Handbook of Distributed Feedback Laser Diodes

Geert Morthier
Patrick Vankwikelberge

SFB
Nichtlineare Dynamik

Physikalische Bibliothek
Fachbereich 5
Technische Universität Darmstadt
Hochschulstraße 4
D-64289 Darmstadt

J/4778

Artech House, Inc.
Boston • London

Contents

Foreword xi

Preface xiii

Chapter 1 Introduction to Fabry-Perot and Distributed Feedback Laser Diodes 1
1.1 Historical Background 2
1.2 Laser Diode Device Structure 4
1.3 Operation of the Laser Diode 10
1.3.1 The Basic Concept of Fabry-Perot Laser Diodes 10
1.3.2 Optical Material Parameters 12
1.3.3 Thermal Aspects of Laser Diodes 13
1.4 Essential Laser Diode Characteristics 15
1.4.1 Static Characteristics 15
1.4.2 Dynamic Characteristics 17
1.5 Use of Laser Diodes in Optical Communications Systems 19
1.6 Dynamic Single-Mode Laser Diodes 21
1.6.1 Short-Cavity Lasers 21
1.6.2 Coupled-Cavity Lasers 22
1.6.3 Injection-Locked Lasers 23
1.6.4 Laser Diodes With Distributed Optical Feedback 23
1.7 Organization of This Book 26
References 26

Chapter 2 Rate Equation Theory of Laser Diodes 29
2.1 Carrier Density Rate Equation 30
2.2 Photon Density Rate Equation 31
2.3 Phase Equations 32
2.4 Introducing Noise in the Rate Equations 33
2.5 Optical Gain and Absorption 36
2.5.1 Bulk Materials 38

2.5.2 Quantum Wells 39
2.5.3 Strained-Layer Quantum Wells 41
2.5.4 Gain Suppression 42
2.6 Some Well-Known Solutions of the Rate Equations 44
2.6.1 The Static Side-Mode Suppression 46
2.6.2 FM and AM Behavior 46
2.6.3 Harmonic Distortion Characteristics 50
2.6.4 Large-Signal Characteristics 52
2.6.5 Power Spectrum, Linewidth, and Intensity Noise 55
2.7 The Influence of External Reflections 58
References 58

Chapter 3 Coupled-Mode Theory of DFB Laser Diodes 61
3.1 The Physical Processes Inside a Laser Diode 62
3.1.1 The Electrical Process: Electrical Carrier Transport 62
3.1.2 The Electro-Optic Process: The Carrier-Photon Interactions 62
3.1.3 The Optical Process: Optical Wave Propagation 63
3.1.4 The Thermal Process: Heat Transport 64
3.2 The Need for Simplification 64
3.3 Assumptions About the Modeled Laser Structure 64
3.4 Optical Wave Propagation 66
3.4.1 Description of the Optical Field 66
3.4.2 The Scalar Wave Equation 68
3.4.3 The Langevin Force 69
3.4.4 Reduction Toward the Coupled-Wave Equations 70
3.5 Discussion of the Coupled-Mode Wave Equations 75
3.5.1 The Bragg and Maximum Gain Wavelengths 75
3.5.2 Influence of Radiation Modes in Higher Order Gratings 76
3.5.3 Longitudinal Rate Equations for the Optical Field 79
3.5.4 The Instantaneous Optical Frequencies 81
3.5.5 Comments on Spontaneous Emission 81
3.6 The Electrical Transport Problem 83
3.6.1 The Carrier Rate Equation 83
3.6.2 Current or Voltage Drive of the Laser 85
3.7 The Standing-Wave Effect in Gain-Coupled Lasers 86
3.8 Boundary Conditions 88
References 90

Chapter 4 Applying the Coupled-Mode Theory 93
4.1 Threshold Solutions for Simple DFB Lasers 94
4.1.1 AR-Coated Index- and Gain-Coupled DFB Lasers 95
4.1.2 The Stopband or Energy Gap 100

4.1.3 DFB Lasers With Reflecting Facets 101
4.1.4 The λ/4 Phase-Shifted DFB Laser 102
4.1.5 Second-Order Index-Coupled DFB Lasers 104
4.2 Numerical Solutions of the Coupled-Mode Model 105
4.3 The Narrowband Approach for Solving the Coupled-Mode Model 106
4.3.1 Threshold Analysis 108
4.3.2 Continuous-Wave Analysis 109
4.3.3 Small-Signal Dynamic Analysis 111
4.3.4 Noise Analysis 112
4.3.5 Large-Signal Dynamic Analysis 113
4.4 The Broadband Approach for Solving the Coupled-Mode Model 113
4.5 Derivation of the Rate Equations 114
4.6 Longitudinal Spatial Hole Burning 117
4.7 Coupling Coefficients for DFB Lasers 117
References 119

Chapter 5 A Closer Look at the Carrier Injection 123
5.1 Heterojunctions and Semi-Insulating Materials 124
5.1.1 Heterojunctions 124
5.1.2 Semi-Insulating InP 128
5.2 Carrier Leakage Over Heterobarriers 131
5.3 Carrier Injection in Gain-Guided and Weakly Index-Guided Lasers 134
5.4 Lateral Current Leakage in Index-Guided Structures 136
5.5 Parasitic Elements 140
5.6 Microwave Effects 143
5.7 Circuit Modeling of Leakage and Parasitics 144
References 145

Chapter 6 The Spectrum of DFB Laser Diodes 147
6.1 Amplified Spontaneous Emission 148
6.2 Side-Mode Rejection and Yield of DFB Lasers 155
6.3 Degradation of the SMSR by Spatial Hole Burning 159
6.4 DFB Lasers With Reduced Spatial Hole Burning 167
6.4.1 Nonuniform Injection 168
6.4.2 Special Index-Coupled Structures 169
6.4.3 Gain-Coupled Lasers 173
6.5 The Wavelength Tunability of DFB Lasers 177
6.6 Measurement of the ASE Spectrum in DFB Lasers 179
6.7 Extraction of Device Parameters From the Spectrum 182
References 184

Chapter 7 The IM and FM Behavior of DFB Laser Diodes 187

7.1 Measuring the IM Response of Laser Diodes 187
7.2 Measuring the FM Response of Laser Diodes 189
7.2.1 FM Measurements Based on Fabry-Perot Interferometers 189
7.2.2 The Gated, Delayed Self-Homodyne Technique 190
7.2.3 Characterization of Laser Chirp Using Fiber Dispersion 192
7.3 The IM Response 193
7.3.1 The Subgigahertz IM Response 193
7.3.2 The Spatial Hole Burning Cutoff Frequency 195
7.3.3 The High-Frequency (>GHz) IM Response 196
7.4 The FM Response 198
7.4.1 The FM Response of Fabry-Perot Lasers 198
7.4.2 The FM Response of DFB Lasers 200
7.5 Lateral Spatial Hole Burning 210
7.6 Dynamics of Quantum-Well Lasers 212
7.7 Designing High-Speed DFB Lasers 215
References 216

Chapter 8 Harmonic and Intermodulation Distortion in DFB Laser Diodes 219
8.1 Measuring the Harmonic Distortion 220
8.2 Influence of the Relaxation Oscillations 221
8.3 Influence of Gain Suppression 224
8.4 Influence of Spatial Hole Burning 226
8.5 Influence of Leakage Currents 237
8.6 Dips in the Bias and Frequency Dependence of the Distortion 240
8.7 Relation With CSO and CTB 241
8.8 Designing Highly Linear DFB Lasers 245
References 248

Chapter 9 Noise Characteristics of DFB Laser Diodes 251
9.1 Measuring Noise Characteristics 252
9.2 FM Noise in DFB Lasers 254
9.2.1 Frequency Dependence of the FM Noise Spectrum 254
9.2.2 Methods for the Calculation of the FM Noise of Complex Laser Structures 255
9.3 Linewidth of DFB Lasers 259
9.4 Causes of Linewidth Rebroadening in DFB Lasers 261
9.4.1 The Presence of Side Modes 261
9.4.2 Gain Suppression 264
9.4.3 Dispersion in the Feedback 266

9.5 Relative Intensity Noise of DFB Lasers 269
9.5.1 Frequency Dependence of the RIN in Single-Mode Lasers 270
9.5.2 Factors Determining the Low-Frequency RIN 271
9.6 Designing Highly Coherent DFB Lasers 273
References 275

Chapter 10 Fabrication and Packaging of DFB Laser Diodes 279
10.1 Laser Diode Fabrication Techniques 280
10.1.1 Liquid-Phase Epitaxy 281
10.1.2 Molecular Beam Epitaxy 282
10.1.3 Metal-Organic Vapor-Phase Epitaxy 283
10.2 Grating Fabrication Techniques 284
10.3 Packaging of DFB Laser Diodes 285
10.3.1 Electrical Aspects 286
10.3.2 Optical Aspects 287
References 291

Chapter 11 Epilogue 293
11.1 Trends in Optical Transmission and the Impact on DFB Lasers 293
11.2 Future Directions in Design and Manufacturing of DFB Lasers 296
References 298

Glossary 301

List of Symbols 303

About the Authors 305

Index 307