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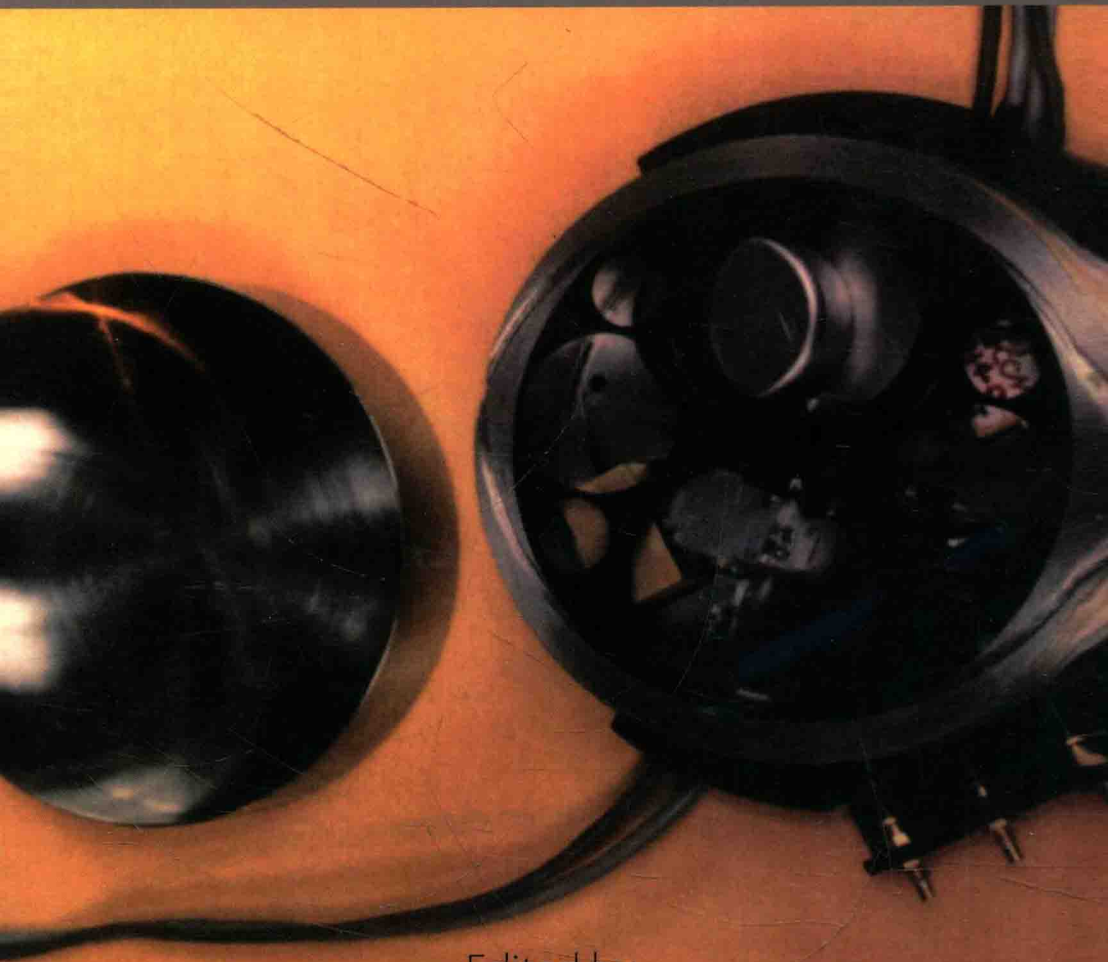
FIBER OPTIC SENSORS

An Introduction for Engineers and Scientists



Edited by

Eric Udd

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Fiber Optic Sensors

An Introduction for Engineers and Scientists

EDITED BY ERIC UDD

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Fiber Optic Sensors

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Preface

For many applications ideal sensors would have such attributes as low weight, small size, low power, environmental ruggedness, immunity to electromagnetic interference, good performance specifications, and low cost. As technology has advanced, the need for these sensors has become increasingly acute in such areas as aerospace, defense, manufacturing, medicine, and construction. The convergence of fiber optic technology, which was largely driven by the telecommunication industry in the 1970s and 1980s, in combination with low-cost optoelectronic components for such commercial markets as compact disk players, personal copiers, and laser printers, has enabled fiber optic sensor technology to approach its ideal potential for many applications.

This book provides engineers, scientists, graduate students, and advanced undergraduates with an introduction to the rapidly emerging field of fiber optic sensors. I began to work on this book in 1981; however, because of the rapid expansion of the field from a few workers scattered worldwide in the late 1970s to thousands of active participants by the late 1980s, it became increasingly difficult for one person alone to produce a book that was both current and of sufficient depth. This led to my decision in early 1987 to solicit help from my colleagues in the fiber optic sensor field to generate this book by writing chapters on their own areas of expertise. I was extremely gratified that all of my first choices responded positively and with enthusiasm. Each contributor has worked extensively in the fiber optic sensor field, and many have produced extensive collections of internationally recognized work. Insofar as possible, each contributor endeavored to make his chapter independent so that the book can serve as a ready reference. At the same time, the book follows the outline of the original introductory text I was preparing, which in turn has been used to support short courses I have taught with considerable success at UCLA, Optical Engineering Conferences, and McDonnell Douglas. Thus the book can also be used to support advanced undergraduate and graduate-level science and engineering courses as well as industrial seminars on fiber optic sensors.

The book begins with an introduction and overview of critical components utilized by fiber optic sensors. This part of the book, which includes the first five chapters, covers optical fibers, light sources, detectors, and optical modulators and serves the dual purpose of introducing the fundamental building blocks of fiber optic sensors and pointing out many of the connections between these elements and fiber optic sensor technology. These connections are then reinforced and expanded on in later sections of the book. Many aspects of these chapters may also be of interest to readers wanting to expand their background in telecommunications, as these basic components form the heart of most conventional and advanced telecommunication systems. In Chapter 1, Eric Udd provides a brief overview of the emergence of fiber optic sensor technology and predictions on where it may be headed. Chapter 2, on optical fibers, by Paul Blaszyk, Dan Nolan, and Eric Udd 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, by Eric Udd is a brief introduction to these components from the point of view of a fiber optic sensor developer. In Chapter 4, Bill Spillman writes about optical detectors from a similar point of view. Chapter 5, on optical modulators, by Len Johnson describes both bulk and integrated optical modulators used for phase and frequency shifting.

The second section of the book covers fiber optic sensors. The section begins with a discussion of extrinsic or hybrid fiber optic sensors. For these types of fiber optic sensors, the fiber carries a signal to and from an optical black box that impresses information onto the light beam, often in the form of amplitude or polarization modulation. Chapter 6, by Gordon Mitchell, opens with an overview of intensity sensors for monitoring temperature, position, and other environmental effects, followed by a more detailed discussion of the Fabry–Perot-based fiber optic sensor, which is one of the earliest fiber optic sensors to be exploited successfully commercially. In Chapter 7, Bill Spillman discusses the grating-based fiber optic sensor, which has been used for hydrophones and displacement sensors. This is followed by Chapter 8, also by Bill Spillman, which provides an excellent introduction to polarization and describes the effectiveness of this approach in implementing a powerful class of fiber optic sensors. Intrinsic or all-fiber sensors are covered in Chapters 9 through 11 where the sensing takes place through the interaction of a light beam with an environmentally perturbed optical fiber. The environmental effect for this type of sensor is usually based on changes in the effective optical path length of the light beam as a consequence of its action on the optical fiber. The net result is a phase shift that can be measured to a high degree of accuracy using interferometric techniques. These fiber sensors have the potential for extremely high performance and may replace entire classes of high-value sensors in use today.

In Chapter 9, Eric Udd describes the Sagnac interferometer and passive ring resonator classes of sensors, which may be used as rotation sensors to replace existing gyroscopes. This promises to be one of the highest-value applications of fiber optic sensors, with markets valued in many hundreds of millions of dollars. These sensors may also be used to sense other environmental effects, and the techniques for doing so are reviewed. In Chapter 10, Tony Dandridge describes the Mach–Zehnder and Michelson interferometers, which have important applications in undersea acoustic sensing. These sensors offer extraordinary sensitivity and have the potential of being multiplexed into arrays of hundreds of sensors. In Chapter 11, Alan Kersey proceeds to describe these multiplexing techniques as well as distributed fiber optic sensing, which offers an important alternative to arrays of sensors for many applications.

The final section of the book illustrates the potential of fiber optic sensor technology by focusing on specific applications. In Chapter 12, Frank Bucholtz provides a detailed description and examples of magnetic sensors based on the Faraday effect, magnetostriction, and Lorentz forces. These sensors are already in use monitoring current for electrical utilities and offer the prospect of widespread commercial and military use. John Berthold follows in Chapter 13 with an overview of the many uses of fiber optic technology in industry. Included in this chapter are examples of temperature, pressure, fluid level, flow, position, vibration, chemical analysis, and current–voltage measurements, followed by a discussion of issues associated with the industrial application of fiber optic sensor technology. The book concludes with Chapter 14, in which Eric Udd provides an overview of the emerging field of fiber optic smart structures. This field merges fiber optic sensor technology with the mechanical and material sciences to form one of the most exciting and rapidly growing development areas.

An undertaking of this sort would not have been possible without the efforts and support of many people. First and foremost I would like to thank my contributors, who dedicated themselves to delivering high-quality manuscripts in a timely manner. I would also like to thank my patient editors at John Wiley & Sons, especially Ms. Beatrice Shube for her early effort in helping me initiate this book and to Mr. George Telecki for helping me finish it. McDonnell Douglas has continually supported my efforts to develop fiber optic technology, and I would like to acknowledge management support from my friend and mentor Richard Cahill, Dr. Roger Roberts, Gerald Johnston, William Branch, Charlie Marvin, Dave Karnes, Ken Francis, Dan Green, and many others. I am also heavily indebted to my coworkers at McDonnell Douglas, especially John Paul

Theriault, Stuart Higley, Dr. Steve Watanabe, Dr. Wil Otaguro, Dave Tubbs, Dr. John Gallager, Al Joseph, Dr. Herb Smith, Jeff Russom, Ric Baldini, Tim Clark, Tom Weaver, Jim Moore, John Marcin, Ray Wagoner, and the nearly two hundred other teammates of the McDonnell Douglas Fiber Optic Working Group. My wife, Holly, and daughters, Emelia and Ingrid, are owed my thanks for being patient with my efforts.

Finally, I would like to dedicate my part in bringing this book to reality to the memory of Dr. Wolfgang K. Schuebel of Wright-Patterson Air Force Base, who championed fiber optic gyro development in the United States.

Huntington Beach, California ERIC UDD

Fiber Optic Sensors

Contents

1

The Emergence of Fiber Optic Sensor Technology

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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 majority of environmental sensors in existence today as well as opening up entire markets where sensors with comparable capability do not exist. Figures 1.1 through 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

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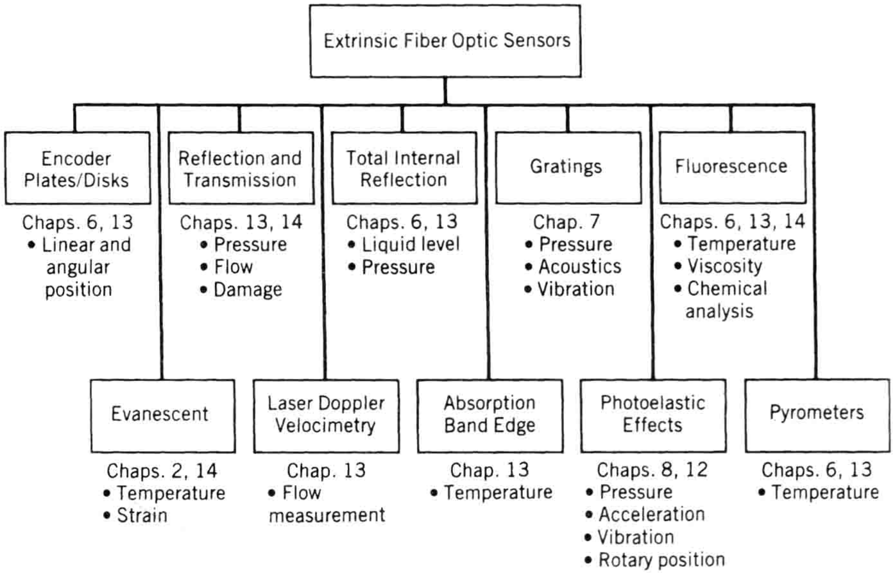

Figure 1.1. Extrinsic or hybrid fiber optic sensors: light transits into and out of the fiber to reach the sensing region.

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 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 commonly are used interchangeably. A large and important subclass of intrinsic or all-fiber sensors are the interferometric sensors of Fig. 1.3. Many of the highest-performance sensors fall into this group. The fiber sensors of Figs. 1.1 through 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 interferometric sensors, many of which have been or are still being built in an extrinsic or hybrid form.

From Figs. 1.1 through 1.3 it is apparent that virtually any environmental effect that can be conceived of can be converted to an optical signal to