OPTICAL GUIDED WAVES AND DEVICES

Richard Syms John Cozens

Department of Electrical and Electronic Engineering Imperial College of Science, Technology and Medicine

McGRAW-HILL BOOK COMPANY

London · New York · St Louis · San Francisco · Auckland · Bogotá · Caracas Hamburg · Lisbon · Madrid · Mexico · Milan · Montreal · New Delhi · Panama Paris · San Juan · São Paulo · Singapore · Sydney · Tokyo · Toronto

CONTENTS

Acknowledgements		
1.	Overview 1.1 Guided wave optical devices 1.2 Rationale	1 1 7
2.	Electromagnetic fields and plane waves 2.1 Maxwell's equations	9 9
	 2.2 The differential form of Maxwell's equations 2.3 Harmonically-varying fields and the wave equation 2.4 Plane waves 2.5 Power flow 2.6 The propagation of general time-varying signals 	15 17 19 27 30
3.	Material effects 3.1 Introduction 3.2 The origin of the dielectric constant 3.3 Material dispersion 3.4 The origin of electrical conductivity 3.5 Anisotropic media 3.6 Non-linear effects 3.7 The electro-optic effect	37 37 38 42 45 49 55
4.	3.8 Stress-related effects The optics of beams 4.1 Scalar theory 4.2 Spherical waves 4.3 Lenses 4.4 Diffraction theory	65 72 72 72 76 80

vi CONTENTS

	4.5 Fraunhofer diffraction	82
	4.6 Fresnel diffraction and Gaussian beams	84
	4.7 Transformation of Gaussian beams by lenses	88
	4.8 Mirrors and resonators	92
5.	Reflection and refraction at a single interface	100
	5.1 The behaviour of light at a dielectric interface	100
	5.2 Superposition of fields	101
	5.3 Boundary matching	103
	5.4 Electromagnetic treatment of the interface problem	105
	5.5 Modal treatment of the dielectric interface problem	114
	5.6 Surface plasma waves	115
6.	The slab waveguide	120
	6.1 Guided waves in a metal guide	120
	6.2 Guided waves in a slab dielectric waveguide	122
	6.3 Other types of mode	129
	6.4 The weak-guidance approximation	132
	6.5 The orthogonality of modes	134
	6.6 The power carried by a mode	136
	6.7 The expansion of arbitrary fields in terms of modes	137
	6.8 Application of the overlap principle	138
7.	Planar waveguide integrated optics	145
	7.1 Overview of planar waveguide components	145
	7.2 Phase matching at a single interface	145
	7.3 The FTIR beamsplitter	148
	7.4 The prism coupler	150
	7.5 Phase matching for guided modes	155
	7.6 Refractive optical components	157
	7.7 Gratings	161
	7.8 Gratings in guided wave optics	169
8.	Optical fibres and fibre devices	179
	8.1 Optical fibre types	179
	8.2 Loss in silica and fluoride glass fibre	181
	8.3 Step-index optical fibres	182
	8.4 Parabolic-index optical fibres	187
	8.5 Signal dispersion	195
	8.6 Mode conversion in fibres	197
	8.7 Coupling to fibres	200
	8.8 Fibre interconnects	204
	8.9 Fibre-based components	209

CO	NΊ	FI	JTS	vii

9. Channel waveguide integrated optics	217
9.1 Channel waveguide types	217
9.2 Input and output coupling	222
9.3 Sources of propagation loss	224
9.4 Polarizers	227
9.5 Mirrors	228
9.6 Tapers and Y-junctions	231
9.7 Phase modulators	235
9.8 Frequency shifting and high-speed operation	239
9.9 Interferometers	243
10. Coupled mode devices	250
10.1 Introduction	250
10.2 The directional coupler—basic principles	250
10.3 The directional coupler—theoretical analysis	253
10.4 Solution of the equations at synchronism	257
10.5 Asynchronous solution	258
10.6 Fibre directional couplers	260
10.7 Coupling between dissimilar waveguides	263
10.8 Sidelobe suppression using tapered coupling	266
10.9 The reflection grating filter—basic principles	267
10.10 The reflection grating filter—theoretical analysis	270
10.11 Solution of the equations at synchronism	272
10.12 Asynchronous solution	273
10.13 Fibre gratings	274
10.14 Other coupled mode interactions	275
11. Optoelectronic interactions in semiconductors	282
11.1 Wave-particle duality	282
11.2 Photons	284
11.3 Electrons	287
11.4 Band theory	295
11.5 Effective mass	304
11.6 Carrier statistics	307
11.7 Intrinsic and extrinsic semiconductors	311
11.8 Detailed balance	316
11.9 Rate equations	318
12. Optoelectronic devices	326
12.1 The p-n junction diode	326
12.2 Electro-optic semiconductor devices	339
12.3 Photodiodes	341
12.4 The light-emitting diode	346
12.5 The semiconductor laser: basic operation	356
12.6 The semiconductor laser: steady-state analysis	366

viii CONTENTS

	12.7 The semiconductor laser: modulation	371
	12.8 DBR and DFB lasers	373
	12.9 Array lasers	378
	12.10 Surface-emitting lasers	383
	12.11 Travelling-wave laser amplifiers	385
13.	Optical device fabrication	390
	13.1 Overview	390
	13.2 Planar processing	390
	13.3 Substrate growth and preparation	391
	13.4 Deposition and growth of material	393
	13.5 Material modification	401
	13.6 Etching	406
	13.7 Lithography	411
	13.8 Optical fibre fabrication	417
14.	Systems and applications	428
	14.1 Introduction	428
	14.2 The planar integrated optic RF spectrum analyser	428
	14.3 The planar integrated optic disc read head	432
	14.4 Guided-wave optical chip-to-chip interconnects	433
	14.5 The channel waveguide integrated optic A-to-D converter	434
	14.6 Optical fibre sensors	437
	14.7 The integrated optic fibre gyroscope	439
	14.8 High-speed, guided wave optical communications	442
	14.9 Fibre lasers and amplifiers	447
An	swers to selected problems	453
Sul	bject index	492