Field Guide to

Fiber Optic Sensors

William B. Spillman, Jr.
Eric Udd

SPIE Field Guides
Volume FG34

John E. Greivenkamp, Series Editor

SPIE PRESS
Bellingham, Washington USA

Library of Congress Preassigned Control Number Data

Spillman, William B., author.
Field Guide to Fiber Optic Sensors / William B. Spillman, Jr. and Eric Udd
pages cm. – (The field guide series; FG34)
Includes bibliographical references and index.
ISBN 978-1-62841-334-2
1. Fiber optics–Design and application. 2. Sensor design. I. Title.
TA1800 2014
681.2–dc23

2014954702

Published by

SPIE
P.O. Box 10
Bellingham, Washington 98227-0010 USA
Phone: 360.676.3290
Fax: 360.647.1445
Email: Books@spie.org
www.spie.org

Copyright © 2014 Society of Photo-Optical Instrumentation Engineers (SPIE)

All rights reserved. No part of this publication may be reproduced or distributed in any form or by any means without written permission of the publisher.

The content of this book reflects the thought of the author(s). Every effort has been made to publish reliable and accurate information herein, but the publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Printed in the United States of America.
First printing.

SPIE.

Introduction to the Series

Welcome to the *SPIE Field Guides*—a series of publications written directly for the practicing engineer or scientist. Many textbooks and professional reference books cover optical principles and techniques in depth. The aim of the *SPIE Field Guides* is to distill this information, providing readers with a handy desk or briefcase reference that provides basic, essential information about optical principles, techniques, or phenomena, including definitions and descriptions, key equations, illustrations, application examples, design considerations, and additional resources. A significant effort will be made to provide a consistent notation and style between volumes in the series.

Each *SPIE Field Guide* addresses a major field of optical science and technology. The concept of these *Field Guides* is a format-intensive presentation based on figures and equations supplemented by concise explanations. In most cases, this modular approach places a single topic on a page, and provides full coverage of that topic on that page. Highlights, insights, and rules of thumb are displayed in sidebars to the main text. The appendices at the end of each *Field Guide* provide additional information such as related material outside the main scope of the volume, key mathematical relationships, and alternative methods. While complete in their coverage, the concise presentation may not be appropriate for those new to the field.

The *SPIE Field Guides* are intended to be living documents. The modular page-based presentation format allows them to be updated and expanded. We are interested in your suggestions for new *Field Guide* topics as well as what material should be added to an individual volume to make these *Field Guides* more useful to you. Please contact us at **fieldguides@SPIE.org**.

John E. Greivenkamp, *Series Editor*
College of Optical Sciences
The University of Arizona

Keep information at your fingertips with the SPIE Field Guides:

- *Adaptive Optics*, Second Edition, Robert Tyson & Benjamin Frazier
- *Atmospheric Optics*, Larry Andrews
- *Binoculars and Scopes*, Paul Yoder, Jr. & Daniel Vukobratovich
- *Diffractive Optics*, Yakov Soskind
- *Digital Micro Optics*, Bernard Kress
- *Displacement Measuring Interferometry,* Jonathan Ellis
- *Fiber Optic Sensors*, William Spillman, Jr. & Eric Udd
- *Geometrical Optics*, John Greivenkamp
- *Holography*, Pierre Alexandre Blanche
- *Illumination*, Angelo Arecchi, Tahar Messadi, & John Koshel
- *Image Processing*, Khan M. Iftekharuddin & Abdul Awwal
- *Infrared Systems, Detectors, and FPAs*, Second Edition, Arnold Daniels
- *Interferometric Optical Testing*, Eric Goodwin & Jim Wyant
- *Laser Pulse Generation*, Rüdiger Paschotta
- *Lasers*, Rüdiger Paschotta
- *Lens Design*, Julie Bentley & Craig Olson
- *Microscopy*, Tomasz Tkaczyk
- *Nonlinear Optics*, Peter Powers
- *Optical Fabrication*, Ray Williamson
- *Optical Fiber Technology*, Rüdiger Paschotta
- *Optical Lithography*, Chris Mack
- *Optical Thin Films*, Ronald Willey
- *Optomechanical Design and Analysis*, Katie Schwertz & James Burge
- *Physical Optics*, Daniel Smith
- *Polarization*, Edward Collett
- *Probability, Random Processes, and Random Data Analysis*, Larry Andrews
- *Radiometry*, Barbara Grant
- *Special Functions for Engineers*, Larry Andrews
- *Spectroscopy*, David Ball
- *Terahertz Sources, Detectors, and Optics*, Créidhe O'Sullivan & J. Anthony Murphy
- *Visual and Ophthalmic Optics*, Jim Schwiegerling

Fiber optic sensor work began in the mid-1970s with a variety of multimode fiber optic sensors and early iterations of Sagnac and Mach–Zehnder interferometers. Concerted efforts developed fiber optic gyros and acoustics sensors in the form of hydrophones; fiber gyros are currently used for aircraft and spacecraft navigation, including the Spirit and Opportunity rovers on Mars. They are used for naval and land navigation, in robots that mow soccer fields and clean floors, and in remote-controlled helicopters that spray crops. Acoustic technology originally developed for undersea surveillance is now used to support oil and gas exploration and extraction operations.

In the mid-1980s the field of fiber optic smart structures emerged as a way to monitor the health and integrity of structures through the manufacturing process, during installation, and throughout the lifetime of the structure. Distributed sensors based on Raman and Brillouin scattering have been used to support cure monitoring on large concrete structures such as dams and to monitor oil holes and pipelines.

The continued improvement and reduction in costs associated with fiber optic technology associated with fiber sensors permit application areas that were previously inaccessible. These trends are expected to continue as new techniques become available and older ones are successfully adapted to new applications.

This Field Guide provides a broad introduction to a variety of fiber optic sensors that have been successfully developed from the 1970s to the present. We hope that the included examples inspire readers with ideas for new sensors and applications.

William B. Spillman, Jr.
Floyd, Virginia

Eric Udd
Fairview, Oregon

Table of Contents

Glossary xi

Introduction 1
- What Is a Fiber Optic Sensor? 1
- Why Use a Fiber Optic Sensor? 2
- Light as an Electromagnetic Wave 3
- Light Modulation 4
- Optical Signal-to-Noise Ratio 5
- Transduction 6
- Some Optical Transducer Mechanisms 7

Components 8
- Optical Fibers and Modes 8
- Optical Fiber Types 9
- Light-Emitting Diode 10
- Semiconductor Laser Diode 11
- Photodiode Detector 12
- Avalanche Photodiode Detector 13
- Color Sensors 14
- Connectors and Splices 15
- Lenses and GRIN Lenses 16
- Waveplates 17
- Polarizers 18
- Diffraction Gratings 19
- Fiber Bragg Gratings 20
- Modulators 21

Sensor Design 22
- Specification and Transducer Selection 22
- Component Selection 23
- Sensor Modeling 24

Intrinsic Multimode Sensors 25
- FTIR Sensor Theory 25
- FTIR Hydrophone 26
- FTIR Fluid-Level Sensor 27
- Microbend Sensor Theory 28
- Microbend Pressure Sensor 29
- Macrobend Sensor Theory 30

Table of Contents

Macrobend Pressure Sensor 31
Modal Domain Sensor Theory 32
Modal Domain Vibration Sensor 33

Extrinsic Multimode Sensors 34
In-Line Fiber Coupling Theory 34
Fiber Coupling Pressure Sensor 35
Polarization Theory 36
Polarization Rotation Sensor 37
Photoelastic Sensor Theory 38
Photoelastic Pressure and Acoustic Sensing 39
Diffraction Grating Theory 40
Diffraction Grating Rotation Sensor 41
Schlieren Grating Theory 42
Schlieren Displacement and Acoustic Sensors 43
Chirped Grating Sensor Theory 44
Chirped Grating Displacement Sensor 45
Magneto-Optic Sensor Theory 46
Magneto-Optic Speed Sensor 47
Optrode Sensor Theory 48
Optrode pH Sensor 49
Fluorescence Theory 50
Fluorescence Temperature Sensor 51
Blackbody Theory 52
Blackbody Temperature Sensor 53
Optical Time Domain Reflectometry Theory 54
Optical Time Domain Wavefront Speed Detector 55
Evanescent-Wave Theory 56
Evanescent-Wave Chemical Sensor 57

Interferometers 58
Single-Mode Interferometers 58
Mach–Zehnder Interferometers 59
Mach–Zehnder Hydrophone 60
Mach–Zehnder Transducer Geometries 61
Michelson Interferometer 62
Sagnac Theory 63

Table of Contents

Sagnac Rotation Sensor/Fiber Optic Gyro 64
Sagnac Acoustic Sensor 65
Sagnac Interferometer Strain Sensor 66

Bragg Gratings 67
Bragg Grating Fabrication 67
Bragg Grating Theory 68
Bragg Grating Simultaneous Strain and Temperature 69
Bragg Grating Transverse Strain 70
Bragg Grating Pressure Sensor 71

Fiber Etalon 72
Fiber Etalon Theory 72
Fiber Etalon Sensors 73

Multiplexing 74
Time Division Multiplexing 74
Wavelength Division Multiplexing 75
Optical Frequency Domain Reflectometry 76
Frequency Division Multiplexing 77
Coherence Multiplexing 78
Spatial Multiplexing 79

Distributed Sensors 80
Distributed Raman Sensor 80
Distributed Brillouin Sensor 81
Brillouin Distributed Sensor Capabilities 82
Distributed Sagnac Sensor 83
Distributed Sagnac–Mach–Zehnder Sensor 84

Applications 85
Sagnac Secure-Communication System 85
Low-Coherence Strain-Sensor System 86
Civil Structure Applications 87
Damage-Assessment Microbend Sensor 88
Position Sensors 89

Table of Contents

Smart Bed 90
Catheter Shape Sensing 91
Radiation Dosage Sensing 92
Proximity Fiber Sensors 93
Oil and Gas Applications 94
Strain Imaging and Monitoring Composite Materials 95
Plastic Optical Fibers 96
Integrated Optics 97
Fiber Light Sources 98
Polarization-Preserving Optical Fibers 99
Fiber Depolarizer 100

Useful Techniques 101
Manually Scribing and Breaking a Fiber 101
Using UV Curing Epoxy 102
Experimental Use of a Lock-In Amplifier 103

Equation Summary 104

Bibliography 110

Index 114

Glossary

a	Fiber core radius
A	Amplitude or some constant value
APD	Avalanche photodiode
B	Bandwidth
$\mathbf{B}$	Magnetic flux vector
c	Speed of propagation of an electromagnetic wave
c_e	Effective speed of light
d	Grating period, Bragg grating period, or lateral misalignment
d_0, d_1	Chirped grating parameters
D_i	Distance from a photodetector to the i^{th} element
d_{ij}	Distance between optical elements i and j
e	Electric charge or base of natural logarithms
$\mathbf{E}$	Electric-field vector
EH	Hybrid mode with more electric field than magnetic field $\perp$ to the direction of propagation
f	Frequency (in Hertz), or the lens focal length
F	Finesse
F	Power emitted by a blackbody
FBG	Fiber Bragg grating
f_D	Disk rotation frequency
FDM	Frequency division multiplexing
f_M	Modulation frequency
FTIR	Frustrated total internal reflection
f_σ	Material stress-optic coefficient
Ge	Germanium
GRIN	Graded index
h	Height
h	Planck's constant
HE	Hybrid mode with more magnetic field than electric field $\perp$ to the direction of propagation
He-Ne	Helium-neon
I	Optical power
i_0	Reverse "dark current"
I_B	Background optical power
I_d	Dark current
i_s	Photocurrent
$\mathbf{k}$	Wave vector

Glossary

k_B	Boltzman's constant
L	Length of a GRIN lens
LED	Light-emitting diode
m	Diffraction order
n	Index of refraction
N	Number of slots around a disk edge, or number of excited electrons
NA	Optical-fiber numerical aperture
n_{eff}	Effective index of refraction
OD	Optical density
OFDR	Optical frequency domain reflectometry
OTDR	Optical time domain reflectometry
p	Pitch of a GRIN lens
P	Pressure or detected optical power
PD	Photodiode
P_e	Photoelastic constant
P_{min}	Minimum detectable acoustic pressure
PVF	Polyvinyl fluoride
r	$\perp$ distance from optical axis
$\mathbf{r}$	Position vector
R	Electrical resistance or responsivity
R	Reflectivity
R_E, R_T	Fluorescent decay constants
RGB	Red–green–blue
R_p	p-polarized intensity reflectivity
R_s	s-polarized intensity reflectivity
s	Optical fiber longitudinal misalignment
s_1	Distance of an object from the center of a lens
s_2	Distance of an image from the center of a lens
S_n	Fluorescent signal level
SNR	Signal-to-noise ratio
t	Time
T	Absolute temperature
T_A	Fiber axial displacement fractional transmission
TDM	Time division multiplexing
TE	Mode with an electric field $\perp$ to the direction of propagation
TEM	Mode with both magnetic and electric fields $\perp$ to the direction of propagation

Glossary

T_i	Transducer function
TIR	Total internal reflection
T_L	Fiber longitudinal fractional transmission
TM	Mode with magnetic field ⊥ to the direction of propagation
UV	Ultraviolet
V	V-number, or voltage
V_B	Reverse bias voltage
VOD	Velocity of detonation
V_R	Voltage from a reference photodetector
W	Watts
WDM	Wavelength division multiplexing
z	FTIR variable
α	Fractional transmission factor, fluorescent decay probability, or thermal expansion coefficient
α_m	Angle of the m^{th} diffraction order
β	Mode-propagation constant, or FTIR variable
ΔE	Energy-level difference in fluorescent decay
ε	Dielectric permittivity, or mechanical strain
ζ	Thermo-optic coefficient
η	Quantum efficiency
θ	Angle
θ_D	Angle of diffraction
λ	Wavelength
λ_B	Wavelength Bragg grating maximum reflection
Λ	Microbend optimum deformer spacing
μ	Magnetic susceptibility
μW	Microwatts
σ	Linear stress
τ	e^{-1} fluorescent decay time
ϕ	Phase
ω	Angular frequency in radians/sec