameter and carries the modulated light signal from the source to the detector. The input measurand information can be extracted from this modulated optical signal. Depending on the type of fiber sensor and its operating principle, the sensor system can operate either in transmission mode or in reflection mode, which is elaborated in later sections of this chapter.

1.3 MEASUREMENT CAPABILITIES AND ADVANTAGES OF OPTICAL FIBER SENSORS

One of the biggest advantages of fiber sensors is that it has the capability to measure a wide range of parameters based on the end user requirement, once a proper fiber sensor type is used. Some of the measurement capabilities of fiber sensors are given as follows (but not limited to):

- Strain, pressure, force
- Rotation, acceleration
- Electric and magnetic fields

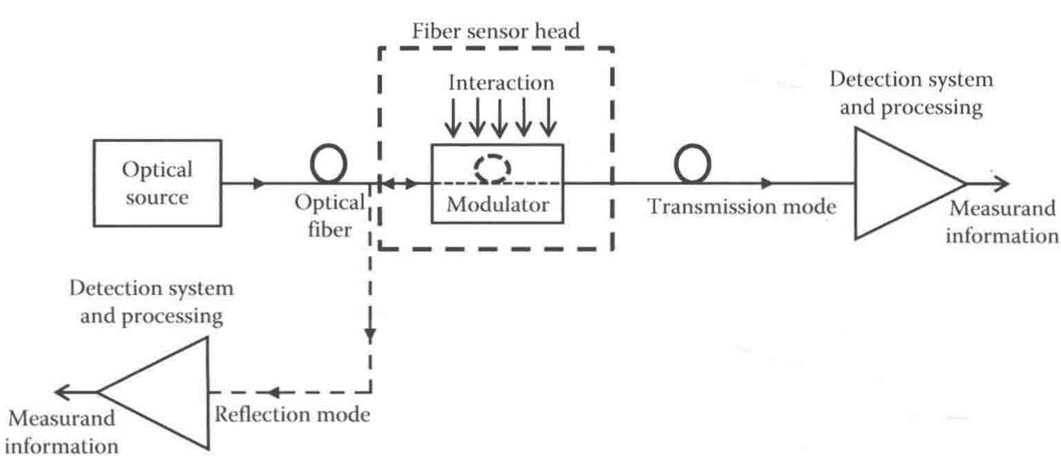

FIGURE 1.1 Basic concept of an optical fiber sensor.

- Acoustics and vibration
- Temperature, humidity
- pH and viscosity
- Biosensing single molecules, chemicals, and biological elements such as DNA, single viruses, and bacteria

Given the advancement in the development of optical fibers and instrumentation, the development and measurement capabilities of optical fiber sensors have also increased and are currently being employed in many structural health monitoring (SHM) and biomedical applications [7–9]. On the advantages of optical fiber sensors, they share all the benefits of optical fibers and are excellent candidates for monitoring environmental/external changes. Some of the advantages of fiber sensors over conventional electronic sensors are listed in the following:

- Lightweight
- Passive/low power
- EMI resistant
- High sensitivity and bandwidth
- Environmental ruggedness
- Complementary to telecom/optoelectronics
- Multiplexing capability
- Multifunctional sensing possibility
- Easy integration into a wide variety of structures
- Robust, more resistant to harsh environments

Though optical fiber sensors have many advantages compared to its electrical counterpart, there are some concerns as well with this technology. Major drawbacks include cost, long-term stability, less efficient transduction mechanism, and complexity in its interrogation systems. Another disadvantage to the fiber sensing system is the unfamiliarity of the end user in dealing with the system. As more research, commercialization, and standardization efforts are ongoing, it is expected that some of the current disadvantages may become extinct in the near future.

1.3.1 Classification of Optical Fiber Sensors

As optical fiber sensors operate by modifying one or more properties of light passing through the fiber, they can be broadly classified as extrinsic or intrinsic. In the extrinsic sensor types, the optical fiber is used as a means to carry light to an external sensing system, while in the intrinsic type, the light does not have to leave the optical fiber to perform the sensing function. The intrinsic fiber sensor types are more attractive and widely researched as this scheme has many advantages compared to extrinsic, such as their in-fiber nature and the flexibility in the design of the fiber sensor head.

Furthermore, depending on the light property that is modified, optical fiber sensors can be mainly classified into four main categories:

- Intensity-modulated sensor
- Phase-modulated (interferometric) sensor
- Polarization-modulated (polarimetric) sensor
- Wavelength-modulated (spectrometric) sensor

Optical fiber sensors can also be further classified based on its spatial positioning as well as based on the measurement capabilities. A summary of the different classifications of OFS is shown in Table 1.1.

As given in Table 1.1, according to the spatial distribution of the measurand, fiber sensors can be classified. For example, a point sensor can be used to sense measurands from discrete points, and