CHAPTER 1

INTRODUCTION

Optical fiber is a thready material that makes use of optical total internal reflection (TIR) to guide light waves. The fiber loss was predicted low enough to transmit optical signals for long distances in the 1960s, and the low loss silica fiber was fabricated in the 1970s. Since then, optical fibers have been used in telecommunication systems in tremendous amounts and with great success. Their applications in sensor and other science and technology fields are also developed quickly, playing increasingly important roles in various fields.

1.1 HISTORICAL REVIEW AND PERSPECTIVE

The optical fiber was proposed and fabricated earlier in the 1920s [1,2], demonstrating light propagation in a glass waveguide based on the principle of TIR. The invention of optical fiber broke the limitation of the straight propagation of light. Fibers with cladding were invented later to reduce propagation loss, caused by the outer medium of air, for the earlier fibers without cladding. This improvement resulted in practical applications using optical fibers, such as image transmissions in bundles [3]. It was predicted theoretically in 1966 by K.C. Kao in his initiative

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paper that optical fiber with extremely low loss could be realized, and its application to telecommunications was proposed [4]. Soon after, a fiber with loss down to a few tens dB/km was fabricated [5]. Combined with lasers, especially the semiconductor laser, which came into being in the same decade [6–8], the fiber technology gave an impetus to the emergence of optical communication technology, which is now recognized as one of the bases of the modern information society.

A great number of improvements to fiber performance were achieved. It was found that silica fiber is the most suitable material for low-cost and high-quality fabrication technologies. Matched with the development of semiconductor lasers, three low loss bands at 850, 1,300, and 1,550 nm were fully exploited. Fiber dispersion properties were also investigated in detail. The single mode fiber showed much lower dispersion, superior to multimode fibers. In the 1980s, optical fiber communication systems were built for practical telecommunication applications [9]. An important milestone in optical communications was the success of wavelength division multiplexing (WDM) technology, especially dense wavelength division multiplexing (DWDM) in the 1990s, and the issuance of a series of international telecommunication union standards. Optical fiber communication technology, combined with the Internet, has tremendously changed the state of telecommunication all over the world.

Stimulated by the development of optical fiber technologies, a variety of optical devices and components have been developed. Apart from the semiconductor lasers and the photodetectors in different wavelength bands, optical modulators, switches, and WDM filters, and so on, are widely used for high-speed data transportation and networking. It is found that optical fiber is not only a long-distance transportation medium but also a good material of optical devices with special functions, especially for fiber amplifiers, which play a key role for DWDM technology.

The optical fiber is very useful—with unique features in sensor technologies—not only for signal transportation but also as a sensing element itself. Optical fiber sensors (OFS) have obvious merits over electrical sensors and bulky optical sensors. Some fiber sensors show unsubstitutable features, such as fiber optic gyros, nonlinear optical scattering sensors, and fiber gratings. Optical fiber interferometers can be used in many areas, while keeping the merits of high precision and high sensitivity.

Optical fiber sensor technology has grown into a large-scale industry, with its research and development becoming a trending field.

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International conferences on OFS have been held since 1983 every year or so, with several hundred attendants. The OFS sessions are also listed in related international conferences and topic meetings, such as the Optical Fiber Communication Conference, Photonics East and West, International Symposium on Test and Measurement, and Society of Photo-Optical Instrumentation Engineers (SPIE) conferences. Many topical books have been published [10–14]; a great number of research papers can be read in journals, among them some review papers [15–19], which are also referred to in this book.

OFS have found varied applications in human social activities and daily living, from industrial production to cultural activities, from civil engineering to transportation, from medicine and health care to scientific research, and from residence security to national defence. OFS are used widely in manufacturing automation, production quality control; in oil well, tank, and pipeline monitoring, power system monitoring, and communication network monitoring; in building status monitoring and seismological observation; in navigation and vehicle status monitoring; in metrology and scientific instruments; in antiterrorist activities and intrusion alarming; and in many military applications.

The R&D and industry of optical fiber sensors are becoming major stimulants to the economy. According to estimates and forecasts of the Optoelectronics Industry Development Association, the average annual growth rate of fiber optic sensor revenue is about 63% during the period 2005–2010 [20].

1.2 CLASSIFICATIONS OF OPTICAL FIBER SENSORS

A sensor is considered an indispensable part of an information system. In automatically controlled equipment, sensors provide feedback signals for controlling operations; in industrial and civil engineering, sensors indicate basic conditions, such as stress and strain, vibrations, and temperature changes; in applications of security, military, and antiterrorism, they sound alarms; in health care, they are used to detect and transmit biochemical information.

Many kinds of sensors have been invented and developed. Most of them can be categorized into two types—electric and optical sensors—which have their respective merits and demerits. Soon after the invention of fiber, it was found that fiber itself possesses functions to sense external physical changes; its sensitivities were exploited to

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develop a variety of devices and sensors. Fiber sensors carry out a twofold function: acquisition of information and transport of the signals. The OFS shows unique merits, including the following:

- Small size and weight
- Environmental robustness, water- and moist-proof
- Immunity to electromagnetic interference and radio frequency interference
- Capability of remote sensing and distributed sensing
- Safe and convenient; integration with signal transportation
- Capability of multiplexing and multiparameter sensing
- Large bandwidth and higher sensitivity
- Lower cost and economic effectiveness

To construct a fiber sensor application system, various optical devices are needed, just like in optical fiber communication systems. As fiber technologies have grown into a vast industry, and a universal means in research and development as well, almost all optical components and devices find their homologs in optical fiber technology. Devices and components used in sensor technologies can be classified with some overlaps as follows.

According to functions, fiber devices are conventionally divided into active and passive devices, although their division is not exact. Generally, the former can generate or alter optical signals by some electrical methods, such as lasers, amplifiers, modulators, switches, and so on. The passive devices have no electrical means to alter optical signals; their main function is to define paths of optical signals and to configure various optical fiber systems. Couplers, connectors, collimators, attenuators, isolators, circulators, polarization controllers, and wavelength division multiplexers are the most important passive devices in fiber communications and fiber sensors.

According to materials and structures, fiber devices and sensors are roughly categorized into intrinsic and extrinsic devices. If the material that plays the main role is the fiber itself, it is called an intrinsic fiber device; whereas an extrinsic fiber device uses other optical materials incorporated with the fiber. For example, a fiber Mach–Zehnder interferometer is a typical intrinsic fiber device composed of fiber couplers and two fiber sections as the interference beams. Its extrinsic counterpart is lithium niobate electro-optic waveguide modulator connected with input and output fiber pigtails. Many bulky optical

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materials are used to fabricate components and devices in fiber technology, including silica, glass with different compositions, various crystals, semiconductors, polymer, and so on.

The main parameters of a light wave include amplitude, frequency, phase, polarization state, and intensity, which is the square of its amplitude. All of them can carry information, and thus can be used as sensor parameters. According to the parameters, OFS are divided into two categories: intensity-modulated sensors and phase-modulated sensors. For example, a sensor by detecting fiber bending loss is an intensity-modulated sensor, whereas a sensor based on birefringence caused by fiber bending is a phase-modulated sensor. Generally speaking, intensity-modulated sensors cost less, whereas phase-modulated sensors provide higher sensitivity and higher precision.

According to sensing elements, similar to the ordinary optical devices, fiber sensors can be categorized into intrinsic and extrinsic sensors. The former is a sensor that makes use of fiber's sensitivity to environmental conditions, whereas the latter is based on the sensitivity of materials other than fiber. For example, an electric current sensor can be made of fiber by its Faraday effect, so can some crystals with higher Faraday effect coefficients, connected with fibers as input and output leads. In most extrinsic fiber sensors the fiber plays a role of signal transportation, which is an important function in practical applications, and also a reflection of the fiber sensor's merits. Some extrinsic fiber sensors make use of the combined effects of fiber and other optical components, such as the fiber Fabry–Perot interferometer sensors. This book focuses mostly on intrinsic fiber sensors, with some discussion on extrinsic sensors.

According to the properties of sensed parameters, OFS are categorized into many types. The measurands include the following:

1. *Geometrical*: position, displacement, distance, thickness, move/stop signaling, liquid level, and so on.
2. *Mechanical*: strain, stress, pressure, and so on.
3. *Dynamical*: velocity, acceleration, angular velocity, fluid velocity, flow rate, vibration frequency and amplitude, and so on.
4. *Physical*: temperature, electric current, voltage, magnetic field, sound, ultrasonic and acoustic parameters, and so on.
5. *Chemical/biochemical*: flammable gases, toxic gases, specimen analysis, chemical etching detection, and so on.
6. *Miscellaneous*: break detection, fiber losses, intrusion detection, fire alarming, and so on.

The classification of OFS is based on different mechanisms, including the following:

1. *Basic effects of materials*: photoelastic effect and thermal photo effect (strain-induced and thermally induced refractive index change), thermal expansion of materials in optical path.
2. *Fiber interferometers*: Mach–Zehnder interferometers, Michelson interferometers, Fabry–Perot interferometers, Sagnac interferometers, Fizeau interferometer, and so on.
3. *Polarization dependences*: polarization maintaining fiber interferometers, strain-induced birefringence of the fiber, Faraday effect, and so on.
4. *Gratings and filters*: fiber gratings, spectral dependence of fiber couplers, wavelength converters, Doppler effect, and so on.
5. *Nonlinear optical effect and scatterings*: Rayleigh scattering, Raman scattering, Brillouin scattering, Kerr effect, self-phase modulation and cross-phase modulation, and so on.
6. *Mode coupling*: mode coupling by evanescent field, axial mode coupling, and so on.
7. *Loss-related mechanism*: fiber attenuation, end coupling, fiber bending loss, and so on.
8. *Aided with transducers*: various mechanical structures to convert the measurands to parameters of sensor elements.
9. *Aided with external materials*: reactants and fluorescence.

This list cannot cover all kinds of OFS, neither can this book. Among them the most important fiber sensors are introduced and analyzed in the following chapters.

1.3 OVERVIEW OF THE CHAPTERS

This book is intended to introduce basic OFS with emphases on their principles and physics, to provide helpful fundamentals to students and graduate students of the specialty, and to readers working in research and development. Its contents include seven chapters, introduced as follows.

Chapter 2 gives the fundamentals of optical fibers. After a brief introduction in Section 2.1, the electromagnetic theory of conventional step-index optical fibers is provided in Section 2.2. The gradient index

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fiber is analyzed in Section 2.3 based on ray optics, and discussed briefly by wave optics. Section 2.4 introduces some special fibers, including the rare-earth-doped active fiber and the double-cladding fiber, the polarization maintaining fiber, and the photonic crystal fiber.

Chapter 3 is devoted to fiber sensitivities and related devices. Fiber sensitivities to strains and temperature changes induced by different conditions are discussed in Section 3.1, which is the basis of the sensing unit of fiber itself, and is used to develop related fiber devices. Section 3.2 introduces fiber couplers, mainly the 2 × 2 and 3 × 3 directional couplers. Axial mode coupling is also discussed briefly. Fiber loops based on the couplers are analyzed in Section 3.3, such as the fiber Sagnac loop, fiber ring resonator, fiber Mach–Zenhder interferometer, and fiber Michelson interferometer. These devices have been used widely in fiber sensor systems. Section 3.4 discusses the polarization characteristics of fiber, especially the polarization state evolution in propagation under different conditions. Section 3.5 introduces several polarization devices used in the communication and sensor systems.

Chapter 4 focuses on fiber gratings, which play very active roles in fiber sensor technology. Their basic structures and fabrication processes, as well as photosensitivity are introduced in Section 4.1. Section 4.2 is devoted to the theory of fiber grating and the design methods of various gratings. Several special fiber gratings are analyzed in Section 4.3, such as multisection fiber gratings, chirped fiber Bragg gratings, tilt fiber Bragg gratings, and polarization maintaining fiber gratings. Section 4.4 introduces sensitivities of fiber gratings, their applications in sensor technologies, and the related technical issues.

Chapter 5 introduces distributed OFS, which utilize the effects of light scattering in fibers. Section 5.1 gives a brief introduction of elastic scattering (Rayleigh scattering) and inelastic scatterings (Raman scattering and Brillouin scattering). The distributed fiber sensors based on Rayleigh scattering is discussed in Section 5.2, including optical time domain reflectometer (OTDR), polarization OTDR, phase-sensitive OTDR, and optical frequency domain reflectometer. Section 5.3 introduces sensors based on Raman scattering and its application to temperature sensing, that is, the distributed anti-Stokes Raman thermometry. Section 5.4 discusses sensors based on Brillouin scattering, which are sensitive to both strain and temperature. Two sensors are introduced: Brillouin OTDR and Brillouin optical time domain analyzer. They make use of spontaneous and stimulated Brillouin scatterings, respectively. Several other sensors are briefly introduced in Section 5.5, including those composed of fiber loops, based

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on low coherence technology, and those based on speckle effect in fibers.

Chapter 6 reviews several fiber optic sensors with special applications in four sections: gyroscopes, hydrophones, fiber Faraday sensor, and sensors based on surface plasmon waves respectively. These sensors have unique features and special applications. Since there have been professional monographs published, this book does not go into detail, but gives basic concepts and principles, and discusses the basic technical issues for practical applications.

Chapter 7 focuses on the extrinsic fiber Fabry–Perot (F-P) interferometer (EFFPI) sensors, which have a heart element of F-P cavity composed of a fiber facet and a mirror such as the diaphragm fiber optic sensor (DFOS). The structures and principles of EFFPI sensors are introduced in Section 7.1. The theoretical analysis based on Gaussian beam is presented in Section 7.2. Section 7.3 describes the basic characteristics and performance of EFFPI sensors. The last section introduces more applications of the EFFPI sensor and discusses some technical issues.

Appendix 1 provides mathematics formulas useful in fiber sensor analyses. Appendices 2 and 3 give the fundamentals of elasticity and polarization optics, respectively. Appendix 4 lists the specifications of related materials and device products, which are used frequently.

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