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# Characterization of Partially Polarized Light Fields

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# Preface

Polarization involves the vectorial nature of light. In theoretical topics and technological applications of current interest in optical science, the electromagnetic description of the light disturbance and polarization-related phenomena have turned out to be crucial. In fact, they have gained importance in recent years, attracting the attention of numerous scientists in the last decade. Photonics devices, biological optics, optical communications, atmospheric optics, and sensor technologies are examples of research areas where the vectorial features of light are relevant.

In practice, optical radiation exhibits randomness and spatial nonuniformity of the polarization state. These kinds of realistic and general situations are most frequently encountered in the literature, and drastically depart from the simplest model of harmonic plane waves. Keeping in mind the framework of classical optics, this book deals with the analytical problem of describing and characterizing the polarization and spatial structure of nonuniformly polarized fields, along with their evolution when light propagates through optical systems. This is the aim of this work.

In particular, the scope and the contents of the book are essentially focused on the contributions of the authors to four main issues, which correspond to approaching the problem under study from different angles. Thus, in Chap. 1, after a short introduction to the main standard representations of the polarization, we analyze in some detail several recently proposed measurable parameters, of practical use for characterizing, in a global way, the polarization of nonuniformly polarized beam-like fields. Chapter 2 also proposes an overall description, but now the alternative formalism allows a characterization of the polarization distribution and the shape of partially polarized, partially coherent beams. A family of measurable and meaningful parameters is defined, whose determination involves certain averages over the region of the transverse profile where the beam irradiance is significant.

On the other hand, in recent years, the coherence theory, well established for scalar beams, has been investigated with regard to partially polarized fields. It has been shown that, for stochastic electromagnetic beams, the properties concerning coherence and polarization features are, in general, connected with each other. Consequently, fundamental concepts, such as the degree of coherence and the fringe visibility in Young interferometers, should be revisited. This is done in some detail in Chap. 3.

Finally, Chap. 4 is devoted to nonparaxial electromagnetic fields, which arise when light is strongly focused and the beam reaches a waist size even smaller than the wavelength. The theoretical analysis deals with certain kinds of nonparaxial exact solutions of the Maxwell equations. Their polarization features are discussed and, in those cases in which the evanescent waves are significant (highly nonparaxial regime), their field structure is also described.

Although short surveys are provided to review some basic formalisms, the reader is assumed to be familiar with well-known concepts treated in many optics textbooks.

The research work leading to the results reported in this book have been obtained in collaboration with a number of researchers. We would like to acknowledge here their fundamental contribution. We also thank Prof. H. Weber for his interest, helpful suggestions and continuous kindness, which include support during all the experimental work described in Sect. 2.4.3 and performed at the Optisches Institut of the Technische Universität in Berlin. We are indebted to Prof. F. Gori, Dr. M. Santarsiero and Dr. R. Borghi, at the University of Rome 3, for helpful discussions concerning partially polarized Gaussian Schell-model beams. In addition, we are also grateful to Dr. M. Santarsiero and Profs. S. Bosch and A. Carnicer, at Barcelona University, for their kind reading of Chaps. 3 and 4.

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# Contents

# Notation

| Symbol | Name | First appearance in the text (Subsection) |
|---|---|---|
| $[\alpha\beta]_{ij}, i,j = s,p; \alpha,\beta = x,y,u,v$ | | 2.3.2 |
| Det | determinant of a matrix | 1.2.1 |
| $\boldsymbol{E}$ | electric field vector | 1.2.1 |
| $\tilde{\boldsymbol{E}},\tilde{\boldsymbol{H}}$ | spatial Fourier transform of $\boldsymbol{E}$ and $\boldsymbol{H}$ | 4.2.1 |
| $\boldsymbol{e}_1(\phi),\boldsymbol{e}_2(\rho,\phi)$ | | 4.2.3 |
| $\tilde{\boldsymbol{E}}_0(\rho,\phi)$ | | 4.2.1 |
| $\boldsymbol{E}_{azim}$ | azimuthally polarized field | 4.3.3 |
| $\boldsymbol{E}_{closest},\boldsymbol{H}_{closest}$ | closest electric and magnetic fields | 4.4.2 |
| $\boldsymbol{e}_{ev}(\rho,\phi)$ | | 4.5.1 |
| $\boldsymbol{E}_{pr},\boldsymbol{E}_{ev}$ | propagating and evanescent terms of $\boldsymbol{E}$ | 4.2.2 |
| $\boldsymbol{E}_R,\boldsymbol{E}_\theta$ | radial and azimuthal components of $\boldsymbol{E}$ | 1.5.1 |
| $\boldsymbol{E}_{rad}$ | radially polarized field | 4.3.2 |
| $\boldsymbol{E}_s,\boldsymbol{E}_p$ | transverse components of $\boldsymbol{E}$ | 1.2.1 |
| $\boldsymbol{E}_{TE},\boldsymbol{E}_{TM}$ | transverse-electric and transverse-magnetic terms of $\boldsymbol{E}$ | 4.2.3 |
| $\Gamma(\boldsymbol{r}_1,\boldsymbol{r}_2,\tau)$ | mutual coherence function | 1.2.2 |
| $\hat{\Gamma}(\boldsymbol{r}_1,\boldsymbol{r}_2,\tau)$ | | 1.2.2 |
| $g_{12} \equiv g(\boldsymbol{r}_1,\boldsymbol{r}_2)$ | | 3.4 |
| $\boldsymbol{H}$ | magnetic field vector | 4.2.1 |
| $\boldsymbol{H}_{TE},\boldsymbol{H}_{TM}$ | transverse-electric and transverse-magnetic terms of $\boldsymbol{H}$ | 4.2.3 |
| $h(\boldsymbol{r},\boldsymbol{\eta},z)$ | Wigner distribution function | 2.2.1 |
| $\hat{\boldsymbol{H}}(\tilde{\boldsymbol{r}},\tilde{\boldsymbol{\eta}},z)$ | Wigner matrix | 2.3.1 |
| $\hat{\mathfrak{J}}$ | Jones matrix | 1.2.1 |
| $\hat{J}(\boldsymbol{r}_1,\boldsymbol{r}_2,z)$ | coherence-polarization matrix | 1.2.2 |
| $j(\boldsymbol{r}_1,\boldsymbol{r}_2)$ | complex degree of coherence | 1.6.1 |
| $J_{sc}(\boldsymbol{r}_1,\boldsymbol{r}_2)$ | mutual intensity | 1.6.1 |
| $k$ | wavenumber | 1.2.1 |
| $K$ | Kurtosis parameter | 2.9 |
| $\lambda$ | wavelength | 1.2.1 |
| $M^2$ | beam propagation factor | 2.5 |

| Symbol | Name | First appearance in the text (Subsection) |
|---|---|---|
| $\hat{\mathcal{M}}$ | Müller matrix | 1.2.3 |
| $\mu(\boldsymbol{r}_1,\boldsymbol{r}_2)$ | spectral degree of coherence (scalar case) | 3.2.1 |
| $\mu_s$ and $\mu_I$ | intrinsic degrees of coherence | 3.3.2 |
| $\mu_{STF}^2$ | electromagnetic degree of coherence | 3.3.2 |
| $\mu_w$ | Wolf's spectral degree of coherence | 3.3.2 |
| $\tilde{P}$ | weighted degree of polarization | 1.3 |
| $P_G$ | generalized degree of polarization | 2.4.1 |
| $P(\boldsymbol{r})$ | local degree of polarization | 1.2.4 |
| $P_{st}$ | standard degree of polarization | 1.2.4 |
| $Q$ | beam quality parameter | 2.5 |
| $\tilde{\boldsymbol{r}} \equiv \boldsymbol{r}k$ | dimensionless position vector | 2.3.1 |
| $\tilde{\rho}$ | linear/circular polarization content | 1.4.1 |
| $\tilde{\rho}_R,\tilde{\rho}_\theta$ | radial and azimuthal polarization content | 1.5.1 |
| $\boldsymbol{S}$ | Stokes vector | 1.2.3 |
| $\boldsymbol{s}(\rho,\phi)$ | | 4.2.3 |
| $\boldsymbol{s}_{ev}(\rho,\phi)$ | | 4.5.1 |
| $s_i, i = 0,1,2,3$ | Stokes parameters | 1.2.3 |
| $\hat{S}_i, i = 0,1,2,3$ | Stokes matrices | 2.3.2 |
| $\hat{\sigma}_i, i = 0,1,2,3$ | Pauli matrices | 1.2.1 |
| $\tilde{\sigma}_p$ | variance associated to $\tilde{P}$ | 1.3 |
| $\sigma_\rho$ | variance associated to $\tilde{\rho}$ | 1.4.1 |
| $\sigma_R,\sigma_\theta$ | variance associated to $\tilde{\rho}_R,\tilde{\rho}_\theta$ | 1.5.1 |
| $\langle\cdot\rangle_t$ | temporal average | 1.2.2 |
| Tr | trace of a matrix | 1.2.1 |
| $\boldsymbol{u}_R,\boldsymbol{u}_\theta$ | radial and azimuthal unitary vector | 1.5.1 |
| $\mathcal{V}$ | visibility | 3.2.2 |
| $\omega$ | angular frequency | 1.2.1 |
| $W(\boldsymbol{r}_1,\boldsymbol{r}_2)$ | cross-spectral density function | 2.1 |
| $\hat{W}(\boldsymbol{r}_1,\boldsymbol{r}_2)$ | cross-spectral density matrix | 2.3.1 |
| $\langle x^m y^n u^p v^q \rangle$ | beam irradiance moments | 2.2.1 |
| $\hat{\zeta}_i, i = 0,1,2,3$ | | 2.3.4 |
| $z_R$ | Rayleigh length | 2.7 |

# List of Acronyms

| Acronym | Name |
|---|---|
| APF | azimuthally polarized field |
| APP | anisotropic pure phase plate |
| BCP matrix | beam coherence-polarization matrix |
| CDT | cross-spectral density tensor |
| CSD | cross-spectral density |
| GSM field | Gaussian Schell-model field |
| MSC field | mean-square coherent field |
| MZT system | Mach-Zehnder-type system |
| NP field | nonpolarized field |
| NUPP field | nonuniformly partially polarized field |
| NUTP field | nonuniformly totally polarized field |
| PGSM field | partially polarized Gaussian Schell-model field |
| RPF | radially polarized field |
| RPM field | radially-polarized-maintained field |
| SA | spherical aberration |
| SDC | spectral degree of coherence |
| SDT | spectral density tensor |
| SPE | spiral phase element |
| SUPA system | spatially-uniform polarization altering system |
| UP field | uniformly polarized field |
| UPP field | uniformly partially polarized field |
| UTP field | uniformly totally polarized field |
| WDF | Wigner distribution function |