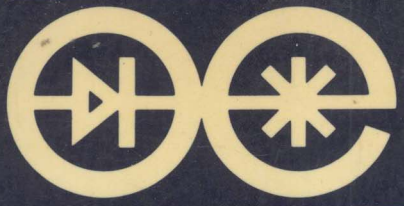

PRENTICE HALL
INTERNATIONAL SERIES
IN OPTOELECTRONICS

Optical Communication Systems

Second Edition

JOHN GOWAR

TN929.1
G2
E.2

9461655

Optical Communication Systems

John Gowar

Second Edition

Prentice Hall

New York London Toronto Sydney Tokyo Singapore

First published 1984
This second edition published 1993 by
Prentice Hall International (UK) Ltd
Campus 400, Maylands Avenue
Hemel Hempstead
Hertfordshire, HP2 7EZ
A division of
Simon & Schuster International Group

© Prentice Hall International (UK) Ltd, 1993

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 the prior permission, in writing, from the publisher.
For permission within the United States of America contact Prentice Hall Inc., Englewood Cliffs, NJ 07632

Typeset in 10/12 pt Times
by P&R Typesetters Ltd, Salisbury, Wiltshire

Printed and bound in Great Britain by
Redwood Books, Trowbridge, Wiltshire

Library of Congress Cataloging-in-Publication Data

Gowar, John, 1938–
Optical communication systems / John Gowar. — 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-13-638727-6
1. Optical communications. I. Title.
TK5103.59.G68 1993
621.382'7—dc20 92-29770
CIP

British Library Cataloguing in Publication Data

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

ISBN 0-13-638727-6 (pbk)

2 3 4 5 97 96 95 94 93

Optical Communication Systems

Prentice Hall International Series in Optoelectronics

Consultant editors: John Midwinter, University College London, UK
Alan Snyder, Australian National University
Bernard Weiss, University of Surrey, UK

Fundamentals of Optical Fiber Communications
W. van Etten and J. van der Plaats

Light Emitting Diodes
K. Gillessen and W. Schairer

Optical Communication Systems
J. Gowar

Optical Sensing Techniques and Signal Processing
T. E. Jenkins

Optical Fiber Communications: Principles and Practice (Second Edition)
J. M. Senior

Lasers: Principles and Applications
J. Wilson and J. F. B. Hawkes

Optoelectronics: An Introduction (Second Edition)
J. Wilson and J. F. B. Hawkes

此为试读,需要完整PDF请访问: www.ertongbook.com

Preface to the second edition

In the decade since the first edition was drafted, optical fiber communication systems have more than fulfilled everything that was then expected of them. A world-wide industry has developed. Interest has focussed mainly on single-mode fiber systems, which have come to dominate all types of high capacity, point-to-point telecommunication in all parts of the world. Not surprisingly, the literature has expanded together with the activity. There are now several journals and many conferences devoted exclusively to the subject. Notable among them are the *IEEE Journal of Lightwave Technology*, the annual Optical Fiber Conference (OFC) in the US and the European Conference on Optical Communication (ECOC). Many thousands of papers are published every year. It is not surprising that revising the first edition has been quite as difficult and time-consuming as writing it was in the first place.

Clearly, a textbook prepared today cannot attempt to treat the subject with the same level of detail and comprehensiveness that was possible ten years ago. Fortunately, the fundamentals have not altered. Very little of the material of the first edition is irrelevant today but some new topics and many new examples have had to be added and some changes of emphasis have been necessary.

As before, the book breaks clearly into an introduction and three parts. The first part deals with the fiber, the second with the components used for the optical source and the detector, and the third with the receiver and general system considerations. I have taken the opportunity to break down the chapters into smaller units and to reorganize some of the material. There is a new chapter (Chapter 6) on inelastic scattering and non-linear propagation and one on coherent systems (Chapter 24). The section on fiber measurements has also been expanded into a new chapter (Chapter 12).

There are certain topics that I have wished to retain, even though they are not essential to the optical fiber systems that dominate current telecommunications. Thus, Chapter 17 takes a broad view of the principles of laser action and Chapter 25 looks specifically at free space transmission. Although this is not of great significance in the context of today's communication systems, the basic ideas apply to several other important applications such as remote sensing and range-finding and I think they are worthy of inclusion.

Superficial treatments of several topics which are normally dealt with rigorously in foundation courses have also been retained. Some of these courses may well be considered to be pre-requisites to a course on optical communications, but it seems right to me, while it still can be done, to gather into a single volume as much as possible of the fundamental material relating to the key aspects and components of

the optical communication system. So, the semiclassical approach to the propagation of radiation through matter, the development of semiconductor theory directed from the beginning towards III–V semiconductors and opto-electronic components, some elementary theory of communications, are all included. I hope that readers whose backgrounds mean that they have not dealt with these topics previously find this useful and that those who have find the revision interesting.

My intention was to make the book as self-contained as possible. I have therefore strictly limited the references cited to those where pre-requisite or supportive material may be found and to a few classic and easily accessible papers and texts which lead the reader on to more advanced treatments and topics. When specific data have been taken from a particular source, reference is given in the text. Readers wishing to keep up with the latest developments will find that *Electronics Letters* and the *IEEE Journal of Lightwave Technology* cover the subject particularly well. In the latter, look out for the special issues on particular topics, such as the March 1990 issue on 'Coherent systems' or the February 1991 issue on 'Fiber amplifiers'. Two other IEEE journals which often devote special issues to subjects related to optical communications are the *Journal on Selected Areas in Communications* (e.g. the August 1990 issue on 'Dense wavelength division multiplexing techniques for high capacity and multiple access communication systems') and the *Journal of Quantum Electronics* (mainly on semiconductor laser progress). The invited review papers often provide an excellent introduction to the literature for those wishing to make a more detailed study.

Once again there are many people I have to thank either for their help on specific matters or for their general support. In particular, may I single out my colleagues Dr D. T. Bickley, Dr C. J. Railton and the late Professor K. F. Sander for assistance with various mathematical aspects and my wife Ann for providing the support that makes authorship possible.

J. Gowar
Bristol
June 1992

Contents

Preface to the second edition xv

1 A general introductory discussion 1
1.1 Historical perspective 1
1.2 The measurement of information and the capacity of a telecommunication channel 6
1.3 Communication system architecture 15
1.4 The basic optical communication system 19
1.5 Definition of attenuation, pulse-duration and bandwidth 22
Problems 27
References 28
Summary 29

PART 1

2 Elementary discussion of propagation in dielectric waveguides 33
2.1 Introduction 33
2.2 Step-index fibers: numerical aperture and multipath dispersion 34
2.3 Propagation and multipath dispersion in graded-index fibers 40
2.4 Modes and rays 46
2.5 The slab waveguide 49
Problems 56
References 57
Summary 57

3 Material dispersion 58
3.1 Refractive index: theory 58
3.2 The refractive indices of bulk media: experimental values 64
3.3 Time dispersion in bulk media 69
3.4 The wavelength of minimum dispersion 73
Problems 76
Summary 76

4 Total dispersion in multimode and monomode fibers 78
4.1 The combined effect of material and multipath dispersion in multimode fibers 78

4.2 The combined effect of material and waveguide dispersion in monomode fibers 82
Problem 85
Summary 85

5 Attenuation mechanisms in optical fibers 86
5.1 Introduction 86
5.2 Absorption 89
5.3 Scattering 93
5.4 Other very low-loss materials 96
5.5 All-plastic and polymer-clad-silica (PCS) fibers 98
5.6 Damage by ionizing radiation 102
Problems 104
Summary 105

6 Inelastic scattering and non-linear propagation effects 107
6.1 Stimulated Brillouin and stimulated Raman scattering 107
6.2 Doped fiber amplifiers 112
6.3 Other intensity-dependent effects 113
Problems 118
Summary 119

7 System considerations 120
7.1 The optimum wavelength for silica fibers 120
7.2 The ultimate bandwidth limitation 126
7.3 A comparison between optical fibers and conventional electrical transmission lines 128
Problems 131
Summary 132

8 Electromagnetic wave propagation in step-index fiber 133
8.1 Solutions of the wave equation 133
8.2 Solutions for the propagation constant 137
8.3 Variation of the propagation constants with frequency 145
8.4 The weakly guiding approximation 148
8.5 Power density distribution 150
8.6 Number of propagating modes 152
8.7 Time dispersion in step-index fibers 153
8.7.1 Transit times 153
8.7.2 Intermode dispersion 155
8.7.3 Intramode (chromatic) dispersion 157
Problems 159
References 159
Summary 159

9 Wave and ray propagation in graded-index fibers **161**
9.1 Introduction 161
9.2 The number of guided modes 162
9.3 The propagation constant 164
9.4 Intermode dispersion 166
9.4.1 Neglecting material dispersion 166
9.4.2 Including material dispersion 169
9.4.3 R.M.S. intermode dispersion 173
9.5 Intramode dispersion 179
9.6 Total dispersion 180
9.7 Mode coupling 181
Problems 187
Summary 188

10 Single-mode fibers **190**
10.1 Types of single-mode fiber 190
10.1.1 Introduction 190
10.1.2 Standard single-mode fiber 191
10.1.3 Dispersion-shifted fiber 192
10.1.4 Dispersion-flattened fiber 194
10.1.5 Practical fiber profiles 195
10.2 Mode spot size 197
10.3 HE_{11} mode propagation characteristics 200
Problems 205
Reference 206
Summary 206

11 The fabrication of fibers, cables and passive components **207**
11.1 Fiber production methods 207
11.1.1 Introduction 207
11.1.2 Crucible methods 208
11.1.3 Vapour deposition methods 208
11.1.4 Fiber pulling and coating 215
11.1.5 Comparison between vapour deposition methods 219
11.2 Fiber strength 221
11.3 Cables 222
11.4 Splices and connectors 230
11.4.1 Introduction 230
11.4.2 Splices 231
11.4.3 Connectors 233
11.5 Couplers 236
Problems 239
References 239
Summary 239

12 Fiber parameters: specification and measurement **241**
12.1 Introduction 241
12.2 The refractive-index profile 243
12.3 Near- and far-field intensity distributions 244
12.4 Attenuation measurements 247
12.5 Bandwidth measurements 249
12.6 Cutoff wavelength 252
References 252
Summary 253

PART 2

13 Sources and detectors **257**
13.1 Introduction 257
13.2 Semiconductor sources 258
13.3 Semiconductor detectors 259
13.4 The choice of semiconductor 259
13.5 The organization of Part 2 260
Summary 260

14 Basic semiconductor properties **262**
14.1 Intrinsic and impurity semiconductors 262
14.1.1 Intrinsic semiconductors 262
14.1.2 Impurity semiconductors 270
14.2 The p–n junction 272
14.2.1 The p–n junction in equilibrium 272
14.2.2 The biassed p–n junction 273
14.3 Carrier recombination and diffusion 277
14.3.1 Minority carrier lifetime 277
14.3.2 The diffusion length 278
14.3.3 Surface recombination velocity 280
14.4 Injection efficiency 281
14.5 The depletion layer 283
14.6 An equivalent circuit for the p–n junction 285
14.7 Heterojunctions 287
14.7.1 Types of heterojunction 287
14.7.2 Heterojunction characteristics 291
14.7.3 Heterojunction injection efficiency 293
Problems 296
Reference 297
Summary 297

此为试读,需要完整PDF请访问: www.ertongbook.com

15 Injection luminescence **299**
15.1 Recombination processes 299
15.2 The spectrum of recombination radiation 301
15.3 Direct and indirect band-gap semiconductors 306
15.4 The internal quantum efficiency 309
15.5 Behaviour at high frequency 313
15.6 The double heterostructure 319
15.6.1 Introduction 319
15.6.2 Useful properties of the double heterostructure 320
15.6.3 Internal quantum efficiency of a double heterostructure 323
15.6.4 Carrier confinement 324
15.6.5 Modulation bandwidth 327
15.7 Fabrication of heterostructures 329
15.8 Quantum wells and superlattices 332
Problems 334
Reference 335
Summary 335

16 The design of LEDs for optical communication **337**
16.1 The external quantum efficiency 337
16.2 The Burrus-type double heterostructure surface-emitting LED (DH-SLED) 339
16.3 The stripe-geometry, edge-emitting LED (ELED) 344
16.4 LED-to-fiber launch efficiency 345
16.5 Lensed LED-to-fiber launch systems 346
16.6 LED designs 350
Problems 353
Summary 353

17 The basic principles of laser action **355**
17.1 Spontaneous emission, stimulated emission and absorption 355
17.2 The condition for laser action 357
17.3 Types of laser 361
17.3.1 Introduction 361
17.3.2 Gas lasers 362
17.3.3 Solid-state lasers 363
17.3.4 Dye lasers 367
17.3.5 Semiconductor lasers 367
17.4 Features of laser radiation 373
17.4.1 Cavity modes 373
17.4.2 Laser linewidth 376
17.4.3 Generation of pulses 378
Problems 379
References 380
Summary 380

18 Semiconductor lasers 382
18.1 The theory of laser action in semiconductors 382
18.1.1 The condition for gain 382
18.1.2 Rates of stimulated and spontaneous emission 384
18.1.3 The effect of refractive index 385
18.1.4 Calculation of the gain coefficient 386
18.1.5 The relation of the gain coefficient to the current density 387
18.2 Some simplified calculations 389
18.2.1 An estimate of the gain coefficient 389
18.2.2 Theoretical variation of the gain coefficient 391
18.2.3 The threshold current density 394
18.2.4 The differential quantum efficiency 398
18.3 Modulation frequency response 399
18.3.1 Small signal frequency response 399
18.3.2 Step response 401
18.3.3 Frequency modulation (chirp) 404
18.4 Noise in semiconductor lasers 405
Problems 407
References 408
Summary 408

19 Semiconductor lasers for optical fiber communication systems 410
19.1 Introduction 410
19.2 Methods for obtaining the stripe geometry 412
19.3 Optical and electrical characteristics of Fabry–Perot lasers 417
19.3.1 Spectral characteristics 417
19.3.2 Power and voltage characteristics 420
19.4 Quantum-well lasers and laser arrays 424
19.5 Single frequency semiconductor lasers 428
19.5.1 Introduction 428
19.5.2 Distributed feedback (DFB) lasers 430
19.6 The reliability of DH semiconductor LEDs and lasers 434
19.7 The transmitter module 437
Problems 439
References 439
Summary 439

20 Semiconductor photodiode detectors 441
20.1 General principles 441
20.2 Quantum efficiency 444
20.3 The choice of materials and device structures 447
20.3.1 The silicon p–i–n photodiode 447
20.3.2 The germanium photodiode 449
20.3.3 Heterojunction photodiodes 450

20.3.4 Schottky barrier photodiodes 452
20.3.5 Photodiode detectors for wavelengths longer than 1.7 μm 453
20.4 Impulse and frequency response of a p–i–n photodiode 453
20.4.1 Equivalent circuit 453
20.4.2 Carrier transit time 456
20.5 Noise in p–i–n photodiodes 461
Problems 462
References 464
Summary 464

21 Avalanche photodiode detectors and photomultiplier tubes 465
21.1 The multiplication process 465
21.1.1 Introduction 465
21.1.2 Avalanche multiplication theory 468
21.1.3 Experimental behaviour 471
21.2 APD designs 472
21.3 APD bandwidth 476
21.4 APD noise 478
21.5 Photomultiplier tubes 483
Problems 486
References 487
Summary 487

PART 3

22 The receiver amplifier 491
22.1 Introduction 491
22.2 Sources of receiver noise 494
22.3 Circuits, devices and definitions 495
22.4 Signal-to-noise ratio in the voltage amplifier circuit 497
22.5 Signal-to-noise ratio in the transimpedance feedback amplifier 501
22.6 The ideal quantum-limited receiver 504
22.7 Amplifier design examples 505
22.7.1 High input resistance or integrating amplifier 505
22.7.2 Voltage amplifier with low input resistance 507
22.7.3 Explicit solution 510
22.7.4 A worked example 511
Problems 512
References 514
Summary 514

23 The regeneration of digital signals 516
23.1 Causes of regeneration error 516
23.1.1 The ideal digital system 516

23.1.2 Causes of regeneration error 518
23.1.3 Filter characteristics designed to minimize intersymbol interference 520
23.1.4 The eye diagram 521
23.2 The quantum limit to detection 524
23.3 The effect of amplifier noise and thermal noise on the error probability 526
23.3.1 Probability of error when shot noise is negligible 526
23.3.2 Probability of error when multiplied shot noise is comparable to other sources of noise 530
23.3.3 System optimization 534
23.4 Noise penalties in practical systems 535
23.4.1 Introduction 535
23.4.2 Non-zero extinction ratio 535
23.4.3 Finite pulse width and timing jitter 535
23.4.4 Power amplitude variations; modal noise 536
Problems 540
Summary 541

24 Coherent systems **543**
24.1 Introduction 543
24.2 Methods of modulation 544
24.3 The coherent receiver 547
24.3.1 Homodyne and heterodyne detection 547
24.3.2 Noise in a coherent receiver 551
24.3.3 Polarization control in fiber systems 552
24.4 The homodyne receiver 552
24.4.1 Receiver sensitivity 552
24.4.2 Laser linewidth 556
24.5 The heterodyne receiver 557
24.5.1 The range of possible systems 557
24.5.2 Receiver sensitivity with synchronous demodulation 559
24.5.3 Asynchronous and self-synchronous demodulation 562
24.6 Phase-diversity receivers 565
References 567
Summary 567

25 Unguided optical communication systems **569**
25.1 Introduction 569
25.2 Transmission parameters 570
25.2.1 Beam divergence 570
25.2.2 Atmospheric attenuation 576

25.3 Sources and detectors 577
25.3.1 Introduction 577
25.3.2 Neodymium laser sources 578
25.3.3 Carbon dioxide laser sources 579
25.3.4 Laser arrays 580
25.4 Examples of unguided optical communication systems 581
25.4.1 Terrestrial systems 581
25.4.2 A proposed optical system for communication in near-space 584
Problems 586
References 587
Summary 587

26 Optical fiber communication systems 589
26.1 Introduction 589
26.2 The economic merits of optical fiber systems 592
26.2.1 An overview 592
26.2.2 Telecommunications 594
26.2.3 Local distribution services 598
26.2.4 Computer networks, local data transmission and telemetry 601
26.3 Digital optical fiber telecommunication systems 602
26.3.1 Introduction 602
26.3.2 First generation systems 602
26.3.3 Second generation systems 605
26.3.4 Future systems 609
26.4 Data communication networks 611
26.4.1 Introduction 611
26.4.2 Network topologies 614
26.4.3 Medium access control protocols 617
26.4.4 System examples 619
26.5 Analog systems 623
26.5.1 Advantages and disadvantages of analog modulation 623
26.5.2 Direct intensity modulation at baseband 623
26.5.3 The use of a frequency-modulated subcarrier 627
26.6 The optical ether 628
Problems 631
References 632
Summary 632

Appendix 1 The root mean square pulse width 635
A1.1 Definition of r.m.s. pulse width 635
A1.2 The summation of independent pulse broadening effects 636

Appendix 2 The electromagnetic wave equation 638
A2.1 The wave equation in an isotropic medium 638
A2.2 Solution in an inhomogeneous medium 639
A2.3 Solutions in cylindrical coordinates 641
A2.4 Solutions of the wave equation in graded-index fiber 643

Appendix 3 Ray trajectories in graded-index fiber 648
A3.1 Basis of the ray model 648
A3.2 Derivation of a parametric equation for the ray trajectory 650
A3.3 Solutions to the ray equations 654
A3.4 Multipath dispersion 658
A3.5 Leaky rays 658

Appendix 4 Near-field and far-field distributions 660
A4.1 Diffraction theory 660
A4.2 A circular Gaussian beam 664
A4.3 An elliptical Gaussian beam 665
A4.4 The uniformly illuminated circular aperture 666
A4.5 The LP_{10} fiber propagation mode 666
A4.6 Relationships between the different methods for determining the mode-field diameter 667

Appendix 5 Radiometry and photometry 669

Appendix 6 The frequency response of a laser diode 673
A6.1 Steady-state conditions 673
A6.2 Small perturbations about the steady state 675

Appendix 7 The impulse response of a filter with antisymmetric frequency response 677
A7.1 Definition of frequency response 677
A7.2 Response to an impulse at $t = 0$ 677
A7.3 Impulse response at $t = nT$, where n is an integer 678

Appendix 8 Answers to numerical problems 679

Index **685**

此为试读,需要完整PDF请访问: www.ertongbook.com