
Contents

| | | |
|----------|---|----|
| 1 | Vectorial Propagation of Light | 1 |
| 1.1 | Maxwell's Equations and Free-Space Solutions | 2 |
| 1.2 | The Vector and Scalar Potentials | 8 |
| 1.3 | Time-Harmonic Solutions | 10 |
| 1.4 | Classical Description of Polarization | 12 |
| 1.4.1 | Stokes Vectors, Jones and Muller Matrices | 17 |
| 1.4.2 | The Poincaré Sphere | 20 |
| 1.5 | Partial Polarization | 22 |
| 1.5.1 | Coherently Polarized Waves | 24 |
| 1.5.2 | Incoherently Depolarized Waves | 28 |
| 1.5.3 | Pseudo-Depolarized Waves | 31 |
| 1.5.4 | A Heterogeneous Ray Bundle | 33 |
| | References | 36 |
| 2 | The Spin-Vector Calculus of Polarization | 37 |
| 2.1 | Motivation | 37 |
| 2.2 | Vectors, Length, and Direction | 39 |
| 2.2.1 | Bra and Ket Vectors | 39 |
| 2.2.2 | Length and Inner Products | 41 |
| 2.2.3 | Projectors and Outer Products | 42 |
| 2.2.4 | Orthonormal Basis | 43 |
| 2.3 | General Vector Transformations | 44 |
| 2.3.1 | Operator Relations | 44 |
| 2.4 | Eigenstates, Hermitian and Unitary Operators | 46 |
| 2.4.1 | Hermitian Operators | 47 |
| 2.4.2 | Unitary Operators | 48 |
| 2.4.3 | Connection between Hermitian and Unitary Matrices | 49 |
| 2.4.4 | Similarity Transforms | 49 |
| 2.4.5 | Construction of General Unitary Matrix | 50 |
| 2.4.6 | Group Properties of $SU(2)$ | 51 |
| 2.5 | Vectors Cast in Jones and Stokes Spaces | 52 |

| | | |
|----------|---|-----------|
| 2.5.1 | Complete Measurement of the Polarization Ellipse | 52 |
| 2.5.2 | Pauli Spin Matrices | 54 |
| 2.5.3 | The Pauli Spin Vector | 55 |
| 2.5.4 | Spin-Vector Identities | 56 |
| 2.5.5 | Conservation of Length | 58 |
| 2.5.6 | Orthogonal Polarization States | 59 |
| 2.5.7 | Non-Orthogonal Polarization States | 60 |
| 2.5.8 | Pauli Spin Operators | 61 |
| 2.6 | Equivalent Unitary Transformations | 63 |
| 2.6.1 | Group Properties of $SU(2)$ and $O(3)$ | 65 |
| 2.6.2 | Matrix Entries of R in a Fixed Coordinate System | 66 |
| 2.6.3 | Vector Expression of R in a Local Coordinate System | 67 |
| 2.6.4 | Select Vector Identities | 70 |
| 2.6.5 | Euler Rotations | 71 |
| 2.6.6 | Some Relevant Transformation Applications | 72 |
| | References | 78 |
| 3 | Interaction of Light and Dielectric Media | 79 |
| 3.1 | Introduction of Media Terms into Maxwell's Equations | 80 |
| 3.2 | Constitutive Relation Tensors | 85 |
| 3.3 | The kDB System | 87 |
| 3.4 | The Lorentz Force | 90 |
| 3.5 | Isotropic Materials | 90 |
| 3.5.1 | Permittivity of Isotropic Materials | 91 |
| 3.5.2 | Propagation in Isotropic Materials | 94 |
| 3.5.3 | Refraction at an Interface | 96 |
| 3.5.4 | Reflection and Transmission for TE Waves | 96 |
| 3.5.5 | Reflection and Transmission for TM Waves | 99 |
| 3.5.6 | Total Internal Reflection | 101 |
| 3.6 | Birefringent Materials | 105 |
| 3.6.1 | Propagation in Uniaxial Materials | 106 |
| 3.6.2 | Refraction at an Interface | 112 |
| 3.6.3 | Total Internal Reflection | 117 |
| 3.6.4 | Polarization Transformation | 120 |
| 3.7 | Gyrotropic Materials | 122 |
| 3.7.1 | Magnetic Material Classes | 123 |
| 3.7.2 | Permittivity of Diamagnetic Materials | 124 |
| 3.7.3 | Propagation in Gyrotropic Materials | 126 |
| 3.7.4 | Faraday Rotation | 129 |
| 3.7.5 | The Verdet Constant | 132 |
| 3.7.6 | Faraday Rotation in Ferrous Materials | 133 |
| 3.8 | Optically Active Materials | 135 |
| 3.8.1 | Propagation in Bi-Isotropic Media | 138 |
| | References | 142 |

| | |
|--|-----|
| 4 Elements and Basic Combinations | 143 |
| 4.1 Wavelength-Division Multiplexed Frequency Grid | 143 |
| 4.2 Properties of Select Materials | 146 |
| 4.2.1 Isotropic Glass Materials | 146 |
| 4.2.2 Birefringent Crystals..... | 147 |
| 4.2.3 Iron Garnets | 150 |
| 4.2.4 Packaging Alloys | 153 |
| 4.3 Fabry-Perot and Gires-Tournois Interferometers | 154 |
| 4.3.1 Fabry-Perot Response | 157 |
| 4.3.2 Gires-Tournois Response | 161 |
| 4.4 Temperature Dependence of Select Birefringent Crystals..... | 163 |
| 4.4.1 Experimental Setup | 163 |
| 4.4.2 Quadratic Temperature-Dependence Model | 166 |
| 4.4.3 Association of Resonant Peak Shift With Temperature Coefficients | 167 |
| 4.4.4 Group Index and Thermal-Optic Coefficients..... | 168 |
| 4.4.5 Passive Temperature Compensation | 170 |
| 4.5 Compound Crystals For Off-Axis Delay | 173 |
| 4.6 Polarization Retarders | 178 |
| 4.6.1 Half-Wave and Quarter-Wave Waveplates | 179 |
| 4.6.2 Birefringent Waveplate Technologies | 182 |
| 4.6.3 Waveplate Combinations | 184 |
| 4.6.4 Elementary Polarization Control | 191 |
| 4.6.5 TIR Polarization Retarders | 196 |
| 4.7 Single and Compound Prisms | 198 |
| 4.7.1 Wollaston and Rochon Prisms | 199 |
| 4.7.2 Kaifa Prism | 202 |
| 4.7.3 Shirasaki Prism | 204 |
| References | 208 |
| 5 Collimator Technologies | 211 |
| 5.1 Collimator Assemblies..... | 213 |
| 5.2 Gaussian Optics | 219 |
| 5.2.1 q Transformation and ABCD Matrices | 224 |
| 5.2.2 ABCD Ray Tracing..... | 227 |
| 5.2.3 Action of a Single Lens..... | 228 |
| 5.2.4 Action of a GRIN Lens | 230 |
| 5.2.5 Some Limitations of the ABCD Matrix..... | 232 |
| 5.3 Select Collimators Analyzed with the ABCD Matrix | 234 |
| 5.4 Fiber-to-Fiber Coupling by a Lens Pair | 239 |
| 5.4.1 Coupling Coefficients | 242 |
| References | 245 |

| | | |
|----------|--|-----|
| 6 | Isolators | 247 |
| 6.1 | Polarizing Isolator | 247 |
| 6.2 | Comparison of Lens Systems | 252 |
| 6.3 | Deflection-Type Isolators | 254 |
| 6.4 | Displacement-Type Isolators | 259 |
| 6.5 | Two-Stage Isolators | 263 |
| 6.6 | PMD-Compensated Isolators | 266 |
| | References | 271 |
| 7 | Circulators | 273 |
| 7.1 | Polarizing Circulator | 274 |
| 7.2 | Historical Development | 277 |
| 7.3 | Displacement Circulators | 279 |
| 7.4 | Deflection Circulators | 284 |
| 7.5 | Summary | 294 |
| | References | 295 |
| 8 | Properties of PDL and PMD | 297 |
| 8.1 | Polarization-Dependent Loss | 298 |
| 8.1.1 | Definitions | 299 |
| 8.1.2 | Change of Polarization State | 304 |
| 8.1.3 | Repolarization | 306 |
| 8.1.4 | PDL Evolution Equations | 308 |
| 8.2 | Polarization-Mode Dispersion | 312 |
| 8.2.1 | A PMD Primer | 313 |
| 8.2.2 | Fundamental Derivations | 327 |
| 8.2.3 | Connection Between Jones and Stokes Space | 330 |
| 8.2.4 | Concatenation Rules for PMD | 333 |
| 8.2.5 | PMD Evolution Equations | 338 |
| 8.2.6 | Time-Domain Representation | 342 |
| 8.2.7 | Fourier Analysis of the DGD Spectrum | 364 |
| 8.3 | Combined Effects of PMD and PDL | 371 |
| 8.3.1 | Frequency-Dependence of the Polarization State | 372 |
| 8.3.2 | Non-Orthogonality of PSP's | 374 |
| 8.3.3 | PMD and PDL Evolution Equations | 376 |
| 8.3.4 | Separation of PMD and PDL | 378 |
| | References | 381 |
| 9 | Statistical Properties of Polarization in Fiber | 385 |
| 9.1 | Polarization Evolution Model | 388 |
| 9.1.1 | Random Birefringent Orientation | 389 |
| 9.1.2 | Random Component Birefringence | 391 |
| 9.2 | Polarization Diffusion | 392 |
| 9.3 | RMS Differential-Group Delay Evolution | 397 |
| 9.4 | PMD Statistics | 399 |

| | | |
|--------------|--|------------|
| 9.4.1 | Probability Densities | 401 |
| 9.4.2 | Autocorrelation Functions | 408 |
| 9.4.3 | Mean-DGD Measurement Uncertainty | 414 |
| 9.4.4 | Discrete Waveplate Model | 417 |
| 9.4.5 | Karhunen-Loëve Expansion of Brownian Motion | 419 |
| 9.5 | PDL Statistics | 422 |
| | References | 425 |
| 10 | Review of Polarization Test and Measurement | 429 |
| 10.1 | SOP Measurement | 430 |
| 10.2 | PDL Measurement | 432 |
| 10.3 | PMD Measurement | 436 |
| 10.3.1 | Mean DGD Measurement | 438 |
| 10.3.2 | PMD Vector Measurement | 440 |
| 10.3.3 | Polarization OTDR | 450 |
| 10.4 | Programmable PMD Sources | 451 |
| 10.4.1 | Sources of DGD and Depolarization | 454 |
| 10.4.2 | ECHO Sources | 463 |
| 10.5 | Receiver Performance Validation | 478 |
| | References | 483 |
| A | Addition of Multiple Coherent Waves | 491 |
| B | Select Magnetic Field Profiles | 493 |
| | References | 496 |
| C | Efficient Calculation of PMD Spectra | 497 |
| D | Multidimensional Gaussian Deviates | 505 |
| Index | | 509 |