
Contents

Preface to the Third Edition	xv
Polarized Light: A History	xvii

PART I Introduction to Polarized Light

Chapter 1 Introduction	3
Reference	7
Chapter 2 Polarization in the Natural Environment	9
2.1 Sources of Polarized Light	9
2.2 Polarized Light in the Atmosphere.....	9
2.2.1 The Sky: Rayleigh Scattering and Polarization	9
2.2.2 Rainbows	10
2.2.3 Clouds, Halos, and Glories.....	14
2.2.3.1 Clouds	14
2.2.3.2 Haloes	14
2.2.3.3 Glories.....	15
2.2.4 The Sun	15
2.3 Production of Polarized Light by Animals	16
2.3.1 Scarabaeidae (Scarab Beetles).....	16
2.3.2 Squid and Cuttlefish	22
2.3.3 Mantis Shrimp.....	23
2.4 Polarization Vision in the Animal Kingdom.....	24
References	28
Chapter 3 Wave Equation in Classical Optics	31
3.1 Introduction	31
3.2 The Wave Equation	31
3.2.1 Plane-Wave Solution.....	33
3.2.2 Spherical Waves	34
3.2.3 Fourier Transform Method.....	35
3.2.4 Mathematical Representation of the Harmonic Oscillator Equation	36
3.2.5 Note on the Equation of a Plane.....	38
3.3 Young's Interference Experiment.....	39
3.4 Reflection and Transmission of a Wave at an Interface	43
Chapter 4 The Polarization Ellipse.....	49
4.1 Introduction	49
4.2 The Instantaneous Optical Field and the Polarization Ellipse.....	50

4.3	Specialized (Degenerate) Forms of the Polarization Ellipse.....	52
4.4	Elliptical Parameters of the Polarization Ellipse	54
	References	58
Chapter 5	Stokes Polarization Parameters.....	59
5.1	Introduction	59
5.2	Derivation of Stokes Polarization Parameters.....	60
5.2.1	Linear Horizontally Polarized Light (LHP).....	63
5.2.2	Linear Vertically Polarized Light (LVP).....	64
5.2.3	Linear +45° Polarized Light ($L +45$).....	64
5.2.4	Linear -45° Polarized Light ($L -45$).....	64
5.2.5	Right Circularly Polarized Light (RCP).....	64
5.2.6	Left Circularly Polarized Light (LCP).....	65
5.3	Stokes Vector.....	65
5.3.1	Linear Horizontally Polarized Light (LHP).....	66
5.3.2	Linear Vertically Polarized Light (LVP).....	66
5.3.3	Linear +45° Polarized Light ($L +45$).....	66
5.3.4	Linear -45° Polarized Light ($L -45$).....	66
5.3.5	Right Circularly Polarized Light (RCP).....	66
5.3.6	Left Circularly Polarized Light (LCP).....	67
5.4	Classical Measurement of Stokes Polarization Parameters.....	71
5.5	Stokes Parameters for Unpolarized and Partially Polarized Light	75
5.6	Additional Properties of Stokes Polarization Parameters	77
5.7	Stokes Parameters and the Coherency Matrix	87
5.8	Stokes Parameters and the Pauli Matrices	90
	References	91
Chapter 6	Mueller Matrices for Polarizing Components.....	93
6.1	Introduction	93
6.2	Mueller Matrix of a Linear Diattenuator (Polarizer).....	95
6.3	Mueller Matrix of a Linear Retarder.....	100
6.4	Mueller Matrix of a Rotator	103
6.5	Mueller Matrices for Rotated Polarizing Components.....	105
6.6	Generation of Elliptically Polarized Light	111
6.7	Mueller Matrix of a Depolarizer	114
	References	115
Chapter 7	Fresnel Equations: Derivation and Mueller Matrix Formulation.....	117
7.1	Introduction	117
7.2	Fresnel Equations for Reflection and Transmission	117
7.2.1	Definitions	117
7.2.2	Boundary Conditions	118
7.2.3	Derivation of Fresnel Equations.....	119
7.3	Mueller Matrices for Reflection and Transmission at an Air-Dielectric Interface.....	127
7.4	Special Forms for Mueller Matrices for Reflection and Transmission.....	135
7.4.1	Normal Incidence	136
7.4.2	Brewster Angle.....	137

7.4.3	45° Incidence	138
7.4.4	Total Internal Reflection.....	141
7.5	Emission Polarization	145
	References	147
Chapter 8	Mathematics of the Mueller Matrix	149
8.1	Introduction	149
8.2	Constraints on the Mueller Matrix	150
8.3	Eigenvector and Eigenvalue Analysis.....	151
8.4	Example Eigenvector Analysis.....	155
8.4.1	Eigenvector Analysis.....	156
8.4.2	Noise.....	157
8.5	The Lu–Chipman Decomposition.....	160
8.6	Decomposition Order	170
8.7	Decomposition of Depolarizing Matrices with Depolarization Symmetry	171
8.8	Decomposition Using Matrix Roots.....	174
8.9	Summary	174
	References	174
Chapter 9	Mueller Matrices for Dielectric Plates	177
9.1	Introduction	177
9.2	The Diagonal Mueller Matrix and the <i>ABCD</i> Polarization Matrix	177
9.3	Mueller Matrices for Single and Multiple Dielectric Plates.....	186
	References	199
Chapter 10	The Jones Matrix Formalism	201
10.1	Introduction	201
10.2	The Jones Vector	202
10.3	Jones Matrices for the Polarizer, Retarder, and Rotator.....	206
10.4	Applications of the Jones Vector and Jones Matrices	211
10.5	Jones Matrices for Homogeneous Elliptical Polarizers and Retarders	222
	References	230
Chapter 11	The Poincaré Sphere	233
11.1	Introduction	233
11.2	Theory of the Poincaré Sphere.....	234
11.2.1	Note on the Derivation of Law of Cosines and Law of Sines in Spherical Trigonometry.....	244
11.3	Projection of the Complex Plane onto a Sphere	250
11.4	Applications of the Poincaré Sphere	258
	References	266
Chapter 12	Fresnel–Arago Interference Laws	267
12.1	Introduction	267
12.2	Stokes Vector and Unpolarized Light.....	267

12.3	Young's Double Slit Experiment	268
12.4	Double Slit with Parallel Polarizers: The First Law.....	271
12.5	Double Slit with Perpendicular Polarizers: The Second Law	273
12.6	Double Slit and the Third Law	274
12.7	Double Slit and the Fourth Law	276
	References	278

PART II Polarimetry

Chapter 13	Introduction	281
Chapter 14	Methods of Measuring Stokes Polarization Parameters	283
14.1	Introduction	283
14.2	Classical Measurement Method: Quarter-Wave Retarder and Polarizer Method	283
14.3	Measurement of Stokes Parameters Using a Circular Polarizer	287
14.4	Null-Intensity Method	291
14.5	Fourier Analysis Using a Rotating Quarter-Wave Retarder	294
14.6	Method of Kent and Lawson	297
14.7	Simple Tests to Determine the State of Polarization of an Optical Beam	304
	References	310
Chapter 15	Measurement of the Characteristics of Polarizing Elements	311
15.1	Introduction	311
15.2	Measurement of Attenuation Coefficients of a Polarizer (Diattenuator).....	311
15.2.1	First Measurement Method	313
15.2.2	Second Measurement Method.....	316
15.2.3	Third Measurement Method.....	317
15.3	Measurement of the Phase Shift of a Retarder.....	318
15.3.1	First Method	318
15.3.2	Second Method.....	320
15.3.3	Third Method	323
15.4	Measurement of Rotation Angle of a Rotator.....	324
15.4.1	First Method	324
15.4.2	Second Method.....	326
Chapter 16	Stokes Polarimetry	327
16.1	Introduction	327
16.2	Rotating Element Polarimetry	327
16.2.1	Rotating Analyzer Polarimeter	327
16.2.2	Rotating Analyzer and Fixed Analyzer Polarimeter.....	329
16.2.3	Rotating Retarder and Fixed Analyzer Polarimeter.....	329
16.2.4	Rotating Retarder and Analyzer Polarimeter.....	329
16.2.5	Rotating Retarder and Analyzer Plus Fixed Analyzer Polarimeter	331
16.3	Oscillating Element Polarimetry	331
16.3.1	Oscillating Analyzer Polarimeter.....	332

16.3.2	Oscillating Retarder with Fixed Analyzer Polarimeter	334
16.3.3	Oscillating Retarder and Analyzer Polarimeter	335
16.4	Phase Modulation Polarimetry	337
16.4.1	Phase Modulator and Fixed Analyzer Polarimeter	337
16.4.2	Dual Phase Modulator and Fixed Analyzer Polarimeter	338
16.5	Techniques in Simultaneous Measurement of Stokes Vector Elements.....	339
16.5.1	Division of Wavefront Polarimetry	339
16.5.2	Division of Amplitude Polarimetry.....	340
16.5.2.1	Four-Channel Polarimeter Using Polarizing Beam Splitters.....	340
16.5.2.2	Azzam's Four-Detector Photopolarimeter.....	340
16.5.2.3	Division of Amplitude Polarimeters Using Gratings	346
16.5.2.4	Division of Amplitude Polarimeter Using a Parallel Slab	347
16.6	Optimization of Polarimeters	348
	References	351
Chapter 17	Mueller Matrix Polarimetry	353
17.1	Introduction	353
17.1.1	Polarimeter Types.....	353
17.1.2	Rotating Element Polarimeters	355
17.1.3	Phase-Modulating Polarimeters	356
17.2	Dual Rotating Retarder Polarimetry	357
17.2.1	Polarimeter Description	357
17.2.2	Mathematical Development: Obtaining the Mueller Matrix.....	357
17.2.3	Modulated Intensity Patterns	361
17.2.4	Error Compensation	362
17.2.5	Optical Properties from the Mueller Matrix	367
17.2.6	Measurements.....	369
17.2.7	Spectropolarimetry.....	369
17.2.8	Measurement Matrix Method.....	370
17.3	Other Mueller Matrix Polarimetry Methods.....	371
17.3.1	Modulator-Based Mueller Matrix Polarimeter.....	372
17.3.2	Mueller Matrix Scatterometer.....	373
17.3.3	Four-Detector Photopolarimeter	374
	References	375
Chapter 18	Techniques in Imaging Polarimetry.....	377
18.1	Introduction	377
18.2	Historical Perspective.....	378
18.3	Measurement Considerations	379
18.3.1	Spectral Considerations.....	379
18.3.2	One-Dimensional Polarimeters.....	380
18.3.3	Two-Dimensional Polarimeters.....	380
18.3.4	Three-Dimensional Polarimeters	381
18.3.5	Full Stokes Polarimeters	381

18.3.6	Active Imaging Polarimeters.....	381
18.3.6.1	Mueller Matrix and Other Active Imaging Systems.....	382
18.3.6.2	Lidar Systems	382
18.3.7	Spectropolarimetric Imagers.....	383
18.4	Measurement Strategies and Data Reduction Techniques	384
18.4.1	Data Reduction Matrix Techniques.....	384
18.4.2	Fourier Modulation Techniques	385
18.4.3	Channeled Spectropolarimeters	387
18.5	General Measurement Strategies: Imaging Architecture for Integrated Polarimeters	388
18.5.1	Division of Time (DoTP) Polarimeter.....	388
18.5.2	Division of Amplitude Polarimeters (DoAmP).....	389
18.5.3	Division of Aperture Polarimeter (DoAP).....	390
18.5.4	Division of Focal Plane (DoFP) Array Polarimeters	391
18.6	System Considerations.....	392
18.6.1	Alignment and Calibration of Imaging Polarimeters	392
18.6.2	Experimental Determination of Data Reduction Matrix	392
18.6.3	Calibration of Fourier-Based Rotating Retarder Systems.....	393
18.6.4	Polarization Aberrations and Image Misalignment	393
18.6.5	Optimization.....	393
18.7	Summary	395
	References	396
Chapter 19	Channeled Polarimetry for Snapshot Measurements	401
19.1	Introduction	401
19.2	Channeled Polarimetry.....	402
19.2.1	Introduction to Channeled Spectropolarimetry	402
19.2.2	Introduction to Channeled Imaging Polarimetry	406
19.2.3	Calibration Algorithms	408
19.2.3.1	CS Calibration	408
19.2.3.2	CIP Calibration.....	411
19.3	Channeled Spectropolarimetry	413
19.3.1	CS with a Dispersive Spectrometer.....	413
19.3.2	Fourier Transform CS	415
19.4	Channeled Imaging Polarimetry	416
19.4.1	Prismatic CIP	416
19.4.2	Savart Plate CIP	420
19.4.3	Dispersion Compensation in CIP	423
19.4.3.1	DC in Prismatic CIP.....	423
19.4.3.2	DC in Savart Plate CIP	424
19.5	Sources of Error in Channeled Polarimetry	426
19.5.1	Reconstruction Artifacts (CS and CIP).....	426
19.5.2	Temperature Variations (CS and CIP).....	427
19.5.3	Dichroism (CS and CIP).....	428
19.5.4	Dispersion (CS)	429
19.6	Mueller Matrix Channeled Spectropolarimeters.....	429
19.7	Channeled Ellipsometers.....	431
	References	432

PART III Applications

Chapter 20	Introduction	437
Chapter 21	Crystal Optics.....	439
21.1	Introduction	439
21.2	Review of Concepts from Electromagnetism.....	440
21.3	Crystalline Materials and Their Properties.....	442
21.4	Crystals.....	443
21.4.1	Index Ellipsoid	448
21.4.2	Natural Birefringence.....	451
21.4.3	Wave Surface.....	451
21.4.4	Wavevector Surface.....	454
21.5	Application of Electric Fields: Induced Birefringence and Polarization Modulation	455
21.6	Magneto-Optics.....	461
21.7	Liquid Crystals	463
21.8	Modulation of Light.....	465
21.9	Photoelastic Modulators	466
21.10	Concluding Remarks	467
	References	468
Chapter 22	Optics of Metals	471
22.1	Introduction	471
22.2	Maxwell's Equations for Absorbing Media.....	472
22.3	Principal Angle of Incidence Measurement of Refractive Index and Absorption Index of Optically Absorbing Materials.....	481
22.4	Measurement of Refractive Index and Absorption Index at an Incident Angle of 45°	489
	References	501
Chapter 23	Polarization Optical Elements.....	503
23.1	Introduction	503
23.2	Polarizers.....	503
23.2.1	Absorption Polarizers: Polaroid	503
23.2.2	Absorption Polarizers: Polarcor	509
23.2.3	Wire Grid Polarizers	510
23.2.4	Plasmonic Lenses as Circular Polarizers	511
23.2.5	Polarization by Refraction (Prism Polarizers).....	512
23.2.6	Polarization by Reflection	514
23.3	Retarders.....	514
23.3.1	Birefringent Retarders.....	515
23.3.2	Variable Retarders.....	518
23.3.3	Achromatic Retarders.....	519
23.3.3.1	Infrared Achromatic Retarder	520
23.3.3.2	Achromatic Waveplate Retarders	523

23.4	Rotators.....	524
23.4.1	Optical Activity.....	524
23.4.2	Faraday Rotation.....	526
23.4.3	Liquid Crystals.....	526
23.5	Depolarizers.....	526
	References.....	527
Chapter 24	Ellipsometry.....	529
24.1	Introduction.....	529
24.2	Fundamental Equation of Classical Ellipsometry.....	530
24.3	Classical Measurement of the Ellipsometric Parameters Psi (ψ) and Delta (Δ).....	532
24.4	Solution of the Fundamental Equation of Ellipsometry.....	541
24.4.1	Stokes's Treatment of Reflection and Refraction at an Interface.....	559
24.5	Further Developments in Ellipsometry: Mueller Matrix Representation of ψ and Δ	560
	References.....	567
Chapter 25	Form Birefringence and Meanderline Retarders.....	569
25.1	Introduction.....	569
25.2	Form Birefringence.....	569
25.3	Meanderline Elements.....	570
	References.....	572
<i>PART IV Classical and Quantum Theory of Radiation by Accelerating Charges</i>		
Chapter 26	Introduction to Classical and Quantum Theory of Radiation by Accelerating Charges.....	575
	References.....	576
Chapter 27	Maxwell's Equations for Electromagnetic Fields.....	577
	Reference.....	582
Chapter 28	The Classical Radiation Field.....	583
28.1	Field Components of the Radiation Field.....	583
28.2	Relation between Unit Vector in Spherical Coordinates and Cartesian Coordinates.....	585
28.3	Relation between Poynting Vector and Stokes Parameters.....	588
	References.....	594

Chapter 29	Radiation Emitted by Accelerating Charges.....	595
29.1	Stokes Vector for a Linearly Oscillating Charge.....	595
29.2	Stokes Vector for an Ensemble of Randomly Oriented Oscillating Charges.....	598
29.2.1	Note on Use of Hooke's Law for a Simple Atomic System.....	601
29.3	Stokes Vector for a Charge Rotating in a Circle.....	601
29.4	Stokes Vector for a Charge Moving in an Ellipse.....	604
Chapter 30	Radiation of an Accelerating Charge in the Electromagnetic Field.....	607
30.1	Motion of a Charge in an Electromagnetic Field.....	607
30.1.1	Motion of an Electron in a Constant Electric Field.....	608
30.1.2	Motion of a Charged Particle in a Constant Magnetic Field.....	610
30.1.3	Motion of an Electron in a Crossed Electric and Magnetic Field....	614
30.2	Stokes Vectors for Radiation Emitted by Accelerating Charges.....	618
30.2.1	Stokes Vector for a Charge Moving in an Electric Field.....	621
30.2.2	Stokes Vector for a Charge Accelerating in a Constant Magnetic Field.....	623
30.2.3	Stokes Vector for a Charge Moving in a Crossed Electric and Magnetic Field.....	625
	References.....	625
Chapter 31	The Classical Zeeman Effect.....	627
31.1	Historical Introduction.....	627
31.2	Motion of a Bound Charge in a Constant Magnetic Field.....	628
31.3	Stokes Vector for the Zeeman Effect.....	637
	References.....	642
Chapter 32	Further Applications of the Classical Radiation Theory.....	645
32.1	Relativistic Radiation and the Stokes Vector for a Linear Oscillator.....	645
32.2	Relativistic Motion of a Charge Moving in a Circle: Synchrotron Radiation.....	652
32.3	Čerenkov Effect.....	659
32.4	Thomson and Rayleigh Scattering.....	670
	References.....	678
Chapter 33	The Stokes Parameters and Mueller Matrices for Optical Activity and Faraday Rotation.....	679
33.1	Introduction.....	679
33.2	Optical Activity.....	680
33.3	Faraday Rotation in a Transparent Medium.....	687
33.4	Faraday Rotation in a Plasma.....	691
	References.....	693

Chapter 34	Stokes Parameters for Quantum Systems	695
34.1	Introduction	695
34.2	Relation between Stokes Polarization Parameters and Quantum Mechanical Density Matrix.....	696
34.3	Note on Perrin's Introduction of Stokes Parameters, the Density Matrix, and Linearity of Mueller Matrix Elements.....	705
34.4	Radiation Equations for Quantum Mechanical Systems.....	710
34.5	Stokes Vectors for Quantum Mechanical Systems.....	714
34.5.1	Particle in an Infinite Potential Well	714
34.5.2	One-Dimensional Harmonic Oscillator	716
34.5.3	Rigid Rotator	717
	References	721
Appendix A:	Conventions in Polarized Light	723
Appendix B:	Jones and Stokes Vectors	725
Appendix C:	Jones and Mueller Matrices	727
Appendix D:	Relationships between the Jones and Mueller Matrix Elements	731
Appendix E:	Vector Representation of the Optical Field: Application to Optical Activity	733
Bibliography	745
Index	747