Contents

Foreword V

Table of the Coauthors XIX

Appearance Models 27

Chromatic Adaptation 27

Perceived Attributes of Color Perception 27

	Pretace XXI
1	Introduction 1
	Peter Bodrogi and Tran Quoc Khanh
	Reference 5
2	The Human Visual System and Its Modeling for Lighting
	Engineering 7
	Peter Bodrogi and Tran Quoc Khanh
2.1	Visual System Basics 7
2.1.1	The Way of Visual Information 7
2.1.2	Perception 8
2.1.3	Structure of the Human Eye 8
2.1.4	The Pupil 9
2.1.5	Accommodation 10
2.1.6	The Retina 10
2.1.7	Cone Mosaic and Spectral Sensitivities 12
2.1.8	Receptive Fields and Spatial Vision 14
2.2	Radiometry and Photometry 16
2.2.1	Radiant Power (Radiant Flux) and Luminous Flux 18
2.2.2	Irradiance and Illuminance 19
2.2.3	Radiant Intensity and Luminous Intensity 19
2.2.4	Radiance and Luminance 20
2.2.5	Degrees of Efficiency for Electric Light Sources 21
2.3	Colorimetry and Color Science 22
2.3.1	Color Matching Functions and Tristimulus Values 24
2.3.2	Color Appearance, Chromatic Adaptation, Color Spaces, and Color



2.3.2.1

2.3.2.2

VIII	Contents	
•	2.3.2.3	CIELAB Color Space 29
	2.3.2.4	The CIECAM02 Color Appearance Model 31
	2.3.3	Modeling of Color Difference Perception 36
	2.3.3.1	MacAdam Ellipses 36
	2.3.3.2	u', v' Chromaticity Diagram 36
	2.3.3.3	CIELAB Color Difference 37
	2.3.3.4	CAM02-UCS Uniform Color Space and Color Difference 38
	2.3.4	Blackbody Radiators and Phases of Daylight in the x, y Chromaticity
		Diagram 39
	2.4	LED Specific Spectral and Colorimetric Quantities 41
	2.4.1	Peak Wavelength (λ _p) 41
	2.4.2	Spectral Bandwidth at Half Intensity Level ($\Delta \lambda_{0.5}$) 42
	2.4.3	Centroid Wavelength (λ _C) 43
	2.4.4	Colorimetric Quantities Derived from the Spectral Radiance
		Distribution of the LED Light Source 43
	2.4.4.1	Dominant Wavelength (λ_D) 43
	2.4.4.2	Colorimetric Purity (p _C) 43
	2.5	Circadian Effect of Electromagnetic Radiation 44
	2.5.1	The Human Circadian Clock 44
		References 47
	3	LED Components – Principles of Radiation Generation and
		Packaging 49
		Holger Winkler, Quang Trinh Vinh, Tran Quoc Khanh, Andreas Benker,
		Charlotte Bois, Ralf Petry, and Aleksander Zych
	3.1	Introduction to LED Technology 49
	3.2	Basic Knowledge on Color Semiconductor LEDs 50
	3.2.1	Injection Luminescence 50
	3.2.2	Homo-Junction, Hetero-Junction, and Quantum Well 52
	3.2.2.1	Homo-Junction 52
	3.2.2.2	Hetero-Junction 53
	3.2.2.3	Quantum Well 54
	3.2.3	Recombination 56 Direct and Indirect Recombination 56
	3.2.3.1 3.2.3.2	Direct and Indirect Recombination 56 Radiative and Nonradiative Recombinations and Their Simple
	3.2.3.2	Theoretical Quantification 57
	3.2.4	Efficiency 60
	3.2.4.1	Internal Quantum Efficiency (η_i) 60
	3.2.4.2	Injection Efficiency (η_{ini}) 60
	3.2.4.3	Light Extraction Efficiency ($\eta_{\text{extraction}}$) 60
	3.2.4.4	External Quantum Efficiency ($\eta_{\rm ext}$) 62
	3.2.4.5	Radiant Efficiency (η_e , See Section 2.2.5, Eq. (2.13)) 62
	3.2.4.6	Luminous Efficacy (η_v) 62
	3.2.5	Semiconductor Material Systems – Efficiency, Possibilities, and
		Limits 63

	Contents	x
3.2.5.1	Possible Semiconductor Systems 63	
3.2.5.2	Semiconductor Systems for Amber – Red Semiconductor LEDs 64	
3.2.5.3	Semiconductor Systems for UV-Blue-Green Semiconductor LEDs 66	
3.2.5.4	The Green Efficiency Gap of Color Semiconductor LEDs 66	
3.3	Color Semiconductor LEDs 67	
3.3.1	Concepts of Matter Waves of de Broglie 68	
3.3.2	The Physical Mechanism of Photon Emission 68	
3.3.3	Theoretical Absolute Spectral Power Distribution of a Color Semiconductor LED 70	
3.3.4	Characteristic Parameters of the LEDs Absolute Spectral Power Distribution 70	
3.3.5	Role of the Input Forward Current 71	
3.3.6	Summary 71	
3.4	Phosphor Systems and White Phosphor-Converted LEDs 72	
3.4.1	Introduction to Phosphors 72	
3.4.2	Luminescence Mechanisms 79	
3.4.3	Aluminum Garnets 82	
3.4.4	Alkaline Earth Sulfides 86	
3.4.5	Alkaline Earth Ortho-Silicates 89	
3.4.6	Alkaline Earth Oxy-Ortho-Silicates 92	
3.4.7	Nitride Phosphors 93	
3.4.7.1	CASN 94	
3.4.7.2	2-5-8-Nitrides 97	
3.4.7.3	1-2-2-2 Oxynitrides 99	
3.4.7.4	β-SiAlON <i>103</i>	
3.4.8	Phosphor-Coating Methods 104	
3.4.9	Challenges of Volumetric Dispensing Methods 106	
3.4.10	Influence of Phosphor Concentration and Thickness on LED Spectra 107	
3.5	Green and Red Phosphor-Converted LEDs 109	
3.5.1	The Phosphor-Converted System 109	
3.5.2	Chromaticity Considerations 111	
3.5.3	Phosphor Mixtures for the White Phosphor-Converted LEDs 112	
3.5.4	Colorimetric Characteristics of the Phosphor-Converted LEDs 115	
3.6	Optimization of LED Chip-Packaging Technology 118	
3.6.1	Efficiency Improvement for the LED Chip 120	
3.6.2	Molding and Positioning of the Phosphor System 122	
3.6.3	Substrate Technology – Integration Degree 127 References 130	
4	Measurement and Modeling of the LED Light Source 133 Quang Trinh Vinh, Tran Quoc Khanh, Hristo Ganev, and Max Wagner	
41	LED Radiometry Photometry and Colorimetry 133	

×	Contents	
	4.1.1	Spatially Resolved Luminance and Color Measurement of LED Components 134
	4.1.2	Integrating Sphere Based Spectral Radiant Flux and Luminous Flux Measurement 139
	4.2	Thermal and Electric Behavior of Color Semiconductor LEDs 143
	4.2.1	Temperature and Current Dependence of Color Semiconductor LED Spectra 143
	4.2.1.1	Temperature Dependence of Color Semiconductor LED Spectra 143
	4.2.1.2	Current Dependence of Color Semiconductor LED Spectra 144
	4.2.2	Temperature and Current Dependence of Radiant Flux and Radiant Efficiency of Color Semiconductor LEDs 145
	4.2.2.1	Temperature Dependence of Radiant Flux and Radiant Efficiency of Color Semiconductor LEDs 145
	4.2.2.2	Current Dependence of Radiant Flux and Radiant Efficiency of Color Semiconductor LEDs 146
	4.2.2.3	Conclusion 147
	4.2.3	Temperature and Current Dependence of the Chromaticity Difference of Color Semiconductor LEDs 147
	4.2.3.1	Temperature Dependence of the Chromaticity Difference of the Color Semiconductor LEDs 147
	4.2.3.2	Current Dependence of Chromaticity Difference of the Color Semiconductor LEDs 148
	4.3	Thermal and Electric Behavior of White Phosphor-Converted LEDs 149
	4.3.1	Temperature and Current Dependence of Warm White PC-LED Spectra 149
	4.3.1.1	Temperature Dependence of Warm White PC-LED Spectra 150
	4.3.1.2	Current Dependence of Warm White PC-LED Spectra 151
	4.3.2	Current Limits for the Color Rendering Index, Luminous Efficacy, and White Point for Warm White PC-LEDs 152
	4.3.2.1	General Considerations 152
	4.3.2.2	Comparison of Color Rendering Index and Luminous Efficacy 153
	4.3.2.3	White Point of the Warm White PC-LEDs 153
	4.3.3	Temperature and Current Dependence of the Luminous Flux and
		Luminous Efficacy of Warm White PC-LEDs 153
	4.3.3.1	Temperature Dependence of the Luminous Flux and Luminous Efficacy of Warm White PC-LEDs 154
	4.3.3.2	Current Dependence of Luminous Flux and Luminous Efficacy of Warm White PC-LEDs 155
	4.3.4	Temperature and Current Dependence of the Chromaticity Difference of Warm White PC-LEDs 156
	4.3.4.1	Temperature Dependence of the Chromaticity Difference of Warm White PC-LEDs 156

4.3.4.2	Current Dependence of the Chromaticity Difference of Warm White PC-LEDs 157
4.4	Consequences for LED Selection Under Real Operation Conditions 157
4.4.1	Chromaticity Differences Between the Operating Point and the Cold Binning Point 157
4.4.2	Chromaticity Difference Between the Operating Point and the Hot Binning Point 158
4.5	LED Electrical Model 160
4.5.1	Theoretical Approach for an Ideal Diode 160
4.5.2	A LED Experimental Electrical Model Based on the Circuit Technology 163
4.5.3	An Example for a Limited Electrical Model for LEDs 163
4.5.3.1	Limited Operating Range 163
4.5.3.2	Mathematical Description of the LEDs Forward Current in the Limited Operating Range 164
4.5.3.3	An Example for the Application of the Limited Electrical Model 165
4.5.3.4	Evaluation and Improvement of the Electrical Model 167
4.6	LED Spectral Model 167
4.6.1	Spectral Models of Color Semiconductor LEDs and White PC-LEDs 167
4.6.1.1	Mathematical Approach 168
4.6.2	An Example for a Color Semiconductor LED Spectral Model 174
4.6.2.1	Experiments on Spectral Models for Color Semiconductor LEDs 174
4.6.3	An Example for a PC-LED Spectral Model 178
4.6.3.1	Experiments for the Spectral Models of White PC-LEDs 178
4.7	Thermal Relationships and Thermal LED Models 181
4.7.1	Thermal Relationships in LEDs 181
4.7.1.1	Thermal Structure of a Typical LED 182
4.7.1.2	A Typical Equivalent Thermal Circuit 182
4.7.1.3	External Thermal Resistance 183
4.7.2	One-Dimensional Thermal Models 185
4.7.2.1	The First Order Thermal Circuit 185
4.7.2.2	Second Order Thermal Circuit 187
4.7.2.3	The nth Order Thermal Circuit 188
4.7.2.4	The Transient Function and Its Weighting Function 189
4.7.2.5	Conclusions 190
4.8	Measurement Methods to Determine the Thermal Characteristics of LED Devices 190
4.8.1	Measurement Methods and Procedures 190
4.8.1.1	Selection of an Available Measurement Method 190
4.8.1.2	Description of the Cooling Measurement Procedure 191

XII	Contents	
	4.8.2	Description of a Typical Measurement System and Its Calibration 192
	4.8.2.1	Components and Structure of the Measurement System 192
	4.8.2.2	Determination of Thermal Power and Calibration Factor for Several LEDs 193
	4.8.3	Methods of Thermal Map Decoding 194
	4.8.3.1	Decoding of the Thermal Map by the Method of the Structure Function 194
	4.8.3.2	Thermal Map Decoding by the Euclidean Algorithm 195
	4.9	Thermal and Optical Behavior of Blue LEDs, Silicon Systems, and Phosphor Systems 197
	4.9.1	Selection of LEDs and Their Optical Behavior 197
	4.9.2	Efficiency of the LEDs 197
	4.9.3	Results of Thermal Decoding by the Structure Function Method 198
	4.9.4	Results of Thermal Decoding by the Method of the Euclidean Algorithm 200
	4.10	Aging Behavior of High-Power LED Components 201
	4.10.1	Degradation and Failure Mechanisms of LED Components 202
	4.10.2	Research on the Aging Behavior of High-Power-LEDs 204
	4.10.2.1	Change of Spectral Distribution and Chromaticity Coordinates 205
	4.10.2.2	Change of Electrical and Thermal Behavior 209
	4.10.2.3	Change of Luminous Flux – Lumen Maintenance 212
	4.11	Lifetime Extrapolation 214
	4.11.1	TM 21-Method 215
	4.11.2	Border Function (BF) 215
	4.11.3	Vector Acceleration (Temperature Acceleration – Vector Method – Denoted by TA – V) 217
	4.11.4	Arrhenius Behavior 217
	4.11.5	Groups of LEDs 218
	4.11.6	Exponential Function (Belonging to the Definition "Other Mathematical Fit Functions, Flexible (MFF-FLEX)") 218
	4.11.7	Root Function (Belonging to the Definition "Other Mathematical Fit Functions, Flexible (MFF-FLEX)") 218
	4.11.8	Quadratic Function (Belonging to the Definition "Other Mathematical Fit Functions, Flexible (MFF-FLEX)") 220
	4.11.9	Limits of the Extrapolation Procedure 221
	4.11.10	Conclusions 221
	4.12	LED Dimming Behavior 222
	4.12.1	Overview on the Dimming Methods 223
	4.12.2	Experiments: Setup and Results 224
	4.12.2.1	Experimental Setup 224
	4.12.2.2	Test Results for White LEDs 225
	41223	Test Results for Red I FDs 227

References 229

5	Photopic Perceptual Aspects of LED Lighting 233 Peter Bodrogi, Tran Quoc Khanh, and Dmitrij Polin
5.1	Introduction to the Different Aspects of Light and Color
	Quality 233
5.2	Color Rendering Indices: CRI, CRI2012 242
5.2.1	CIE CRI Color Rendering Index 243
5.2.2	Deficiencies of the CIE CRI Color Rendering Method 246
5.2.3	CRI2012 Color Rendering Index 247
5.2.3.1	Test Color Samples in the CRI2012 Method 249
5.2.3.2	Root Mean Square and Nonlinear Scaling 251
5.3	Semantic Interpretation of Color Differences and Color Rendering
	Indices 253
5.3.1	Experimental Method of the Semantic Interpretation of Color
	Differences 254
5.3.2	Semantic Interpretation Function $R(\Delta E')$ for CAM02-UCS Color Differences 256
5.3.3	Semantic Interpretation of the CRI2012 Color Rendering
	Indices 257
5.3.4	Semantic Interpretation of the CIE CRI Color Rendering
	Indices 258
5.4	Object Specific Color Rendering Indices of Current White LED Light
	Sources 261
5.4.1	Spectral Reflectances of Real Colored Objects 261
5.4.2	Color Rendering Analysis of a Sample Set of White LEDs 266
5.4.2.1	Definition of the Sample Set of White LEDs 266
5.4.2.2	Definition of the Sample Set of Object Reflectances 268
5.4.2.3	Examples for the Relationship among the Color Rendering Indices in
	Terms of the Semantic Interpretation Scale (R) 269
5.4.2.4	Object Specific Color Rendering Bar Charts with Semantic
	Interpretation Scales (R) 270
5.4.3	Summary 272
5.5	Color Preference Assessment: Comparisons Between CRI, CRI2012,
	and CQS 273
5.5.1	CQS: The Color Quality Scale 275
5.5.1.1	Components of the CQS Method 275
5.5.1.2	Discussion of the CQS Method 279
5.5.2	Relationship between the Color Quality Scale (CQS Q_a , Q_p) and the Color Rendering Indices (CRI, CRI2012) 280
5.6	Brightness, Chromatic Lightness, and Color Rendering of White LEDs 285
5.6.1	Modeling the Chromaticity Dependence of Brightness and Lightness 287
5.6.1.1	CIE Brightness Model 287

The Study of the Present Authors on Flicker Perception and the

Stroboscopic Effect with an LED Luminaire 325

a LED-Luminaire 323

Experimental Setup 325

The Subjects' Tasks 325

Conclusions 331
References 331

Experimental Results 329

5.11.3

5.11.3.1

5.11.3.2

5.11.3.3

5.11.4

6	Mesopic Perceptual Aspects of LED Lighting 337
	Tran Quoc Khanh, Peter Bodrogi, Stefan Brückner, Nils Haferkemper, and
	Christoph Schiller
6.1	Foundations and Models of Mesopic Brightness and Visual
	Performance 337
6.1.1	Visual Tasks in the Mesopic Range 337
6.1.2	Mesopic Vision and Its Modeling 338
6.1.3	The Mesopic Visual Performance Model of the CIE 344
6.2	Mesopic Brightness under LED Based and Conventional Automotive
	Front Lighting Light Sources 347
6.2.1	Experimental Method 348
6.2.2	Mean Results of Brightness Matching 349
6.2.3	Interobserver Variability of Mesopic Brightness Matching 350
6.2.4	Conclusion 353
6.3	Mesopic Visual Performance under LED Lighting Conditions 353
6.4	Visual Acuity in the Mesopic Range with Conventional Light Sources
	and White LEDs 357
6.4.1	Introduction 357
6.4.2	Test Method 358
6.4.2.1	Test Chart 359
6.4.3	Letter Contrast Acuity Results 361
6.5	Detection and Conspicuity of Road Markings in the Mesopic
	Range 362
6.5.1	Introduction 362
6.5.2	Spectral Characterization of Light Sources and Road Markings 363
6.5.2.1	Automotive Light Sources 364
6.5.2.2	Light Sources for Street Lighting 364
6.5.2.3	Spectral Characteristics of Road Markings 365
6.5.3	Contrast Calculations 366
6.5.4	Results and Evaluation 367
6.6	Glare under Mesopic Conditions 368
6.6.1	Introduction: Categories of Glare Effects 368
6.6.2	Causes and Models of the Glare Phenomenon 370
6.6.2.1	Disability Glare 370
6.6.2.2	Discomfort Glare 375
6.6.3	Discomfort Glare under Mesopic Conditions - Spectral Behavior
	and Mechanisms 376
6.6.3.1	Introduction 376
6.6.3.2	Experimental Method of a Discomfort Glare Experiment 377
6.6.3.3	Results and Discussion of the Discomfort Glare Experiment 378
6.6.4	Experiments to Determine the Spectral Sensitivity of Disability Glare
	in the Mesopic Range under Traffic Lighting Conditions 379
6.6.5	Glare in the Street Lighting with White LED and Conventional Light
	Sources 383

xvi	Contents	
•	6.7	Bead String Artifact of PWM Controlled LED Rear Lights at Different Frequencies 388
	6.7.1	Introduction 389
	6.7.2	A visual experiment on the bead string artifact 390
	6.7.2.1	Key Question 390
	6.7.2.2	Experimental Setup 391
	6.7.2.3	Peripheral Observation 391
	6.7.2.4	Foveal Observation 392
	6.7.3	Results of the Visual Experiment on the Bead String Artifact 392
	6.7.3.1	Effect of Viewing Condition (Peripheral vs Foveal) 393
	6.7.3.2	Effect of the Observer's Age 393
	6.7.4	Conclusion 394
	6.8	Summarizing Remarks to Chapter 6 394 References 395
	7	Optimization and Characterization of LED Luminaires for Indoor Lighting 399 Quang Trinh Vinh and Tran Quoc Khanh
	7.1	Indoor Lighting – Application Fields and Requirements 399
	7.2	Basic Aspects of LED-Indoor Luminaire Design 403
	7.2.1	LED, Printed Circuit Board, Electronics 403
	7.2.2	Optical Systems 405
	7.2.3	Controller-Regulation Electronics 406
	7.2.4	Thermal Management 407
	7.3	Selection Criteria for LED Components and Units 409
	7.3.1	Geometry 410
	7.3.2	Spectral and Colorimetric Angular Distribution 411
	7.3.3	Warm/Cold White LED 412
	7.3.4	Color Shift 412
	7.3.5	Forward Voltage 413
	7.3.6	Choice of the Optimal Current for LEDs 413
	7.3.7	Thermal Resistance 413
	7.4	Application Fields with Higher Color and Lighting
		Requirements 414
	7.4.1	Museum and Gallery Lighting 414
	7.4.2	Film and TV Lighting 416
	7.4.3	Shop Lighting 419
	7.4.4	Requirements for LED Luminaires with High Color Quality 420
	7.5	Principles of LED Radiation Generation with Higher Color Quality and One Correlated Color Temperature 421
	7.6	Optimization and Stabilization of Hybrid LED Luminaires with High
		Color Rendering Index and Variable Correlated Color
		Temperature 426
	7.6.1	Motivation and General Consideration 426
	7.6.1.1	Hybrid LED lamp and spectral LED models 427

7.6.1.2	Lighting Quality Parameters, Their Limits and Proposals for the
	Most Appropriate LED-Combination for Hybrid LED Lamps 427
7.6.1.3	Two Methodical Demonstration Examples and Their Tasks 427
7.6.2	Spectral Reflectance of Color Objects in Museum, Shop and Film
	Lighting 428
7.6.2.1	Analysis of the Spectral Reflectance Curves of the Color
	Objects 429
7.6.2.2	Color Objects and Their Spectral Reflectance Curves in the Museum
	(Oil Paintings) 430
7.6.2.3	Qualification and Prioritization of the Color Objects for the
	Optimization of Museum Lighting 431
7.6.3	Optimization Process for the Hybrid LED Combination with High
	Color Quality 433
7.6.3.1	Role of LED Components and Primary Proposals for LED
	Selection 433
7.6.3.2	LED Selection for the Most Available LED Combination of the
	Hybrid LED Lamp 433
7.6.3.3	Optimization of the Hybrid LED Lamp for Oil Color Paintings 434
7.6.3.4	Optimized Spectral Power Distributions of the Hybrid
764	LED-Lamps 436
7.6.4	Stabilization of the Lighting Quality Aspects of the Hybrid LED
7641	Lamp 438
7.6.4.1	Control System Structure for the Stabilization of Lighting Quality 439
7.6.4.2	Results of Optimization and Stabilization 440
7.0.4.2	References 442
	References 172
8	Optimization and Characterization of LED Luminaires for Outdoor
	Lighting 443
	Tran Quoc Khanh, Quang Trinh Vinh, and Hristo Ganev
8.1	Introduction 443
8.2	Construction Principles of LED Luminaire Units 445
8.2.1	Mechanical Unit 445
8.2.2	Electronic Unit 446
8.2.3	Optical System 449
8.3	Systematic Approach of LED Luminaire Design for Street
	Lighting 451
8.3.1	General Aspects 451
8.3.2	Definition of Specifications - Collection of Ideas 451
8.3.3	LED Characterization and Selection 456
8.3.4	Thermal and Electronic Dimensioning 458
8.4	Degradation Behavior of LED Street Luminaires 460
8.5	Maintenance Factor for LED Luminaires 463
8.5.1	Basic Aspects of Maintenance Factor 463

xvIII	Contents	
'	8.5.2	Basic Aspects of the Maintenance Factor of LED Street
		Luminaires 467
	8.6	Planning and Realization Principles for New LED Installations 471
	8.6.1	Technical Approach 473
	8.6.1.1	Phase 1: Coordination 473
	8.6.1.2	Phase 2: Measurement and Evaluation of the Old System 473
	8.6.1.3	Phase 3: Lighting Measurement and Evaluation of the LED
		System 474
	8.6.2	Qualification of the LED Luminaires and Selection of the
		Luminaires 476
	8.6.3	Installation and Measurement of the LED System 477
	8.6.3.1	Phase 4: Documentation by the Scientific Partner and Public Opinion
		Poll 478
		References 478
	9	Summary 479
		Peter Bodrogi and Tran Quoc Khanh

Index 483