Contents

Part I Physics of High Speed Lasers

1 Basic Description of Laser Diode Dynamics by Spatially Averaged Rate Equations: Conditions of Validity ........................ 3
  1.1 The “Local” Rate Equations ........................................... 3
  1.2 Spatially Averaged Rate Equations and their Range of Validity ..... 5

2 Basic “Small-Signal” Modulation Response ............................... 11

3 Distortions in Direct Modulation of Laser Diodes ......................... 19
  3.1 Perturbation Analytic Prediction of Fundamental Distortions in Directly Modulated Laser Diodes ....................... 19
  3.2 Intermodulation Distortion............................................. 22

4 Direct Modulation Beyond X-Band by Operation at High Optical Power Density ................................................. 29

5 Improvement in Direct-Modulation Speed by Enhanced Differential Optical Gain and Quantum Confinement .................. 35
  5.1 Demonstration of the Explicit Dependence of Direct-Modulation Bandwidth on Differential Gain by Low-Temperature Operation ........................................... 35
    5.1.1 Direct-Modulation Results ....................................... 35
    5.1.2 Parasitic-Free Photo Mixing Modulation Experiment ...... 38
  5.2 Attainment of High-Modulation Bandwidths Through Quantum-Confined Materials................................. 40

6 Dynamic Longitudinal Mode Spectral Behavior of Laser Diodes Under Direct High-Frequency Modulation ............... 45
  6.1 Introduction....................................................................... 45
  6.2 Experimental Observations ............................................. 46
  6.3 Time Evolution Equations for Fractional Modal Intensities ...... 50
  6.4 A Two-Mode Laser.......................................................... 51
6.5 Solution to the Many-Mode Problem ........................................ 55
  6.5.1 An Approximate Analytic Solution
  of \( \alpha_0 \sum_j \frac{1}{1 + c_j^2} = 1 \) ......................................... 58

6.6 Lasing Spectrum Under CW High-Frequency Microwave Modulation .................................. 59

6.7 Dynamic Wavelength “Chirping” Under Direct Modulation .......... 61

6.8 Summary and Conclusions ............................................... 62

7 Signal-Induced Noise in Fiber Links ..................................... 65
  7.1 Introduction .............................................................. 65
  7.2 Measurements .......................................................... 67
  7.3 Analysis and Comparison With Measurements ....................... 72
    7.3.1 Mode-Partition Noise and Noise Transposition
     in Fiber Links Using Multimode Lasers ............................. 73
    7.3.2 Transposed Interferometric Noise in Fiber
     Links Using Single-Frequency Lasers ............................... 78
  7.4 Mode-Partition Noise in an Almost Single-Mode Laser ............. 82
  7.5 Conclusion ................................................................ 83

Part II Direct Modulation of Semiconductor Lasers
Beyond Relaxation Oscillation

8 Illustration of Resonant Modulation ..................................... 87

9 Resonant Modulation of Monolithic Laser Diodes
  at Millimeter-Wave Frequencies ......................................... 93
  9.1 Active Mode-Locking .................................................. 95
  9.2 Passive Mode-Locking ............................................... 97

10 Performance of Resonant Modulation in the Millimeter-Wave Frequency Range:
  Multi-Subcarrier Modulation ......................................... 101

11 Resonant Modulation of Single-Contact Lasers ..................... 107

Part III Fiber Transmission Effects, System Perspectives
and Innovative Approach to Broadband mm-Wave Subcarrier
Optical Signals

12 Fiber Chromatic Dispersion Effects of Broadband
  mm-Wave Subcarrier Optical Signals and Its Elimination ............. 115
  12.1 Effects on Multichannel Digital Millimeter-Wave Transmission ....... 115
  12.2 Elimination of Fiber Chromatic Dispersion Penalty
     on 1,550 nm Millimeter-Wave Optical Transmission ............. 120
### Contents

**13 Transmission Demonstrations** ...........................................125
13.1 1550-nm Transmission of Digitally Modulated 28-GHz Subcarriers Over 77 km of Non-Dispersion Shifted Fiber ............................................................ 125
13.2 39 GHz Fiber-Wireless Transmission of Broadband Multi-Channel Compressed Digital Video ........................................................... 130

**14 Application of Linear Fiber Links to Wireless Signal Distribution: A High-level System Perspective** ................................................................. 135

**15 Improvements in Baseband Fiber Optic Transmission by Superposition of High-Frequency Microwave Modulation** .......... 141
15.1 Introduction ............................................................................. 141
15.2 Interferometric Noise ............................................................ 142
15.2.1 Superimposed High-Frequency Modulation: External Phase Modulation .......................................................... 144
15.2.2 Directly Modulated Laser Diode ........................................ 147
15.2.3 Superimposed Modulation With Band-Pass Gaussian Noise ......................................................................................... 149
15.3 Multimode Fiber: Modal Noise .................................................. 152
15.4 Conclusion ............................................................................. 153

**16 Millimeter-Wave Signal Transport Over Optical Fiber Links by “Feed-Forward Modulation”** ....................................... 155
16.1 Principle of “Feed-Forward Modulation” for mm-Wave Signal Transport Over an Optical Carrier ........................................................... 155
16.2 Demonstration of “Feed-Forward Modulation” for Optical Transmission of Digitally Modulated mm-Wave Subcarrier ................................................... 161

**17 Frequency Planning for Minimal Intermodulation Distortion** .......... 165
17.1 Introduction ............................................................................. 165
17.2 Algorithms for Single-Link Frequency Planning .............. 166
17.2.1 Babcock Spacing ............................................................. 166
17.2.2 Okinaka’s Algorithm .......................................................... 168
17.3 Multi-Link Frequency Planning Algorithm ......................... 170
17.3.1 Modified Okinaka Algorithm for Multi-Link Frequency Planning .................................................................................. 171
17.3.2 Measurements ................................................................... 173
17.4 Discussion and Conclusion ...................................................... 176

**18 Erbium Fiber Amplifiers in Linear Lightwave Transmission** ................................................................. 177
18.1 Introduction ............................................................................. 177
18.2 Distortion Characteristics ..................................................... 178
18.2.1 EDFA Distortion Model .................................................. 178
18.2.2 Experimental Results .......................................................... 181
18.2.3 Comparisons Between Distortions in Laser Diode with EDFA............................................. 187
18.3 CNR Optimization ........................................................... 188
  18.3.1 Operation Point ......................................................... 189
  18.3.2 Fan-Out and Fiber Loss .............................................. 192
  18.3.3 CNR Versus Length of EDFA ..................................... 193
18.4 Discussions and Conclusions ............................................. 195

Part IV Appendices

A Notes on RF Link Metrics .................................................. 199
  A.1 Notes on Relation Between Distortion Products, Noise,
      Spurious-Free Dynamic Range (SFDR) ............................ 199
  A.2 Notes on Intermodulation Distortion in a Multichannel
      Subcarrier Transmission System: CTB and CSO ................. 201
      A.2.1 Composite Triple Beat (CTB) ................................ 201
      A.2.2 Composite Second-Order Intermodulation
          (CSO) Distortion ................................................ 203
  A.3 Graphical Illustrations of RF Signals ............................... 204

B Ultrahigh Frequency Photodiodes and Receivers ..................... 207
  B.1 Ultrahigh Speed PIN Photodiodes .................................. 207
  B.2 Resonant Receivers .................................................... 211

C High Frequency Optical Modulators ..................................... 213
  C.1 Mach Zehnder Interferometric Optical Modulator ................. 214
  C.2 Electroabsorption Optical Modulator ............................... 215

D Modulation Response of Superluminescent Lasers .................. 219
  D.1 Introduction .......................................................... 219
  D.2 The Small Signal Superluminescent Equations
      and Numerical Results ............................................ 220
  D.3 Effect of a Small but Finite Mirror Reflectivity ................. 224

E Broadband Microwave Fiber-Optic Links With RF Phase
    Control for Phased-Array Antennas ................................ 229

F Small Signal Traveling Wave Rate Equations
    for Erbium-Doped Fiber Amplifiers .................................. 235

G Applications of High Frequency Linear Fiber-Optic Links
    in Defense Systems .................................................... 237
  G.1 Electronic Counter Measure: Aerial Towed Fiber-Optic Decoy ..... 237
  G.2 Nuclear Test Diagnostic Instrumentation .......................... 238

References ........................................................................ 241

Index ............................................................................. 253