

Contents

<i>Preface</i>	<i>page xi</i>
1 The need for compact blue-green lasers	1
1.1 A short historical overview	1
1.2 Applications for compact blue-green lasers	3
1.2.1 Optical data storage	3
1.2.2 Reprographics	5
1.2.3 Color displays	6
1.2.4 Submarine communications	8
1.2.5 Spectroscopic applications	12
1.2.6 Biotechnology	14
1.3 Blue-green and beyond	17
References	17
Part 1 Blue-green lasers based on nonlinear frequency conversion	20
2 Fundamentals of nonlinear frequency upconversion	20
2.1 Introduction	20
2.2 Basic principles of SHG and SFG	21
2.2.1 The nature of the nonlinear polarization	21
2.2.2 Frequencies of the induced polarization	23
2.2.3 The d coefficient	28
2.2.4 The generated wave	30
2.2.5 SHG with monochromatic waves	34
2.2.6 Multi-longitudinal mode sources	34
2.2.7 Pump depletion	38
2.3 Spatial confinement	43
2.3.1 Boyd–Kleinman analysis for SHG with circular gaussian beams	43
2.3.2 Guided-wave SHG	51

2.4	Phasematching	56
2.4.1	Introduction	56
2.4.2	Birefringent phasematching	57
2.4.3	Quasi-phasematching (QPM)	71
2.4.4	Waveguide phasematching	90
2.4.5	Other phasematching techniques	97
2.4.6	Summary	101
2.5	Materials for nonlinear generation of blue-green light	101
2.5.1	Introduction	101
2.5.2	Lithium niobate (LN)	101
2.5.3	Lithium tantalate (LT)	108
2.5.4	Potassium titanyl phosphate (KTP)	110
2.5.5	Rubidium titanyl arsenate (RTA)	115
2.5.6	Other KTP isomorphs	119
2.5.7	Potassium niobate (KN)	119
2.5.8	Potassium lithium niobate (KLN)	121
2.5.9	Lithium iodate	123
2.5.10	Beta barium borate (BBO) and lithium borate (LBO)	124
2.5.11	Other materials	126
2.6	Summary	130
	References	130
3	Single-pass SHG and SFG	149
3.1	Introduction	149
3.2	Direct single-pass SHG of diode lasers	151
3.2.1	Early experiments with gain-guided lasers	151
3.2.2	Early experiments with index-guided lasers	154
3.2.3	High-power index-guided narrow-stripe lasers	156
3.2.4	Multiple-stripe arrays	157
3.2.5	Broad-area lasers	160
3.2.6	Master oscillator–power amplifier (MOPA) configurations	161
3.2.7	Angled-grating distributed feedback (DFB) lasers	169
3.3	Single-pass SHG of diode-pumped solid-state lasers	170
3.3.1	Frequency-doubling of 1064-nm Nd:YAG lasers	177
3.3.2	Frequency-doubling of 946-nm Nd:YAG lasers	177
3.3.3	Sum-frequency mixing	178
3.4	Summary	178
	References	179

<i>Contents</i>		vii
4	Resonator-enhanced SHG and SFG	183
4.1	Introduction	183
4.2	Theory of resonator enhancement	187
4.2.1	The impact of loss	189
4.2.2	Impedance matching	191
4.2.3	Frequency matching	193
4.2.4	Approaches to frequency locking	194
4.2.5	Mode matching	207
4.3	Other considerations	213
4.3.1	Temperature locking	213
4.3.2	Modulation	214
4.3.3	Bireflection in monolithic ring resonators	215
4.4	Summary	220
	References	220
5	Intracavity SHG and SFG	223
5.1	Introduction	223
5.2	Theory of intracavity SHG	224
5.3	The “green problem”	229
5.3.1	The problem itself	229
5.3.2	Solutions to the “green problem”	231
5.3.3	Single-mode operation	235
5.4	Blue lasers based on intracavity SHG of 946-nm Nd:YAG lasers	245
5.5	Intracavity SHG of Cr:LiSAF lasers	249
5.6	Self-frequency-doubling	250
5.6.1	Nd:LN	251
5.6.2	NYAB	252
5.6.3	Periodically-poled materials	253
5.6.4	Other materials	253
5.7	Intracavity sum-frequency mixing	253
5.8	Summary	255
	References	256
6	Guided-wave SHG	263
6.1	Introduction	263
6.2	Fabrication issues	264
6.3	Integration issues	269
6.3.1	Feedback and frequency stability	270
6.3.2	Polarization compatibility	276
6.3.3	Coupling	282
6.3.4	Control of the phasematching condition	283
6.3.5	Extrinsic efficiency enhancement	284

viii	<i>Contents</i>	
	6.4 Summary	286
	References	287
Part 2	Upconversion lasers: Physics and devices	292
7	Essentials of upconversion laser physics	292
	7.1 Introduction to upconversion lasers and rare-earth optical physics	292
	7.1.1 Overview of rare-earth spectroscopy	295
	7.1.2 Qualitative features of rare-earth spectroscopy	296
	7.2 Elements of atomic structure	303
	7.2.1 The effective central potential	303
	7.2.2 Electronic structure of the free rare-earth ions	306
	7.3 The Judd–Ofelt expression for optical intensities	324
	7.3.1 Basic formulation	325
	7.3.2 The Judd–Ofelt expression for the oscillator strength	329
	7.3.3 Selection rules for electric dipole transitions	336
	7.4 Nonradiative relaxation	338
	7.5 Radiationless energy transfer	341
	7.6 Mechanisms of upconversion	345
	7.6.1 Resonant multi-photon absorption	345
	7.6.2 Cooperative upconversion	348
	7.6.3 Rate equation formulation of upconversion by radiationless energy transfer	357
	7.6.4 The photon avalanche	360
	7.7 Essentials of laser physics	363
	7.7.1 Qualitative picture	364
	7.7.2 Rate equations for continuous-wave amplification and laser oscillation	365
	7.8 Summary	382
	References	383
8	Upconversion lasers	385
	8.1 Historical introduction	385
	8.2 Bulk upconversion lasers	397
	8.2.1 Upconversion pumped Er^{3+} infrared lasers	398
	8.2.2 Er^{3+} visible upconversion lasers	410
	8.2.3 Tm^{3+} upconversion lasers	420
	8.2.4 Pr^{3+} upconversion lasers	424
	8.2.5 Nd^{3+} upconversion lasers	425
	8.3 Upconversion fiber lasers	427
	8.3.1 Er^{3+} fiber lasers; ${}^4S_{3/2} \rightarrow {}^4I_{15/2}$ transition at 556 nm	433

<i>Contents</i>		ix
8.3.2	Tm ³⁺ fiber lasers	436
8.3.3	Pr ³⁺ fiber lasers	445
8.3.4	Ho ³⁺ fiber lasers, $^5S_2 \rightarrow ^5I_8$ transition at ~ 550 nm	455
8.3.5	Nd ³⁺ fiber lasers	457
8.4	Prospects	458
	References	460
Part 3	Blue-green semiconductor lasers	468
9	Introduction to blue-green semiconductor lasers	468
9.1	Overview	468
9.2	Overview of physical properties of wide-bandgap semiconductors	470
9.2.1	Lattice matching	470
9.2.2	Epitaxial lateral overgrowth (ELOG)	472
9.2.3	Basic physical parameters	474
9.3	Doping in wide-gap semiconductors	475
9.4	Ohmic contacts for <i>p</i> -type wide-gap semiconductors	478
9.4.1	Ohmic contacts to <i>p</i> -AlGaInN	479
9.4.2	New approaches to <i>p</i> -contacts	481
9.4.3	Ohmic contacts to <i>p</i> -ZnSe: bandstructure engineering	482
9.5	Summary	484
	References	484
10	Device design, performance, and physics of optical gain of the InGaN QW violet diode lasers	487
10.1	Overview of blue and green diode laser device issues	487
10.2	The InGaN MQW violet diode laser: Design and performance	488
10.2.1	Layered design and epitaxial growth	488
10.2.2	Diode laser fabrication and performance	496
10.3	Physics of optical gain in the InGaN MQW diode laser	501
10.3.1	On the electronic microstructure of InGaN QWs	506
10.3.2	Excitonic contributions in green-blue ZnSe-based QW diode lasers	509
10.4	Summary	513
	References	513
11	Prospects and properties for vertical-cavity blue light emitters	517
11.1	Background	517
11.2	Optical resonator design and fabrication: Demonstration of optically-pumped VCSEL operation in the 380–410-nm range	518

x	<i>Contents</i>	
	11.2.1 All-dielectric DBR resonator	519
	11.2.2 Stress engineering of AlGaIn/GaN DBRs	521
	11.3 Electrical injection: Demonstration resonant-cavity LEDs	524
	11.4 Summary	530
	References	530
12	Concluding remarks	533
	References	536
	<i>Index</i>	537