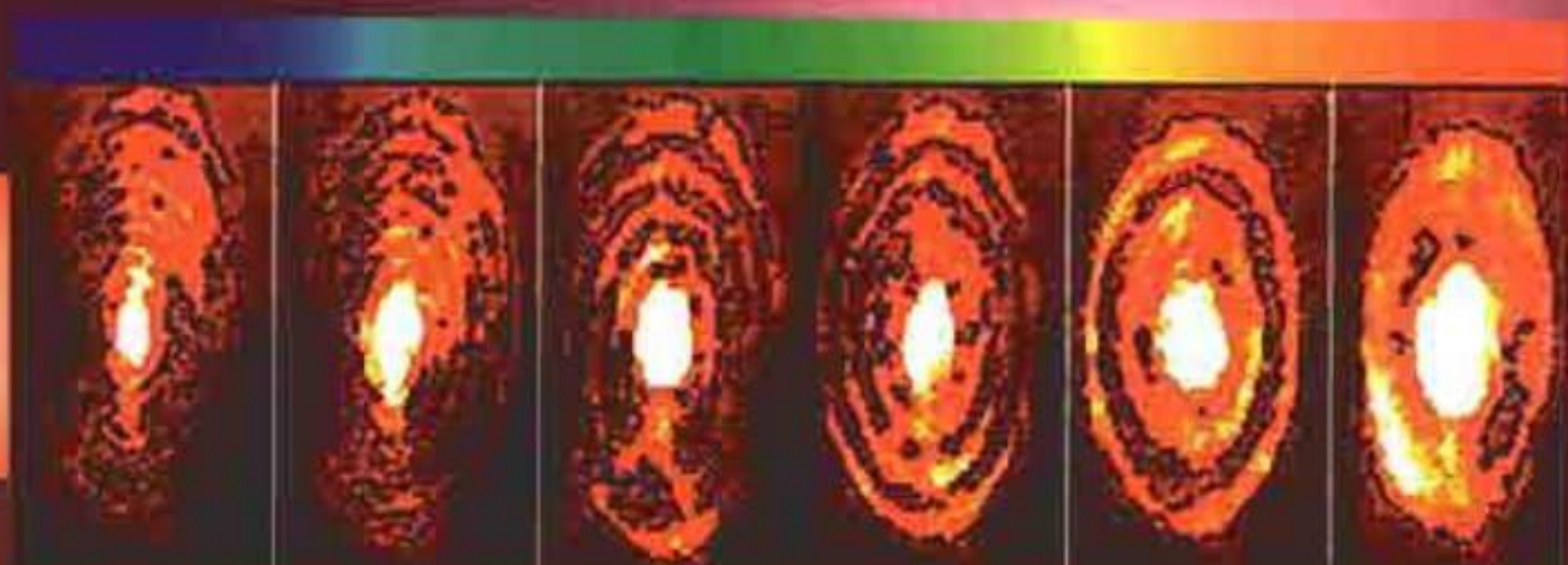


# FIBER BRAGG GRATINGS

RAMAN KASHYAP



1542.12nm

1542.35nm

1542.99nm

1543.25nm

1543.34nm

1543.51nm

OPTICS AND PHOTONICS



# **Fiber Bragg Gratings**

# **OPTICS AND PHOTONICS**

(formerly Quantum Electronics)

**EDITED BY**

**PAUL L. KELLY**

*Tufts University  
Medford, Massachusetts*

**IVAN KAMINOW**

*Lucent Technologies  
Holmdel, New Jersey*

**GOVIND AGRAWAL**

*University of Rochester  
Rochester, New York*

A complete list of titles in this series appears at the end of this volume.

# Fiber Bragg Gratings

***Raman Kashyap***

*BT Laboratories, Martlesham Heath  
Ipswich, United Kingdom*



ACADEMIC PRESS

San Diego London Boston  
New York Sydney Tokyo Toronto

The cover picture shows the near-field photographs of radiation mode patterns of several low-order counterpropagating modes ( $LP_{0n}$ ). These are excited by the forward propagating core mode in a 6-mm-long, side-tap grating with a  $2^\circ$  blaze angle, written into the core of a single mode fiber. *Artwork by Arjun Kashyap.*

This book is printed on acid-free paper. ©

Copyright © 1999 by Academic Press  
All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in writing from the publisher.

ACADEMIC PRESS  
*a division of Harcourt Brace & Company*  
525 B Street, Suite 1900, San Diego, CA 92101-4495, USA  
<http://www.apnet.com>

ACADEMIC PRESS  
24-28 Oval Road, London, NW1 7DX, UK  
<http://www.hbuk.co.uk/ao/>

Library of Congress Catalog Card Number: 99-60954

International Standard Book Number: 0-12-400560-8

Printed in the United States of America

99 00 01 02 03 IP 9 8 7 6 5 4 3 2 1

*For Monika, Hannah, and in memory of  
Prof. Kedar Nath Kashyap*

*This page intentionally left blank*

# Contents

<b>Preface</b>	<b>xiii</b>
<b>Chapter 1 Introduction</b>	<b>1</b>
1.1 Historical perspective	2
1.2 Materials for glass fibers	4
1.3 Origins of the refractive index of glass	6
1.4 Overview of chapters	8
References	10
<b>Chapter 2 Photosensitivity and Photosensitization of Optical Fibers</b>	<b>13</b>
2.1 Photorefractivity and photosensitivity	14
2.2 Defects in glass	16
2.3 Detection of defects	19
2.4 Photosensitization techniques	20
2.4.1 Germanium-doped silica fibers	21
2.4.2 Germanium–boron codoped silicate fibers	27
2.4.3 Tin–germanium codoped fibers	29
2.4.4 Cold, high-pressure hydrogenation	29
2.4.5 Rare-earth-doped fibers	34
2.5 Densification and stress in fibers	35
2.6 Summary of photosensitive mechanisms in germanosilicate fibers	36
2.7 Summary of routes to photosentization	38
2.7.1 Summary of optically induced effects	42
References	44
<b>Chapter 3 Fabrication of Bragg Gratings</b>	<b>55</b>
3.1 Methods for fiber Bragg grating fabrication	55



3.1.1	The bulk interferometer	55
3.1.2	The phase mask	57
3.1.3	The phase mask interferometer	62
3.1.4	Slanted grating	69
3.1.5	The scanned phase mask interferometer	71
3.1.6	The Lloyd mirror and prism interferometer	74
3.1.7	Higher spatial order masks	77
3.1.8	Point-by-point writing	80
3.1.9	Gratings for mode and polarization conversion	80
3.1.10	Single-shot writing of gratings	83
3.1.11	Long-period grating fabrication	84
3.1.12	Ultralong-fiber gratings	85
3.1.13	Tuning of the Bragg wavelength, moiré, Fabry–Perot, and superstructure gratings	88
3.1.14	Fabrication of continuously chirped gratings	93
3.1.15	Fabrication of step-chirped gratings	99
3.2	Type II gratings	101
3.3	Type IIA gratings	101
3.4	Sources for holographic writing of gratings	102
3.4.1	Low coherence sources	102
3.4.2	High coherence sources	104
	References	108
<b>Chapter 4 Theory of Fiber Bragg Gratings</b>		<b>119</b>
4.1	Wave Propagation	121
4.1.1	Waveguides	122
4.2	Coupled-mode theory	125
4.2.1	Spatially periodic refractive index modulation	127
4.2.2	Phase matching	130
4.2.3	Mode symmetry and the overlap integral	131
4.2.4	Spatially periodic nonsinusoidal refractive index modulation	133
4.2.5	Types of mode coupling	134
4.3	Coupling of counterpropagating guided modes	142
4.4	Codirectional coupling	145
4.5	Polarization couplers: Rocking filters	148
4.6	Properties of uniform Bragg gratings	152
4.6.1	Phase and group delay of uniform period gratings	155

4.7	Radiation mode couplers	157
4.7.1	Counterpropagating radiation mode coupler: The side-tap grating	157
4.7.2	Copropagating radiation mode coupling: Long- period gratings	171
4.8	Grating simulation	178
4.8.1	Methods for simulating gratings	178
4.8.2	Transfer matrix method	179
4.9	Multilayer analysis	185
4.9.1	Rouard's method	185
4.9.2	The multiple thin-film stack	186
	References	189
<b>Chapter 5 Apodization of Fiber Gratings</b>		<b>195</b>
5.1	Apodization shading functions	197
5.2	Basic principles and methodology	199
5.2.1	Self-apodization	200
5.2.2	The amplitude mask	203
5.2.3	The variable diffraction efficiency phase mask	205
5.2.4	Multiple printing of in-fiber gratings applied to apodization	206
5.2.5	Position-weighted fabrication of top-hat reflection gratings	208
5.2.6	The moving fiber/phase mask technique	211
5.2.7	The symmetric stretch apodization method	216
5.3	Fabrication requirements for apodization and chirp	221
	References	223
<b>Chapter 6 Fiber Grating Band-pass Filters</b>		<b>227</b>
6.1	Distributed feedback, Fabry–Perot, superstructures, and moiré gratings	229
6.1.1	The distributed feedback grating	229
6.1.2	Superstructure band-pass filter	239
6.2	The Fabry–Perot and moiré band-pass filters	242
6.3	The Michelson interferometer band-pass filter	246
6.3.1	The asymmetric Michelson multiple-band-pass filter	255
6.4	The Mach-Zehnder interferometer band-pass filter	260

6.4.1	Optical add-drop multiplexers based on the GMZI-BPF	263
6.5	The optical circulator based OADM	265
6.5.1	Reconfigurable OADM	270
6.6	The polarizing beam splitter band-pass filter	272
6.7	In-coupler Bragg grating filters	276
6.7.1	Bragg reflecting coupler OADM	278
6.7.2	Grating-frustrated coupler	284
6.8	Side-tap and long-period grating band-pass filters	288
6.9	Polarization rocking band-pass filter	293
6.10	Mode converters	297
6.10.1	Guided-mode intermodal couplers	297
	References	300
<b>Chapter 7 Chirped Fiber Bragg Gratings</b>		<b>311</b>
7.1	General characteristics of chirped gratings	312
7.2	Chirped and step-chirped gratings	317
7.2.1	Effect of apodization	324
7.2.2	Effect of nonuniform refractive index modulation on grating period	330
7.3	Super-step-chirped gratings	332
7.4	Polarization mode dispersion in chirped gratings	336
7.5	Systems measurements with DCGs	339
7.5.1	Systems simulations and chirped grating performance	342
7.6	Other applications of chirped gratings	346
	References	347
<b>Chapter 8 Fiber Grating Lasers and Amplifiers</b>		<b>355</b>
8.1	Fiber grating semiconductor lasers: The FGSL	355
8.2	Static and dynamic properties of FGLs	362
8.2.1	Modeling of external cavity lasers	366
8.2.2	General comments on FGLs	369
8.3	The fiber Bragg grating rare-earth-doped fiber laser	370
8.4	Erbium-doped fiber lasers	372
8.4.1	Single-frequency erbium-doped fiber lasers	374
8.5	The distributed feedback fiber laser	377
8.5.1	Multifrequency sources	379
8.5.2	Tunable single-frequency sources	380

8.6	Bragg grating based pulsed sources	380
8.7	Fiber grating resonant Raman amplifiers	383
8.8	Gain-flattening and clamping in fiber amplifiers	385
8.8.1	Amplifier gain equalization with fiber gratings	387
8.8.2	Optical gain control by gain clamping	391
8.8.3	Analysis of gain-controlled amplifiers	395
8.8.4	Cavity stability	396
8.8.5	Noise figure	397
	References	398
<b>Chapter 9 Measurement and Characterization of Gratings</b>		<b>409</b>
9.1	Measurement of reflection and transmission spectra of Bragg gratings	410
9.2	Perfect Bragg gratings	417
9.3	Phase and temporal response of Bragg gratings	418
9.3.1	Measurement of the grating profile	426
9.3.2	Measurement of internal stress	432
9.4	Strength, annealing, and lifetime of gratings	435
9.4.1	Mechanical strength	435
9.4.2	Bragg grating lifetime and thermal annealing	436
9.4.3	Accelerated aging of gratings	440
	References	441
<b>Index</b>		<b>447</b>

*This page intentionally left blank*

# Preface

The field of fiber Bragg gratings is almost exactly twenty years old, dating back to its discovery by Ken Hill and co-workers in Canada. It grew slowly at first, but an important technological advance by Gerry Meltz and co-workers 10 years later, renewed worldwide interest in the subject. I was instrumental in setting up the first International Symposium on photosensitivity of optical fibers, jointly with Francois Ouellette in 1991, a meeting with 22 presentations and attended by approximately 50 researchers. Since, we have seen three further international conferences solely devoted to fiber Bragg gratings, the last of which was attended by approximately 300 researchers. As the applications of Bragg gratings are numerous, publications appear in widely differing conferences and journals. Surprisingly, apart from several review articles covering the most elementary aspects, no monograph is available on the subject and the quantity of available literature is spread across a number of specialist journals and proceedings of conferences. Thus, progress and the current state of the art are difficult to track, despite the approaching maturity of the field. More recently, poling of glass optical fibers has resulted in an electro-optic coefficient almost rivaling that of lithium niobate.

Germanium, the core dopant of low loss, fused silica optical fiber, is a rich defect former; ultraviolet radiation can strongly modify the nature of the defects causing large changes in the local refractive index. The mechanisms contributing to photosensitivity are complicated and still being debated. They depend on the types of defects present, dopants, and the presence of hydrogen whether in the molecular or in the ionic state. The lack of a thorough understanding has not, however, prevented the exploitation of the effect in a large number of applications. The very large index changes reported to date ( $\sim 0.03$ ) allow, for the first time, the fabrication of ultra-short ( $\sim 100 \mu\text{m}$  long) broadband, high-reflectivity Bragg gratings in optical fibers. The maximum index change may be an

order of magnitude larger still, leading to many more exciting possibilities. There are a number of methods of the holographic inscription of Bragg gratings, with the phase-mask technique holding a prominent position.

This book was born as a result of growing demands for yet more review articles on the subject. It aims to fill the gap by bringing together the fundamentals of fiber gratings, their specific characteristics, and many of the applications. The book covers much of the fundamental material on gratings and should be of interest to beginners, advanced researchers, as well as those interested in the fabrication of many types of gratings.

It is impossible to cover the massive advances made in this field in a book of this size, a field that continues to grow at an enormous rate despite recent commercialization. A large reference list is provided, to allow the interested reader to seek out specific topics in more detail. The purpose of this book is therefore to introduce the reader to the extremely rich area of the technology of fiber Bragg, with a view to providing insight into some of the exciting prospects. It begins with the principles of fiber Bragg gratings, photosensitization of optical fibers, Bragg grating fabrication, theory, properties of gratings, and specific applications, and concludes with measurement techniques.

*BT Laboratories,  
Ipswich IP5 3RE,  
United Kingdom  
July 1998*

*Raman Kashyap*

# Acknowledgments

I am grateful to many individuals who have either directly contributed to the book or so generously provided material for it. I thank the members of the European ACTS Program, PHOTOS, whose efforts have greatly contributed to the growing knowledge in this area. In particular, I am indebted to Marc Douay, Bertrand Poumellec, René Salathe, Pierre Sansonetti, Isabelle Riant, Fatima Bhakti, Hans Limberger, and Christian Bungarzaneau, for providing several original exemplary figures and simulations. I thank Ken Hill, Jacques Albert, Stanislav Chernikov, Turan Erdogan, Phillip Russell, Feodor Timofeev, Malin Permanante, Raoul Stubbe, Vince Handerek, Sotiris Kanellopoulos, Tom Strasser, Peter Krug, Takashi Mizuochi, Nadeem Rizvi, Doug Williams, Alistair Poustie, Steve Kershaw, and Mike Brierley for their assistance with figures, Arjun Kashyap for the arrangement on the front cover, and others who have also provided data for inclusion in the book.

Melanie Holmes's vast contribution on radiation mode coupling is humbly acknowledged. I especially thank her for the many philosophical discussions, fun arguments and Mars bars exchanged on the subject! Jenny Massicott has generously contributed and provided significant help with the section on gain controlled amplifiers. 'Thanks' must go to Richard Wyatt for reading the manuscript so quickly and Marcello Segatto for his many constructive comments.

A special thank you to Domenico Giannone for his painstaking and careful reading of parts of the manuscript, and to Hans Georg Fröhlich and Simon Wolting for undertaking fun experiments during their summer student-ships. Monica de Lacerda-Rocha provided numerous measurements on chirped gratings. Walter Margulis and Isabel Cristina Carvalho are acknowledged for the amusing times in the lab in Rio, proving that writing in-fiber gratings on a piece of Amazonian hardwood "optical bench" is easy, even late at night! Bernhard Lesche and Isabel Cristina Carvalho



contributed to interesting discussions during the writing of the book. Martin Burley kept me amused with his music and sense of humor during the lulls in writing.

The IEEE, IEE, OSA and Elsevier Science are acknowledged for provision of copyright permission on several figures. I also gratefully acknowledge D. W. Smith of BT Laboratories for his generous support and provision of computer facilities for the production of the manuscript.

Finally, I am deeply appreciative of Monika and Hannah, whose unquestioning patience, support and provision of earthly comforts formed essential ingredients in the birth of this book.

# **Fiber Bragg Gratings**

*This page intentionally left blank*