

Contents

1	Analysis and Calculation of Three-Wave Interaction in Nonlinear Optical Crystal	1
1.1	Tensors, Polarizability Tensors, and Electric Polarization Vectors	1
1.1.1	Definition of Tensors [1]	1
1.1.2	Tensor Algebraic Calculation	2
1.1.3	Polarizability Tensors [2].....	4
1.1.4	Classical Description of Polarizability	5
1.1.5	Nonlinear Electric Polarization Vectors in Three-Dimensional Spaces	8
1.1.6	Macroscopic Qualities of Polarizability Tensor	9
1.2	Optical Characters of Nonlinear Crystals	10
1.2.1	Optical Classification of Nonlinear Optical Crystals	10
1.2.2	Propagation of Monochromatic Plane Wave in Nonlinear Crystals	11
1.3	Phase Matching and Nonlinear Coefficients of Three-Wave Interaction in Uniaxial Crystals	17
1.3.1	The Phase-Matching Conditions and the Angular Phase Matching	18
1.3.2	Walk-off Angle	23
1.3.3	Acceptance Angles of Angular Phase Matching	24
1.3.4	Noncritical Phase Matching	28
1.3.5	Effective Nonlinear Coefficient of Three-Wave Interaction	31
1.4	Phase Matching and Nonlinear Coefficients of the Three-Wave Interaction in Biaxial Crystals	35
1.4.1	Phase Matching in Biaxial Crystals	35
1.4.2	Calculation of the Effective Nonlinear Coefficient in Biaxial Crystals	39

1.4.3	Calculation of the Phase-Matching Angle and the Effective Nonlinear Coefficient in Typical Biaxial Crystals	45
1.5	Calculation of the Acceptance Parameters of Three-Wave Interaction	52
1.5.1	Small Signal Approximation	53
1.5.2	Efficiency and Acceptance Parameters for Phase Mismatching	61
1.6	Walk-Off Angle in Biaxial Crystal	66
1.6.1	Calculation of the Walk-Off Angle in Biaxial Crystal	67
1.6.2	Effect of the Walk-Off Angle in Biaxial Crystal	69
1.7	Thermal Effects and Its Effect on the Three-Wave Interaction	74
1.7.1	Self-thermal Effects	74
1.7.2	Temperature Distribution	76
1.7.3	Effect of the Temperature Distribution on Efficiency	82
1.8	Noncollinear Phase Matching	83
1.8.1	Noncollinear Phase Matching in Uniaxial Crystals [23]	83
1.8.2	Noncollinear Phase Matching in Biaxial Crystals	88
1.9	Examples of Nonlinear Crystals	90
1.9.1	$B-BaB_2O_4$ (BBO)	90
1.9.2	LiB_3O_5 (LBO)	96
1.9.3	$KTiPO_4$ (KTP)	102
1.9.4	$CsLiB_6O_{10}$ (CLBO)	108
1.9.5	KBBF	116
	References	123
2	Nonlinear Optical Frequency Mixing Theory	125
2.1	Coupled Wave Equations [1–9]	126
2.1.1	Steady-State Coupled Wave Equations	126
2.1.2	Transient Coupled Wave Equations	127
2.1.3	Manley–Rowe Relations	128
2.2	Steady-State Small-Signal Solution of Optical Frequency Doubling and Mixing	129
2.3	General Solution to Steady-State Coupled Wave Interaction Equation	131
2.3.1	Frequency Doubling Solution of Type-I Phase Matching	134
2.3.2	Frequency Doubling Solution of Type-II Phase Matching	140
2.4	Frequency Doubling Solution of 3-Dimensional Coupled Wave Equation [3, 5]	150
2.5	Theory and Experiments of Extracavity Frequency Doubling	153
2.5.1	Extracavity Frequency Doubling with Focused Gaussian Beams	154
2.5.2	Examples for Extracavity Frequency Doubling	158

2.6	Theory of Gaussian-Like Distribution: Basis for Multimode (Mixed Mode) Frequency Doubling	160
2.6.1	Transverse Distribution of Multimode Beam	160
2.6.2	Characteristics of Multimode Beam	167
2.6.3	Propagation and Transformation of Gaussian-Like Beam In a Homogeneous Medium	168
2.6.4	Measurement of Multimode Coefficient M	170
2.7	Frequency Doubling of Gaussian-Like Beams [1].....	173
	References	177
3	Theory and Technology of Frequency Doubling and Frequency Mixing Lasers	179
3.1	Analysis of Rate Equations for Intracavity SHG Laser	180
3.1.1	Derivation of Rate Equations	180
3.1.2	Solutions of Rate Equations and Result Analysis	183
3.2	Design and Experimental Study on Fundamental Mode SHG YAG Laser	185
3.2.1	Optimal Operation Conditions of SHG Devices in Fundamental Mode SHG YAG Laser	186
3.2.2	Optimal Operation Conditions of Acousto-Optic Modulator in Fundamental Mode SHG YAG Laser	192
3.2.3	Parameters of the Resonant Cavity in Fundamental Mode SHG YAG Laser	194
3.2.4	Optimal Output Coupling of Intracavity Frequency Doubling Laser	197
3.2.5	Analysis of the Stability of the Fundamental Mode SHG YAG Laser	202
3.2.6	Designing the Water-Cooling System of Fundamental Mode SHG YAG Laser	204
3.2.7	The Experimental Result and the Gross Structure Design of Fundamental Mode SHG YAG Laser	206
3.3	High Power Multimode Intracavity Frequency Doubling YAG Laser	209
3.3.1	The Principle of Improvement in Frequency Doubling Efficiency with Quasi-Continuous-Wave Operation	210
3.3.2	Analysis of Thermal Effects under Quasi-Continuous-Wave Operation and Related Experiments [10].....	213
3.4	Frequency Mixing of Ultrashort Pulse	217
3.4.1	Group Velocity Characteristic in a Dispersive Medium [28, 29]	218

3.4.2	Phase Matching Conditions for Ultrashort Pulses and Effects of Group-Velocity Mismatching and Dispersion	222
3.4.3	Harmonic Wave Generation of Ultrashort Pulses [29]	225
3.4.4	Four-Wave Mixing of Ultrashort Pulses	241
	References	243
4	Optical Parametric Oscillator	245
4.1	Analysis on the Characteristics of the Pulsed OPO	247
4.1.1	The OPO Model and Its Coupled Wave Equation	247
4.1.2	Characteristic Analysis of the Long Pulse Pumped OPO	251
4.2	Synchronously Pumped Optical Parametric Oscillator	257
4.2.1	The Model and the Coupled Wave Equations of Singly Resonant Synchronously Pumped Optical Parametric Oscillator [19]	258
4.2.2	The Solution Ignoring Walk-Off Effect and Group Velocity Dispersion	260
4.2.3	Influence of Walk-Off Effect	262
4.2.4	Influence of Group Velocity and the Final Expression	263
4.2.5	Characteristic Analysis of Synchronously Pumped Optical Parametric Oscillator	265
4.3	Conversion Efficiency and Linewidth Characteristics of OPO	267
4.3.1	The Effect of the Relative Phase and the Detuning of Three Waves on Conversion Efficiency	267
4.3.2	Linewidth of OPO	274
4.4	Examples of OPOs Based on Typical Crystals	281
4.4.1	Barium-Beta-Borate OPO [20, 22–37]	281
4.4.2	Lithium-Triborate OPO [21, 38–46]	283
4.4.3	Silver-Gallium-Selenide (AgGaSe_2) OPO [47–51]	284
4.4.4	Kalium-Titan-Phosphate Crystal and KTP-OPO [52–61]	284
4.4.5	Magnesium-Oxide: LiNbO_3 (MgO) OPO [64–66]	289
4.4.6	Experimental Results in Temperature Tuning Singly and Doubly Resonant Oscillators Based on $\text{MgO} : \text{LiNbO}_3$	300
4.5	Terahertz-Wave Parametric Oscillator and Generator	308
4.5.1	Introduction of Terahertz Wave	308
4.5.2	The Theory of TPG Using Polaritons	310
4.5.3	The Theoretical Experiments	313
4.6	Future Tendency	315
	References	317

5	Quasi-Phase-Matching Technology	319
5.1	Introduction	319
5.1.1	Development of QPM Technology	319
5.1.2	QPM Materials	323
5.1.3	Applications of Quasi-Phase Matching	328
5.2	Principles of QPM	332
5.2.1	Theory	332
5.2.2	Three-Wave Coupled Equation for QPM	333
5.2.3	Optical Pulse Compression Using QPM SHG Devices [76]	336
5.3	QPM–OPO Tuning Technology	340
5.3.1	Temperature Tuning	340
5.3.2	Angle Tuning	343
5.3.3	Grating Period Tuning [56]	355
5.4	Typical Experiments with Periodically Poled Crystals	357
5.4.1	MultiWavelength Conversion by QPM	357
5.4.2	Efficient, CW OPO Experiments [60, 95]	361
5.4.3	Efficient, High Power, or High Energy OPO and OPG Experiments	363
5.4.4	Broadband Light Sources Using QPM Devices	365
5.4.5	Two-dimensional QPM Gratings [22]	368
5.4.6	Terahertz Generation with PPLN [85, 86]	370
5.4.7	Optical Pulse Compression [76, 77]	375
5.4.8	Actively Electro-Optic Q-Switching Using PPLN [98]	377
5.4.9	Totally Internal Reflecting (TIR)-PPLN-OPG	378
	References	380
6	Principle, Device, and Technology of Diode-Pumped Solid-State Laser	383
6.1	Introduction of Diode-Pumped Solid-State Laser	383
6.1.1	Early Stage: The 1960s	383
6.1.2	Slow Development Stage: The 1970s	384
6.1.3	Vigorous Development Stage: the 1980s	384
6.1.4	Rapid Development Stage: From the 1990s	385
6.2	Fundamental Principles of DPL	386
6.2.1	Optical Pumping System	386
6.2.2	Design of Resonator	387
6.3	Thermal Effect of DPL	396
6.3.1	Thermal Effect of Diode Side-Pumped Solid-State Laser	396
6.3.2	Thermal Effect of Diode End-Pumped Solid-State Laser	404

6.4	Continuous-Wave DPL.....	410
6.4.1	The Characteristic Analysis of Diode End-Pumped Nd:YAG Laser Operating at Quasi-Three-Level System [35].....	410
6.4.2	Diode End-Pumped CW Solid-State Laser	412
6.4.3	Diode Side-Pumped CW Solid-State Laser	414
6.4.4	Diode-Pumped CW Multiwavelength Laser	415
6.5	All-Solid-State Pulse Laser	416
6.5.1	Q-Switched DPL.....	416
6.5.2	Mode-Locked DPL	419
6.6	Generation of Terahertz Radiation via Difference Frequency Generation	421
6.6.1	Collinear Phase-Matched THz-Wave Radiation by DFG in Gap Crystal Using a Dual-Wavelength OPO [77].....	422
6.6.2	THz-Wave Surface-Emitted DFG in PPLN Waveguide [80]	424
6.6.3	The Development of THz-Wave Radiation by DFG	427
	References.....	430
7	RGB-DPL and High Power DPL	433
7.1	RGB-DPL	433
7.1.1	Red DPL	433
7.1.2	Green DPL	439
7.1.3	Blue DPL	447
7.1.4	Laser Display with RGB-DPL.....	453
7.2	High Power DPL	455
7.2.1	High Power Rod DPL	455
7.2.2	High Power Slab DPL	458
7.2.3	High Power Disk DPL.....	461
7.3	Fiber DPL and Photonic Crystal Fiber (Laser)	464
7.3.1	Fiber DPL Laser	464
7.3.2	PCF Laser	476
	References.....	483
8	Solid Tunable Laser Technology	489
8.1	Overview of Solid Laser Materials Doped with Paramagnetic Ions	489
8.1.1	Solid Materials Doped with Cr^{3+} and V^{2+}	489
8.1.2	Solid Materials Doped with Ni^{2+} , Co^{2+} [4–32]	491
8.1.3	Solid Materials Doped with Ce^{3+}	492
8.2	Tunable Alexandrite Laser	494
8.2.1	Physical Properties of $\text{Cr:BeAl}_2\text{O}_2$	495
8.2.2	Optical Properties of $\text{Cr:BeAl}_2\text{O}_4$	495
8.2.3	$\text{Cr:BeAl}_2\text{O}_4$ Laser	496

8.3	Tunable Forsterite Laser	498
8.3.1	Structure and Luminescent Mechanism of Cr:Mg ₂ SiO ₄	500
8.3.2	Theoretical Analysis of Pulse-Pumped Cr:Mg ₂ SiO ₄ Laser	508
8.3.3	Output Characteristics Analysis of Cr:Mg ₂ SiO ₄ Laser	511
8.3.4	Experimental Results of Cr:Mg ₂ SiO ₄ Laser	517
8.4	Tunable Cr:LiSAF Laser	520
8.4.1	Properties of Cr:LiSAF	521
8.4.2	Tunable Cr:LiSAF Laser	522
8.5	Color-Center Laser	524
8.5.1	Basic Properties of Color-Center Crystal	524
8.5.2	The Energy Level Structure and Optical Properties of Color Center	528
8.5.3	Several <i>F</i> Centers Used as Laser Active Medium	530
8.5.4	Some Important Color Center Lasers	532
8.5.5	Characteristics and Experimental Study of LiF:F ₂ , LiF:F ₂ ⁺ , and LiF:F ₂ ⁻ Color-Center Laser	532
	References	542
9	Tunable Titanium Doped Sapphire (Ti:Sapphire) Laser	545
9.1	Physical–Chemical and Spectral Properties of Ti:Sapphire Crystal	547
9.1.1	Crystal Structure of Ti:Sapphire	547
9.1.2	Energy Level of Ti:Sapphire Crystal	547
9.1.3	Absorption Spectrum of Ti:Sapphire Crystal	549
9.1.4	Fluorescent Spectrum of Ti:Sapphire Crystal	551
9.1.5	Growth Method of Ti:Sapphire Crystal	552
9.2	Continuous-Wave Ti:Sapphire Lasers	554
9.2.1	Output Characteristics of End-Pumped CW Ti:Sapphire Laser	555
9.2.2	Cavity Design of CW Ti:Sapphire Laser	566
9.2.3	Experiment of CW Ti:Sapphire Laser	573
9.3	Quasi-Continuous-Wave Ti:Sapphire Laser	577
9.3.1	Temporal Characteristics of Ti:Sapphire Laser	578
9.3.2	Output Power of Ti:Sapphire Laser	590
9.3.3	Experiment of QCW Ti:Sapphire Laser	594
9.3.4	Ti:Sapphire Laser Pumped by Copper Vapor Laser	600
9.4	Pulsed Ti:Sapphire Laser	601
9.4.1	Types of Pulsed Ti:Sapphire Laser	601
9.4.2	Dynamics of Pulsed Ti:Sapphire Laser [58]	604
9.5	Ultrashort Pulsed Ti:Sapphire Laser	620
9.5.1	Active Mode-Locked Ti:Sapphire Laser	620
9.5.2	Passive Mode-Locked Ti:Sapphire Laser with Saturable Absorber	620

9.5.3	Synchronously Pumped Mode-Locking Ti:Sapphire Laser [61, 62]	622
9.5.4	Auxiliary Cavity Mode-Locked Ti:Sapphire Laser	623
9.5.5	Mode-Locked Ti:Sapphire Laser with Microdot Mirror [67]	627
9.5.6	Self-Mode-Locked Ti:Sapphire Laser	628
9.5.7	The Amplification of the Femtosecond Ti:Sapphire Laser	637
9.6	Narrow Linewidth and Frequency Stabilized Ti:Sapphire Laser	638
9.7	All-Solid-State Ti:Sapphire Laser	639
	References	641
10	Other Laser Tunable Technologies	643
10.1	Tunable Dye Laser	643
10.1.1	Physical–Chemical and Spectral Properties of Organic Dye	643
10.1.2	Continuous-Wave (CW) and Quasi- Continuous-Wave (QCW) Dye Laser	648
10.1.3	Pulsed and Flashlamp-pumped Dye Laser	650
10.2	Stimulated Raman Laser	653
10.2.1	Discontinuous Tuning Raman Laser	654
10.2.2	Raman Laser Pumped by CW Tunable Laser	654
10.2.3	Spin-Flip Raman Laser	655
10.3	Fiber Raman Laser	657
10.3.1	Raman Spectrum of Fiber	657
10.3.2	Loss Characteristics of Fiber	658
10.3.3	Raman Gain and Effective Interaction Length	659
10.3.4	The Nonuniformity of Raman Gain	660
10.3.5	Fiber Choice	660
10.3.6	Raman Effect and Group Velocity Dispersion of Picosecond Pulses in Long Fiber	661
10.3.7	Fiber Raman Laser	661
10.4	Tunable High-Pressure Infrared Laser	664
10.4.1	Operating Principle of Tunable High-pressure Infrared Laser	664
10.4.2	Experiment of Tunable High-Pressure Infrared Laser	671
10.5	Excimer Laser [69]	673
10.5.1	Characteristics and Operating Principle of Excimer Lasers	674
10.5.2	Some Kinds of Primary Excimer Lasers	680
	References	681
	Index	685