



Optical Fiber Communications

Principles and Practice

Third Edition



JOHN M. SENIOR

Optical Fiber Communications



We work with leading authors to develop the strongest educational materials in engineering, bringing cutting-edge thinking and best learning practice to a global market.

Under a range of well-known imprints, including Prentice Hall, we craft high quality print and electronic publications which help readers to understand and apply their content, whether studying or at work.

To find out more about the complete range of our publishing, please visit us on the World Wide Web at: www.pearsoned.co.uk

Optical Fiber Communications Principles and Practice

Third edition

John M. Senior

assisted by

M. Yousif Jamro



An imprint of Pearson Education

Harlow, England • London • New York • Boston • San Francisco • Toronto • Sydney • Singapore • Hong Kong
Tokyo • Seoul • Taipei • New Delhi • Cape Town • Madrid • Mexico City • Amsterdam • Munich • Paris • Milan

Pearson Education Limited

Edinburgh Gate
Harlow
Essex CM20 2JE
England

and Associated Companies throughout the world

Visit us on the World Wide Web at:
www.pearsoned.co.uk

First published 1985

Second edition 1992

Third edition published 2009

© Prentice Hall Europe 1985, 1992

© Pearson Education Limited 2009

The right of John M. Senior to be identified as author of this work has been asserted by him in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without either the prior written permission of the publisher or a licence permitting restricted copying in the United Kingdom issued by the Copyright Licensing Agency Ltd, Saffron House, 6–10 Kirby Street, London EC1N 8TS.

All trademarks used herein are the property of their respective owners. The use of any trademark in this text does not vest in the author or publisher any trademark ownership rights in such trademarks, nor does the use of such trademarks imply any affiliation with or endorsement of this book by such owners.

ISBN: 978-0-13-032681-2

British Library Cataloguing-in-Publication Data

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

Library of Congress Cataloging-in-Publication Data

Senior, John M., 1951–

Optical fiber communications : principles and practice / John M. Senior, assisted by
M. Yousif Jamro. — 3rd ed.

p. cm.

Includes bibliographical references and index.

ISBN-13: 978-0-13-032681-2 (alk. paper) 1. Optical communications. 2. Fiber optics.

I. Jamro, M. Yousif. II. Title.

TK5103.S59.S46 2008

621.382'75—dc22

2008018133

10 9 8 7 6 5 4 3 2 1
12 11 10 09 08

Typeset in 10/12 Times by 35

Printed and bound by Ashford Colour Press Ltd, Gosport

The publisher's policy is to use paper manufactured from sustainable forests.

To Judy and my mother Joan, and in memory of my father Ken

Contents

<i>Preface</i>	xix
<i>Acknowledgements</i>	xxiii
<i>List of symbols and abbreviations</i>	xxxii
Chapter 1: Introduction	1
1.1 Historical development	1
1.2 The general system	5
1.3 Advantages of optical fiber communication	7
References	10
Chapter 2: Optical fiber waveguides	12
2.1 Introduction	12
2.2 Ray theory transmission	14
2.2.1 Total internal reflection	14
2.2.2 Acceptance angle	16
2.2.3 Numerical aperture	17
2.2.4 Skew rays	20
2.3 Electromagnetic mode theory for optical propagation	24
2.3.1 Electromagnetic waves	24
2.3.2 Modes in a planar guide	26
2.3.3 Phase and group velocity	28
2.3.4 Phase shift with total internal reflection and the evanescent field	30
2.3.5 Goos–Haenchen shift	35
2.4 Cylindrical fiber	35
2.4.1 Modes	35
2.4.2 Mode coupling	42
2.4.3 Step index fibers	43
2.4.4 Graded index fibers	46
2.5 Single-mode fibers	54
2.5.1 Cutoff wavelength	59
2.5.2 Mode-field diameter and spot size	60
2.5.3 Effective refractive index	61

2.5.4	Group delay and mode delay factor	64
2.5.5	The Gaussian approximation	65
2.5.6	Equivalent step index methods	71
2.6	Photonic crystal fibers	75
2.6.1	Index-guided microstructures	75
2.6.2	Photonic bandgap fibers	77
	Problems	78
	References	82

Chapter 3: Transmission characteristics of optical fibers 86

3.1	Introduction	87
3.2	Attenuation	88
3.3	Material absorption losses in silica glass fibers	90
3.3.1	Intrinsic absorption	90
3.3.2	Extrinsic absorption	91
3.4	Linear scattering losses	95
3.4.1	Rayleigh scattering	95
3.4.2	Mie scattering	97
3.5	Nonlinear scattering losses	98
3.5.1	Stimulated Brillouin scattering	98
3.5.2	Stimulated Raman scattering	99
3.6	Fiber bend loss	100
3.7	Mid-infrared and far-infrared transmission	102
3.8	Dispersion	105
3.9	Chromatic dispersion	109
3.9.1	Material dispersion	110
3.9.2	Waveguide dispersion	113
3.10	Intermodal dispersion	113
3.10.1	Multimode step index fiber	114
3.10.2	Multimode graded index fiber	119
3.10.3	Modal noise	122
3.11	Overall fiber dispersion	124
3.11.1	Multimode fibers	124
3.11.2	Single-mode fibers	125
3.12	Dispersion-modified single-mode fibers	132
3.12.1	Dispersion-shifted fibers	133
3.12.2	Dispersion-flattened fibers	137
3.12.3	Nonzero-dispersion-shifted fibers	137

3.13	Polarization	140
3.13.1	Fiber birefringence	141
3.13.2	Polarization mode dispersion	144
3.13.3	Polarization-maintaining fibers	147
3.14	Nonlinear effects	151
3.14.1	Scattering effects	151
3.14.2	Kerr effects	154
3.15	Soliton propagation	155
	Problems	158
	References	163

Chapter 4: Optical fibers and cables 169

4.1	Introduction	169
4.2	Preparation of optical fibers	170
4.3	Liquid-phase (melting) techniques	171
4.3.1	Fiber drawing	172
4.4	Vapor-phase deposition techniques	175
4.4.1	Outside vapor-phase oxidation process	176
4.4.2	Vapor axial deposition (VAD)	178
4.4.3	Modified chemical vapor deposition	180
4.4.4	Plasma-activated chemical vapor deposition (PCVD)	181
4.4.5	Summary of vapor-phase deposition techniques	182
4.5	Optical fibers	183
4.5.1	Multimode step index fibers	184
4.5.2	Multimode graded index fibers	185
4.5.3	Single-mode fibers	187
4.5.4	Plastic-clad fibers	190
4.5.5	Plastic optical fibers	191
4.6	Optical fiber cables	194
4.6.1	Fiber strength and durability	195
4.7	Stability of the fiber transmission characteristics	199
4.7.1	Microbending	199
4.7.2	Hydrogen absorption	200
4.7.3	Nuclear radiation exposure	201
4.8	Cable design	203
4.8.1	Fiber buffering	203
4.8.2	Cable structural and strength members	204