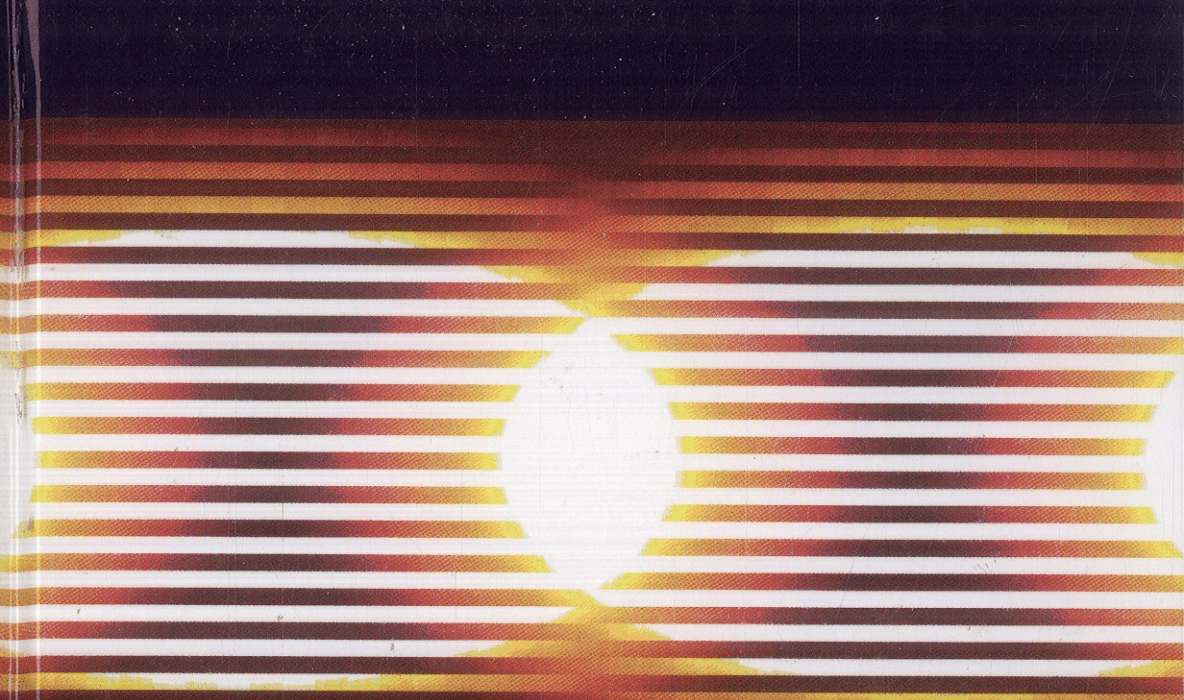




Microwaves Photonic Links

Components and Circuits

Christian Rumelhard

Catherine Algani

Anne-Laure Billabert

ISTE

 **WILEY**

Table of Contents

Preface	xiii
Abbreviation Glossary	xvii
Chapter 1 General Points	1
1.1. Microwave photonic links	1
1.2. Link description	4
1.3. Signal to transmit	5
1.3.1. Microwave signal	5
1.3.2. Microwave carrier for a digital signal	5
1.3.3. UWB signal	6
1.3.4. Optical carrier	6
1.3.5. Summary	6
1.4. Limitations of microwave photonic links	7
1.4.1. Limitations due to the materials constituting the different elements	7
1.4.2. Noise sources in microwave photonic links	8
1.4.3. Nonlinearities	13
1.5. The components and characteristics of microwave photonic links	13
Chapter 2 Generation and Modulation of Light	15
2.1. Laser	15
2.1.1. General points	15
2.1.2. Semiconductor laser structure and optical gain in the active zone	17
2.1.3. Operation of a Fabry-Perot laser	19

2.1.4. Optical confinement factor and rate equations.	21
2.1.5. Static mode of laser operation (or CW mode of operation).	24
2.1.6. Dynamic mode of laser operation: RF small signal response	26
2.1.7. RIN laser noise	28
2.1.8. Increase in $1/f$ of RIN and superposition of a small signal and noise	31
2.1.9. Different laser configurations	32
2.1.10. CAD laser models	41
2.1.11. Laser measurements and temperature stabilization	47
2.2. Electro-optic modulator: EOM.	49
2.2.1. General physical principles.	50
2.2.2. Pockels or linear electro-optical effect.	50
2.2.3. Mach-Zehnder electro-optic modulator	53
2.2.4. Single-Drive MZM: one driving electrode	55
2.2.5. Dual-drive MZM: two driving electrodes.	69
2.2.6. Real Mach-Zehnder modulator: characteristics and performances	71
2.2.7. Mach-Zehnder modulator technology	73
2.3. Electro-absorption modulator: EAM	75
2.3.1. Electro-absorption effect	75
2.3.2. FKE	80
2.3.3. Stark effect	80
2.3.4. Quantum well structures	82
2.3.5. MEA operation	82
2.3.6. Characteristics of an EAM	85
2.3.7. EML: EAM integrated to a DFB laser.	86
2.3.8. EAM electrical modeling for ultra-fast signal simulation.	87
Chapter 3 Optical Fibers and Amplifiers.	93
3.1. Optical fibers	93
3.1.1. General	93
3.1.2. Material attenuation	96
3.1.3. Material refraction index and dispersion	98
3.1.4. Total reflection, numerical aperture, transmitted maximum frequency	100
3.1.5. Step-index fiber	105
3.1.6. Graded index fiber	107
3.1.7. Single-mode fiber.	110
3.1.8. Plastic optical fibers	114

3.2. Optical amplifiers	118
3.2.1. Semiconductor optical amplifiers: SOA.	119
3.2.2. EDFAs	120
3.3. Appendix: modal analysis of propagation in a fiber.	122
3.3.1. Maxwell equations	122
3.3.2. Maxwell equations in a cylindrical fiber	123
3.3.3. Continuity and characteristic equation conditions	127
3.3.4. Research of different propagation modes	128
3.3.5. Approximation of linearly polarized modes	132
Chapter 4 Photodetectors	137
4.1. Photodetector definition	137
4.2. Photodiodes	138
4.2.1. Presentation	138
4.2.2. Light absorption in a semiconductor	139
4.2.3. p-i-n photodiode	142
4.2.4. Metal-semiconductor-metal or MSM photodiode.	145
4.2.5. Equivalent circuits for p-i-n and MSM photodiodes	147
4.2.6. Nonlinearities	147
4.2.7. UTC photodiodes	149
4.2.8. Charge compensation	150
4.2.9. Partially depleted absorption zone	151
4.2.10. Lateral lighting	152
4.2.11. Lateral lighting: progressive wave structure	153
4.2.12. Lateral lighting: periodic structures.	156
4.2.13. Resonant optical cavity photodetector	157
4.2.14. Diluted waveguides and evanescent mode coupling	160
4.2.15. Summary	161
4.3. Phototransistors	163
4.3.1. Bipolar or field-effect phototransistors?	163
4.3.2. GaAlAs/GaAs and InGaP/GaAs phototransistors.	165
4.3.3. InP/InGaAs phototransistors	167
4.3.4. Si/SiGe phototransistors	172
4.3.5. Resonant optical cavities for phototransistors	176
4.3.6. Phototransistor simulations and models	176
4.3.7. Influence of the base load impedance	180
4.3.8. Summary	183
4.4. Appendix	184
4.4.1. Lattice matched layers pseudomorphic layer, metamorphic layer	184
4.4.2. Velocity overshoot effect	186
4.4.3. Heterojunction bipolar phototransistor	188

Chapter 5 Performance of Microwave Photonic Links	193
5.1. Microwave photonic links: diagrams and definitions	193
5.1.1. Direct modulation link diagram and definitions.	193
5.1.2. External modulation link diagram and definitions	197
5.1.3. Simplified link diagram and first gain computation	198
5.2. Optomicrowave S-parameters and gains of each photonic link component	201
5.2.1. Introduction	201
5.2.2. Optomicrowave laser S-parameters and optomicrowave gain	202
5.2.3. Optomicrowave optical fiber S-parameters and optomicrowave gain	203
5.2.4. Photodiode optomicrowave S-parameters and gain	204
5.2.5. Localized component external modulator optomicrowave S-parameters and gain	205
5.2.6. Distributed component external modulator optomicrowave S-parameters and gain	207
5.2.7. Summary of all S-parameters and optomicrowave gain . . .	209
5.3. Microwave photonic links optomicrowave S-parameters and gains	210
5.3.1. Direct modulation microwave photonic link S-parameters	210
5.3.2. Direct modulation microwave photonic link gains	211
5.3.3. Localized external modulator microwave photonic link S-parameters	212
5.3.4. Localized external modulator microwave photonic link gains	213
5.3.5. Distributed external modulator microwave photonic link S-parameters	213
5.3.6. Distributed external modulator microwave photonic link gains	214
5.3.7. Link gain computation generalization	215
5.4. Comparison of different link gains	218
5.4.1. Direct modulation link gain computation	218
5.4.2. Localized external modulator link gain computation.	219
5.4.3. Distributed external modulator link gain computations . . .	220
5.5. Direct modulation microwave photonic link optomicrowave noise figures	221
5.5.1. Link noise figure diagram and computation method	221
5.5.2. Laser noise figure.	223
5.5.3. Optical fiber noise figure	223
5.5.4. Photodiode noise figure	224

5.5.5. Direct modulation link noise figure	224
5.5.6. Matching effect at the input of a direct modulation link. . .	225
5.5.7. Generalization of a link noise figure computation	226
5.6. External modulation microwave photonic link optomicrowave noise figure	227
5.6.1. Equivalent diagram and steps recall	227
5.6.2. Localized external modulator noise figure	227
5.6.3. Distributed external modulator noise figure	228
5.6.4. New evaluation of photodetector noise figure	230
5.6.5. Localized external modulator microwave photonic link noise figure.	231
5.6.6. Matched input localized external modulator microwave photonic link noise figure	231
5.6.7. Distributed external modulator microwave photonic link noise figure.	232
5.7. Comparisons of different link noise figures.	232
5.7.1. Evaluation of direct modulation link noise figure.	232
5.7.2. Evaluation of localized external modulator link noise figure.	234
5.7.3. Evaluation of matched input localized external modulator link noise figure.	235
5.7.4. Evaluation of distributed external modulator link noise figures	236
5.7.5. Output noise power	237
5.7.6. Some effectively measured noise figure values	239
5.8. Microwave photonic link nonlinearity: distortion phenomena	241
5.8.1. Single microwave signal nonlinearity	241
5.8.2. Several input microwave signals nonlinearity	242
5.8.3. Wideband input signal nonlinearity	244
5.8.4. Nonlinearity combination of microwave photonic link components	245
5.9. Microwave photonic link interference-free dynamic range . . .	246
5.9.1. Single input signal microwave photonic link interference-free dynamic range.	246
5.9.2. Several-input signal microwave photonic link interference-free dynamic range.	247
5.9.3. Some effectively measured interference-free dynamic range values	249
5.10. Appendix.	250
5.10.1. Relation between parameters S, Z, Y, and ABCD	250
5.10.2. Equation choice for the computation of microwave photonic link optomicrowave noise figure	251

5.10.3. Calculation of a two-input signal microwave photonic link interference-free dynamic range.	261
Chapter 6 Complement to Microwave Photonic Link Performances	267
6.1. Microwave signal attenuation during double sideband modulation	267
6.1.1. Double sideband modulation recall.	267
6.1.2. Recall of single-mode optical fiber propagation characteristics	268
6.1.3. Optical fiber double sideband modulated signal propagation	270
6.1.4. Double sideband-modulated signal photodetection at the optical fiber output	271
6.2. Modulator structures for optical carrier or high and low sideband removal.	273
6.2.1. Optical modulation recall.	273
6.2.2. Single sideband or carrier suppression optical modulators	274
6.2.3. Carrier suppression and single sideband optical modulator	277
6.3. Degradation of a microwave signal spectral purity by an optical link	280
6.3.1. Phenomenon description	280
6.3.2. Some definitions concerning the noise around a microwave carrier	281
6.3.3. Amplitude and phase noise in an optical link	282
6.3.4. Phase noise computation of a microwave signal transmitted by an optical link	284
6.3.5. Amplitude noise computation of a microwave signal transmitted by an optical link	286
Chapter 7 Electronic Amplifiers in Microwave Photonic Links. . .	289
7.1. Electronic amplifiers in optical links	289
7.2. Amplifiers in the optical link emitter	289
7.2.1. Different roles of electronic amplifiers on optical emitter	289
7.2.2. Emission: modulator or laser input amplifiers	290
7.3. Receiver: amplifiers at the photodetector output	293
7.3.1. General points	293
7.3.2. Transimpedance amplifiers.	294
7.3.3. Distributed amplifiers	296

7.3.4. Combination of transimpedance and distributed amplifiers.	298
7.3.5. Narrowband amplifiers	298
7.3.6. Preamplifier after a phototransistor.	299
7.3.7. Other circuits after a phototransistor.	299
7.4. Appendix: analog and microwave amplifiers	300
7.4.1. General points	300
7.4.2. Analog amplifiers.	300
7.4.3. Microwave amplifier: expression of transistor reflection coefficients.	304
7.4.4. Microwave amplifiers: gain expressions	306
7.4.5. Unilateralized transistor model: two-port network matching computation.	307
7.4.6. Non-unilateralized transistor: general case of a transistor with $S_{12} \neq 0$	312
7.4.7. Low noise amplifier	313
7.4.8. General models of low signal microwave amplifiers.	315

Chapter 8 Simulation and Measurement of Microwave

Photonic Links	321
8.1. State of the art and context	321
8.1.1. Objective	321
8.1.2. Choice of simulation software.	321
8.1.3. Different ADS simulation techniques	322
8.2. Microwave optical link models.	324
8.2.1. Two-port network approach	324
8.2.2. Electro-optic transducer: the laser	325
8.2.3. Transmission guiding: the optical fiber	329
8.2.4. The optoelectric transducer: the photodiode	334
8.3. Nonlinearity effects in the link	337
8.3.1. Nonlinearity sources	337
8.3.2. 1 dB compression point and first-order dynamic of the link.	338
8.3.3. Third-order intermodulation and third-order interference-free dynamic range of the link	339
8.4. Link noise modeling	340
8.4.1. Noise in the laser	340
8.4.2. The optical fiber	342
8.4.3. Noise in the photodiode.	342
8.4.4. Direct modulation link noise figure	343
8.4.5. Noise power at the receiver	344

8.5. Other types of modulation of signals transmitted on an optical fiber	348
8.5.1. Ultra-wideband signal modulation	348
8.5.2. External modulation	353
8.5.3. Generation of microwave signal by frequency beating	358
8.6. Conclusion	361
8.7. Appendix	362
8.7.1. MB-OOK modulation	362
8.7.2. OFDM modulation	363
Bibliography.	367
Index.	393