

Contents

Preface XXIII

Introduction XXV

36	Human Eye	1
36.1	Introduction	3
36.1.1	Basic Structure of the Eye	3
36.1.2	Optical Data of the Eye	6
36.1.3	Neuronal Structure	8
36.1.4	Threshold Sensitivity	11
36.1.5	Movements of the Eye	12
36.1.6	Stiles–Crawford Effect	12
36.1.7	Image Processing in the Brain	13
36.2	Optical System of the Eye	16
36.2.1	Accommodation	16
36.2.2	Axes of the Eye	19
36.3	Photometry and Adaptation	20
36.3.1	Iris	20
36.3.2	Adaptation	21
36.3.3	Dark Adaptation	22
36.3.4	Photometry of the Eye	23
36.3.5	Dazzling	24
36.3.6	Interpupillary Distance	25
36.4	Schematic Optical Models of the Eye	25
36.4.1	Introduction	25
36.4.2	Data of Some Schematic Eyes	28
36.4.3	Sample Calculations	33
36.5	Color Vision	40
36.5.1	Spectral Sensitivity of the Eye	40
36.5.2	Transmission of the Eye	43
36.6	Optical Performance of the Eye	45
36.6.1	Introduction	45
36.6.2	Point Spread Function	45

36.6.3	Field Aberrations	46
36.6.4	Chromatic Aberrations	47
36.6.5	Modulation Transfer Function	50
36.6.6	Visual Acuity	57
36.6.7	Resolution	58
36.6.8	Stray Light	62
36.6.9	Measuring the Performance of the Eye	62
36.7	Binocular Vision	63
36.7.1	Introduction	63
36.7.2	Convergence	65
36.7.3	Stereo Vision and Depth Discrimination	67
36.8	Eye Defects	69
36.8.1	Introduction	69
36.8.2	Myopia	70
36.8.3	Hyperopia	70
36.8.4	Astigmatism	72
36.8.5	Aniseikonia	72
36.8.6	Color Aberrations	72
36.8.7	Spreading and Aging Effects	73
36.8.8	Cataract	75
36.9	Correction of Eye Aberrations	75
36.9.1	Correcting Refraction by Spectacles	75
36.9.2	Binoculars with Corrected Oblique Astigmatism	78
36.9.3	More Complicated Spectacle Shapes	82
36.9.4	Contact Lenses	83
36.9.5	Intra Ocular Lenses	85
36.9.6	Corneal Surgery	86
36.10	Literature	87
37	Eyepieces	89
37.1	Introduction	91
37.2	Eyepiece Design Considerations	92
37.2.1	Eye Relief	93
37.2.2	Resolution of the Human Eye	93
37.2.3	Accommodation	93
37.2.4	Distortion	94
37.2.5	Field Curvature and Astigmatism	95
37.2.6	Pupil Size	96
37.2.7	Lateral Chromatic Aberration	96
37.2.8	Spherical Aberration of the Exit Pupil	97
37.2.9	Raytracing Eyepieces	97
37.3	Evolution of Eyepieces	99
37.4	Single-lens Eyepiece (Loupe)	102
37.4.1	Standard Magnification	103
37.4.2	Magnification with Distinct Vision	103

37.4.3	Magnification with Lens in Close Proximity to Object	103
37.4.4	Visby Lens	104
37.5	Two-lens Eyepieces	105
37.5.1	Huygenian Eyepiece	105
37.5.2	Ramsden Eyepiece	107
37.6	Solid Eyepieces	109
37.6.1	Steinheil Monocentric Eyepiece	109
37.7	Orthoscopic Eyepieces	110
37.7.1	Kellner Eyepiece	110
37.7.2	Abbe Orthoscopic Eyepiece	111
37.7.3	König Eyepiece	112
37.7.4	Bertele Eyepiece	113
37.8	Achromatic and Medium-field Eyepieces	115
37.8.1	Plössl Eyepiece	115
37.8.2	Zeiss Astroplan	116
37.8.3	Bertele Eyepiece	117
37.9	Wide-field Eyepieces	118
37.9.1	Von Hofe Eyepiece	118
37.9.2	Erfle Eyepiece	119
37.9.3	Diffraction Eyepiece	120
37.9.4	Zeiss Binocular Eyepiece	122
37.9.5	Scidmore Eyepiece	123
37.9.6	Wild Eyepiece	124
37.9.7	Bertele Eyepiece	125
37.9.8	Yanari Long Eye Relief Eyepiece	126
37.9.9	Köhler Eyepiece	127
37.9.10	Nagler 1 Eyepiece	129
37.9.11	Nagler 2 Eyepiece	131
37.9.12	Dilworth Eyepiece	132
37.10	Compensating Eyepieces	133
37.10.1	Pretoria Eyepiece	133
37.11	Zoom Eyepieces	135
37.12	Terrestrial Eyepiece	136
37.13	Exotic Eyepieces	137
37.13.1	Aspheric-Plastic Eyepiece	137
37.14	Microscope Eyepieces	138
37.15	Eyepiece Design Data	140
37.16	Literature	153
38	Elementary Systems	155
38.1	Introduction	157
38.2	Magnifier Lenses	157
38.2.1	Principle of a Magnifier Lens	157
38.2.2	Magnifier Designs	159
38.2.3	Biocular Magnifier	162

38.3	Data Disk and Pick-up Lenses	165
38.3.1	Introduction	165
38.3.2	Disk Objective Lenses	170
38.4	Plastic Optics	174
38.4.1	Introduction	174
38.4.2	Optical Properties of the Materials	177
38.4.3	Special Design Aspects	179
38.5	Objective Lenses for Focusing and Collimation	183
38.5.1	Introduction	183
38.5.2	Beam Collimation	184
38.5.3	Monochromatic Objective Lenses	185
38.5.4	Achromate	188
38.5.5	Improved Objective Lenses	191
38.6	Mangin Mirror	196
38.6.1	Principle	196
38.6.2	More Complicated Mangin Systems	198
38.7	Offner System	201
38.8	Dyson System	204
38.9	Retroreflecting Systems	205
38.9.1	Introduction	205
38.9.2	Sphere with Reflecting Rear Surface	206
38.9.3	Double Hemisphere with Reflecting Rear Surface	209
38.9.4	Concentric Shell Setup	210
38.9.5	Offner Setup as Retroreflector	211
38.9.6	Lens–Mirror System	212
38.9.7	Refractive Axicon Retroreflector	215
38.9.8	Corner Cube Reflector	216
38.9.9	Luneburg Gradient Lens	218
38.10	Telecentric Systems	219
38.10.1	Introduction	219
38.10.2	Design Aspects	222
38.11	Beam Delivery Systems	228
38.11.1	Introduction	228
38.11.2	Diameter Adaptation with Telescopes	230
38.11.3	Beam Transport over Large Distances	232
38.11.4	Transmission of Truncated Gaussian Beams	233
38.11.5	Diffraction Effects by Truncation	239
38.11.6	Gaussian Beams with Aberrations	242
38.11.7	Beam Cleanup	246
38.12	Literature	250
39	Photographic Lenses	253
39.1	Introduction	256
39.1.1	Overview	256
39.1.2	Performance Criteria	262

39.1.3	Sensor Types and Formats	263
39.1.4	Depth of Field	265
39.1.5	Applications	267
39.2	Singlets	268
39.2.1	Landscape Lens	268
39.2.2	Achromatic Landscape Lens	271
39.3	Petzval Lenses	272
39.3.1	Petzval Portrait Lens	272
39.3.2	Petzval Projection Lens	276
39.3.3	R-Biotar	276
39.4	Symmetrical Doublets	277
39.4.1	Introduction	277
39.4.2	Steinheil Periskop	278
39.4.3	Rapid Rectilinear or Aplanatic Lens	278
39.4.4	Dagor Lens	280
39.4.5	Orthostigmatic Lens	283
39.5	Quasi-symmetrical Doublets	284
39.5.1	Antiplanet	284
39.5.2	Angulon	285
39.5.3	Protar	285
39.5.4	Unar	287
39.5.5	Tessar	287
39.6	Triplet Lenses	290
39.6.1	Triplet Design	290
39.6.2	Cooke Triplet	293
39.6.3	Split Triplets	295
39.6.4	Inverse Triplet	296
39.6.5	Heliar	297
39.6.6	Pentac	298
39.6.7	Hektor Lens	299
39.7	Quadruplet Lenses	299
39.7.1	Introduction	299
39.7.2	Dogmar or Celor Lens	299
39.7.3	Plasmat	301
39.7.4	Biotar, Planar or Double Gauss Lenses	303
39.7.5	More Complicated Double Gauss Lenses	307
39.8	Quasi-symmetrical Wide-angle Systems	309
39.8.1	Introduction	309
39.8.2	Hypergon	310
39.8.3	Topogon	313
39.8.4	Hologon	315
39.8.5	Metrogon	317
39.8.6	Pleogon	318
39.8.7	Biogon	319
39.8.8	Super Angulon	323

39.9	Less Symmetrical Lenses	324
39.9.1	Ernostar	324
39.9.2	Sonnar	326
39.10	Wide-angle Retrofocus Lenses	327
39.10.1	The Retrofocus Principle	327
39.10.2	Retrofocus Lenses	329
39.10.3	Distagon	332
39.10.4	Flektogon	333
39.10.5	Vivitar	335
39.10.6	SLR Camera Lenses	336
39.11	Extremely Wide-angle or Fish-eye Lenses	338
39.11.1	Fish-eye Lenses	338
39.11.2	Pleon	343
39.11.3	Distortion of Fish-eye Lenses	343
39.11.4	Pupil Variation	347
39.11.5	Panoramic Lenses	351
39.12	Telephoto Lenses	352
39.12.1	Telephoto Principle	352
39.12.2	Telephoto Lenses	354
39.13	Special Systems	358
39.13.1	Catadioptric Photographic Lenses	358
39.13.2	Compact Camera Lenses	362
39.13.3	Modern Aspherical Plastic Lenses	363
39.13.4	Telecentric Lenses	366
39.13.5	Photographic Zoom Lenses	368
39.13.6	Camera Lenses in UV and IR	371
39.13.7	Accessories	372
39.14	Special Aspects of Camera Lenses	373
39.14.1	Vignetting	373
39.14.2	Stopping Down a Photographic Lens	375
39.14.3	Internal Focusing with Floating Elements	379
39.14.4	Stray Light and Ghost Images	381
39.15	Literature	388
40	Infrared Systems	391
40.1	Introduction	392
40.2	Special Aspects of Infrared Imaging	392
40.2.1	Spectral Bands	392
40.2.2	Infrared Radiation from the Object to the Image	394
40.2.3	Radiation and Emissivity	397
40.2.4	Atmospheric Transmittance	400
40.2.5	Detectors	402
40.2.6	Materials	406
40.3	Basic Infrared Imaging Systems	411
40.3.1	Afocal System and Imager	411

40.3.2	Afocal System and Reimager	412
40.3.3	Reimager	413
40.3.4	Objective with a Rear Exit Pupil	414
40.3.5	Objective for an Uncooled Detector	414
40.4	Special Characteristics of Infrared Systems	415
40.4.1	Diffractional Surfaces	415
40.4.2	Athermalization	416
40.4.3	Narcissus	418
40.5	Advanced Infrared Imaging Systems	422
40.5.1	Infrared Achromats and Objective Lenses	422
40.5.2	Afocal Telescopes	429
40.5.3	Afocal Zoomable Telescopes	431
40.5.4	Advanced Reimager	433
40.5.5	Multiple Waveband Achromats and Systems	436
40.5.6	Compound Systems	437
40.6	Literature	441
41	Zoom Systems	445
41.1	Introduction	447
41.1.1	Fundamental Considerations	447
41.1.2	Principle of Smallest Changes	451
41.1.3	Configurations of Zoom Systems	454
41.1.4	Mechanical and Optical Compensation	457
41.1.5	Development of a Zoom System	459
41.2	Mechanically Compensated Zoom Systems	460
41.2.1	Introduction	460
41.2.2	Finite Image Two-component Zoom System	461
41.2.3	Three-component Zoom System	466
41.2.4	Four-component Zoom System	469
41.2.5	Zoom System with Three Movable Components	469
41.2.6	Symmetrical Afocal Zoom System	470
41.2.7	General Three-component Afocal Zoom System	475
41.2.8	Zoom Systems with Fixed Pupil Location	478
41.3	Optically Compensated Zoom Systems	482
41.3.1	Introduction	482
41.3.2	Three-component System	487
41.3.3	Approximate Solution for a Three-component System	488
41.3.4	Solution of the Three-Component System According to Kingslake	491
41.3.5	Solution of a Three-component Afocal Zoom System	493
41.3.6	Symmetrical Afocal Five-component Zoom System	495
41.4	Correction of Zoom Systems	498
41.4.1	Introduction	498
41.4.2	Simple Example for Performance Variation	500
41.4.3	Seidel Aberrations	503
41.4.4	Color Aberrations	505

41.4.5	Stop Position	506
41.5	Example Systems	508
41.5.1	Mechanically Compensated Three-component Systems	508
41.5.2	Mechanically Compensated Four-component Systems	511
41.5.3	Systems With More Than Four Moving Groups	516
41.5.4	Optically Compensated Zoom Systems	521
41.6	Special Aspects	525
41.6.1	Gaussian Brackets	525
41.6.2	Description of Zoom Systems with Differential Equations	526
41.6.3	Solid State Zoom Systems	528
41.6.4	Mirror Zoom Systems	530
41.6.5	Focusing of Camera Zoom Systems	532
41.6.6	Adjustment of a Zoom System	535
41.7	Literature	538
42	Microscope Optics	541
42.1	Introduction	543
42.1.1	Overview	543
42.1.2	Combined Color Correction	548
42.1.3	Complete System of the Microscope	551
42.2	Objective Lenses	555
42.2.1	Introduction	555
42.2.2	Quality Classes	559
42.2.3	Design of High-performance Objective Lenses	566
42.2.4	Achromate Lens	568
42.2.5	Lister Objective	569
42.2.6	Amici Objective	573
42.2.7	High Aperture Lenses	575
42.2.8	Flat Field Lenses	587
42.2.9	Correcting Objectives	595
42.2.10	Long-distance Objective Lenses	599
42.2.11	Catadioptric Objectives	605
42.2.12	Objectives for Fluorescence Microscopy	622
42.2.13	UV Lenses	623
42.3	Microscopic Imaging System	629
42.3.1	Defocused Use of High NA Lenses	629
42.3.2	Immersion and Cover Glass	636
42.3.3	Index Mismatch in the Object Space	638
42.3.4	Objective Pupil and Telecentricity	644
42.3.5	Tube Optic	650
42.3.6	Conoscopic Observation	655
42.4	Illumination Optic	656
42.4.1	Introduction	656
42.4.2	Köhler Illumination	661
42.4.3	Collector Optic	662

- 42.4.4 Condenser Optics for Bright-field Illumination 665
- 42.4.5 Condenser Optic for Dark-field Illumination 668
- 42.4.6 TIRF Illumination 671
- 42.5 Stereo Microscope 674
- 42.5.1 Introduction 674
- 42.5.2 Telescope Setup 676
- 42.5.3 Greenough Setup 679
- 42.5.4 Magnification-changing Systems 680
- 42.5.5 Special Combination Setup 681
- 42.6 Confocal Laser Scanning Microscopes 682
- 42.6.1 Introduction 682
- 42.6.2 Scan Lens 685
- 42.6.3 Pinhole Optic 688
- 42.6.4 Nipkow Microscope 689
- 42.6.5 Illumination System of a Confocal Microscope 691
- 42.7 Special Aspects 691
- 42.7.1 Accessories 691
- 42.7.2 Autofluorescence 692
- 42.7.3 Transmission and Throughput 694
- 42.7.4 Adjustment of Microscope Lenses 699
- 42.7.5 Focusing at Low Fresnel Numbers 701
- 42.7.6 Solid Immersion Lenses 709
- 42.7.7 Thermal Effects 714
- 42.8 Literature 718

- 43 Telescopes 723**
- 43.1 Introduction 726
- 43.2 Refracting Telescopes 727
- 43.2.1 Achromatic Refractor Telescopes 727
- 43.2.2 Apochromatic Refractor Telescopes 730
- 43.2.3 Apochromatic Telescopes Without Anomalous Dispersion Glasses 742
- 43.3 Reflecting Telescopes 744
- 43.4 Single-mirror Reflecting Telescopes 745
- 43.4.1 Spherical Mirror 745
- 43.4.2 Parabolic Mirror (Newton Telescope) 745
- 43.5 Two-mirror Reflecting Telescopes 746
- 43.5.1 Cassegrain Telescope 746
- 43.5.2 Ritchey–Chretien Telescope 750
- 43.5.3 Dall–Kirkham Telescope 750
- 43.5.4 Pressmann–Camichel Telescope 751
- 43.5.5 Gregorian Telescope 751
- 43.5.6 Schwarzschild Aplanatic Telescopes 753
- 43.5.7 Couder Anastigmat 756
- 43.5.8 Loveday Telescope 756
- 43.6 Three-mirror Reflection Telescopes 758

- 43.6.1 Paul–Baker Telescope 758
- 43.6.2 Willstrop Mersenne–Schmidt Telescope 760
- 43.6.3 Korsch Three-mirror, Single-axis Telescope 762
- 43.6.4 Robb Three-mirror Telescope 763
- 43.6.5 Korsch Three-mirror Four-reflection Telescope 764
- 43.7 Other Three- and Four-mirror Reflecting Telescopes 765
- 43.8 Two-mirror Schiefspiegler (Oblique Reflector) Telescopes 766
- 43.8.1 Kutter Schiefspiegler 767
- 43.8.2 Herrig Schiefspiegler 769
- 43.8.3 Yolo Telescope 771
- 43.9 Three-mirror Schiefspiegler Telescopes 772
- 43.9.1 Kutter and Buchroeder Tri-Schiefspiegler 772
- 43.9.2 Stevick–Paul Schiefspiegler 773
- 43.9.3 Brunn Schiefspiegler 775
- 43.9.4 Shafer Schiefspiegler 776
- 43.9.5 Solano Schiefspiegler 777
- 43.9.6 General Solutions for Three-mirror Schiefspiegler Telescopes 777
- 43.10 Four-mirror Schiefspiegler 781
- 43.10.1 Shafer–Mersenne Telescope 781
- 43.10.2 Shafer Four- and Five-mirror Unobscured Telescopes 782
- 43.10.3 Afocal Four-mirror Telescope 783
- 43.10.4 General Solutions for Four-mirror Schiefspiegler Telescopes 784
- 43.11 Three-mirror Off-axis Anastigmats (TMA) 786
- 43.11.1 Re-imaging TMA 787
- 43.11.2 Non-re-imaging TMA 788
- 43.11.3 Walrus 789
- 43.12 Two-axis Telescopes 790
- 43.12.1 Korsch Three-mirror, Two-axis Telescope 790
- 43.12.2 Two-axis Telescopes Derived from the Mersenne and Schmidt Principle 791
- 43.13 Catadioptric Telescopes 793
- 43.13.1 Mangin Telescope 793
- 43.13.2 Schmidt Telescope 794
- 43.13.3 Wright–Väisälä Telescope 797
- 43.13.4 Baker–Super-Schmidt Telescope 797
- 43.13.5 Baker–Nunn Camera 798
- 43.13.6 Wynne Telescope 799
- 43.13.7 Schmidt–Cassegrain Telescope 799
- 43.13.8 Schmidt–Gregorian Telescope 801
- 43.13.9 Sigler Telescope 801
- 43.13.10 Houghton Telescope 802
- 43.13.11 Buchroeder–Houghton Telescope 803
- 43.13.12 Houghton–Cassegrain Telescope 804
- 43.13.13 Lurie–Houghton Telescope 805
- 43.13.14 Bouwers–Maksutov Telescope 806

- 43.14 Catadioptric Maksutov–Cassegrain Telescopes 809
- 43.14.1 Maksutov–Gregory Telescope 809
- 43.14.2 Maksutov–Rumak Telescope 810
- 43.14.3 Aspherical Maksutov Telescope 811
- 43.14.4 Bouwers–Cassegrain with Weak Corrector Lens 811
- 43.14.5 Schmidt–Bouwers Telescope 813
- 43.14.6 Compact Maksutov Telescope 813
- 43.14.7 Klevtsov 814
- 43.14.8 Other Forms of Catadioptric Telescopes 816
- 43.14.9 Schupmann Medial Telescope 817
- 43.14.10 Schupmann Brachymedial 821
- 43.15 Telescopes with Field Correctors 821
- 43.15.1 Field-flattening Lens 822
- 43.15.2 Correctors for a Parabolic Mirror (Newton Telescope) 823
- 43.15.3 Correctors for a Spherical Mirror 825
- 43.15.4 Corrector for Cassegrain and RC Telescopes 826
- 43.15.5 Focal Reducers 827
- 43.15.6 Focal Extenders 828
- 43.16 The Effects of Aperture Obscuration 829
- 43.16.1 Central Obstruction 830
- 43.16.2 Spider Obstruction 834
- 43.17 Telescope Design Prescriptions 835
- 43.18 Literature 861

- 44 Lithographic Projection Lenses 865**
- 44.1 Introduction 866
- 44.2 Physical Optics Aspects 868
- 44.2.1 Projection Techniques 868
- 44.2.2 Resolution 870
- 44.2.3 Information Transfer 873
- 44.2.4 Illumination and Coherence 874
- 44.2.5 Materials 878
- 44.2.6 Polarization 881
- 44.3 Performance of Lithographic Lenses 883
- 44.3.1 Requirements 883
- 44.3.2 Representations of Performance 884
- 44.3.3 Chromatic Aberrations 893
- 44.3.4 Petzval Curvature 897
- 44.3.5 Telecentricity 898
- 44.4 Evolution of Lithographic Lens Systems 900
- 44.4.1 Introduction 900
- 44.4.2 Change of Wavelength 904
- 44.4.3 The Size Problem 905
- 44.4.4 Aspherical Systems 906
- 44.4.5 Immersion Systems 909

44.4.6	Catadioptric Systems	909
44.4.7	Mirror Systems	913
44.5	Examples of Lithographic Systems	914
44.5.1	Introduction	914
44.5.2	Early Lithographic Lenses	916
44.5.3	Refractive Projection Lenses	917
44.5.4	Multi-axis Catadioptric Systems with Cubes	925
44.5.5	Multi-axis Catadioptric Systems with Mirrors	926
44.5.6	EUV Mirror Systems	930
44.6	Literature	938
45	Miscellaneous System Types	941
45.1	Relay Systems	943
45.1.1	Introduction	943
45.1.2	Basic Systems	944
45.1.3	System with Variable Magnification	950
45.1.4	More Complicated Relay Systems	951
45.1.5	The 4f system	953
45.1.6	Combination of Relay Systems	956
45.1.7	Riflescope	957
45.1.8	Periscope	958
45.1.9	Endoscope	961
45.2	Scan Systems	965
45.2.1	Introduction	965
45.2.2	Scanning Components	967
45.2.3	$F\text{-}\tilde{\nu}$ Scan Lenses	974
45.2.4	Scanner Resolution	976
45.2.5	Scan Lens Design	977
45.2.6	Scan Lens Examples	979
45.3	Projection Systems	984
45.3.1	Introduction	984
45.3.2	Film Projection	985
45.3.3	Digital Light Projection	988
45.3.4	Color Management	991
45.3.5	Front Projection Lenses	995
45.3.6	DMD Light Projection Lenses	997
45.3.7	Rear Projection TV Systems	1001
45.3.8	HUD Projection Systems	1002
45.3.9	HMD Projection Systems	1004
45.3.10	Retinal Scanner Systems	1011
45.4	Interferometer Lenses	1012
45.4.1	Collimator Lenses	1012
45.4.2	Refractive Null Corrector Lenses	1016
45.4.3	Diffraction Null Corrector Systems	1025
45.5	Autofocus Systems	1028

45.5.1	Introduction	1028
45.5.2	Astigmatic Sensor	1031
45.5.3	Confocal Sensor	1037
45.5.4	Chromatic Confocal Sensor	1039
45.5.5	Triangulation	1041
45.6	Spectroscopic Systems	1043
45.6.1	Introduction	1043
45.6.2	Prism Spectrometer	1044
45.6.3	Grating Spectrometer	1045
45.6.4	Spectrometer with Rowland Grating	1046
45.6.5	Czerny–Turner Setup	1049
45.6.6	Fery Prism Systems	1051
45.7	Literature	1052
Index		1057

