

Contents

Mid-Infrared 2–5 μm Heterojunction Laser Diodes

André Joullié, Philippe Christol, Alexei N. Baranov and Aurore Vicet ... 1

1. Introduction	1
2. Historical	3
3. State of the Art	5
3.1. Typical Heterojunction Laser Structure	5
3.2. Maximum Temperature of Operation	9
3.3. Maximum Operating Temperature in the 2–5 μm Wavelength Domain	11
4. Antimonide Quantum Well Laser Diodes for the 2–3 μm Spectral Range	13
4.1. Strained GaInAsSb Alloys and Quantum Wells	14
4.2. Fabrication of Antimonide Quantum Well Laser Diodes	20
4.3. Antimonide QW Laser Diodes for the 2.0–2.3 μm Spectral Range	23
4.4. GaInAsSb QW Laser Diodes Emitting beyond 2.3 μm	28
4.5. Characterization of Antimonide-Based Laser Diodes Dedicated to Gas Detection	33
5. 3–5 μm Interband Type-II Laser Diodes	40
5.1. InAsSb/InAs Type-II Multi-quantum Well Laser	41
5.2. InAs/GaInSb Type-III “W” Laser	45
6. Conclusion	48
References	50

High Performance Quantum Cascade Lasers and Their Applications

Daniel Hofstetter and Jérôme Faist 61

1. Introduction	61
2. Gain Region Designs	64
2.1. Basic Working Principles of QC Lasers	64
2.2. Three Quantum Well Gain Region	66

2.3.	Gain Region with Double-phonon Resonance	66
3.	Fabrication Technologies	68
3.1.	Surface Grating with Lateral Current Injection	68
3.2.	Lasers with InP Regrowth	70
3.3.	Junction Down Mounting	70
4.	Measurement Results	71
4.1.	Measurement Setup	71
4.2.	DFB Laser with Lateral Current Injection in the 5 μm and 10 μm Band	72
4.3.	DFB Lasers with InP Over-Grown Grating	80
4.4.	High Power Junction Down Mounted Lasers	82
4.5.	Room Temperature Continuous Wave Operation of QC Lasers	84
5.	Applications	86
5.1.	Photo-Acoustic Spectroscopy	86
5.2.	Optical Data Link Using a QC Laser	89
6.	Conclusions	92
	References	92

Mid-IR Difference Frequency Generation

	Cornelia Fischer and Markus W. Sigrist	97
1.	Introduction to Tunable Mid-IR Laser Sources	97
2.	Basic Principles of Nonlinear Optics and Difference Frequency Generation	100
2.1.	Frequency Conversion Processes	100
2.2.	Nonlinear Optical Coefficient	103
2.3.	Phase Matching	105
3.	Material Considerations	118
3.1.	Selection of Nonlinear Medium	119
3.2.	Pump and Signal Laser Sources for Difference Frequency Generation	121
4.	Difference Frequency Laser Systems Reported in the Literature ...	122
4.1.	Difference Frequency Laser Sources	122
4.2.	Difference Frequency Laser Sources Applied in Gas Sensing .	122
5.	Detailed Description of a Mid-IR DFG Laser Source	125
5.1.	Experimental Set-Up and System Performance	125
5.2.	Nd:YAG Pump Laser	126
5.3.	External Cavity Diode Laser	127
5.4.	Tuning with Periodically Poled LiNbO ₃	128
5.5.	Detection Schemes	129
6.	Applications of Mid-IR Difference Frequency Laser Systems in Gas Sensing	131
6.1.	General Considerations	131

6.2. Examples of Gas Spectroscopy Performed with Our DFG Laser Source	132
7. Conclusions and Outlook	135
References	136

Pulsed Mid-IR Optical Parametric Oscillators

Konstantin Vodopyanov	141
1. Introduction	141
2. Principle of OPO Operation	142
3. OPOs in the 2–5 μm Range	145
3.1. Comparison of NLO Materials	145
3.2. OPOs Based on PP LN	146
3.3. OPOs Based on PP KTP and PP RTA	149
3.4. OPOs Based on PP KTA	151
3.5. OPOs Using Conventional Phase-matching in Oxides	151
4. OPOs in the 4–20 μm Range	153
4.1. Comparison of NLO Materials Suitable for $\lambda > 5\mu\text{m}$	153
4.2. OPOs Based on AGS and AGSe	154
4.3. OPOs Based on ZGP	155
4.4. OPOs Based on Other Crystals	160
5. Traveling-Wave Optical Parametric Generators (OPGs)	161
5.1. OPGs Based on PP LN	162
5.2. OPGs Based on ZGP	163
5.3. OPGs Based on GaSe	164
5.4. OPGs Based on CGA	165
6. Narrow-Linewidth OPOs	165
6.1. Using Intracavity Spectral-Narrowing Elements	166
6.2. Narrow-Linewidth Optical Parametric Generator–Optical Parametric Amplifier (OPG–OPA) Systems	167
6.3. OPOs with Injection Seeding	168
6.4. Using a Doubly Resonant Cavity	169
7. Emerging Nonlinear Optical Materials for Mid-IR Applications ...	171
8. Summary and Concluding Remarks	173
References	174

Mid-Infrared Ultrafast and Continuous-Wave Optical Parametric Oscillators

Majid Ebrahimzadeh	179
1. Introduction	179
2. Optical Parametric Process	181
2.1. Optical Parametric Gain	183
2.2. Optical Parametric Amplification	184

2.3. Mid-Infrared Parametric Generation	186
3. Mid-Infrared OPO Devices	188
3.1. Nonlinear Material	188
3.2. Laser Pump Source	190
4. Mid-Infrared Nonlinear Materials	191
5. Mid-Infrared Ultrafast OPOs	196
5.1. Mid-Infrared Picosecond OPOs	197
5.2. Mid-Infrared Femtosecond OPOs	201
6. Mid-Infrared Continuous-Wave OPOs	207
7. Summary	212
References	214

Mid-Infrared Fiber Lasers

Markus Pollnau and Stuart D. Jackson	219
1. Introduction	219
2. Fiber Materials	220
2.1. Silicates	221
2.2. Fluorides	222
2.3. Chalcogenides	222
2.4. Ceramics	222
3. Fiber, Pump, and Resonator Geometries	223
3.1. Fiber Designs for Cladding Pumping	223
3.2. Fiber-Laser Resonators	225
3.3. Thermal Issues	226
4. Spectroscopic and Laser Properties of Rare-Earth Ions	226
4.1. Spectra of Rare-Earth Ions in Glasses	227
4.2. Intraionic Processes	228
4.3. Interionic Processes	230
4.4. Overview of Mid-Infrared Fiber Lasers	232
5. Thulium-Doped Fiber Lasers at 1.9–2.0 μm and 2.3–2.5 μm	233
5.1. Three-Level Lasers at 1.9–2.0 μm	233
5.2. Four-Level Lasers at 2.3–2.5 μm	234
6. Holmium-Doped Fiber Lasers at 2.1 μm and 2.9 μm	235
6.1. Three-Level Lasers at 2.1 μm	236
6.2. Four-Level Lasers at 2.9 μm	237
7. Erbium-Doped Fiber Lasers at 2.7–2.8 μm	238
7.1. Excited-State Absorption and Cascade Lasing	238
7.2. Lifetime Quenching by Pr^{3+} Co-Doping	239
7.3. Energy Recycling by Energy-Transfer Upconversion	240
8. Fiber Lasers at Wavelengths Beyond 3 μm	242
8.1. ZBLAN Fiber Lasers at 3.22 μm , 3.45 μm , and 3.95 μm	243
8.2. Future Mid-Infrared Fiber Lasers	243
9. Conclusions	244
References	245

Crystalline Mid-Infrared Lasers

Irina T. Sorokina	255
1. Introduction	255
2. Historical Overview	257
3. Principles of Solid-State Lasers	260
3.1. Spectroscopic Background	261
3.2. Influence of Spectroscopic Parameters on Laser Properties ...	281
3.3. Reaching the Threshold	283
4. Laser Design Considerations	285
4.1. Pump Sources	285
4.2. Cavity Design	286
4.3. Tuning Methods	289
4.4. Q-switched and Mode-Locked Operation	292
5. Mid-Infrared Lasers	294
5.1. TM^{2+} -Doped Lasers	295
5.2. Color Center Lasers	310
5.3. Rare-Earth Doped Lasers	314
6. Conclusion and Outlook	321
References	323

Crystalline and Fiber Raman Lasers

T. T. Basiev, V. V. Osiko, A. M. Prokhorov and E. M. Dianov	351
1. Introduction (Historical and Theoretical Background)	351
2. Nanosecond SRS Based on $\text{Ba}(\text{NO}_3)_2$ Crystals	355
3. LiIO_3 Raman Lasers	361
4. Picosecond Raman Lasers Based on KGW Crystals	362
5. Nanosecond Raman Lasers Based on KGW Crystals	366
6. Search for New SRS Materials and Comparative Spectroscopy Study	368
7. New BaWO_4 SRS Crystals	371
8. BaWO_4 and SrWO_4 Nanosecond Raman Lasers	372
8.1. Mid-IR BaWO_4 Raman Laser	374
8.2. Mid-IR Lasing in a $\text{Cr}^{2+}:\text{ZnSe}$ Crystal with BaWO_4 Raman Laser Pumping	376
9. BaWO_4 Picosecond Raman Frequency Shifters	376
10. PbWO_4 SRS Shifters and Raman Lasers	379
11. Diode-Pumped CW Raman Fiber Lasers	380
11.1. Raman Fiber Lasers Based on Germanosilicate Fibers	381
11.2. Phosphosilicate Fiber-Based Raman Lasers	382
12. Conclusion	388
References	388

Narrow-Linewidth Tunable Terahertz-Wave Sources Using Nonlinear Optics

Kodo Kawase, Jun-ichi Shikata and Hiromasa Ito 397

1. Introduction	397
2. Theory of THz-Wave Parametric Generation Using Polaritons	399
3. Injection-Seeded THz-Wave Parametric Generator (is-TPG)	402
3.1. Experimental Setup	403
3.2. Power Enhancement	404
3.3. Spectrum Narrowing	406
3.4. Wide Tunability	408
4. Arrayed Silicon Prism Coupler for a THz-Wave Parametric Oscillator	411
4.1. Experimental Setup	412
4.2. Experimental Results	413
5. Tunable THz-Wave Generation from DAST Crystal Using Dual Signal-Wave Parametric Oscillation of PPLN	416
5.1. Experimental Setup	417
5.2. Experimental Results	418
6. Conclusion	419
References	420

Mid-Infrared and THz Coherent Sources Using Semiconductor-Based Materials

Hiroshi Takahashi, Hidetoshi Murakami, Hideyuki Ohtake
and Nobuhiko Sarukura 425

1. Introduction	425
2. THz Radiation from Semiconductor-Based Materials	426
2.1. Photoconductive Switch	426
2.2. Quantum Confined Structure	431
2.3. Semiconductor Surface	437
2.4. Nonlinear Optical Process	440
3. Concluding Remarks	442
References	442

Mid-Infrared Laser Applications in Spectroscopy

Frank K. Tittel, Dirk Richter and Alan Fried 445

1. Solid-State Mid-IR Spectroscopic Laser Sources	445
1.1. Class "A" Laser Sources	447
1.2. Class "B" Laser Sources	455
2. Fundamentals of Absorption Spectroscopy for Trace Gas Detection	462

3. Spectroscopic Techniques: Signal Enhancement and Noise Reduction	466
3.1. Balanced Beam and Balanced Ratiometric Detection (Noise Reduction)	467
3.2. Wavelength and Frequency-Modulation Spectroscopy (Noise Reduction)	470
3.3. Long Optical Path Length Spectroscopy (Signal Enhancement)	472
3.4. Cavity-Enhanced Spectroscopy Methods (Signal Enhancement)	473
3.5. Photoacoustic and Photothermal Spectroscopy (Signal Enhancement)	478
4. Mid-Infrared Spectroscopic Applications	480
4.1. Detailed Examples Using Selected Spectroscopic Sources and Techniques	481
5. Summary and Outlook	496
References	497

Mid-IR Laser Applications in Medicine

Benedikt Jean and Thomas Bende	511
--------------------------------------	-----

1. Introduction	511
1.1. Absorbers and Naturally Occurring Chromophores	512
1.2. Laser Sources	514
2. Laser-Tissue Interaction	516
2.1. Photothermal Laser-Tissue Interaction	516
2.2. IR Photothermal Ablation	521
2.3. Photospallation	522
2.4. Collateral Thermal Damage	523
3. Experimental Photothermal Ablation Using Free Electron Lasers (FEL)	524
3.1. Collateral Thermal Effects as a Function of Wavelength	525
3.2. Photomechanical Interaction	525
3.3. The Influence of Specific Absorbers in the Target Material ..	525
3.4. Feedback Laser Control	527
4. Clinical Laser Applications	529
4.1. Gynecology	529
4.2. Otorhinolaryngology (ENT)	530
4.3. Neurosurgery	530
4.4. Dermatology	531
4.5. Urology	533
4.6. Dental Surgery	533
4.7. Ophthalmology	535
4.8. Cardiovascular Surgery, Angioplasty	535

XVI Contents

5. Perspective of a Tuneable IR Laser Source 536
References 538

Index 545