Semiconductor Laser Engineering, Reliability and Diagnostics

A Practical Approach to High Power and Single Mode Devices

Peter W. Epperlein

WILEY
Semiconductor Laser Engineering, Reliability and Diagnostics
Semiconductor Laser Engineering, Reliability and Diagnostics

A Practical Approach to High Power and Single Mode Devices

Peter W. Epperlein
To Eleonore

My beloved wife and closest friend

With deep gratitude and affection
Contents

Preface xix
About the author xxiii

PART 1 DIODE LASER ENGINEERING 1
Overview 1

1 Basic diode laser engineering principles 3
Introduction 4
1.1 Brief recapitulation 4
   1.1.1 Key features of a diode laser 4
      1.1.1.1 Carrier population inversion 4
      1.1.1.2 Net gain mechanism 6
      1.1.1.3 Optical resonator 9
      1.1.1.4 Transverse vertical confinement 11
      1.1.1.5 Transverse lateral confinement 12
      1.1.2 Homojunction diode laser 13
      1.1.3 Double-heterostructure diode laser 15
      1.1.4 Quantum well diode laser 17
         1.1.4.1 Advantages of quantum well heterostructures for diode lasers 22
            Wavelength adjustment and tunability 22
            Strained quantum well lasers 23
            Optical power supply 25
            Temperature characteristics 26
      1.1.5 Common compounds for semiconductor lasers 26
   1.2 Optical output power – diverse aspects 31
      1.2.1 Approaches to high-power diode lasers 31
         1.2.1.1 Edge-emitters 31
         1.2.1.2 Surface-emitters 33
      1.2.2 High optical power considerations 35
         1.2.2.1 Laser brightness 36
         1.2.2.2 Laser beam quality factor $M^2$ 36
## CONTENTS

1.2.3 Power limitations 37
   1.2.3.1 Kinks 37
   1.2.3.2 Rollover 38
   1.2.3.3 Catastrophic optical damage 38
   1.2.3.4 Aging 39

1.2.4 High power versus reliability tradeoffs 39

1.2.5 Typical and record-high cw optical output powers 40
   1.2.5.1 Narrow-stripe, single spatial mode lasers 40
   1.2.5.2 Standard 100 μm wide aperture single emitters 42
   1.2.5.3 Tapered amplifier lasers 43
   1.2.5.4 Standard 1 cm diode laser bar arrays 44

1.3 Selected relevant basic diode laser characteristics 45
   1.3.1 Threshold gain 45
   1.3.2 Material gain spectra 46
      1.3.2.1 Bulk double-heterostructure laser 46
      1.3.2.2 Quantum well laser 47
   1.3.3 Optical confinement 49
   1.3.4 Threshold current 52
      1.3.4.1 Double-heterostructure laser 52
      1.3.4.2 Quantum well laser 54
      1.3.4.3 Cavity length dependence 54
      1.3.4.4 Active layer thickness dependence 56
   1.3.5 Transverse vertical and transverse lateral modes 58
      1.3.5.1 Vertical confinement structures – summary 58
         *Double-heterostructure* 58
         *Single quantum well* 58
         *Strained quantum well* 59
         *Separate confinement heterostructure SCH and graded-index SCH (GRIN-SCH)* 59
         *Multiple quantum well (MQW)* 59
      1.3.5.2 Lateral confinement structures 60
         *Gain-guiding concept and key features* 60
         *Weakly index-guiding concept and key features* 62
         *Strongly index-guiding concept and key features* 63
      1.3.5.3 Near-field and far-field pattern 64
   1.3.6 Fabry–Pérot longitudinal modes 67
   1.3.7 Operating characteristics 69
      1.3.7.1 Optical output power and efficiency 72
      1.3.7.2 Internal efficiency and optical loss measurements 74
      1.3.7.3 Temperature dependence of laser characteristics 74
   1.3.8 Mirror reflectivity modifications 77

1.4 Laser fabrication technology 81
   1.4.1 Laser wafer growth 82
      1.4.1.1 Substrate specifications and preparation 82
CONTENTS ix

1.4.1.2 Substrate loading 82
1.4.1.3 Growth 83

1.4.2 Laser wafer processing 84
1.4.2.1 Ridge waveguide etching and embedding 84
1.4.2.2 The p-type electrode 84
1.4.2.3 Ridge waveguide protection 85
1.4.2.4 Wafer thinning and the n-type electrode 85
1.4.2.5 Wafer cleaving; facet passivation and coating; laser optical inspection; and electrical testing 86

1.4.3 Laser packaging 86
1.4.3.1 Package formats 87
1.4.3.2 Device bonding 87
1.4.3.3 Optical power coupling 89
1.4.3.4 Device operating temperature control 95
1.4.3.5 Hermetic sealing 95

References 96

2 Design considerations for high-power single spatial mode operation 101

Introduction 102
2.1 Basic high-power design approaches 103
2.1.1 Key aspects 103
2.1.2 Output power scaling 104
2.1.3 Transverse vertical waveguides 105
2.1.3.1 Substrate 105
2.1.3.2 Layer sequence 107
2.1.3.3 Materials; layer doping; graded-index layer doping 108
   Materials 108
   Layer doping 113
   Layer doping – n-type doping 113
   Layer doping – p-type doping 113
   Graded-index layer doping 114
2.1.3.4 Active layer 114
   Integrity – spacer layers 114
   Integrity – prelayers 115
   Integrity – deep levels 115
   Quantum wells versus quantum dots 116
   Number of quantum wells 119
2.1.3.5 Fast-axis beam divergence engineering 121
   Thin waveguides 122
   Broad waveguides and decoupled confinement heterostructures 122
   Low refractive index mode puller layers 124
   Optical traps and asymmetric waveguide structures 126
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread index or passive waveguides</td>
<td>127</td>
</tr>
<tr>
<td>Leaky waveguides</td>
<td>128</td>
</tr>
<tr>
<td>Spot-size converters</td>
<td>128</td>
</tr>
<tr>
<td>Photonic bandgap crystal</td>
<td>130</td>
</tr>
<tr>
<td>2.1.3.6 Stability of the fundamental transverse vertical mode</td>
<td>133</td>
</tr>
<tr>
<td>2.1.4 Narrow-stripe weakly index-guided transverse lateral waveguides</td>
<td>134</td>
</tr>
<tr>
<td>2.1.4.1 Ridge waveguide</td>
<td>134</td>
</tr>
<tr>
<td>2.1.4.2 Quantum well intermixing</td>
<td>135</td>
</tr>
<tr>
<td>2.1.4.3 Weakly index-guided buried stripe</td>
<td>137</td>
</tr>
<tr>
<td>2.1.4.4 Slab-coupled waveguide</td>
<td>138</td>
</tr>
<tr>
<td>2.1.4.5 Anti-resonant reflecting optical waveguide</td>
<td>140</td>
</tr>
<tr>
<td>2.1.4.6 Stability of the fundamental transverse lateral mode</td>
<td>141</td>
</tr>
<tr>
<td>2.1.5 Thermal management</td>
<td>144</td>
</tr>
<tr>
<td>2.1.6 Catastrophic optical damage elimination</td>
<td>146</td>
</tr>
<tr>
<td>2.2 Single spatial mode and kink control</td>
<td>146</td>
</tr>
<tr>
<td>2.2.1 Key aspects</td>
<td>146</td>
</tr>
<tr>
<td>2.2.1.1 Single spatial mode conditions</td>
<td>147</td>
</tr>
<tr>
<td>2.2.1.2 Fundamental mode waveguide optimizations</td>
<td>150</td>
</tr>
<tr>
<td>Waveguide geometry; internal physical mechanisms</td>
<td>150</td>
</tr>
<tr>
<td>Figures of merit</td>
<td>152</td>
</tr>
<tr>
<td>Transverse vertical mode expansion; mirror reflectivity; laser length</td>
<td>153</td>
</tr>
<tr>
<td>2.2.1.3 Higher order lateral mode suppression by selective losses</td>
<td>154</td>
</tr>
<tr>
<td>Absorptive metal layers</td>
<td>154</td>
</tr>
<tr>
<td>Highly resistive regions</td>
<td>156</td>
</tr>
<tr>
<td>2.2.1.4 Higher order lateral mode filtering schemes</td>
<td>157</td>
</tr>
<tr>
<td>Curved waveguides</td>
<td>157</td>
</tr>
<tr>
<td>Tilted mirrors</td>
<td>158</td>
</tr>
<tr>
<td>2.2.1.5 Beam steering and cavity length dependence of kinks</td>
<td>158</td>
</tr>
<tr>
<td>Beam-steering kinks</td>
<td>158</td>
</tr>
<tr>
<td>Kink versus cavity length dependence</td>
<td>159</td>
</tr>
<tr>
<td>2.2.1.6 Suppression of the filamentation effect</td>
<td>160</td>
</tr>
<tr>
<td>2.3 High-power, single spatial mode, narrow ridge waveguide lasers</td>
<td>162</td>
</tr>
<tr>
<td>2.3.1 Introduction</td>
<td>162</td>
</tr>
<tr>
<td>2.3.2 Selected calculated parameter dependencies</td>
<td>163</td>
</tr>
<tr>
<td>2.3.2.1 Fundamental spatial mode stability regime</td>
<td>163</td>
</tr>
<tr>
<td>2.3.2.2 Slow-axis mode losses</td>
<td>163</td>
</tr>
<tr>
<td>2.3.2.3 Slow-axis near-field spot size</td>
<td>164</td>
</tr>
<tr>
<td>2.3.2.4 Slow-axis far-field angle</td>
<td>166</td>
</tr>
<tr>
<td>2.3.2.5 Transverse lateral index step</td>
<td>167</td>
</tr>
</tbody>
</table>
CONTENTS

2.3.2.6 Fast-axis near-field spot size 167
2.3.2.7 Fast-axis far-field angle 168
2.3.2.8 Internal optical loss 170

2.3.3 Selected experimental parameter dependencies 171
2.3.3.1 Threshold current density versus cladding layer composition 171
2.3.3.2 Slope efficiency versus cladding layer composition 172
2.3.3.3 Slope efficiency versus threshold current density 172
2.3.3.4 Threshold current versus slow-axis far-field angle 172
2.3.3.5 Slope efficiency versus slow-axis far-field angle 174
2.3.3.6 Kink-free power versus residual thickness 174

2.4 Selected large-area laser concepts and techniques 176
2.4.1 Introduction 176
2.4.2 Broad-area (BA) lasers 178
2.4.2.1 Introduction 178
2.4.2.2 BA lasers with tailored gain profiles 179
2.4.2.3 BA lasers with Gaussian reflectivity facets 180
2.4.2.4 BA lasers with lateral grating-confined angled waveguides 182
2.4.3 Unstable resonator (UR) lasers 183
2.4.3.1 Introduction 183
2.4.3.2 Curved-mirror UR lasers 184
2.4.3.3 UR lasers with continuous lateral index variation 187
2.4.3.4 Quasi-continuous unstable regrown-lens-train resonator lasers 188
2.4.4 Tapered amplifier lasers 189
2.4.4.1 Introduction 189
2.4.4.2 Tapered lasers 189
2.4.4.3 Monolithic master oscillator power amplifiers 192
2.4.5 Linear laser array structures 194
2.4.5.1 Introduction 194
2.4.5.2 Phase-locked coherent linear laser arrays 194
2.4.5.3 High-power incoherent standard 1 cm laser bars 197

References 201

PART 2 DIODE LASER RELIABILITY 211
Overview 211

3 Basic diode laser degradation modes 213
Introduction 213
3.1 Degradation and stability criteria of critical diode laser characteristics 214
3.1.1 Optical power; threshold; efficiency; and transverse modes 214
3.1.1.1 Active region degradation 214
3.1.1.2 Mirror facet degradation 215
### CONTENTS

3.1.1.3 Lateral confinement degradation 215
3.1.1.4 Ohmic contact degradation 216
3.1.2 Lasing wavelength and longitudinal modes 220

3.2 Classification of degradation modes 222
3.2.1 Classification of degradation phenomena by location 222
3.2.1.1 External degradation 222
  
  *Mirror degradation* 222
  *Contact degradation* 223
  *Solder degradation* 224
3.2.1.2 Internal degradation 224
  
  *Active region degradation and junction degradation* 224

3.2.2 Basic degradation mechanisms 225
3.2.2.1 Rapid degradation 226
  
  *Features and causes of rapid degradation* 226
  *Elimination of rapid degradation* 229
3.2.2.2 Gradual degradation 229
  
  *Features and causes of gradual degradation* 229
  *Elimination of gradual degradation* 230
3.2.2.3 Sudden degradation 231
  
  *Features and causes of sudden degradation* 231
  *Elimination of sudden degradation* 233

3.3 Key laser robustness factors 234

References 241

### 4 Optical strength engineering 245

Introduction 245

4.1 Mirror facet properties – physical origins of failure 246

4.2 Mirror facet passivation and protection 249
  4.2.1 Scope and effects 249
  4.2.2 Facet passivation techniques 250
    4.2.2.1 E2 process 250
    4.2.2.2 Sulfide passivation 251
    4.2.2.3 Reactive material process 252
    4.2.2.4 N2IBE process 252
    4.2.2.5 I-3 process 254
    4.2.2.6 Pulsed UV laser-assisted techniques 255
    4.2.2.7 Hydrogenation and silicon hydride barrier layer process 256
  4.2.3 Facet protection techniques 258

4.3 Nonabsorbing mirror technologies 259
  4.3.1 Concept 259
  4.3.2 Window grown on facet 260
    4.3.2.1 ZnSe window layer 260
    4.3.2.2 AlGaInP window layer 260
5.2.4 Exponential distribution
5.2.4.1 Introduction 294
5.2.4.2 Properties 295
5.2.4.3 Areas of application 297
5.3 Reliability data plotting 298
5.3.1 Life-test data plotting 298
5.3.1.1 Lognormal distribution 298
5.3.1.2 Weibull distribution 300
5.3.1.3 Exponential distribution 303
5.4 Further reliability concepts 306
5.4.1 Data types 306
5.4.1.1 Time-censored or time-terminated tests 306
5.4.1.2 Failure-censored or failure-terminated tests 307
5.4.1.3 Readout time data tests 307
5.4.2 Confidence limits 307
5.4.3 Mean time to failure calculations 309
5.4.4 Reliability estimations 310
5.5 Accelerated reliability testing – physics–statistics models 310
5.5.1 Acceleration relationships 310
5.5.1.1 Exponential; Weibull; and lognormal distribution acceleration 311
5.5.2 Remarks on acceleration models 312
5.5.2.1 Arrhenius model 313
5.5.2.2 Inverse power law 315
5.5.2.3 Eyring model 316
5.5.2.4 Other acceleration models 318
5.5.2.5 Selection of accelerated test conditions 319
5.6 System reliability calculations 320
5.6.1 Introduction 320
5.6.2 Independent elements connected in series 321
5.6.3 Parallel system of independent components 322
References 323

6 Diode laser reliability engineering program 325
Introduction 325
6.1 Reliability test plan 326
6.1.1 Main purpose; motivation; and goals 326
6.1.2 Up-front requirements and activities 327
6.1.2.1 Functional and reliability specifications 327
6.1.2.2 Definition of product failures 328
6.1.2.3 Failure modes, effects, and criticality analysis 328
6.1.3 Relevant parameters for long-term stability and reliability 330
6.1.4 Test preparations and operation 330
6.1.4.1 Samples; fixtures; and test equipment 330
6.1.4.2 Sample sizes and test durations 331
CONTENTS

6.1.5 Overview of reliability program building blocks 332
  6.1.5.1 Reliability tests and conditions 334
  6.1.5.2 Data collection and master database 334
  6.1.5.3 Data analysis and reporting 335

6.1.6 Development tests 336
  6.1.6.1 Design verification tests 336
    Reliability demonstration tests 336
    Step stress testing 337
  6.1.6.2 Accelerated life tests 339
    Laser chip 339
    Laser module 341
  6.1.6.3 Environmental stress testing – laser chip 342
    Temperature endurance 342
    Mechanical integrity 343
    Special tests 344
  6.1.6.4 Environmental stress testing – subcomponents and module 344
    Temperature endurance 345
    Mechanical integrity 346
    Special tests 346

6.1.7 Manufacturing tests 348
  6.1.7.1 Functionality tests and burn-in 348
  6.1.7.2 Final reliability verification tests 349

6.2 Reliability growth program 349

6.3 Reliability benefits and costs 350
  6.3.1 Types of benefit 350
    6.3.1.1 Optimum reliability-level determination 350
    6.3.1.2 Optimum product burn-in time 350
    6.3.1.3 Effective supplier evaluation 350
    6.3.1.4 Well-founded quality control 350
    6.3.1.5 Optimum warranty costs and period 351
    6.3.1.6 Improved life-cycle cost-effectiveness 351
    6.3.1.7 Promotion of positive image and reputation 351
    6.3.1.8 Increase in customer satisfaction 351
    6.3.1.9 Promotion of sales and future business 351
  6.3.2 Reliability–cost tradeoffs 351

References 353

PART 3 DIODE LASER DIAGNOSTICS 355

Overview 355

7 Novel diagnostic laser data for active layer material integrity; impurity trapping effects; and mirror temperatures 361

Introduction 362

7.1 Optical integrity of laser wafer substrates 362
  7.1.1 Motivation 362
CONTENTS

7.1.2 Experimental details 363
7.1.3 Discussion of wafer photoluminescence (PL) maps 364

7.2 Integrity of laser active layers 366
7.2.1 Motivation 366
7.2.2 Experimental details 367
7.2.2.1 Radiative transitions 367
7.2.2.2 The samples 369
7.2.2.3 Low-temperature PL spectroscopy setup 369
7.2.3 Discussion of quantum well PL spectra 371
7.2.3.1 Exciton and impurity-related recombinations 371
7.2.3.2 Dependence on thickness of well and barrier layer 373
7.2.3.3 Prelayers for improving active layer integrity 375

7.3 Deep-level defects at interfaces of active regions 376
7.3.1 Motivation 376
7.3.2 Experimental details 377
7.3.3 Discussion of deep-level transient spectroscopy results 382

7.4 Micro-Raman spectroscopy for diode laser diagnostics 386
7.4.1 Motivation 386
7.4.2 Basics of Raman inelastic light scattering 388
7.4.3 Experimental details 391
7.4.4 Raman on standard diode laser facets 394
7.4.5 Raman for facet temperature measurements 395
7.4.5.1 Typical examples of Stokes- and anti-Stokes Raman spectra 396
7.4.5.2 First laser mirror temperatures by Raman 398
7.4.6 Various dependencies of diode laser mirror temperatures 401
7.4.6.1 Laser material 402
7.4.6.2 Mirror surface treatment 403
7.4.6.3 Cladding layers; mounting of laser die; heat spreader; and number of active quantum wells 404

References 406

8 Novel diagnostic laser data for mirror facet disorder effects; mechanical stress effects; and facet coating instability 409
Introduction 410
8.1 Diode laser mirror facet studies by Raman 410
8.1.1 Motivation 410
8.1.2 Raman microprobe spectra 410
8.1.3 Possible origins of the $193 \text{ cm}^{-1}$ mode in (Al)GaAs 412
8.1.4 Facet disorder – facet temperature – catastrophic optical mirror damage robustness correlations 413

8.2 Local mechanical stress in ridge waveguide diode lasers 416
8.2.1 Motivation 416
8.2.2 Measurements – Raman shifts and stress profiles 417
8.2.3 Detection of “weak spots” 419
CONTENTS

8.2.3.1 Electron irradiation and electron beam induced current (EBIC) images of diode lasers 419
8.2.3.2 EBIC – basic concept 421
8.2.4 Stress model experiments 422
  8.2.4.1 Laser bar bending technique and results 422
8.3 Diode laser mirror facet coating structural instability 424
  8.3.1 Motivation 424
  8.3.2 Experimental details 424
  8.3.3 Silicon recrystallization by internal power exposure 425
    8.3.3.1 Dependence on silicon deposition technique 425
    8.3.3.2 Temperature rises in ion beam- and plasma enhanced chemical vapor-deposited amorphous silicon coatings 427
  8.3.4 Silicon recrystallization by external power exposure – control experiments 428
    8.3.4.1 Effect on optical mode and P/I characteristics 429
References 430

9 Novel diagnostic data for diverse laser temperature effects; dynamic laser degradation effects; and mirror temperature maps 433
  Introduction 434
  9.1 Thermoreflectance microscopy for diode laser diagnostics 435
    9.1.1 Motivation 435
    9.1.2 Concept and signal interpretation 437
    9.1.3 Reflectance–temperature change relationship 439
    9.1.4 Experimental details 439
    9.1.5 Potential perturbation effects on reflectance 441
  9.2 Thermoreflectance versus optical spectroscopies 442
    9.2.1 General 442
    9.2.2 Comparison 442
  9.3 Lowest detectable temperature rise 444
  9.4 Diode laser mirror temperatures by micro-thermoreflectance 445
    9.4.1 Motivation 445
    9.4.2 Dependence on number of active quantum wells 445
    9.4.3 Dependence on heat spreader 446
    9.4.4 Dependence on mirror treatment and coating 447
    9.4.5 Bent-waveguide nonabsorbing mirror 448
  9.5 Diode laser mirror studies by micro-thermoreflectance 451
    9.5.1 Motivation 451
    9.5.2 Real-time temperature-monitored laser degradation 451
      9.5.2.1 Critical temperature to catastrophic optical mirror damage 451
      9.5.2.2 Development of facet temperature with operation time 453
CONTENTS

9.5.2.3 Temperature associated with dark-spot defects in mirror facets 454
9.5.3 Local optical probe 455
  9.5.3.1 Threshold and heating distribution within near-field spot 455
9.6 Diode laser cavity temperatures by micro-electroluminescence 456
  9.6.1 Motivation 456
  9.6.2 Experimental details – sample and setup 456
  9.6.3 Temperature profiles along laser cavity 457
9.7 Diode laser facet temperature – two-dimensional mapping 460
  9.7.1 Motivation 460
  9.7.2 Experimental concept 460
  9.7.3 First temperature maps ever 460
  9.7.4 Independent temperature line scans perpendicular to the active layer 461
  9.7.5 Temperature modeling 462
    9.7.5.1 Modeling procedure 463
    9.7.5.2 Modeling results and discussion 465
References 466

Index 469
Preface

Scope and purpose

Semiconductor diode lasers have developed dramatically in the last decade as key components in a host of new applications, with optical fibre communications and data storage devices as the original and main driving forces behind the enormous progress in diode laser technologies. The increase of laser output power, accompanied by improved laser reliability and widened laser wavelength range in all single-emitter and multi-element emitter devices, gave rise to the penetration of diode lasers into other mass-markets and emerging applications, such as laser pumping, reprographics, data recording, displays, metrology, medical therapy, materials processing, sophisticated weaponry, and free-space communications. As a consequence, diode lasers continue to represent a high percentage of the worldwide commercial laser revenues, 51% of the $6.4B in 2010 with 10% growth forecasted for 2011 (Laser Focus World, 2011)\(^1\). Huge progress has been made in high power, single transverse mode lasers over recent years, followed by new applications and along with increased requirements for device engineering, reliability engineering and device diagnostics.

This book is a fully integrated novel approach, covering the three closely connected fields of diode laser engineering, reliability engineering and diagnostics in their development context, correlation and interdependence. It is exactly the blend of the underlying basic physics and practical realization, with its all-embracing, complementary issues and topics that has not been dealt with so far in the current book literature in this unique way. This includes practical, problem-related design guidelines as well as degradation-, reliability- and diagnostic-related aspects and issues for developing diode laser products operating in single transverse mode with high power and reliability. And it is this gap in the existing book literature, that is, the gap between device physics in the all-embracing context, and the practical issues of real device exploitation, which is going to be filled by the publication on hand. Research and practical experience gained in industry and higher level education have provided a lot of empirical evidence that the market is in need of a book to fill this gap.

The book provides a novel approach to the development of high power, single transverse mode, edge-emitting (in-plane) diode lasers, through addressing the complementary topics of device engineering (Part I), reliability engineering (Part II) and device diagnostics (Part III) in altogether nine chapters. Diode laser fundamentals and standard material, fabrication and packaging issues are discussed first. In a subsequent section a comprehensive and elaborate account is given on approaches and techniques for designing diode lasers, emitting high optical power in single transverse mode or diffraction limited beams. This is followed by a detailed treatment of the origins of laser degradation including catastrophic optical damage and an exploration of the engineering means to address for effective remedies and enhanced optical strength. The discussion covers also stability criteria of critical diode laser characteristics and key laser robustness factors. Clear design considerations are discussed in great detail in the context of reliability-related concepts and models, and along with typical programs for reliability tests and growth. A final extended third part of advanced diagnostic methods covers in depth and breadth, for the first time in book literature, functionality-impacting factors such as temperature, stress and material instabilities. It also presents the basics of those diagnostic approaches and techniques and discusses the diagnostic results in conjunction with laser product improvement procedures.

Main features

Among the main features characterizing this book are, that it is:

1. Providing a novel approach of high power, single transverse mode, in-plane diode laser development by addressing the three complementary areas of device engineering, reliability engineering and device diagnostics in the same book and thus closes the gap in the current book literature.

2. Addressing not only narrow stripe lasers, but also other single-element and multi-element diode laser devices, such as broad area lasers, unstable resonator lasers, tapered amplifier lasers, phase-locked coherent linear laser arrays and high power incoherent standard 1 cm laser bars, designed by applying the various known principles to achieve high power emission in a single transverse mode or diffraction-limited beam.

3. Furnishing comprehensive practical, problem-oriented guidelines and design considerations by taking into account also reliability related effects, key laser robustness factors, and functionality impacting factors such as temperature, stress and material instabilities, and dealing with issues of fabrication and packaging technologies.

4. Discussing for the first time in depth and breadth diagnostic investigations of diode lasers, and using the results for improving design, growth and processing of the laser device in the development phase.
5. Covering in detail the basics of the diagnostic approaches and techniques, many of which pioneered by the author to be fit-for-purpose, and indicating the applicability of these techniques and approaches to other optical and electrical devices.

6. Demonstrating significance of correlations between laser operating characteristics and material parameters, and showing how to investigate and resolve effectively thermal management issues in laser cavities and mirrors.

7. Providing in-depth insight into laser degradation modes including catastrophic optical damage, and covering a wide range of concepts and technologies to increase the optical robustness of diode lasers.

8. Discussing extensively fundamental concepts and techniques of laser reliability engineering, and providing for the first time in a book details on setting up and operating a typical diode laser reliability test program used in industry for product qualification.

9. Representing an invaluable resource for professionals in industry and academia engaged in diode laser product R&D, for academics, teachers and post-graduates for higher educational purposes, and for interested undergraduates to gain first insights into the aspects and issues of diode laser technologies.

10. Featuring two hundred figures and tables illustrating numerous aspects of diode laser engineering, fabrication, packaging, reliability, performance, diagnostics and applications, and an extensive list of references to all addressed technical topics at the end of each of the nine chapters.

**Addressed niche markets**

The underlying synergetic laser development approach will make this much needed guidebook, a kind of vade mecum of high practical relevance, a great benefit to a broad worldwide readership in industry, higher education, and academic research. Professionals including, researchers and engineers in optoelectronics industries who work on the development of high quality, diode laser products, operating in single transverse mode with high optical output power and high reliability, will regard this book as an invaluable reference and essential source of information. The book will also be extremely useful for academics, teachers and post-graduates for higher educational purposes or satisfying their requirements, if they are just interested in gaining first insights into the aspects and issues associated with the optimization of these diode laser products.

**Book context**

The book is based primarily on the author’s many years of extensive and complex experience in diode laser engineering, reliability and diagnostics. The author
accumulated his highly specialized knowledge and skills in hands-on and managerial roles both in global and start-up companies in cutting-edge optoelectronics industries, including IBM, Hewlett-Packard, Agilent Technologies, and IBM/JDSU Laser Enterprise (today part of Oclaro) – starting in the early nineties with his decisive and formative collaboration, as core member of the Laser Enterprise team, the spin-out of IBM Research, pioneering and commercializing its pre-eminent 980-nm pump laser technology for applications in terrestrial and submarine optical communications networks.

The inspiration to write exactly this book has come from the author’s extensive semiconductor consulting experience, providing a realistic insight into the very obvious need for a practical, synergetic approach to diode laser development, along with the realization that there has not been any such publication available yet to meet these needs - both at industry and higher educational level. The author is confident, therefore, that the book on hand will be welcomed worldwide by the addressed, specialized readership with high, and growing demand, so that further editions are required much earlier than expected.

Acknowledgments

I would like to thank my former colleagues in the various semiconductor laser development departments for many thought-provoking discussions and helpful support, especially to Drs. Hans Brugger, Dan Clark, Dan Guidotti, Andrew Harker, Tony Hawkridge, Amr Helmy, Dan Mars, Andy McKee, Heinz Meier, Pat Mooney, John Oberstar, Mike Parry, Julia Shaw, Simon Stacey and Steve Wang.

Thanks equally go to my customers worldwide for their ongoing, encouraging requests in the past years for writing exactly this all-embracing book.

Special thanks for useful discussions and supportive communication to: Prof. Dan Botez, University of Wisconsin, USA; Prof. Dieter Bimberg, Technical University Berlin, Germany; Prof. Petr Eliseev, University of New Mexico, USA and Lebedev Physics Institute, Russia; Prof. Charlie Ironside, University of Glasgow, UK; Dr. Bob Herrick, JDSU Inc., USA; and Dr. David Parker, SPI Lasers, UK.

Special thanks also to my production editor Gill Whitley for all her cooperation and support, and for shepherding this book to publication with undiminished commitment and reliability. Lastly, I would like to express my deepest thanks to Ashley Gasque, a very experienced, most perceptive and resourceful acquisitions editor with CRC Press, USA, whose idea of a book based on my full-day short course at the SPIE Photonics West 2010, triggered off this publication.

Peter W. Epperlein
Colchester, Essex, UK
May 2012
About the author

Dr. Epperlein is currently Technology Consultant with his own semiconductor technology consulting business, Pwe-PhotonicsElectronics-IssueResolution, and residence in the UK. He provides technical consulting services worldwide to companies in photonics and electronics industries, as well as expert assistance to European institutions through evaluations and reviews of novel optoelectronics R&D projects for their innovative capacities including competitiveness, disruptive abilities, and proper project execution to pre-determined schedules.

He looks back at a thirty year career in cutting-edge photonics and electronics industries with focus on emerging technologies, both in global and start-up companies, including IBM, Hewlett-Packard, Agilent Technologies, Philips/NXP, Essient Photonics and IBM/JDSU Laser Enterprise. He holds Pre-Dipl. (B.Sc.), Dipl. Phys. (M.Sc.) and Dr. rer. nat. (Ph.D.) degrees in physics, magna cum laude, from the University of Stuttgart, Germany.

Dr. Epperlein is a well-recognized authority in compound semiconductor and diode laser technologies. He accumulated the broad spectrum of his professional competencies in most different hands-on and managerial roles, involving design and fabrication of many different optical and electrical devices, and sophisticated diagnostic research with focus on the resolution of issues in design, materials, fabrication and reliability, and including almost every aspect of product and process development from concept to technology transfer and commercialization. He has a proven track record of hands-on experience and accomplishments in research and development of optical and electrical semiconductor devices, including semiconductor diode lasers, light-emitting diodes, optical modulators, quantum well devices, resonant tunneling devices, field-effect transistors, and superconducting tunneling devices and integrated circuits.

His extensive investigations of semiconductor materials and diode laser devices have led to numerous world-first reports on special effects in laser device functionality. Key achievements and important contributions to the improvement of development processes in emerging semiconductor technologies include his pioneering development and introduction of novel diagnostic techniques and approaches. Many have been adopted by other researchers in academia and industry, and his publications of these pioneering experiments received international recognition, as demonstrated by thousands of references, for example, in Science Citation Index and Google, advanced search exact phrase for ‘PW or Peter W Epperlein’. Many of those unique
results added high value to the progress of new product or emerging technology development processes.

Dr. Epperlein authored or co-authored more than seventy peer-reviewed journal and conference technical papers, has given more than thirty invited talks at international conferences and workshops, and published more than ten invention disclosures in the IBM Technical Disclosure Bulletin. He has served as reviewer of numerous proposals for publication in technical journals and he was awarded five IBM Research Division Awards for achievements in diode laser technology, quality management and laser commercialization.

Dr. Epperlein started his career in emerging superconductor technologies in the late seventies, with sophisticated design, modelling and measurements on superconducting materials, tunneling effects, devices and integrated circuits in his more than five years collaboration in the then revolutionary IBM Josephson Junction Superconducting Computer Project (dropped by IBM end of 1983), which included a two-year International Assignment from the IBM Zurich Research Laboratory to the IBM Watson Research Center, N.Y., USA until the mid-eighties.

This term was followed by a fundamental career re-orientation from emerging superconductor to emerging semiconductor technologies, comprising more than twenty-five years in the fields of semiconductor technologies, optoelectronics, fibre-optic communications, and with his first role to start as core member of the pioneering IBM Laser Enterprise (LE) Team, to become a spinout of IBM Research in the early nineties. He contributed significantly to research, development and commercialization of the pre-eminent pump diode laser technology for applications in optical communication networks in the early nineties along with the transition of the LE-Research Team into a competitive market leader IBM/JDSU LE some five years later.
Part I

DIODE LASER ENGINEERING

Overview

The impressive technological advances that resulted in semiconductor diode laser technologies in the last decade can be grouped roughly into four areas: higher optical output power, higher single transverse mode and diffraction-limited output, increased range of lasing wavelengths, and significantly improved reliability (see Part II). Most noteworthy commercial demonstrations in high-power continuous wave (cw) outputs of single-emitter and multi-element emitter laser products, for example, in the 980 nm band, include 0.75 W ex-fiber for single spatial mode, narrow-stripe emitters, 12 W for tapered master oscillator power amplifier emitters with single-mode, diffraction-limited operation, 25 W for standard 100 μm wide aperture single-emitter devices, and 1000 W quasi-cw for standard 1 cm multi-element linear laser arrays with nearly diffraction-limited beams.

The development of novel design approaches including strained quantum wells and quantum cascade structures, as well as the advanced maturity of material systems such as compounds based on GaN, CdS, and GaSb, have significantly extended the operating wavelength range of semiconductor lasers throughout the visible spectrum into the ultraviolet regime down to about 0.375 μm on the short-wavelength side and far into the infrared regime with cw operation within 3–10 μm at room temperature, and beyond 10 μm up to 300 μm at operating temperatures around 77 K on the very long wavelength side. Compressively-strained InGaAs/AlGaAs quantum well lasers emitting in the 980 nm band are typical examples of lasers with wavelengths, which lattice-matched quantum well structures cannot deliver.

This part consists of two chapters. Chapter 1, on basic diode laser engineering principles, includes elaborate descriptions of relevant basic diode laser elements, parameters, and characteristics, aspects of high-power laser design, diode laser structures, materials, fabrication, and packaging technologies, and practical laser performance figures. Chapter 2 is on the design considerations for high-power single spatial mode operation. It provides an extensive account of various approaches and
techniques for the development of high-power semiconductor lasers emitting in a single spatial mode or diffraction-limited beam. The discussion is mainly on design issues and operating parameter dependencies of narrow-stripe, in-plane lasers, but also on other single- and multi-element diode laser devices. This includes broad-area lasers, unstable resonator lasers, tapered amplifier lasers, phase-locked coherent linear laser arrays, and high-power incoherent standard 1 cm laser bars designed by applying the various known principles to realize high-power emission in a single transverse mode or diffraction-limited beam.
Chapter 1

Basic diode laser engineering principles

Main Chapter Topics

1.1 Brief recapitulation
1.1.1 Key features of a diode laser 4
1.1.2 Homojunction diode laser 13
1.1.3 Double-heterostructure diode laser 15
1.1.4 Quantum well diode laser 17
1.1.5 Common compounds for semiconductor lasers 26

1.2 Optical output power – diverse aspects
1.2.1 Approaches to high-power diode lasers 31
1.2.2 High optical power considerations 35
1.2.3 Power limitations 37
1.2.4 High power versus reliability tradeoffs 39
1.2.5 Typical and record-high cw optical output powers 40

1.3 Selected relevant basic diode laser characteristics
1.3.1 Threshold gain 45
1.3.2 Material gain spectra 46
1.3.3 Optical confinement 49
1.3.4 Threshold current 52
1.3.5 Transverse vertical and transverse lateral modes 58
1.3.6 Fabry–Pérot longitudinal modes 67
1.3.7 Operating characteristics 69
1.3.8 Mirror reflectivity modifications 77
Introduction

This chapter starts with a brief recap of the fundamental aspects and elements of diode lasers, including relevant features of the standard device types, with an emphasis on the advantages of quantum heterostructures for their effective use as active regions in the lasers. Common laser material systems are then discussed, along with lasing wavelength-dependent applications and best output power levels achieved in each individual high-power diode laser category for illustration and comparison. Various aspects of high-power issues are presented, including power-limiting factors and reliability tradeoffs. To develop a good understanding of diode laser operation, key electrical, optical and thermal parameters and characteristics are described. The chapter concludes with a description of the basic aspects of diode laser fabrication and packaging technologies.

1.1 Brief recapitulation

1.1.1 Key features of a diode laser

The basic device structure consists of a rectangular parallelepiped of a direct bandgap semiconductor, usually a III–V compound semiconductor such as GaAs, incorporating a forward-biased, heavily doped p–n junction to provide the optical gain medium in a resonant optical cavity, as illustrated schematically in Figure 1.1.

Further basic elements include the optical confinement in the transverse vertical direction perpendicular to the active region and transverse lateral confinement of injected current, carriers and photons parallel to the active layer. Further details of these features will be illustrated below.

1.1.1.1 Carrier population inversion

The operating principle of a semiconductor laser requires the gain medium to be pumped with some external energy source, either electrical or optical, to build up and maintain a nonequilibrium distribution of charge carriers, which has to be large enough to enable a population inversion for the generation of optical gain. Pumping realized by optical excitation of electron–hole pairs is usually only important for the rapid characterization of the quality of the laser material without electrical contacts. The more technologically important technique, however, is direct electrical pumping using a forward-biased semiconductor diode with a heavily doped p–n junction at the center of all state-of-the-art semiconductor injection lasers, that is, diode lasers. The