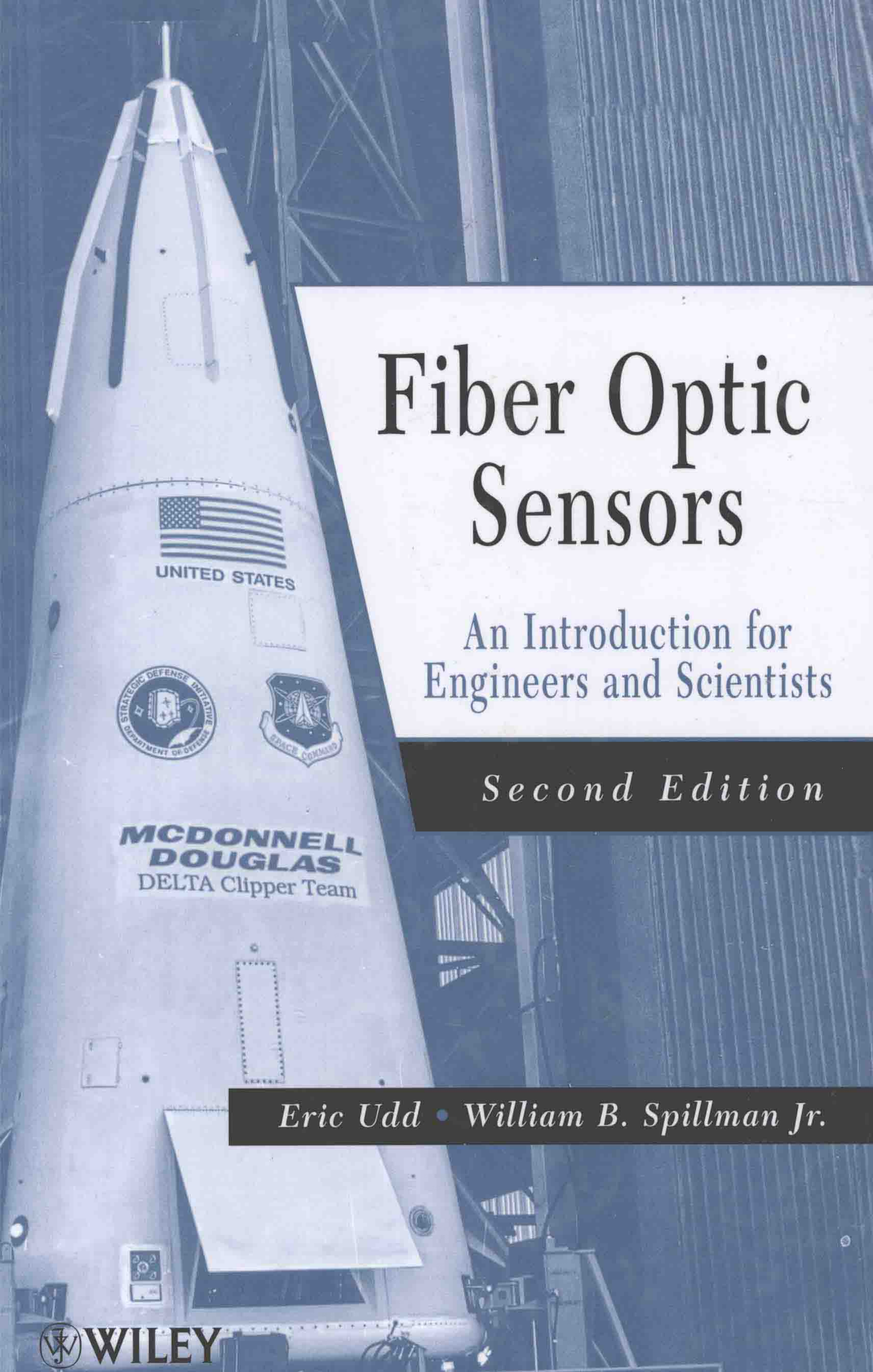

Fiber Optic Sensors

An Introduction for Engineers and Scientists

Second Edition

Eric Udd • William B. Spillman Jr.

WILEY

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Edited by

ERIC UDD

WILLIAM B. SPILLMAN, JR.

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A JOHN WILEY & SONS, INC., PUBLICATION

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data:

Fiber optic sensors : an introduction for engineers and scientists / edited by Eric Udd, William B. Spillman, Jr. -- 2nd ed.
p. cm.
ISBN 978-0-470-12684-4 (hardback)
1. Fiber optics. 2. Optical fiber detectors. I. Udd, Eric. II. Spillman, William B.
TA1800.F5133 2011
681 ' .25–dc22 2010040982

Printed in Singapore

oBook ISBN: 978-1-118-01410-3
ePDF ISBN: 978-1-118-01409-7
ePub ISBN: 978-1-118-01408-0

10 9 8 7 6 5 4 3 2 1

FIBER OPTIC SENSORS

PREFACE

The first fiber optic sensors were the flexible endoscopes developed in the first half of the twentieth century. Their development and use created a revolution in medicine that continues to this day. The modern age of fiber optic sensors was enabled by the development of extremely low-loss optical fibers in the late 1970s. A wide variety of sensor types and applications have been demonstrated for more than 30 years since reports of the very first sensors appeared in the literature.

There have been three distinct waves of fiber optic sensor development that can be identified with the most successful fiber optic sensors associated with them. The most successful sensors of the first wave were the fiber optic gyroscopes based on the Sagnac effect and fiber optic hydrophones based on Mach–Zehnder interferometers. These sensors were developed to the point of practicality with both commercial and military systems based on them in use today. The second wave of fiber optic sensors was based upon Fabry–Perot interferometers, either extrinsic or intrinsic. Very large numbers of applications using these sensors have been reported in the literature. The third wave of fiber optic sensors began with the development of in-line Bragg grating optical filters for optical communication purposes. It was soon found that fiber Bragg gratings, or FBGs, made excellent optical transducers for sensing a number of different parameters. Within each wave of development, however, many additional transducer concepts have been demonstrated and reported.

This book is intended to give an overview of the sensor concepts developed over the modern period of fiber optic sensor development. In this second edition, two new extensive chapters have been added, one on FBG sensor theory and technology and one on fiber optic biosensors. These two areas point to considerable promise for fiber optic sensor development and application in the future.

The editors of this book have been involved in the development of fiber optic sensors from the very beginning. In the early 1980s, the United States Naval Research Laboratory issued two contracts to demonstrate fiber optic hydrophone systems. Eric Udd worked on the single-mode fiber optic hydrophone program at McDonnell Douglas, while Bill Spillman worked on the parallel multimode fiber optic hydrophone program at the Sperry Research Center. It was at that time that the editors became acquainted and discovered that they both were in the early stages of writing books on fiber optic sensors. Since Eric was further along in writing his book, it was decided that Bill would contribute a number of chapters to Eric's book and abandon his own effort. These chapters were included in the first edition of this book. Both Eric and Bill have remained active in the development of fiber optic sensors throughout their careers up until the present.

This edition of the book is comprised of 16 chapters. The first five chapters describe the fiber optic telecommunication technologies that form the basis of fiber optic sensing. Chapters 6–11 cover many different fiber optic sensors that have been reported over the past 30 years. Next, in Chapters 12–14 several specific applications of fiber optic sensors are presented. Finally, in Chapters 15 and 16, the fiber optic sensors most used at present are described in detail and the emerging field of fiber optic biosensors is discussed in some detail.

This book provides engineers, scientists, graduate students, and advanced undergraduates with an introduction to the field of fiber optic sensors. In order to do this, the book contains all the necessary scientific and technical background material to allow an understanding of the sensors described. As can be seen from the table of contents, a great many different sensor types have been developed over the years.

> It is interesting to note that many of the original concepts were impractical due to the lack of a cost-effective technology to implement them. Many of the patents on these concepts have now expired so that they are free to be used by the technical community at large. More important, however, the base of fiber optic and other technologies has progressed to the point that a number of the original concepts that were abandoned are now practical and can be applied to solve today's sensing problems.

As stated previously, the book begins with an introduction and overview of the critical components utilized by fiber optic sensors. Chapter 1 provides a brief overview of the emergence of fiber optic sensor technology and how it has evolved. Chapter 2 is a basic introduction to the types of fibers used in fiber optic sensors and the physical phenomena associated with optical fibers used for sensing. Chapter 3, on light sources, is a brief introduction to these components from the point of view of a fiber optic sensor developer. Chapter 4 describes optical detectors from a similar point of view. Chapter 5 describes both bulk and integrated optical modulators used for phase and frequency shifting.

The chapters that follow contain descriptions of many sensors developed since about 1980. Chapter 6 provides an overview of fiber optic intensity sensors followed by a more detailed discussion of fiber optic sensors based on Fabry–Perot cavities.

These sensors were among the first to be successfully developed commercially. Chapter 7 follows with a discussion of grating-based fiber optic sensors that were developed for use as hydrophones and displacement sensors. Chapter 8 provides an excellent introduction to the concept of polarization and describes the effectiveness of this approach in enabling a powerful class of fiber optic sensors. Chapter 9 covers fiber optic sensors based on the Sagnac effect and passive ring resonators. The fiber optic gyroscope, based on these concepts, was successfully developed and is in commercial use today. Chapter 10 describes the Mach–Zehnder and Michelson interferometers. The Mach–Zehnder interferometer is the basis of many fiber optic hydrophone arrays that are deployed today. Finally, in Chapter 11 a number of techniques are described that can be used to multiplex fiber optic sensors. The chapter also provides an introduction to the important area of distributed fiber optic sensing.

Chapters 12–14 are concerned with a number of applications of fiber optic sensor technology. Chapter 12 covers magnetic sensors based on the Faraday effect, magnetostriction, and Lorentz forces. These sensors have been used in monitoring current for electrical utilities and have served as the basis of speed sensors developed for gas turbine engines and magnetic debris detection. Next in Chapter 13, an overview of fiber optic sensors for industrial applications is provided. Included in the chapter are examples of sensors to measure temperature, pressure, fluid level, flow, position, and other parameters. The challenges of working in the industrial environment are also covered. Chapter 14 discusses smart structures. The smart structure is a concept originally proposed by Eric during the U.S. Air Force Project Forecast II Program in the 1980s whose purpose was to identify critical technologies needed to support future Air Force missions. Smart structure research arose from the field of fiber optic sensing and remains an important and vibrant area of activity today.

Finally, the book contains two new chapters. In Chapter 15, a thorough description is provided on the most commonly used fiber optic sensor today, the FBG sensor. Perhaps more widely than any other fiber optic component, the FBG has found its way into general application in both the telecommunication and the sensor fields. Since their introduction in the late 1980s, FBGs have been used to support stabilization of laser diodes to pump fiber light sources and act as repeater links in telecommunication lines and numerous applications. The worldwide fiber optic communication network consists of many thousands of deployed FBG systems. Researchers in the fiber sensor field were quick to adopt FBGs into their systems for use in strain and temperature sensors. The attributes of FBG sensors enable their integration into aerospace, civil structure, and environmental, naval, and land vehicle systems where accurate monitoring is required over the lifetime of the system. The book concludes with Chapter 16 with an extensive analysis of fiber optic biosensors. The advantages of fiber optic technology have long been appreciated by the biomedical and biotechnology communities. Optical fibers are dielectric and nonconductive, biocompatible, flexible, small in size, and immune to electromagnetic interference. They can also be sterilized using standard medical sterilization techniques. Their initial and still most successful biological/biomedical application has been in the field of endoscopic imaging. More recently, they have been utilized to sense other parameters of interest to the biomedical and biotechnology fields. This chapter provides a historical perspective on the development of fiber optic biosensors and identifies a number of recent concepts that show considerable promise.

No undertaking as comprehensive as that represented by this book could ever be successful without the support of more friends and colleagues than could possibly be named. Bill Spillman would particularly like to thank all past and present contributors to the "Fibre Optic Sensors" series of conferences that began in 1982 in London and have continued to this day. Without the talented and exceptional people who have made those conferences a success, there would be no field of fiber optic sensing today. Bill would also like to especially cite the contributions of Sir D.E.N. Davies, one of the pioneers of the field, and the legions of now very successful students that he trained in his laboratory at University College London. Eric Udd would like to thank his coworkers at McDonnell Douglas who supported much of his early work on fiber optic sensors including Richard Cahill who acted as his mentor during early work on fiber optic gyros and fiber optic acoustic sensors, Bruce Turner and Paul Theriault who provided excellent technical support for many years, and his many colleagues and friends at McDonnell Douglas including Steve Watanabe, Stuart Higley, Al Joseph, Wil Otaguro, Jeff Eck, Russ Johnson, Robert Rice, and Tom Weaver who worked for and/or with him over 16 years he worked at McDonnell Douglas. Eric would also like to thank the many people who worked with and for him at Blue Road Research including John Seim, Mike Morrell, Whitten Schulz, John Corones, Stephen Kreger, Marley and Wesley Kunzler, Bob McMahon, Caryn Major, and Sean Calvert. Eric would like to thank the many people who have sponsored and championed his work on fiber optic sensors over the years especially Wolfgang Schubel of Wright-Patterson AFB for sponsoring his efforts on fiber optic gyros; Jim Dorr and Kelli Corona-Bittick of Production Products who sponsored and teamed on early work on fiber optic grating sensors in composites during his time at Blue Road Research; Eric Haugse of Boeing for sponsoring and teaming on work on smart structure projects for aircraft; Greg Ruderman of Edwards AFB and Scott Hyde and Mont Johnson of ATK Launch Systems for their support on utilizing fiber grating sensors on launch systems; Dirk Heider of the Composite Research Center at the University of Delaware for work on composite manufacturing; Joel Conte at UCSD for work on civil structures; and Drew Nelson of Stanford, and Jay Spingarn and Tom Bennett of Sandia National Labs for work on multiaxis fiber grating strain sensors. Finally, Eric would like to thank the hundreds of people he has not been able to mention here who have sponsored his work, supported conferences he has attended and organized, his hundreds of students over the past 30 years, and the many, many people who have provided technical support and advice.

Eric Udd

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ABOUT THE AUTHORS

Eric Udd is President of Columbia Gorge Research, a company he founded with the objective of helping move fiber optic sensor technology into field applications. He started his work on fiber optic sensor technology at McDonnell Douglas in 1977 with the invention of the closed-loop fiber optic gyro and quickly became a manager of a fiber optic sensor group and in 1989 was elected a McDonnell Douglas Fellow. In 1993, he left McDonnell Douglas to move his family to Oregon and founded Blue Road Research to continue his fiber optic sensor work. In 2000, Blue Road Research was acquired by Standard MEMS and in January 2006 he left to found Columbia Gorge Research. Mr. Udd has been principal investigator on over 100 projects for DOD, NASA, DOE, and many commercial customers. These efforts have included the development of rotation, acceleration, acoustic, vibration, pressure, temperature, strain, corrosion, and moisture sensors. The fields of application he has supported include aerospace, naval applications, ground vehicles, civil structures, medical applications, machining, composite manufacturing, oil and gas exploration and extraction, and energy and environmental monitoring.

Mr. Udd has 44 issued U.S. Patents and several more pending on fiber optic technology, has written and presented over 150 papers, and has chaired over 30 international conferences on fiber optic sensor technology. He has edited and contributed chapters to many books on fiber optic sensors. Mr. Udd is a Fellow and has served as a Director of SPIE—the International Society of Optical Engineering. He is a Fellow of the Optical Society of America (OSA) and a member of IEEE and LEOS. Mr. Udd was the 2009 Recipient of the David Richardson Medal from OSA for his work on "Fiber optic sensors and the field of fiber optic smart structures."

Bill Spillman received his Ph.D. from Northeastern University in 1977 in experimental solid-state physics. The title of his thesis was "Low-temperature high-pressure dielectric measurements of the paraelectric–ferroelectric phase transition in the hydrogen-bonded arsenates and their deuterated isomorphs." Since that time he worked in industry at the Sperry Corporate Research Center, Geo-Centers, Inc., Hercules Inc., and the Goodrich Corporation prior to joining Virginia Tech as an Associate Professor of Physics and Director of the Virginia Tech Applied Biosciences Center in 1999. He has now retired from Virginia Tech but remains active as a technical consultant to a number of firms and as an expert witness. He has been involved with the fields of fiber optic sensing and smart structures since their beginning up to the present day. He has been awarded 46 U.S. and 51 non-U.S. patents and is the author or coauthor of more than 180 technical publications, 16 book chapters and edited proceedings, and 2 video short courses. He was a coeditor of the CRC Press Sensors Series of Monographs and has served on the editorial boards of the journals *Measurement Science & Technology*, *Optical Engineering*, *Smart Materials and Structures*, *Journal of Optics A: Pure and Applied Optics*, and the *International Journal of Optomechatronics*. In 1997, Bill was elected a Fellow of the SPIE. He was elected a Fellow and Chartered Physicist in 2001 and a Chartered Scientist in 2004 by the Institute of Physics in the United Kingdom. In 2006, Bill was given a lifetime achievement award by the SPIE for his work on smart materials and structures.

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CONTENTS

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THE EMERGENCE OF FIBER OPTIC SENSOR TECHNOLOGY

Eric Udd
Columbia Gorge Research, Fairview, Oregon

Telecommunications have been revolutionized by fiber optic technology. The revolution began with limited system applications needing superior performance provided by fiber optics. The revolution became a rout as mass production techniques coupled with technical improvements resulted in superior performance at lower cost than those of alternative approaches. Simultaneous improvements and cost reductions in optoelectronic components in combination with mass commercial production led to similar displacements and the emergence of new product areas, including compact disc players, personal copiers, and laser printers. A third revolution is emerging as designers combine the product outgrowths of fiber optic telecommunications with optoelectronic devices to create fiber optic sensors.

The areas of opportunity are staggering and include the potential of replacing the many of the environmental sensors in existence today as well as opening up entirely new markets where sensors with comparable capability do not exist. Figures 1.1–1.3 provide an overview of the types of fiber optic sensors that are being developed and the environmental parameters that are most often associated with each type of sensor. The chapters of this book that correspond to each of the sensors are also indicated. Figure 1.1 lays out the various types of extrinsic or hybrid fiber optic sensors. Extrinsic fiber optic sensors are distinguished by the characteristic that sensing takes place in a region outside the fiber. Hybrid fiber optic sensors are similar and can be thought of as a "black box" sensor for which fibers are used to carry light to the box and data

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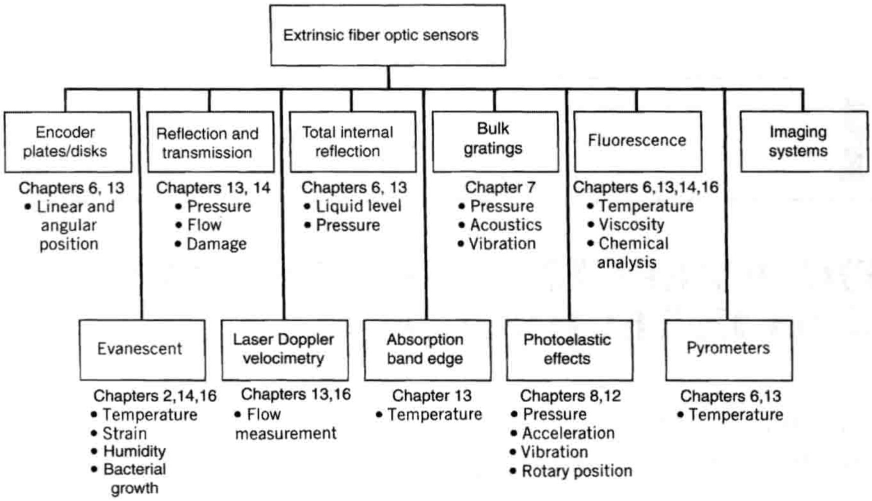

Figure 1.1 Extrinsic or hybrid fiber optic sensors: light transmits into and out of the fiber to reach the sensing region.

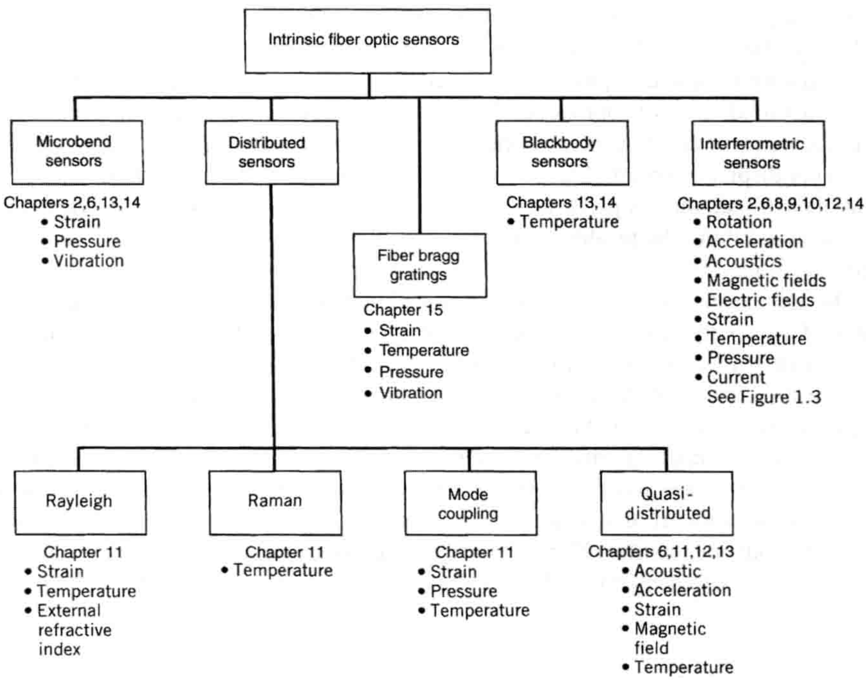

Figure 1.2 Intrinsic or all-fiber fiber optic sensors: the environmental effect is converted to a light signal within the fiber.

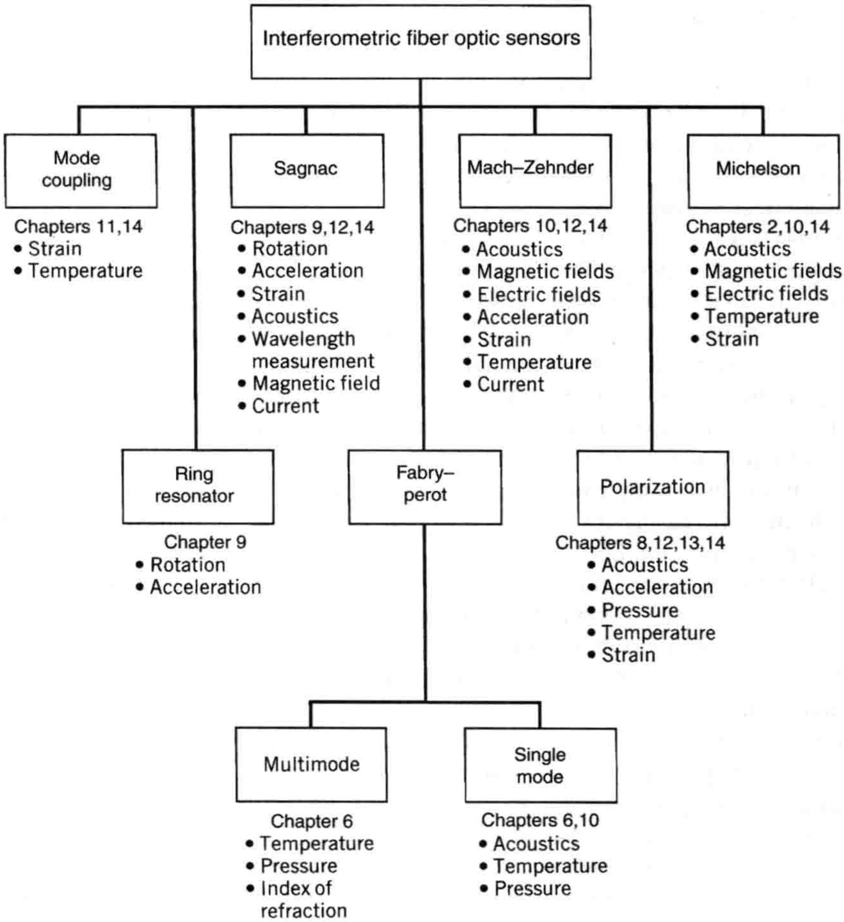

Figure 1.3 Interferometeric fiber sensors.

back. For most cases, the two terms can be applied interchangeably. A major distinction arises for the case of power by light sensors when a light beam is used to power an electronic sensor and data are carried back via a fiber optic data link. In this case, the hybrid designation would appear to be more appropriate.

Figure 1.2 shows a diagram illustrating many of the intrinsic or all-fiber-optic sensors. "Intrinsic" and "all-fiber" indicate that the sensing takes place within the fiber itself. In this case, the two designations can be and are commonly used interchangeably. A large and important subclass of intrinsic or all-fiber sensors is the interferometric sensors of shown in Fig. 1.3. Many of the highest-performance sensors fall into this group. The fiber sensors of Figs. 1.1–1.3 have been grouped into categories that are representative of their most common current state of development. Crossovers may occur; perhaps the most important example is the case of the interferometric sensors, many of which have been or are still being built in extrinsic or hybrid form.

From Figs. 1.1–1.3, it is apparent that virtually any environmental effect that can be conceived of can be converted to an optical signal to be interpreted. The usual case is that each environmental effect may be measured by dozens of fiber optic sensor approaches. The key is often to design the sensor so that only the desired environmental effect is measured.

Initial penetration of fiber optic sensors into markets has been driven by performance advantages. Some of these advantages are compared to conventional electronic sensors in Table 1.1. Fiber optic sensors offer an all-passive dielectric approach that is often crucial to successful applications, including electrical isolation of patients in medicine, elimination of conductive paths in high-voltage environments, and compatibility with placement in materials. The light weight and small size of these devices are critical to such areas as aerospace and provide substantial advantages to many products. Coupled to the issue of size and weight is immunity to electromagnetic interference. Conventional electrical sensors often require heavy shielding, significantly increasing cost, size, and weight. Environmental ruggedness provides key opportunities for fiber optic sensors, including high-temperature operation and all-solid-state configurations capable of withstanding extreme vibration and shock levels. Complementing these attributes are high sensitivity and bandwidth of fiber optic sensors. When multiplexed in arrays of sensors, the large bandwidth of the optical fibers offers distinct advantages in their ability to transport the resultant data.

Early work on fiber optic sensors generally fell into two distinct categories. Relatively simple fiber optic sensors were developed rapidly into commercial products, often by small firms, to perform measurements in specialized markets. An early example was the measurement of temperature in high-voltage environments. More complex fiber sensors such as fiber optic gyroscopes and acoustic hydrophones arrays were pursued by large industrial firms, complemented by government programs in an effort to access potentially large, high-payoff markets. Initial penetration into markets directly competing with conventional sensor technology from 1980 to 2000 was slow, due largely to the high cost of a limited

TABLE 1.1 Advantages of Fiber Optic Sensors

Passive (all-dielectric)
Light weight
Small size
Immunity to electromagnetic interference
High-temperature performance
Large bandwidth
Environmental ruggedness to vibration and shock
High sensitivity
Electrical and optical multiplexing
Component costs driven by large commercial telecommunication and optoelectronic market