

Contents

Preface *XI*

List of Contributors *XIII*

1	VECSEL Semiconductor Lasers: A Path to High-Power, Quality Beam and UV to IR Wavelength by Design	1
	<i>Mark Kuznetsov</i>	
1.1	Introduction	1
1.2	What Are VECSEL Semiconductor Lasers	2
1.2.1	History of VECSELS: Semiconductor Lasers, Optical Pumping, and External Cavity	2
1.2.2	Basic Principles of Operation: VECSEL Structure and Function	6
1.2.3	Basic Properties of VECSEL Lasers: Power Scaling, Beam Quality, and Intracavity Optical Elements	9
1.2.3.1	Power Scaling	9
1.2.3.2	Beam Quality	10
1.2.3.3	Laser Functional Versatility Through Intracavity Optical Elements	11
1.2.4	VECSEL Wavelength Versatility Through Materials and Nonlinear Optics	12
1.2.4.1	Wavelength Versatility Through Semiconductor Materials and Structures	12
1.2.4.2	Wavelength Versatility Through Nonlinear Optical Conversion	14
1.3	How Do You Make a VECSEL Laser	16
1.3.1	Semiconductor Gain Medium and On-Chip Bragg Mirror	16
1.3.1.1	Semiconductor Gain Design for VECSELS	16
1.3.1.2	On-Chip Multilayer Laser Bragg Mirror	21
1.3.1.3	Semiconductor Wafer Structure	22
1.3.2	Optical Cavity: Geometry, Mode Control, and Intracavity Elements	24
1.3.3	Optical and Electrical Pumping	29
1.3.4	VECSEL Laser Characterization	33
1.4	Demonstrated Performance of VECSELS and Future Directions	38

1.4.1	Demonstrated Power Scaling and Wavelength Coverage	38
1.4.2	Commercial Applications	45
1.4.3	Current and Future Research Directions	48
1.4.4	Future of VECSEL Lasers: Scalable Power with Beam Quality from UV to IR	54
	References	57
2	Thermal Management, Structure Design, and Integration Considerations for VECSELS	73
	<i>Stephane Calvez, Jennifer E. Hastie, Alan J. Kemp, Nicolas Laurand, and Martin D. Dawson</i>	
2.1	Introduction	73
2.2	VECSEL Structure Design	74
2.2.1	Material System Selection	74
2.2.2	Gain	76
2.2.3	Mirrors	79
2.2.4	Subcavity Designs	80
2.2.5	Growth	81
2.2.6	Structure Characterization	82
2.2.7	Laser Cavity	83
2.3	Thermal Management	84
2.3.1	Introduction: Why Is Thermal Management Important?	84
2.3.2	Thermal Management Strategies in VECSELS	85
2.3.3	Modeling of Heat Flow in VECSELS: Guidelines	87
2.3.4	The Thin Device and Heat Spreader Approaches at 1 and 2 μm	87
2.3.5	Important Parameters: The Thermal Conductivity of the Mirror Structure, Submount, and Heat Spreader	89
2.3.6	Power Scaling of VECSELS	91
2.3.7	Wavelength Versatility	94
2.4	Laser Performance and Results	96
2.4.1	Power	96
2.4.2	Efficiency	100
2.4.3	Tuning	103
2.5	Integration	105
2.5.1	Microchip	105
2.5.2	Pump Integration	107
2.5.3	Fiber-Tunable VECSELS	109
2.6	Conclusions	111
	References	111
3	Red Semiconductor Disk Lasers by Intracavity Frequency Conversion	119
	<i>Oleg Okhotnikov and Mircea Guina</i>	
3.1	Introduction	119
3.2	SDL with Frequency Doubling	121

3.2.1	General Principle of Frequency Doubling	121
3.2.2	Power Scaling of SDLs	124
3.3	SDL Frequency Doubled to Red	126
3.3.1	Dilute Nitride Heterostructures for 1.2 μm Light Emission	127
3.3.2	Plasma-Assisted MBE Growth of Dilute Nitrides	128
3.3.3	Design and Characteristics of Dilute Nitride Gain Media	130
3.3.4	Performance of 1220 nm SDL	133
3.3.5	SDL Intracavity Light Conversion to Red–Orange	136
3.4	Conclusions	139
	References	139
4	Long-Wavelength GaSb Disk Lasers	143
	<i>Benno Rösener, Marcel Rattunde, John-Mark Hopkins, David Burns, and Joachim Wagner</i>	
4.1	Introduction	143
4.2	The III-Sb Material System	144
4.3	Epitaxial Layer Design and Growth of III-Sb Disk Laser Structures	146
4.3.1	Basic Structural Layout	147
4.3.2	Sample Growth and Post-Growth Analysis	149
4.3.3	Epitaxial Design of In-Well-Pumped SDLs	153
4.3.4	Sb-Based Active Regions on GaAs/AlGaAs DBRs	155
4.4	High-Power 2.X μm Disk Lasers	157
4.4.1	Initial Experiments	157
4.4.2	Sb-Based SDLs Using Intracavity Heat Spreaders	158
4.4.3	In-Well-Pumped Sb-Based Semiconductor Disk Lasers	163
4.4.4	Sb-Based Semiconductor Disk Lasers on GaAs Substrates	166
4.5	Tunable, Single-Frequency Lasers	167
4.5.1	Tunability	168
4.5.2	Single-Frequency Operation	172
4.5.3	Experimental Results of a 2.3 μm Single-Frequency SDL	176
4.6	Disk Lasers At and Above 3 μm Wavelength	179
4.7	Conclusions	179
	References	181
5	Semiconductor Disk Lasers Based on Quantum Dots	187
	<i>Udo W. Pohl and Dieter Bimberg</i>	
5.1	Introduction	187
5.2	Size Quantization in Optical Gain Media	187
5.2.1	Quantum Dots in Lasers	189
5.2.2	Species of Quantum Dots	191
5.2.3	Energies of Confined Charge Carriers	191
5.2.4	Quantum Dot Lasers	196
5.2.4.1	Edge-Emitting Quantum Dot Lasers	196
5.2.4.2	Surface-Emitting Quantum Dot Lasers	198

5.3	Development of Disk Lasers Based on Quantum Dots	200
5.3.1	Concepts of Gain Structures	200
5.3.2	Adjustment of Quantum Dot Emission Wavelength	202
5.3.2.1	Tuning of Stranski–Krastanow Quantum Dots	203
5.3.2.2	Tuning of Submonolayer Quantum Dots	204
5.3.3	Characteristics of Quantum Dot Disk Lasers	205
5.3.3.1	Disk Lasers with Stranski–Krastanow Quantum Dots	205
5.3.3.2	Disk Lasers with Submonolayer Quantum Dots	207
5.4	Conclusions	207
	References	208
6	Mode-Locked Semiconductor Disk Lasers	213
	<i>Thomas Südmeyer, Deran J.H.C Maas, and Ursula Keller</i>	
6.1	Introduction	213
6.1.1	Ultrafast Lasers	213
6.1.2	Ultrafast Semiconductor Lasers	215
6.1.3	Application Areas	216
6.2	SESAM Mode Locking of Semiconductor Disk Lasers	219
6.2.1	Macroscopic Key Parameters of a SESAM	220
6.2.1.1	Nonlinear Optical Reflectivity	220
6.2.1.2	Temporal SESAM Response	225
6.2.2	Pulse Formation	227
6.2.2.1	Model for the Pulse Shaping	229
6.2.2.2	Mode-Locking Stability and the Importance of Gain and SESAM Saturation	231
6.2.2.3	Importance of Group Delay Dispersion	232
6.2.3	SESAM Designs	233
6.2.3.1	SESAM Structure for Field Enhancement Control	233
6.2.3.2	Comparison of Quantum Well and Quantum Dot SESAMs	236
6.3	Mode Locking Results	239
6.3.1	Introduction	239
6.3.2	Mode-Locked VECSELS with High Average Output Power	240
6.3.2.1	Power Scaling of Mode-Locked VECSELS	240
6.3.2.2	Experimental Results	242
6.3.2.3	Outlook	243
6.3.3	VECSEL Mode Locking at High Repetition Rates	244
6.3.3.1	Mode Locking with Similar Area on Gain and Absorber (1:1 Mode Locking)	245
6.3.3.2	Mode-Locked VECSELS with up to 50 GHz	245
6.3.3.3	Outlook	246
6.3.4	Femtosecond Mode-Locked VECSELS	246
6.3.4.1	Introduction	246
6.3.4.2	Mode Locking Results	247
6.3.5	Electrically Pumped Mode-Locked VECSELS	247

6.4	Mode-Locked Integrated External-Cavity Surface-Emitting Laser (MIXSEL)	248
6.4.1	Introduction	248
6.4.2	Integration Challenges	249
6.4.3	Results	251
6.4.4	Outlook	252
6.5	Summary and Outlook	254
	References	256
7	External-Cavity Surface-Emitting Diode Lasers	263
	<i>Aram Mooradian, Andrei Shchegrov, Ashish Tandon, and Gideon Yoffe</i>	
7.1	Introduction	263
7.2	Device Design and Performance	264
7.3	Mode Control, Cavity Design, and Thermal Lensing	270
7.4	High-Power Arrays and Multielement Devices	274
7.4.1	Design of the Chip	276
7.5	Carrier Dynamics	286
7.5.1	Mode Locking	287
7.6	Nonlinear Optical Conversion with Surface-Emitting Diode Lasers: Design and Performance	287
7.6.1	Visible Laser Sources: Applications and Requirements	287
7.6.2	Cavity Design Optimization and Trade-Offs for Second Harmonic Generation with Surface-Emitting Diode Lasers	289
7.6.3	Nonlinear Crystals Used in Intracavity Frequency Conversion	291
7.6.4	Low-Noise, High Mode Quality, Continuous-Wave Visible Laser Sources for Instrumentation Applications	294
7.6.5	Compact Visible Sources Scalable to Array Architecture	297
	References	301
	Index	305

