

Contents

Foreword — VII

Preface to the second edition — XI

Preface to the first edition — XIII

About the authors — XVII

List of symbols — XXXI

1	Introduction to optical imaging and photography — 1
1.1	Objective of the present book — 3
1.2	Basics of radiometry and photometry — 6
1.2.1	Radiant energy, flux, fluence and intensity — 7
1.2.2	Solid angle and radiant intensity — 8
1.2.3	Irradiance and radiance — 9
1.2.4	Lambertian surface — 10
1.2.5	Radiant exposure — 11
1.2.6	Photometric quantities — 12
1.3	Basic concepts of image characterization — 14
1.3.1	Imaging, “image points” and resolution — 14
1.3.2	Imaging issues — 18
1.3.3	The space bandwidth number — 18
1.4	Resolution issues and requirements for images — 20
1.4.1	Resolution and angle of view of the human eye — 20
1.4.2	Remarks to reasonable number of “image points” and SBN in photography — 25
1.4.3	Magnified images — 25
1.5	Imaging and focusing — 28
1.5.1	Focusing and f-number — 28
1.5.2	Imaging and imaging conditions — 29
1.5.3	Relations between imaging and focusing, SBN and image quality — 31
1.5.4	Circle of confusion — 33
1.6	Digital input and output devices — 34
1.6.1	Image acquisition with a photodiode array: simple man’s view — 34
1.6.2	Image reproduced from a digital device, artefacts, Moiré effect — 36
1.6.3	Similarity to spectroscopy — 41
1.6.4	Space bandwidth number of digital devices — 43
1.6.5	Image observation from digital screens — 48

1.7	Optical glass —	49
1.7.1	Structure of silica based glasses —	49
1.7.2	Optical dispersion in glasses —	52
1.8	Metamaterials, metasurfaces and metalenses —	56
2	Basic concepts of photography and still cameras —	59
2.1	Pinhole camera —	59
2.2	Camera with a lens —	64
2.3	Illuminance and f-number —	70
2.4	Exposure —	73
2.5	Key parameters for photographic exposure —	75
2.5.1	Sensitivity and speed S —	76
2.5.2	Exposure determination and exposure value —	78
2.5.3	Exposure value and relative brightness change —	83
2.5.4	Optimum aperture and critical f-number —	84
2.6	Examples of camera systems —	86
2.6.1	Single lens reflex camera —	86
2.6.1.1	Characteristics and camera body —	86
2.6.1.2	Film formats and camera lenses —	90
2.6.2	Digital single lens reflex camera —	92
2.6.2.1	Characteristics —	92
2.6.2.2	Camera lenses —	94
2.6.2.3	Examples for DSLR cameras —	95
2.6.3	Digital compact camera —	97
2.6.3.1	Characteristics —	97
2.6.3.2	Consequences of the compact setup —	99
2.6.3.3	Examples for compact cameras —	100
2.6.4	Other types of digital cameras and further developments —	101
2.6.4.1	Mirrorless interchangeable lens camera and single lens translucent camera —	101
2.6.4.2	Mobile phone camera and miniature camera —	103
2.6.5	Cameras for scientific and industrial purposes —	106
3	Imaging optics —	108
3.1	Principles of geometrical optics —	108
3.1.1	Huygens' principle, Helmholtz equation and rays —	108
3.1.2	Ray equation, Snell's law and reflection loss —	110
3.1.3	Gaussian beam propagation —	113
3.1.4	Image formation —	115
3.2	Thick lenses —	121
3.2.1	Basic lens equations for thick lenses —	121
3.2.2	Types of lenses and lens shapes —	124

3.3	Ray path calculation by the matrix method —	127
3.3.1	Ray translation matrix —	128
3.3.2	Ray refraction matrix —	129
3.3.3	Thick-lens and thin-lens matrix —	130
3.3.4	Ray transfer matrix for optical systems —	132
3.3.5	Examples of simple camera lens setups —	135
3.3.6	Ray transfer method for Gaussian beams —	142
3.3.6.1	Vortex equation for a ball lens —	143
3.3.6.2	System matrix for a fiber ball lens system —	145
3.3.6.3	Gaussian beam propagation —	146
3.3.6.4	Comparison of theoretical approaches with experimental results —	149
3.3.7	Software-based computational methods —	152
3.3.7.1	Ray tracing —	152
3.3.7.2	Beam propagation —	153
3.4	Limitations of light rays —	154
3.4.1	Controlling the brightness: aperture stops and pupils —	155
3.4.2	Controlling the field of view: field stops and windows —	159
3.4.3	Properties and effects of stops, pupils and windows —	160
3.4.4	Controlling vignetting in lens systems —	165
3.4.5	Telecentric lens setup —	170
3.4.6	Depth of field and depth of focus —	173
3.5	Lens aberrations —	178
3.5.1	Spherical aberration —	180
3.5.2	Coma —	185
3.5.3	Astigmatism —	188
3.5.4	Curvature of field —	192
3.5.5	Distortion —	196
3.5.6	Chromatic aberration —	200
3.5.6.1	Achromatic doublet: two thin lenses of different materials —	203
3.5.6.2	Achromatic doublet: two thin lenses of identical materials with separation —	205
3.5.6.3	Complex achromatic systems —	206
3.5.7	Aspheric surfaces —	207
4	Sensors and detectors —	213
4.1	General, films, photodiode arrays —	213
4.1.1	Introduction and overview of 2D detectors —	213
4.1.2	Introduction to color reproduction —	215
4.1.3	Films—Principle of the photographic silver halide film imaging process —	217

- 4.1.4 Photographic reversal films and color films — **224**
 - 4.1.4.1 Reversal films — **224**
 - 4.1.4.2 Color negative and color slide films — **225**
- 4.2 Electronic sensors: photodiode arrays — **227**
 - 4.2.1 Optoelectronic principles of a photodiode — **227**
 - 4.2.2 Charge detection and conversion — **233**
- 4.3 Formats and sizes — **239**
 - 4.3.1 Formats and sizes of films and digital sensors — **239**
 - 4.3.2 Full format and crop factor — **242**
- 4.4 CCD sensors — **244**
 - 4.4.1 Basics — **244**
 - 4.4.2 CCD operation principles — **246**
 - 4.4.2.1 Full frame transfer CCD — **247**
 - 4.4.2.2 Interline transfer CCD — **247**
 - 4.4.2.3 Frame transfer CCD — **248**
 - 4.4.2.4 Frame-Interline-Transfer-CCD — **248**
- 4.5 CMOS sensors — **248**
 - 4.5.1 Basics — **248**
 - 4.5.2 General issues of CCD and CMOS sensors and comparison of both sensor types — **250**
 - 4.5.2.1 Chip architecture — **250**
 - 4.5.2.2 Exposure and readout — **251**
 - 4.5.2.3 Comparison of CCD and CMOS sensors — **252**
- 4.6 CCD and CMOS systems — **254**
 - 4.6.1 Fill factor and optical microlens array — **254**
 - 4.6.2 Optical low pass and infrared filters — **258**
 - 4.6.3 Color information — **259**
- 4.7 Noise and background — **265**
 - 4.7.1 Basics — **265**
 - 4.7.2 Noise distributions — **267**
 - 4.7.3 Temporal noise — **269**
 - 4.7.4 Spatial noise — **274**
 - 4.7.5 Blooming, smear, image lag and cross-talk — **275**
 - 4.7.5.1 Blooming — **275**
 - 4.7.5.2 Smear — **276**
 - 4.7.5.3 Image lag — **276**
 - 4.7.5.4 Cross talk — **276**
 - 4.7.6 Total noise — **277**
- 4.8 Dynamic range, signal-to-noise ratio and detector response — **281**
 - 4.8.1 Dynamic range — **281**
 - 4.8.2 Signal-to-noise ratio — **285**
 - 4.8.3 Binning — **287**

- 4.8.4 Requirements — **289**
- 4.8.5 Detector response — **291**
 - 4.8.5.1 Response curves of films — **291**
 - 4.8.5.2 Response curves of electronic detectors — **294**
 - 4.8.5.3 Comparison of the response curves of electronic detectors and those of films — **297**
- 4.8.6 Data quantization and depth resolution — **298**
- 4.8.7 Examples of photon conversion characteristics — **303**
- 4.8.8 “ISO-gain” for digital sensors — **305**
- 4.8.9 The “universal” curve — **309**
- 4.9 Basics of image processing and modification — **311**
 - 4.9.1 Sensor field corrections — **311**
 - 4.9.2 Basic image corrections — **315**
 - 4.9.2.1 Image processors and raw converters — **315**
 - 4.9.2.2 Raw data — **317**
 - 4.9.2.3 Digital Negatives — **319**
 - 4.9.3 De-mosaicing — **320**
 - 4.9.4 Tone mapping — **321**
 - 4.9.5 Further tone mapping, HDR and final remarks — **328**
 - 4.9.5.1 Increase of dynamic range: HDR and DRI — **330**
 - 4.9.5.2 Additional and final remarks — **333**
- 4.10 Advanced and special sensors and sensor systems — **335**
 - 4.10.1 Sensor with stacked color information — **335**
 - 4.10.2 Sensor with a color-sorting metalens array — **337**
 - 4.10.3 Pixel interleaved array CCD — **340**
 - 4.10.4 BSI CCD and BSI CMOS — **342**
 - 4.10.5 Advances in CMOS technology — **344**
 - 4.10.5.1 Scientific CMOS sensors — **344**
 - 4.10.5.2 Advances for small pixels: textures, depth increase and deep trench isolation — **345**
 - 4.10.5.3 CMOS stacking technology — **348**
 - 4.10.6 Hardware technologies for dynamic range extension — **349**
 - 4.10.6.1 Staggered HDR technology — **349**
 - 4.10.6.2 Split pixel and subpixel technology — **350**
 - 4.10.6.3 Dual or multiple conversion gain — **351**
 - 4.10.6.4 Full well adjusting method, skimming HDR — **353**
 - 4.10.6.5 Sensor with complementary carrier collection — **353**
 - 4.10.6.6 Logarithmic high-dynamic range CMOS sensor — **353**
 - 4.10.7 Sensors with large pixel number and/or special pixels — **354**
 - 4.10.7.1 Multipixel cell technology — **354**
 - 4.10.7.2 Polarized sensors — **356**
 - 4.10.7.3 Phase detection autofocus — **356**

- 4.10.7.4 Time of flight sensors — **360**
- 4.10.8 Advancements for the IR region: deep depletion CCD — **361**
- 4.11 Image converters and image intensifiers — **362**
 - 4.11.1 Image converters — **362**
 - 4.11.2 Basics of light signal intensifiers — **365**
 - 4.11.3 Microchannel plate intensifiers — **367**
 - 4.11.4 Intensified CCD and CMOS cameras — **372**
 - 4.11.5 Electron-multiplying CCD — **376**
- 4.12 Curved sensors — **378**

5 Fourier optics — 385

- 5.1 Fundamentals — **385**
 - 5.1.1 Basics, electric field, amplitude and phase and remarks in advance — **385**
 - 5.1.2 Background of Fourier optics, diffraction with coherent light — **388**
 - 5.1.3 “4-*f*-system” — **392**
 - 5.1.4 Imaging and point spread function — **396**
 - 5.1.4.1 Point spread function (PSF) — **396**
 - 5.1.4.2 Width of the point spread function and invariants — **400**
 - 5.1.5 Optical transfer function, modulation transfer function and phase transfer function — **402**
 - 5.1.5.1 Convolution and optical transfer function OTF — **402**
 - 5.1.5.2 OTF of a cylindrical and a spherical lens — **406**
 - 5.1.5.3 Cut-off frequency — **407**
 - 5.1.5.4 OTF, MTF, PTF — **408**
 - 5.1.6 Resolution, maximum frequency and contrast — **410**
 - 5.1.6.1 Maximum frequency — **410**
 - 5.1.6.2 Resolution and contrast — **412**
 - 5.1.7 Differences for imaging with coherent and incoherent light — **413**
 - 5.1.8 Space bandwidth product — **416**
 - 5.1.9 Image manipulation — **419**
 - 5.1.9.1 Low and high-pass filters — **419**
 - 5.1.9.2 Unsharp masking — **421**
- 5.2 Discussion of the MTF — **423**
 - 5.2.1 Test objects, MTF, contrast, spatial frequency units — **423**
 - 5.2.1.1 Bar gratings — **425**
 - 5.2.1.2 More realistic MTF curves — **427**
 - 5.2.2 Image quality characterization by means of a single MTF value — **429**
 - 5.2.3 OTF and MTF of a system — **429**
 - 5.2.4 MTF of lenses, objectives and the human eye — **431**
 - 5.2.4.1 Wavefront aberrations — **431**
 - 5.2.4.2 Defocusing — **432**

- 5.2.4.3 Apodization — **437**
- 5.2.4.4 Dependence on wavelength and f-number and cut-off frequency — **437**
- 5.2.4.5 MTF of the human eye — **439**
- 5.2.5 MTF of sensors — **440**
 - 5.2.5.1 Films — **441**
 - 5.2.5.2 Digital sensors — **441**
- 5.2.6 MTF of a camera system and its components — **447**
- 5.2.7 MTF curves of cameras — **448**
 - 5.2.7.1 MTF curves of cameras with curved image sensors — **452**
 - 5.2.7.2 Megapixel delusion? — **454**
- 5.2.8 Sharpness, perceived sharpness, acutance and noise reduction — **456**
- 5.2.9 Judgment of MTF curves — **461**
- 5.3 Resolution, SBN, MTF and PSF — **465**
 - 5.3.1 Resolution in general — **465**
 - 5.3.2 Relations between resolution, SBN and MTF with respect to optics only — **467**
 - 5.3.3 Relations with respect to the sensor and the whole camera system — **472**
 - 5.3.4 System-PSF and integrated pixel signals — **473**

6 Camera lenses — 478

- 6.1 Requirements for camera lenses — **478**
- 6.2 Short history of photographic lenses — **480**
 - 6.2.1 Simple photographic lenses — **481**
 - 6.2.2 Petzval portrait lens — **482**
 - 6.2.3 Early symmetric lenses — **483**
 - 6.2.4 Early anastigmats consisting of new and old achromats — **484**
 - 6.2.5 Anastigmats consisting of three lens groups — **487**
 - 6.2.6 Double-Gauss anastigmats consisting of four lens groups or more — **489**
- 6.3 Long focus lenses — **492**
 - 6.3.1 Telephoto principle — **493**
 - 6.3.2 Focusing by moving lens groups — **496**
 - 6.3.3 Examples of modern long focus lenses — **499**
 - 6.3.4 Teleconverters — **502**
- 6.4 Normal lenses — **504**
- 6.5 Wide-angle lenses — **509**
 - 6.5.1 Retrofocus design — **509**
 - 6.5.2 Symmetric lens design–Biogon type — **512**
 - 6.5.3 Properties and examples of modern wide-angle lenses — **513**
 - 6.5.4 Fisheye lenses — **518**

6.6	Varifocal and zoom lenses —	522
6.7	Perspective control—tilt/shift lenses —	527
6.7.1	Scheimpflug principle —	527
6.7.2	Principal function of shift and tilt —	531
6.7.2.1	Shift function —	531
6.7.2.2	Tilt function —	533
6.7.3	Specifications and constructions of PC-lenses for 35 mm format —	535
6.8	Antireflection coating and lens flares —	536
6.8.1	Antireflection coating —	537
6.8.1.1	Single-layer coating —	538
6.8.1.2	Double-layer coating —	540
6.8.1.3	Triple-layer and multilayer coatings —	541
6.8.2	Lens flares —	544
6.8.2.1	Double reflections —	545
6.8.2.2	Structured ghost flares and stray light haze —	547
6.8.3	T-stop —	551
6.9	Depth of focus, depth of field and bokeh —	552
6.9.1	Depth of focus —	552
6.9.2	Depth of field —	553
6.9.2.1	Same lens used with different image formats —	554
6.9.2.2	Same object field with different image formats —	556
6.9.3	Bokeh and starburst effect —	558
6.9.3.1	Bokeh —	558
6.9.3.2	Starburst effect —	561
7	Miniaturized imaging systems and smartphone cameras —	566
7.1	Imaging optics —	567
7.1.1	Physical and optical properties —	567
7.1.1.1	Depth of field and bokeh —	572
7.1.1.2	Focus control —	576
7.1.1.3	Image stabilization —	578
7.1.2	Lens design —	579
7.1.2.1	Standard wide-angle lens —	580
7.1.2.2	Evolution of SPC lens modules —	583
7.1.2.3	Zoom lenses, digital and hybrid zoom —	589
7.2	Sensor systems of smartphone and miniature cameras —	591
7.2.1	CIS properties —	592
7.2.2	Further CIS properties: noise effects —	595
7.3	Camera system performance —	598
7.3.1	MTF in absence of noise —	598
7.3.1.1	Perfect systems —	598

7.3.1.2	Real systems —	602
7.3.1.3	Zoom lenses —	607
7.3.2	Imaging in presence of noise —	610
7.3.3	Summarizing remarks on SPC imaging quality —	616
7.4	Computational imaging —	617
7.4.1	Sharpness control and tonal curve adaptation —	618
7.4.2	Noise reduction —	618
7.4.3	High dynamic range —	621
7.4.4	Portrait mode —	623
7.4.5	Correction of lens aberrations —	625
7.4.6	Final remarks to computational imaging and image processing in general —	626
7.5	Alternative concepts for miniature optics —	629
7.5.1	General description and diffractive optics —	630
7.5.1.1	Diffractive optics —	632
7.5.1.2	Fresnel zone plates —	634
7.5.1.3	Diffractive optics for camera lenses —	635
7.5.1.4	Small diffractive lenses for a miniaturized systems —	636
7.5.2	Optics of metamaterials —	637
7.5.2.1	Basics of negative index of refraction —	638
7.5.2.2	Realization of metamaterials, metasurfaces and metalenses —	639
7.5.3	Spaceplates —	646
7.5.3.1	General issues on spaceplates —	646
7.5.3.2	Realisation of spaceplates and particular issues —	648
8	Characterization of imaging systems —	652
8.1	General —	652
8.2	Evaluation of the optical properties, part 1: vignetting aberrations and optical dynamics —	654
8.2.1	Vignetting and aberrations —	654
8.2.2	Optical dynamics and veiling glare —	658
8.3	Evaluation of the optical properties, part 2: MTF and SFR measurements —	659
8.3.1	Grating-based methods —	659
8.3.1.1	General —	659
8.3.1.2	Bar gratings —	661
8.3.1.3	Siemens stars —	662
8.3.1.4	Influence of tone curve —	665
8.3.1.5	Postprocessing: the effect of sharpening and contrast enhancement —	667
8.3.2	Edge gradient and sampling methods —	668
8.3.2.1	Principle and knife edge method —	668

8.3.2.2	Edge spread function and line spread function —	669
8.3.2.3	Slanted edge method —	671
8.3.3	Random and stochastic methods and noise problems —	674
8.3.3.1	Dead leaves (and related) targets method —	674
8.3.3.2	Influence of image processing (i. e., image manipulation) and SFR —	676
8.3.4	Other methods and a brief comparison of the discussed methods —	679
8.3.5	MTF characterization across the image field —	681
8.3.5.1	Measurements at different positions —	681
8.3.5.2	MTF across the image field —	683
8.3.5.3	Examples of MTF across the image field —	685
8.4	Evaluation of the opto-electronic properties —	688
9	Outlook —	695
9.1	Sensors —	695
9.1.1	Organic CIS, nano crystalline, quantum dots, graphene and other ones —	696
9.1.2	Single photon imaging and quanta image sensors —	697
9.2	Imaging optics —	699
9.2.1	3D imaging —	699
9.2.2	Liquid lens modules —	702
9.3	Further developments and final statement —	703
A	Appendix —	705
A.1	Functions and relations —	705
A.2	Fourier mathematics —	707
A.3	Convolution —	711
A.4	CCD readout —	714
A.5	Camera and sensor data —	717
A.6	Histograms —	721
A.7	Tone mapping and tone curve discussion —	724
A.8	Summary of Fourier optics relations —	729
A.8.1	Remarks —	732
A.8.2	Remark on focusing —	733
A.9	Examples of PSF and MTF in the presence of aberrations —	735
A.10	MTF measurements with a Siemens star off-center —	736
A.11	Maxwell's equations, wave equation, etc. —	738
A.12	Resolution and contrast sensitivity function of the human eye —	740

Bibliography — 743

Picture Credits — 745

Disclaimer — 748

Index — 749

