

Fiber Bragg Gratings

SECOND EDITION

Raman Kashyap



Fiber Bragg Gratings

Second Edition

RAMAN KASHYAP

*École Polytechnique de Montréal, University of Montréal
Montréal, Canada*



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Academic Press is an imprint of Elsevier



Academic Press is an imprint of Elsevier
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA
525 B Street, Suite 1900, San Diego, California 92101-4495, USA
84 Theobald's Road, London WC1X 8RR, UK

Copyright © 2010, Elsevier Inc. 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.

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK: phone: (+44) 1865 843830, fax: (+44) 1865 853333, E-mail: permissions@elsevier.com. You may also complete your request online via the Elsevier homepage (<http://elsevier.com>), by selecting "Support & Contact" then "Copyright and Permission" and then "Obtaining Permissions."

Library of Congress Cataloging-in-Publication Data

Application submitted

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

ISBN: 978-0-12-372579-0

For information on all Academic Press publications
visit our Web site at www.elsevierdirect.com

Printed in the United States of America

09 10 9 8 7 6 5 4 3 2 1

Working together to grow
libraries in developing countries

www.elsevier.com | www.bookaid.org | www.sabre.org

ELSEVIER

BOOK AID
International

Sabre Foundation

Fiber Bragg Gratings

Second Edition

Software Package

This book is accompanied by a special edition of the software, PicWave from Photon Design (www.photond.com/products/picwave.htm), provided to simulate live many of the examples found in this book. By showing the device structures in detail and providing additional results, it will help to gain additional insight into the examples presented in this book.

The software runs on any modern PC with Windows-2000 or later installed, with 1GB of memory or more. It can be downloaded from the books companion Web site, www.elsevierdirect.com/companions/9780123725790 free of charge to owners of this book.

PicWave takes a rather different time-domain travelling wave (TDTW) approach to the frequency-domain based theory presented in this book, and illustrates how similar results can be obtained in the time domain. PicWave is a circuit model and as such is capable of modelling not just linear fiber components but also complex fiber devices such as fiber couplers, splitters and amongst others.

Features illustrated by the software include:

- Behavior of a fiber-Bragg grating, including transmission, reflection, group delay, group velocity dispersion (after Chapter 4)
- Simulation of multi-mode effects, such as grating assisted co-directional coupling from a fiber core to a cladding mode (after Chapter 4)
- Effect of apodization on FBG characteristics (after Chapter 5)
- Simulation of fiber band pass filters, including devices based on single fibers, Mach-Zehnder interferometer circuits and in-coupler gratings (after Chapter 6)
- Behavior of chirped fiber Bragg gratings (after Chapter 7)
- Transmission of digital bit patterns through examples, showing the distortion of signals in the time domain (eye diagrams).

The user is able to run the chosen examples, inspecting all the results available within PicWave, including optical transmission and reflection spectra, group delay, dispersion, time signals and more.

This special version of Picwave is limited to modelling only the passive fibre devices covered in this book. However the full PicWave package is capable of modelling other non-linear and active devices such as laser diodes and SOAs as discussed in Chapter 8.



Dedicated to the memory of my parents, Vimla and Kedar Nath Kashyap.

Preface

Despite the lapse of a decade since the previous edition of this book was published, fiber Bragg gratings continue to flourish and their applications expand. As has been the experience with optical fibers in the past, new discoveries have continued to remain a driver for technological developments. In this respect, the past decade has seen further activity in the poling of glass, fiber Bragg grating sensors, high-power fiber lasers, and the opening of a new research on femtosecond (fs) laser processing, which was just beginning to grow when the first edition came out in print. To reflect these developments, this edition has three new chapters that touch on the topics of sensing, fs laser writing of fiber Bragg gratings (FBGs), and poling of glass and optical fibers. It is hoped that these chapters will bring the book into the mainstream of topical research interest. The basis of the FBG, the refractive index change induced by ultraviolet or fs laser pulses, now stands around a record ~ 0.1 , having met the prediction made in 1999. Truly broadband mirrors spanning 300 nm are now possible *in fiber* with high reflectivity (99%), challenging thin-film technology. In fact, some of the periodic nanostructured gratings formed by fs laser pulses have a glass-air boundary, which leads to the possibility of miniaturizing devices still further with the large refractive index contrast of 0.45. The fs laser has allowed the writing of strong gratings in materials that have traditionally been nonphotosensitive, such as pure silica and ZBLAN glass. The use of high-intensity pulses enables multiphoton absorption to occur, and these pulses also literally rip the electrons out of their orbits to the conduction band, inducing plasmas and carrier heating. The optical damage that results has interesting applications in strong gratings for high-temperature sensing. Indeed, sapphire fiber gratings for high-temperature turbine measurements would not have been possible without fs lasers. High-power lasers have suddenly become commonplace at unusual wavelength, fueled by the downturn in the telecommunications and the rise of the multibillion-dollar biophotonics and sensing industries. FBGs have found their place in peculiar applications such as in the investigation of strain in the human lumbar column. Glass poling, too, has evolved, even though the goal of the 10 pm-V^{-1} electrically induced nonlinearity remains elusive. New polarization controllers, fiber-based Q-switches, and other tunable FBG devices have come of age with optical fiber poling. The low-loss optical fibers for telecommunications made of a fused silica cladding and a germania-doped core still

maintain their pride of place in optical fiber technology. Rare earth dopants in silica and other glasses have made many more applications possible. The advent of photonic crystal fibers are now demonstrating a way to increase the power-handling capacity of optical fibers, although high-quality gratings remain difficult to implement in these fibers. Gratings are being applied to reduce the impact of nonlinearities in fibers, pulse shaping and compression, and signal processing. The mechanisms contributing to photosensitivity continue to be debated, although major advances have been made in this area. There are a number of methods of the holographic inscription of Bragg gratings using ultraviolet radiation or infrared fs pulses, with the phase-mask technique holding a prominent position. These methods have multiplied, with several techniques demonstrated for the fabrication of ultralong gratings. New areas just on the brink of breakthroughs, such as random lasers, are highly compatible with the FBG. It is impossible to cover the massive advances made in this field in a book of this size (even though the second edition is now vastly expanded), a field in which the number of applications has exploded. The book therefore continues to be an introduction to the extremely rich area of the technology of fiber gratings, with a view to providing an insight to some of the exciting prospects, including the principles of fiber Bragg gratings, the photosensitization of optical fibers, Bragg grating fabrication, theory, properties of gratings, specific applications, sensing technology, glass poling, femtosecond processing of glass, and FBG measurement techniques.

Acknowledgments

Writing a book is like planting a tree. One sees it grow and develop branches and roots, leading to connections that permeate throughout the world, with the hundreds of researchers providing the nourishment. At the end, the tree should flourish to shade the ones who nourished it, and those yet to come. Therefore, I am grateful to the scientific community at large for providing the data for this book, now in its much-expanded form. The writing of the second edition poses some problems, as the written data are often still valid and the new must be integrated into the old. The choice has been a difficult one, as the field is now very large, and it is often based on the examples that provide the information required. The book is not therefore intended to be a bibliography of all the research and applications that have been published in the area of laser-induced fiber gratings, for there are too many. Instead, we focus on the technology with the goals of guiding the reader on how to fabricate, use, and implement systems with fiber gratings and shedding light on recent advances in the field.

I am deeply grateful to Walter Margulis for the major contribution he made by writing the chapter on glass poling. Choosing the right person to prepare that chapter was a difficult decision to make until I took the step of asking him, and since, it was to be the best decision I could have made. His dedication and lightening response is evident in the extremely thorough chapter he has written. Without his help, the book would still be somewhere in cyberspace.

I am grateful, too, to my students and researchers, in particular Runnan Liu, Irina Kostko, Mathieu Gagné, Jerome Poulin, Francis Guay, Julie Baron, Aïssa Harhira, and the numerous others who spent time in my labs for their research in the several areas of FBGs. Included among these are Jessica Chauve, Cedric Pruche, Lucien Bojor, and John Machlecler. Galina Nemova's contribution on surface plasmons is most appreciated.

I am indebted to Jacques Albert, Réal Vallée, Sidarath Ramachandran, Ian Bennion, and numerous others who have all generously contributed material included in the new edition. James Brennan and Bertrand Poumellec are gratefully acknowledged for their painstaking review of sections of the first edition and their constructive comments, which I have tried to incorporate in this edition. *Fiber Bragg Gratings* may not have made such progress without the help of Dr. Jürgen Bartschke, who was instrumental in bringing to life the first CW intra-cavity 244 nm laser source in my lab at BT Laboratories in 1989.

His recent visit from Xiton Photonics has renewed an old friendship and perhaps new innovations in gratings. I hope that the theft of his passport did not spoil an otherwise good visit to Montréal!

Finally, I would like to thank Hannah and Monika, whose patience was not only tested to the limits of exasperation, but whose caring and infinite capacity to see the light at the end of the tunnel kept me on the straight and narrow.

Raman Kashyap
Montréal
August 2009

Contents

Preface	xv
Acknowledgments	xvii
1 Introduction	1
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
2 Photosensitivity and Photosensitization of Optical Fibers	15
2.1 Photorefractivity and Photosensitivity	16
2.2 Defects in Glass	18
2.3 Detection of Defects	20
2.4 Photosensitization Techniques	21
2.4.1 Germanium-Doped Silica Fibers	22
2.4.2 Germanium-Boron Codoped Silicate Fibers	26
2.4.3 Tin-Germanium Codoped Fibers	28
2.4.4 Cold, High-Pressure Hydrogenation	29
2.4.5 Rare-Earth-Doped Fibers	34
2.5 Densification and Stress in Fibers	34
2.6 Summary of Photosensitive Mechanisms in Germanosilicate Fibers	35
2.7 Summary of Routes to Photosensitization	37
2.7.1 Summary of Optically Induced Effects	38
2.8 Chemical Composition Gratings	41
3 Fabrication of Bragg Gratings	53
3.1 Methods for Fiber Bragg Grating Fabrication	53
3.1.1 The Bulk Interferometer	53
3.1.2 The Phase Mask	55
3.1.3 The Phase-Mask Interferometer	59

3.1.4	Slanted Grating	65
3.1.5	The Scanned Phase-Mask Interferometer	66
3.1.6	The Lloyd Mirror and Prism Interferometer	69
3.1.7	Higher Spatial Order Masks	72
3.1.8	Point-by-Point Writing	74
3.1.9	Gratings for Mode and Polarization Conversion	75
3.1.10	Single-Shot Writing of Gratings	77
3.1.11	Long-Period Grating Fabrication	78
3.1.12	Ultralong-Fiber Gratings	79
3.1.13	Tuning of the Bragg Wavelength, Moiré, Fabry–Perot, and Superstructure Gratings	81
3.1.14	Fabrication of Continuously Chirped Gratings	86
3.1.15	Fabrication of Step-Chirped Gratings	91
3.1.16	Techniques for Continuous Writing of Fiber Bragg Gratings	93
3.2	Tunable Phase Masks	101
3.2.1	Fabrication of Long-Period Gratings	103
3.3	Type II Gratings	104
3.4	Type IIA Gratings	104
3.5	Sources for Holographic Writing of Gratings	104
3.5.1	Low Coherence Sources	105
3.5.2	High Coherence Sources	106
4	Theory of Fiber Bragg Gratings	119
4.1	Wave Propagation	120
4.1.1	Waveguides	122
4.2	Coupled-Mode Theory	124
4.2.1	Spatially Periodic Refractive Index Modulation	126
4.2.2	Phase Matching	129
4.2.3	Mode Symmetry and the Overlap Integral	130
4.2.4	Spatially Periodic Nonsinusoidal Refractive Index Modulation	132
4.2.5	Types of Mode Coupling	132
4.3	Coupling of Counterpropagating Guided Modes	139
4.4	Codirectional Coupling	142
4.5	Polarization Couplers: Rocking Filters	145
4.6	Properties of Uniform Bragg Gratings	148
4.6.1	Phase and Group Delay of Uniform Period Gratings	151

4.7	Radiation Mode Couplers	152
4.7.1	Counterpropagating Radiation Mode Coupler: The Side-Tap Grating	152
4.7.2	Copropagating Radiation Mode Coupling: Long-Period Gratings	165
4.8	Grating Simulation	171
4.8.1	Methods for Simulating Gratings	171
4.8.2	Transfer Matrix Method	172
4.9	Multilayer Analysis	177
4.9.1	Rouard's Method	177
4.9.2	The Multiple Thin-Film Stack	178
4.10	Grating Design	180
4.10.1	Phase-Only Sampling of Gratings	181
4.10.2	Simulation of Gratings	182
5	Apodization of Fiber Gratings	189
5.1	Apodization Shading Functions	190
5.2	Basic Principles and Methodology	193
5.2.1	Self-Apodization	193
5.2.2	The Amplitude Mask	196
5.2.3	The Variable Diffraction Efficiency Phase Mask	198
5.2.4	Multiple Printing of In-Fiber Gratings Applied to Apodization	199
5.2.5	Position-Weighted Fabrication of Top-Hat Reflection Gratings	201
5.2.6	The Moving Fiber/Phase-Mask Technique	203
5.2.7	The Symmetric Stretch Apodization Method	208
5.3	Fabrication Requirements for Apodization and Chirp	212
6	Fiber Grating Band-Pass Filters	217
6.1	Distributed Feedback, Fabry-Perot, Superstructure, and Moiré Gratings	218
6.1.1	The Distributed Feedback Grating	219
6.1.2	Superstructure Band-Pass Filter	227
6.2	The Fabry-Perot and Moiré Band-Pass Filters	229
6.3	The Michelson Interferometer Band-Pass Filter	233
6.3.1	The Asymmetric Michelson Multiple-Band-Pass Filter	240

6.4	The Mach–Zehnder Interferometer Band-Pass Filter	245
6.4.1	Optical Add–Drop Multiplexers Based on the GMZI-BPF	248
6.5	The Optical Circulator-Based OADM	250
6.5.1	Reconfigurable OADM	254
6.6	The Polarizing Beam Splitter Band-Pass Filter	255
6.7	In-Coupler Bragg Grating Filters	259
6.7.1	Bragg Reflecting Coupler OADM	260
6.7.2	Grating-Frustrated Coupler	266
6.8	Side-Tap and Long-Period Grating Band-Pass Filters	270
6.9	Polarization Rocking Band-Pass Filter	274
6.10	Mode Converters	278
6.10.1	Guided-Mode Intermodal Couplers	278
6.11	Sagnac Loop Interferometer	280
6.12	Gires–Tournois Filters	282
6.13	Tunable Band-Pass Filters	285
6.14	LPG Filters	287
7	Chirped Fiber Bragg Gratings	301
7.1	General Characteristics of Chirped Gratings	301
7.2	Chirped and Step-Chirped Gratings	306
7.2.1	Effect of Apodization	312
7.2.2	Effect of Nonuniform Refractive Index Modulation on Grating Period	317
7.3	Super-Step-Chirped Gratings	319
7.4	Polarization Mode Dispersion in Chirped Gratings	322
7.5	Systems Measurements with DCGs	325
7.5.1	Systems Simulations and Chirped Grating Performance	327
7.6	Other Applications of Chirped Gratings	330
7.6.1	Pulse Shaping with Uniform Gratings	331
7.6.2	Optical Delay Lines	334
7.6.3	Pulse Shaping with Chirped Gratings	336
7.6.4	Pulse Multiplication	336
7.6.5	Beam Forming	337
8	Fiber Grating Lasers and Amplifiers	347
8.1	Fiber Grating Semiconductor Lasers: The FGSL	347
8.2	Static and Dynamic Properties of FGLs	353
8.2.1	Modeling of External Cavity Lasers	357
8.2.2	General Comments on FGLs	359

8.3	The Fiber Bragg Grating Rare-Earth-Doped Fiber Laser	360
8.4	Erbium-Doped Fiber Lasers	362
8.4.1	Single-Frequency Erbium-Doped Fiber Lasers	363
8.5	The Distributed Feedback Fiber Laser	366
8.5.1	Multifrequency Sources	368
8.5.2	Tunable Single-Frequency Sources	369
8.6	Bragg Grating-Based Pulsed Sources	369
8.7	Fiber Grating Resonant Raman Amplifiers	371
8.8	Gain-Flattening and Clamping in Fiber Amplifiers	373
8.8.1	Amplifier Gain Equalization with Fiber Gratings	374
8.8.2	Optical Gain Control by Gain Clamping	378
8.8.3	Analysis of Gain-Controlled Amplifiers	382
8.8.4	Cavity Stability	383
8.8.5	Noise Figure	383
8.9	High-Powered Lasers and Amplifiers	384
8.9.1	Coupling of Laser Diodes to Optical Fiber with FBGs	385
8.9.2	Hybrid Lasers: Dynamic Gratings	386
8.9.3	Fiber Lasers with Saturable Absorbers in the Cavity	388
8.10	Toward Higher-Power Fiber Lasers and Amplifiers	389
8.10.1	Fiber Raman Lasers	392
8.11	Ultrahigh-Power Lasers and Amplifiers	394
9	Measurement and Characterization of Gratings	405
9.1	Measurement of Reflection and Transmission Spectra of Bragg Gratings	406
9.2	Perfect Bragg Gratings	412
9.3	Phase and Temporal Response of Bragg Gratings	413
9.3.1	Measurement of the Grating Profile	420
9.3.2	Measurement of Internal Stress	429
9.4	Strength, Annealing, and Lifetime of Gratings	431
9.4.1	Mechanical Strength	431
9.4.2	Bragg Grating Lifetime and Thermal Annealing	432
9.4.3	Accelerated Aging of Gratings	435
10	Principles of Optical Fiber Grating Sensors	441
10.1	Sensing with Fiber Bragg Gratings	443
10.1.1	Principles of Sensing	443
10.1.2	Fiber Designs for Sensing	445

10.1.3	Point Temperature Sensing with Fiber Bragg Gratings	450
10.1.4	Distributed Sensing with Fiber Bragg Gratings	452
10.1.5	Fourier Transform Spectroscopy of Fiber Bragg Grating Sensors	453
10.1.6	Fiber Bragg Grating Fiber Laser Sensors	456
10.1.7	Measurement of Temperature with Fiber Bragg Gratings	459
10.1.8	Strain Measurements with Fiber Bragg Gratings	461
10.1.9	Fiber Bragg Grating Wavelength Temperature Compensation Techniques	462
10.1.10	Pressure and Loading	467
10.1.11	Chirped Grating Sensors	471
10.1.12	Acceleration	473
10.1.13	Vibration and Acoustic Sensing	475
10.1.14	Magnetic Field Sensing with Fiber Bragg Gratings	476
10.2	Evanescent-Field Refractive Index Sensors	477
10.2.1	Fiber Bragg Grating–Based Refractive Index Sensors	477
10.2.2	Long-Period Gratings–Based Refractive Index Sensors	478
10.2.3	Surface Plasmon-Polariton Sensors	479
10.2.4	Guided Wave Surface Plasmon-Polariton Sensors	480
10.2.5	Theory of the Surface Plasmon-Polariton	481
10.2.6	Optimization of Surface Plasmon-Polariton Sensors	483
10.3	Long-Period Grating (LPG) Sensors	489
10.4	Applications of FBG Sensors	493
10.4.1	Biomedical Sensing: Hydrostatic Pressure Sensing in Medicine	493
10.4.2	Respiration Monitoring	494
10.4.3	Oil, Gas, and Mining	494
10.4.4	Structural Health Monitoring	495
10.4.5	Tilt Sensors	495
10.5	Conclusions and Future Prospects	496
11	Femtosecond-Induced Refractive Index Changes in Glass	503
11.1	Light Propagation in Glass	503
11.1.1	Theoretical Background	505

11.1.2	Point-by-Point Writing of Fiber Bragg Gratings with Femtosecond Lasers	512
11.1.3	Femtosecond Laser Writing with a Phase Mask	513
11.1.4	Infrared Femtosecond Laser Inscription of Fiber Bragg Gratings	517
11.1.5	Strength of Grating	521
11.2	Conclusion	522
12	Poling of Glasses and Optical Fibers	527
12.1	Optical Poling	527
12.1.1	A Grating for Quasi-Phase Matching	529
12.1.2	Recording a Grating for SHG	530
12.2	UV Poling	531
12.3	Thermal Poling of Glass	532
12.3.1	Glass Electrets	532
12.3.2	Creating a Second-Order Nonlinearity	534
12.3.3	Other Poling Techniques	535
12.4	Characterization Techniques	536
12.4.1	Measurement of the Nonlinear Optical Coefficient	536
12.4.2	Etching	540
12.4.3	Elemental Analysis of the Surface and Other Techniques	542
12.5	Fundamental and Practical Issues	544
12.5.1	Cation Mobility	544
12.5.2	Defects and Water	546
12.5.3	Charge Movement	547
12.5.4	Electrodes	549
12.5.5	Spatial Resolution	550
12.6	The Poling Process in Detail	550
12.6.1	Poling for Short Time Intervals	551
12.6.2	Poling for Long Time Intervals	553
12.6.3	Models	555
12.6.4	Erase and Stability	557
12.7	Routes for Increasing the Second-Order Optical Nonlinearity	560
12.7.1	Poling Methods (Optimization and Novel Techniques)	561
12.7.2	Increasing E-Field Breakdown	561
12.7.3	Increase $\chi(3)$ through Poling	561
12.7.4	Increasing $\chi(3)$ through Resonance and Doping	562
12.7.5	Glasses Other Than Silica	562