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Chapter 9

Defining Polarization

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Defining Polarization

Command Mnemonics
(alphabetical)

BIR	CAD	CAO	DEL NEO	DEL POP	JXM
JYM	JXP	JYP	NEO	PFR	POL
POP	POR	PRO	PST	PTP	RVT
ST1	ST2	ST3	UMC	UMF	UMO
UMR					

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Activating Polarization Ray Tracing

Command Mnemonics
(alphabetical)

POL RVT

Command Summary

To activate polarization ray tracing, choose the **Lens** > **System Data** menu, and click **Polarization** in the **System Data** window's navigation tree. This displays the polarization page. Define the controls on this page as described in the table below.

Command Syntax		
Screen Control	**Explanation**	**Default**
POL Yes | No		
Activate Polarization Ray Tracing	Activates or deactivates the polarization ray tracing for options or commands that incorporate polarization information. Select this checkbox (POL Yes) to activate the polarization calculations, or leave de-selected (POL No) to disable them. The status of this command is stored in the LEN file when the lens is saved. **Note:** POL affects AUT, RSI, SIN, the options MTF, PSF, LSF, PMA, PAR; polarization ray tracing is always active in TRA. The effect of birefringent material on the geometrical optical path of the extraordinary ray through the optical system is taken into account in the FIE, SPO, TOR, and VIE options if the BIR EXT command is issued. The ray trace is performed for the ordinary ray if the BIR ORD command is issued.	No.
RVT Yes | No		
Define Polarization State at Final Surface	Defines polarization state at the final surface in the lens model rather than the object surface. Use in conjunction with **Activate Polarization Ray Tracing** (POL Yes) if your model is set up from the receiver to a polarized source. Note that this setting has no effect if polarization ray tracing is not enabled (POL No). The input polarization state associated with a particular field point is used as input at the image surface. The transmission characteristics of the optical system components for polarized light are determined from the reverse ray trace as the polarized light propagates from the image surface to the object surface. This feature is operable in computations that employ polarization ray tracing to calculate transmission along a ray path. In this case, the illumination distribution is calculated on the object surface. It is applicable to the LUM and TRA options, the RSI and SIN commands at the LDM level, and the RAYRSI, RAYSIN, and RAYTRA predefined Macro-PLUS functions. **Note:** The polarization information is given on the object surface if RVT Yes, and on the image surface if RVT No, for the POLGRID and RAYPOL Macro-PLUS functions.	No.

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Tip: You can also select or de-select **Activate Polarization Ray Tracing** in the **Lens** menu.

Specifying the Polarization State - Source Model

Command Mnemonics
(alphabetical)

PST

Command Summary

To specify the polarization source model, choose the **Lens** > **System Data** menu, and click **Polarization** in the **System Data** window's navigation tree. This displays the polarization page. Define the controls in the **Polarization Source** area as described in the table below.

Command Syntax		
Screen Control	**Explanation**	**Default**
PST IDL | DIP		
Polarization Source	Specify polarization source type: **Dipole** source (DIP) **Ideal Lens Model** (IDL)	Ideal Lens Model (IDL)

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Specifying the Polarization State - Polarization Coordinate System

Command Mnemonics
(alphabetical)

PCS

Command Summary

To specify the polarization coordinate system, choose the **Lens** > **System Data** menu, and click **Polarization** in the **System Data** window's navigation tree. This displays the polarization page. Define the controls in the **Polarization Coordinate System** area as described in the table below.

Command Syntax		
Screen Control	**Explanation**	**Default**
PCS STD | COL		
Polarization Coordinate System	Specify polarization coordinate system: **Standard** (STD) – Uses the standard polarization coordinate system, defined by making the X axis perpendicular to the plane that contains the ray direction and a line segment parallel to the Y axis of the surface coordinate system. The Y axis for the standard polarization coordinate system is determined to be in the plane containing the ray direction and a line parallel to the Y axis of the surface coordinate system. **Collimated Beam** (COL) – Describes the polarization state of a diverging or converging beam as though it were collimated. This is done by treating the beam as if it had passed through a collimating lens that is perpendicular to the Z-axis. For this (imaginary) collimated bundle, the polarization state of each ray is described in the X-Y coordinate system of the surface.	COL

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Specifying the Polarization State - Geometrical Representation

Command Mnemonics
(alphabetical)

PFR POR PRO PTP

Command Summary

To specify the polarization state as geometrical, choose the **Lens** > **System Data** menu, and click **Polarization** in the **System Data** window's navigation tree. This displays the polarization page. In the **Polarization State Description** area, select **Geometrical**. Define the controls in the spreadsheet on the polarization page as described in the table below.

Command Syntax		
Screen Control	**Explanation**	**Default**
PFR fraction_of_polarization....f [,z]		
Polarized Fraction	Gives the ratio of the intensity of the polarized portion of the light to the total intensity. Controls the degree of polarization for partially polarized beams. **Range:** 0.0 (unpolarized) to 1.0 (completely polarized).	0.0 (unpolarized).
PTP LIN | CIR or **PTP** ratio....f [,z]		
Major/Minor Axis Ratio	Defines the polarization type (for that portion of the beam that is polarized) as the ratio of the intensity of the minor axis component to the intensity of the major axis component for elliptically polarized light. The two extreme special cases are LIN (equivalent to ratio=0.0) and CIR (equivalent to ratio=1.0). The value of ratio must be between 0.0 and 1.0.	0.0 (LIN).
POR orientation_angle_degr....f [,z]		
Orientation (Deg)	Defines the orientation of the major axis of the polarization ellipse with respect to the Y' axis. (The Y' axis is an axis that is perpendicular to the ray and lies in a plane that contains the ray and a line parallel to the Y axis of the entrance pupil.) The orientation is positive if, when viewing the along the ray "from behind," a clockwise rotation of the Y' axis will move it toward the major axis of the ellipse. The value assigned to the orientation has no effect if the light is circularly polarized.	0.0
PRO LT | RT....f [,z]		
Handedness	Defines the "handedness" of the elliptically polarized beam (i.e., the direction of rotation of the field vector). LT indicates left-handed rotation and RT indicates right-handed rotation. Right-handed means that the field vector rotates clockwise when viewed as the ray approaches the observer. The handedness value has no effect if the light from this field point was defined to be linearly polarized (i.e., PTP LIN).	

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Specifying the Polarization State - Jones Vector Representation

Command Mnemonics
(alphabetical)

JXM JXP JYM JYP

Command Summary

To specify the polarization state using the Jones vector, choose the **Lens** > **System Data** menu, and click **Polarization** in the **System Data** window's navigation tree. This displays the polarization page. In the **Polarization State Description** area, select **Jones Vector**. Define the controls in the spreadsheet on the polarization page as described in the table below.

Command Syntax		
Screen Control	**Explanation**	**Default**
JXM magn_of_x_comp....f [,z]		
Magnitude X	Specifies magnitude of X component of Jones field vector. **Range:** 0 to +1. If both JXM and JYM are zero, the default Jones vector (JXM 0; JYM 1; JXP 0; JYP 0) is set for all fields and zoom positions with the illegal state.	0
JYM magn_of_y_comp....f [,z]		
Magnitude Y	Specifies magnitude of Y component of Jones field vector. **Range:** 0 to +1. If both JXM and JYM are zero, the default Jones vector (JXM 0; JYM 1; JXP 0; JYP 0) is set for all fields and zoom positions with the illegal state.	1
JXP magn_of_x_comp....f [,z]		
Phase X (Deg)	Specifies phase of X component of Jones field vector, in degrees. **Range:** 0 to 180.	0
JYP magn_of_y_comp....f [,z]		
Phase Y (Deg)	Specifies phase of Y component of Jones field vector, in degrees. **Range:** 0 to 180.	0

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Specifying the Polarization State - Stokes Parameters Representation

Command Mnemonics
(alphabetical)

ST1 ST2 ST3

Command Summary

To specify the polarization state using Stokes parameters, choose the **Lens** > **System Data** menu, and click **Polarization** in the System Data window's navigation tree. This displays the polarization page. In the **Polarization State Description** area, select **Stokes Parameter**. Define the controls in the spreadsheet on the polarization page as described in the table below.

Command Syntax		
Screen Control	**Explanation**	**Default**
ST1 Stokes_param_s1....f [,z]		
S1: Horizontal-Vertical	Specifies first Stokes parameter (difference between horizontal and vertical intensity components). **Range:** -1 to +1. The root sum square (RSS) of the three Stokes parameters is the fraction of light polarized. This can vary from 0 to 1.0; if greater than 1.0 the three Stokes parameters will be normalized to an RSS of 1.0, maintaining their ratios.	0
ST2 Stokes_param_s2....f [,z]		
S2: 135-45 Degree	Specifies second Stokes parameter (difference between 135° oriented and 45° oriented intensity components). **Range:** -1 to +1. The RSS of the three Stokes parameters is the fraction of light polarized. This can vary from 0 to 1.0; if greater than 1.0 the three Stokes parameters will be normalized to an RSS of 1.0, maintaining their ratios.	0
ST3 Stokes_param_s3....f [,z]		
S3: Right-Left	Specifies third Stokes parameter (difference between right circularly polarized and left circularly polarized intensity components). **Range:** -1 to +1. The RSS of the three Stokes parameters is the fraction of light polarized. This can vary from 0 to 1.0; if greater than 1.0 the three Stokes parameters will be normalized to an RSS of 1.0, maintaining their ratios.	0

The **S0: Polarization Fraction** field is a display-only field that shows the total intensity of the polarized part of the beam, which is always normalized in CODE V to 1.0. See "Stokes Parameter Representation" on page 9-19 for more information.

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Assigning Polarization Operators to a Surface

Command Mnemonics
(alphabetical)

DEL POP   POP   UMC   UMF   UMO   UMR

Command Summary

To assign a polarization operator to a surface (such as a linear polarizer or ideal retarder), choose the **Lens** > **Surface Properties** menu, and click **Polarization Operator** in the **Surface Properties** window's navigation tree. Define the controls on this page as described in the table below.

Command Syntax	
Screen Control	**Explanation**
POP Sk | Si..j FAR [rotation_degrees]	
Faraday Rotator	Assigns a Faraday rotator to the selected surface (Sk), with the polarization rotated by the number of degrees specified in the **Angle** field (rotation_degrees). The default rotation is 45 degrees. Note that a positive angle specified with rotation_degrees is clockwise when looking along the positive Z axis.
POP Sk | Si..j LIN [attenuation_factor]	
Linear Polarizer/ Attenuation Factor	Assigns an ideal linear polarizer to the selected surface (Sk). This polarizer has its transmitting axis aligned with the Y axis of the local coordinate system for the selected surface. All of the light that is polarized in the direction of the transmitting axis will be passed by this element. The orthogonal polarization component (X) will have its intensity reduced by the attenuation_factor; default attenuation_factor is 1.0 (full attenuation). **Range:** 0.0 (no attenuation/polarization) to 1.0 (full attenuation/polarization). (The attenuation_factor is defined as 1.0-intensity_transmittance, so that a value of 1.0 implies that the "X-polarized light" is completely attenuated). Use CDE command to rotate transmitting axis of linear polarizer. To model the behavior of a typical sheet polarizer, place a POP LIN operator on the back surface of a thin sheet with the appropriate refractive index. For details, see "Modeling of Linear Polarizers, Retarders, Faraday Rotators and Generalized Polarization Devices: Characterization" on page 9-24
POP Sk | Si..j RET [retardation_waves]	
Ideal Retarder/ Retardation (Waves)	Assigns an ideal retarder to the selected surface (Sk). This retarder has its "fast" axis aligned with the Y axis of the local coordinate system for the selected surface. The light polarized in the direction of the fast axis will be unaltered by the retarder. The orthogonal polarization component will have its phase retarded by an amount retardation_waves; default retardation_waves is 0.25 (quarter-wave retarder). Use CDE command to rotate fast axis of retarder.

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Command Syntax	
Screen Control	**Explanation**
POP Sk | Si..j JMX	
Jones Matrix	Assigns a unit Jones matrix to the selected surface (Sk). This command deletes any coatings currently defined on the surface and is equivalent to a perfect refractive coating. The default Jones matrix is: $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ For reflective optical elements, the Jones matrix is: $\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$
JR1 | JR2 | JR3 | JR4 Sk value	
J11/Real **J12/Real** **J21/Real** **J22/Real**	Defines the four real components of the Jones matrix, assuming the POP Sk JMX command has been entered. $\begin{bmatrix} JR1 & JR2 \\ JR3 & JR4 \end{bmatrix}$
JI1 | JI2 | JI3 | JI4 Sk value	
J11/Imaginary **J12/Imaginary** **J21/Imaginary** **J22/Imaginary**	Defines the four imaginary components of the Jones matrix, assuming the POP Sk JMX command has been entered. $\begin{bmatrix} JI1 & JI2 \\ JI3 & JI4 \end{bmatrix}$
GUI command only.	
Perfect Refractive Coating	For Jones matrix only. Applies a perfect refractive coating to the selected surface by changing the J11 and J21 components of the Jones matrix to 1. This button is disabled if the J11 and J21 components are 1, and all other components are 0.
POP Sk USP	
User Defined	Assigns a user-defined surface properties subroutine to the selected surface (Sk). For more details about user-defined surface properties subroutines, including implementation instructions, go to "Implementing User-Defined Surface Properties" on page 1-141.
UMR Sk USP name	
User Defined Function Name	Specifies the user-defined surface properties subroutine or macro function (*name*) to be applied to the selected surface (Sk).
UMF Sk USP name	
External Data File	Specifies a data file (*name*) to be read by the user-defined surface properties subroutine on the selected surface (Sk).

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Command Syntax	
Screen Control	**Explanation**
UMN Sk USP number_of_coefficients	
Coefficient Count	Set the number of coefficients for the user-defined surface properties subroutine on the selected surface (Sk). By default, this number is set to 100. If number_of_coefficients is greater than the current number of coefficients, then the new coefficients are allocated and initialized to zero, with their coupling codes set to 100 (frozen). If the number is less than the current number of coefficients, then the coefficient values greater than number_of_coefficients will be deleted.
UMO USP Sk Cj value [....z]	
Coefficient/Value	Specifies coefficient(s) (Cj and value) associated with the user-defined surface properties subroutine on the selected surface (Sk).
UMC USP Sk Cj coupling_code [....z]	
Coupling Code	Vary/freeze/couple the coefficient value (Cj) for the user-defined surface properties subroutine for the designated surface (Sk). Coupling code values are: **Variable** (0) **Frozen** (100) Or enter the number of the coupling group: 1 to 99 – Couple coefficient to any other with the same num_of_coupling_grp, + or -. In the GUI, the controls for entering coupling codes are located in the **Coupling Editor**. To access this dialog box, right-click on the coefficient value in the **Surface Properties** window and select **Couple Parameter** from the shortcut menu. For more details about coupling codes, go to “Defining Variables and Control Codes” on page 12-3.
DEL POP Sk | Si..j	
No Polarizer	Deletes the ideal polarizer or retarder at surface(s) Sk|Si..j.

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Defining Pseudo-Birefringent Materials

Command Mnemonics
(alphabetical)

BIR   CAD   CAO   DEL NEO   NEO

Command Summary

To define pseudo-birefringent materials, choose the **Lens** > **Surface Properties** menu, and click **Birefringent Materials** in the **Surface Properties** window's navigation tree. Define the controls in the **Birefringent Material Index Difference**, **Crystal Axis Orientation**, and **Ray Tracing for Birefringent Material** areas on this page as described in the table below.

Command Syntax		
Screen Control	**Explanation**	**Default**
NEO [UNI | CUB] Sk index_difference....w		
Birefringent Material Index Difference: **Uniaxial/Cubic**	Specifies value of N_e-N_o for material following the surface; can be positive or negative. In the GUI, the **Uniaxial** field (UNI qualifier) specifies modeling of uniaxial crystals; the **Cubic** field (CUB qualifier) specifies modeling of intrinsic birefringence of cubic crystals. For uniaxial birefringent crystals, a positive *index_difference* specifies that the fast axis is orthogonal to the crystal axis. A negative value specifies that the fast axis is along the crystal axis. For cubic crystals, a positive *index_difference* specifies that the extraordinary ray (e-ray) corresponds to the higher index mode. A negative value (used for CaF_2) specifies that the e-ray corresponds to the lower index mode.	Not applied.
CAO Sk axis_orientation_degr		
Orientation Angle in XY Plane	Specifies angle (in degrees) between crystal axis and surface Y axis. Can also be specified with **Direction Numbers**: **X/Alpha**, **Y/Beta**, and **Z/Gamma** fields (CAD command).	0.0

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Command Syntax		
Screen Control	**Explanation**	**Default**
CAD [UNI] Sk x_dir_num y_dir_num z_dir_num **CAD CUB** Sk ly_dir my_dir ny_dir lz_dir mz_dir nz_dir		
Direction Numbers: **X/Alpha** **Y/Beta** **Z/Gamma** **Y and Z Cubic Crystal Axis Orientations:** **Y/Alpha** **Y/Beta** **Y/Gamma** **Z/Alpha** **Z/Beta** **Z/Gamma**	Specify crystal axis orientation by direction numbers. Range: -1 to 1. For uniaxial birefringent crystals, use the **Direction Numbers** fields to specify the orientation of the crystal axis (on the command line, use the CAD UNI form). The direction numbers do not need to be normalized. Can also be specified with Orientation Angle in XY Plane (CAO command). For cubic crystal intrinsic birefringence, use the **Y and Z Cubic Crystal Axis Orientation** fields (or CAD CUB command) to specify the orientation. To align the crystal axes so that the [100] direction is along the z-axis, use these values (shown here with the CAD CUB command): CAD CUB Sk 0 1 0 -1 0 0 To orient the crystal so that the Z-axis of the lens corresponds to the [110] direction in the crystal, use: CAD CUB Sk 1 0 1 0 1 0 To orient the crystal so that the Z-axis of the lens corresponds to the [111] direction in the crystal, use: CAD CUB Sk (-1/sqrtf(2)) (1/sqrtf(6)) (1/sqrtf(3)) 0 (-sqrtf(2/3)) (1/sqrtf(3)) You can enter the expressions shown above in the **Y and Z Cubic Crystal Axis Orientation** fields by preceding them with an = sign. For example, you would enter the following: =(-1/sqrtf(2)) **Note:** The XYZ coordinate system that CODE V uses is right-handed.	CAO 0.0

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Command Syntax		
Screen Control	**Explanation**	**Default**
BIR Sk EXT | ORD | AVE | AVO | ORO | EXO [….z]		
Ray Tracing for Birefringent Material: **Ordinary Ray** **Extraordinary Ray** **Average Index along Extraordinary Ray** **Average Index along Ordinary Ray** **Ordinary Ray - Ignore Extraordinary Component** **Extraordinary Ray - Ignore Ordinary Component**	For both uniaxial and cubic birefringent materials, specifies the ray trace mode: • **Ordinary Ray** (BIR ORD) traces the ordinary ray. • **Extraordinary Ray** (BIR EXT) traces the extraordinary ray. • **Average Index along Extraordinary Ray** (BIR AVE) traces the extraordinary ray, and the geometrical optical path for the ordinary ray is computed using the average of the extraordinary and ordinary refractive indices. • **Average Index along Ordinary Ray** (BIR AVO) traces the ordinary ray, and the geometrical optical path for the extraordinary ray is computed using the average of the extraordinary and ordinary refractive indices. Note for BIR ORD, BIR EXT, BIR AVE, and BIR AVO: For the ray that is not traced, the effect of birefringent material on the geometrical optical path of the other ray through the optical system is taken into account in all CODE V options that trace rays (i.e., phase difference is accounted for). • **Ordinary Ray - Ignore Extraordinary Component** (BIR ORO) traces the ordinary ray and eliminates the extraordinary field component; i.e., the component of the field in the extraordinary mode direction is set to zero. • **Extraordinary Ray - Ignore Ordinary Component** (BIR EXO) traces the extraordinary ray and eliminates the ordinary field component; i.e., the component of the field in the ordinary mode direction is set to zero. For cubic crystals, the e-ray corresponds to either the higher or lower index mode, depending on whether the **Index Difference** (NEO command) is positive or negative.	BIR ORD
DEL NEO Sk | Si..j		
Delete Birefringent Properties	Deletes all birefringent data on designated surfaces. On the command line, the UNI qualifier deletes only the uniaxial birefringence; the CUB qualifier deletes only the intrinsic birefringence. In the GUI, the **Delete Birefringent Properties** button deletes both uniaxial and intrinsic birefringence data defined in the **Surface Properties** window.	

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Polarization - Usage

Introduction

Much optical design work can be conducted using a strictly geometrical optics model of light. In this model, light propagates along trajectories called rays, and the primary measures of image quality are related to the ray aberrations, i.e., to the deviations of the ray on the image surface from the "ideal" ray position. For some systems, the effects of diffraction on image quality are important and the geometrical optics model must be extended. This can be done by introducing the concept of a geometrical optics wavefront, a surface that is orthogonal to the rays, with equal optical path along the rays from the object point to the wavefront. For the purpose of computing point-spread functions and MTFs, it is usually sufficient to assume that this geometrical wavefront is clipped by a single (possibly vignetted) aperture, the exit pupil, and then to perform a scalar diffraction calculation to account for the propagation from this exit pupil to the image plane. Similarly, there are instances in optical design or analysis when one must take into account the vector nature of light waves. The polarization ray tracing in CODE V is an extension of the geometrical optics model that is sufficiently accurate to allow this extended model to predict many of the features that are due to the vector nature of light waves. The basic model is still that of geometrical optics: light travels along paths called rays. However, vector properties such as polarization state are assigned to these rays, and interactions at surfaces in the optical system alter these vector properties. A fairly thorough exposition of this extension of geometrical optics to include polarization properties of the field can be found in Chapter 3 of the text Born and Wolf, *Principles of Optics* (Pergamon Press, New York, 5th ed., 1975).

A reasonably complete introductory treatment of polarization can be found in most optics texts, and you should consult these texts for a more complete account (see Eugene Hecht and Alfred Zajac, *Optics,* Addison-Wesley, MA 1974; and Francis A. Jenkins and Harvey E. White, *Fundamentals of Optics*, McGraw-Hill, NY 1950). It will be assumed that you have an understanding of the basic concepts of polarized light, including an understanding of the meaning of the following terms: linearly, circularly and elliptically polarized light, partially polarized and unpolarized light and orthogonal polarization states. The treatment that is given here is intended to deal only with those topics that are essential to an understanding of how polarization is handled in CODE V.

You may find, after evaluating the polarization effects in your system, that these effects are unacceptably large. If this is the case, then you must understand how these effects can be reduced without making drastic alterations to the basic design. In many instances the problem can be eliminated by proper specification of multilayer coatings. The technique of polarization aberration "balancing" is one approach that can be helpful in specifying coatings (see R. A. Chipman, *Polarization Aberrations*, Ph.D. Dissertation, Optical Sciences, University of Arizona (1987); and J. P. McGuire, Jr. and R. A. Chipman, "Polarization Aberrations in the SAMEX Solar Vector Magnetograph," *SPIE Proc.* 891 (1988).

Polarization Ray Tracing

Polarization ray tracing is a unification of geometrical ray tracing and thin film matrix theory. Normally, optical systems are modeled as sequences of surfaces separated by refractive media. A polarization ray trace models an optical system as sequences of refractive media separated by optical interfaces. These interfaces can be uncoated air-glass interfaces, single layer coatings, or multilayer coatings, and the coatings may be dispersive and/or absorptive. In addition to the surface interfaces, a polarization operator (e.g, polarizer, retarder, etc.) may be attached to the surface. Geometrical ray tracing is performed between the interfaces (from surface to surface), and then at each surface interface, thin film matrix calculations are performed to compute the changes in the light's amplitude, phase, and polarization state, including the effects of any polarization operators attached to the surface.

The basic objective of the polarization ray trace is to supplement the geometrical ray trace by providing polarization information not available from a general geometrical ray trace. This polarization ray trace allows the propagation of polarization states through the optical system (propagation of polarization vectors) and allows determination of the polarization properties of the ray paths (polarization matrices relating input and output polarization vectors).

The output of the polarization ray trace is used in RSI and SIN ray tracing of single rays, as well as in various CODE V options (see “Use of Polarization Ray Trace Information by CODE V” on page 9-27). In addition, there are several macros written to supplement the standard CODE V polarization ray trace output. These macros, written by the Physics Department of the University of Alabama in Huntsville, are described in “Polarization Analysis Macros” on page 25D-40.

Defining the Input Polarization

Polarization State

To perform polarization calculations during the ray trace, the polarization state of the input beam must be specified, including the percentage of the light which is polarized as well as the magnitudes, phases, etc., of the light. There are three ways in CODE V you can specify the polarization state of the input beam: Jones vectors, Stokes parameters, or a geometrical representation. Each of these representations has different parameters to describe the polarization state and there are defaults for the inputs (although the default state for each representation is different). You can specify the polarization state independently for each field and zoom position, but you must use the same representation type for all fields and zoom positions; mixing of the representations across fields or zooms is not allowed.

You can apply the CODE V polarization model to partially polarized beams, since a partially polarized beam can be decomposed into a sum of a polarized component and an independent (statistically uncorrelated) unpolarized component. Either the CODE V geometrical parameter representation or the Stokes parameter representation can be used for unpolarized or partially polarized beams; the polarization state specified then only applies to the polarized portion of the light. The Jones vector representation assumes the light is 100% polarized. The default case when polarization ray tracing is enabled but no polarization parameters are defined is unpolarized light.

Geometrical Representation (Polarization Ellipse)

The geometrical description of a partially polarized beam used by CODE V describes the polarization in terms of the polarization ellipse and the degree of polarization. A single number (PFR, polarized fraction) specifies the degree of polarization as the ratio of the intensity of the polarized component of the beam to the total intensity of the beam. This ratio will range from 0 (unpolarized) to 1 (completely polarized); the default is 0.

The polarized component of the input beam is described by three additional parameters defining the polarization ellipse. Any polarized beam can be described in terms of its polarization ellipse; both linear and circular polarization are special cases of the more general case of elliptical polarization. The first parameter is PTP (polarization type), which is CIR for circular, LIN for linear, or a number between 0 and 1 representing the ratio of the intensity along the ellipse minor axis to the intensity along the ellipse major axis (1.0 corresponds to CIR, 0.0 corresponds to LIN). The second parameter is POR (polarization orientation), which is the orientation of the ellipse major axis with respect to the polarization Y' axis (see the section on Polarization Coordinate System); the default is 0, meaning initially oriented along the polarization Y' axis. The third parameter is PRO (polarization rotation), which is the direction of rotation of the electric field vector around the ellipse as time progresses (the “handedness”). This is either RT (right) or LT (left); for linear polarization it does not matter which is used (default is RT).

Figure 1 shows a description of the geometrical representation of the input state. Shown is a beam with 70% ellipticity (**PTP** 0.7), with the major axis rotated -20° from the Y axis (**POR** 20), and right handed (**PRO** RT). Note that the field amplitudes are shown; the intensities along each axis are the squares of the amplitudes. This diagram could describe the polarization state of the polarized component for any degree of polarization (PFR ranging from 0 to 1).

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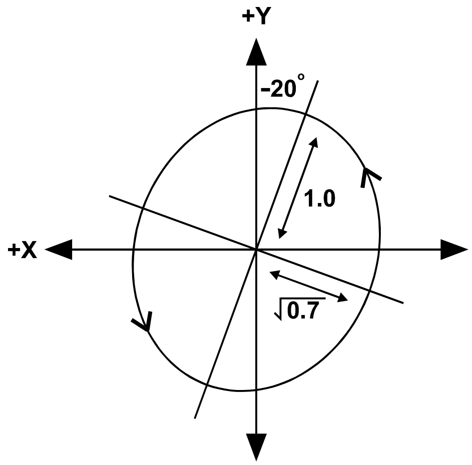

Figure 1. Example of a polarization state defined with geometrical parameters

The default polarization output for RSI or SIN single ray tracing is given in terms of the geometrical parameters PFR, PTP, POR and PRO; this is described in “Use of Polarization Ray Trace Information by CODE V” on page 9-27.

Jones Vector Representation

The Jones vector is a 2 element complex vector directly related to the electric field vector. The two elements are the complex X and Y field vector components; these are entered in CODE V as the magnitude and phase for each component (JXM, JXP and JYM, JYP), with the phase entered in degrees. In practice, only the phase difference is important; one of the phases can usually be set to 0 with the other phase then being the phase difference between the two components.

The magnitudes JXM and JYM range from 0 to +1 and represent electric field amplitudes (not intensities). To specify a negative field amplitude, use the positive value with a phase of 180°. The total intensity in the beam is the sum of the squares of these two amplitudes; this sum is normalized, if necessary. For example, an entry of JXM 0.1 and JYM 0.2 will result in X' and Y' intensities of PXI = 0.2 and PYI = 0.8 (the ratio of the intensities is the square of the ratio of the field amplitudes, and the sum of the intensities is unity). If both JXM and JYM are 0, this is considered an error; a warning is made and the default Jones vector (JXM 0; JYM 1; JXP 0; JYP 0) is specified for all fields and zoom positions for which the error state was entered.

The CODE V Jones vector equivalent of the polarization state shown in Figure 1 is

JXM 0.65758; JYM 0.75339; JYP 96.5739; JXP 0.

Even if the input polarization state is described with Jones vectors, the ray trace output (specified by ROF JNS) is described at each surface in terms of the Jones matrix, which relates the input Jones vector to the output Jones vector at each surface. Note that the Jones matrix listed at a surface is the cumulative Jones matrix along the ray path from the object surface to the current surface. To get the actual Jones vector at each surface, use the macro JVEC (see “Polarization Analysis Macros” on page 25D-40).

The assumed time dependence of a monochromatic electric field is not usually important in optical design or analysis work. However, when dealing with Jones vectors and Jones matrices, it is necessary to know what the assumed time dependence is. CODE V assumes that the electric field varies as Exp(+i ω t). This time dependence is different from that assumed in several optics textbooks, including “Principles of Optics,” by Born & Wolf. The choice of sign on the time dependence of the electric field affects the sign of the phase of

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the Jones vector. In CODE V, right circular light has a Jones vector specified by: JXM = $1/(\sqrt{2})$, JYM = $1/(\sqrt{2})$, JXP = 0, JYP = +90. If using the convention of Born & Wolf, the JYP value for right circular light would be JYP -90.

Stokes Parameter Representation

The Stokes parameters are useful for modeling the results of experimental work, as they are based on intensity measurements. They are based on the intensities I_H, I_V, I_{45}, I_{135}, I_R, and I_L, which are the intensities transmitted through horizontal, vertical, 45° oriented, 135° oriented, right-hand circular, and left-hand circular polarizers, respectively.

There are four Stokes parameters, S_0, S_1, S_2, and S_3 (sometimes referred to as the four components of the Stokes vector), defined as follows:

$$S_0 = I = I_H + I_V = I_{45} + I_{135} = I_R + I_L$$

$$S_1 = I_H - I_V$$

$$S_2 = I_{135} - I_{45}$$

$$S_3 = I_R - I_L$$

All the parameters are real numbers (not complex). S_0 is the total intensity, S_1 is the preference for horizontal over vertical polarization, etc. The degree of polarization (ratio of polarized light to total light) is given by

$$\text{Degree of polarization} = \sqrt{\frac{S_1^2 + S_2^2 + S_3^2}{S_0^2}}$$

In CODE V, the Stokes parameter S_0 is always set to be initially 1.0 (normalized total intensity); thus the polarization state of the input beam is specified by the parameters S_1, S_2, and S_3, input with the commands ST1, ST2, and ST3. The total intensity of the polarized part of the beam is then the RSS of these three parameters. If all three are 0, the light is unpolarized. If the RSS of these three parameters exceeds 1.0, the parameters are normalized such that the ratios are maintained but the RSS equals unity (completely polarized light).

The CODE V Stokes parameter equivalent for the polarization state shown in Figure 1 are ST1 -0.13518; ST2 -0.11343; ST3 0.98431.

Even if the input polarization state is defined by Stokes parameters, there is no direct Stokes parameter ray trace output at each surface. To get Stokes parameter output at each surface, use the macro SVEC (see “Polarization Analysis Macros” on page 25D-40). The macro MMTAB will tabulate the Mueller matrices at each surface; these matrices relate the input Stokes vector to the output Stokes vector at each surface.

Examples of the three different types of polarization state descriptors, geometrical, Jones vector, and Stokes parameters, are given in Table 1 for typical input states.

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Table 1. Typical input polarization states in different polarization representations

Model	Param.	Unpol.	Y-Pol.	X-Pol.	45° Pol.	RH Circ.	LH Circ.
Geometrical	PFR	0	1	1	1	1	1
Parameters	PTP	LIN or CIR	LIN	LIN	LIN	CIR	CIR
	POR	0	0	±90	45	0	0
	PRO	RT or LT	RT or LT	RT or LT	RT or LT	RT	LT
Jones	JXM*	N/A	0	1	0.7071	0.7071	0.7071
Vector	JYM*(	N/A	1	0	0.7071	0.7071	0.7071
	JXP	N/A	0	0	180	0	0
	JYP	N/A	0	0	0	90	-90
Stokes	ST1	0	-1	1	0	0	0
Parameters	ST2	0	0	0	-1	0	0
	ST3	0	0	0	0	1	-1

* Note that the values of JXP and JYP are not themselves physically meaningful; only the *difference* between them is physically meaningful.

Polarization Coordinate System

The electric field associated with a ray is represented as a vector that exists in a 3D coordinate system. However, the electric field must be perpendicular to the direction of propagation of the ray. If you use a coordinate system that has its Z-axis along the ray direction, then the electric field is constrained to lie in the X-Y plane, and this allows the field to be represented as a 2D vector in such a special coordinate system. We refer to such a coordinate system as a polarization coordinate system. The axes of the polarization coordinate system are referred to as the X', Y' and Z' axes. Because the electric field is a 2D vector in a polarization coordinate system, it can be represented with a Jones vector, Stokes parameters, or geometrical descriptors. There are many possible choices for a polarization coordinate system; the only requirement is that the Z' axis must be along the ray. CODE V uses two coordinate systems for polarization ray trace output.

The standard polarization coordinate system (PCS STD) is defined for a specific ray at a specific surface. The origin of the coordinate system is at the point where the ray intersects the surface. The Z' axis is along the ray (in the direction the ray is traveling) with the X'-Y' plane perpendicular to the ray. The Y' axis is perpendicular to the Z' axis and in a plane containing the Z' axis (the ray) and a line parallel to the surface local Y axis. The X' axis is perpendicular to both the Y' and Z' axes, making a right-handed coordinate system.

The standard polarization coordinate system is useful for slow beams, because the ray directions do not vary significantly and the polarization coordinate systems associated with the individual rays are similarly oriented. For fast beams, however, the ray directions do vary significantly. This means that the standard polarization coordinate system associated with a specific ray may have its Z' axis in a substantially different direction than the Z' axis for another ray in the bundle. Thus, although you can specify the polarization state for each ray, it is often difficult to visualize the relationship between the electric field associated with one ray in the bundle and the electric field associated with another ray in the bundle. For these reasons, the collimated coordinate system is available for representing polarization output.

The collimated coordinate system, the default in CODE V, is specified by the command PCS COL. This coordinate system is based on transforming the rays in a bundle into a collimated beam before representing the polarization state. This transformation is strictly an artifice useful for visualization; in actuality, the rays are not transformed, and the ray trace is not affected by the use of this polarization coordinate system for representing polarization output. The details of the collimated representation for an arbitrary ray are as follows: For a ray traveling in an arbitrary direction, imagine an interface that refracts (or reflects) the ray so that it travels parallel to the Z-axis of the surface. If you imagine a decomposition of the incident field into S and P components (S is perpendicular to the plane of incidence, P is in the plane of incidence), this imaginary interface will have a unit transmission for both the S and P components. Imagine that such an interface exists for every ray in the bundle. After passing through such an interface, the bundle is collimated and travelling

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parallel to the Z axis. In this imaginary region, all rays have a common direction of propagation, and the relationships between the electric field vectors for different rays are easy to visualize if the Jones vectors, Stokes parameters, or geometrical descriptors for the rays are known.

Polarization ray trace output data (i.e., geometrical parameters, Jones matrices, or Stokes parameters) are always with respect to the polarization coordinate system. If you wish to see the output described in a globally referenced coordinate system that does not change with each surface, use the POLAR and PVTAB macros after performing the ray trace (see “Polarization Analysis Macros” on page 25D-40).

When using the geometrical descriptors to describe the polarization state, the sign convention associated with the polarization orientation is important. The orientation of the major axis of the polarization ellipse is specified by the angle, theta, between the Y’ axis and the major axis of the ellipse, with a positive angle being a rotation toward the -X’ axis. If you are looking along the ray in the direction of propagation (i.e., looking toward +Z’), the orientation angle theta is defined as positive if a clockwise rotation of Y’ through an angle theta aligns it with the major axis of the polarization ellipse. This is the same as the definition of surface rotation angle CDE.

For specifying the rotation direction or handedness of the field vector, CODE V adheres to the convention prevalent in the optics industry: an elliptically polarized beam is said to be **right-handed** if the tip of the field vector rotates **clockwise** when viewed from the direction in which the beam is approaching. If the tip of the field vector rotates **counter-clockwise** when viewed from this vantage point, the beam is said to be **left-handed**.

Other polarization coordinate systems are useful for describing the effects of polarization devices, coatings etc. These other systems will be described in the section on polarization devices.

Source Models for Polarization Data

Geometrical descriptors, Jones matrix, and Stokes parameters all reference a two-dimensional coordinate system for the polarization state. For an object at infinity, the X'-Y' system is identical for all rays from a single field point. This is not the case, however, for finite object distances. CODE V has two methods of assigning the polarization state for rays leaving a source point. The default method is similar to a dipole model and is specified by PST DIP. When using this source model, the geometrical descriptors, Jones matrix, or Stokes parameters describe the polarization state for the chief ray. A dipole (or pair of dipoles) is set up with its axis in a plane that is perpendicular to the chief ray. The orientation and phase of this dipole(s) are chosen so that its radiation pattern is consistent with the polarization state specified for the chief ray. The only difference between a true dipole model and the model used in CODE V is that the amplitude of the E field is independent of the radiation direction. That is, the vector direction is consistent with a dipole model, but the amplitude is independent of direction.

A second source model that is useful for finite conjugate systems, the “ideal point source” model, is specified with the PST IDL command. To understand how this model works, imagine a collimated beam traveling in the direction of the chief ray. The polarization state of the beam is specified by user input data; then, the beam is brought to a focus by an idealized refractive interface, similar to the one described for the collimated polarization coordinate system. Instead of collimating the light by creating a beam that is parallel to the Z axis as the PCS COL command does, however, the PST IDL command takes a collimated bundle that is traveling in the direction of the chief ray and transforms it into a focused beam that forms a point of light at the object point.

Polarization and Image Quality

The primary use of polarization information by CODE V is its incorporation in many of the diffraction based image evaluation options and also in transmission calculations. A helpful concept in understanding the importance of polarization on image quality is the idea that the point-spread function is the resultant of the interference between the beams emanating from different regions of the exit pupil of an optical system. Because interference effects do not occur between fields that are polarized in orthogonal directions, it can be seen that the polarization state of the field over the exit pupil can have a profound effect on the shape of the

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PSF. CODE V calculates the polarization state of the beam in the exit pupil, and uses this information to compute several diffraction-based image quality metrics.

Modeling Effects that Alter the Polarization State of a Beam

Polarization Effects Modeled by CODE V

There are many interactions that can alter the polarization state of a beam as it passes through an optical system. The polarization ray trace that is implemented by CODE V takes into account many of these interactions. In particular, the polarizing effects of bare and coated dielectric interfaces are accounted for, as are the polarization effects encountered at bare or overcoated metallic mirrors. In addition, idealized polarizers and retarders are modeled by the program and can be placed anywhere in the system. Besides these physical effects, there are effects due strictly to geometry related to the polarization of the field that are important for computing image quality metrics. For example, if a linearly polarized plane wave, with the field polarized so that it lies in the meridional plane is brought to a focus by a system with a large numerical aperture, the field vectors for the rays that lie in the meridional plane will be “tipped” so that they remain orthogonal to the ray direction. Consequently, the fields at opposite sides of the exit pupil in the meridional plane are not parallel, and interference of the fields from opposite sides of the pupil is affected. Since this “tipping” of the field vector does not occur for rays in the sagittal plane, the PSF of such a system will not be rotationally symmetric. Such effects of geometry are an important part of the modeling that is performed by CODE V.

Modeling of Dielectric or Metallic Interfaces

Though CODE V provides defaults for all parameters that need to be specified in order to perform polarization ray tracing, it is expected that most users of the polarization ray tracing capability will not usually rely on the default assumptions. For example, all glass-air interfaces are assumed to have a quarter-wave coating of magnesium fluoride (MgF_2). However, a typical user of the polarization ray tracing will probably want to specify a different coating. Similarly, the default reflecting surface is one that reflects 100% of both the s and p components of the incident field with no phase shift. In order to obtain accurate answers in a system with reflecting surfaces, the material properties of the reflector must be more fully specified. You can fully specify the optical characteristics of a coating stack (reflective or transmissive) in the MUL option. This coating can then be assigned to any surface in the optical system, using the MLT command. When multilayer coatings are assigned to a surface and polarization ray tracing is activated, a full multilayer calculation is performed at each surface for each ray that is traced. This calculation yields the transmittance or reflectance coefficients for both the s an p components for a plane wave that is incident with the same angle of incidence as the ray that is being traced. If the surface is not coated, then the Fresnel equations are used to determine the reflectance or transmittance for the surface. Note that these calculations are also valid at surfaces where total internal reflection occurs.

As the default, all transmitting surfaces in CODE V have the quarter wave MgF_2 coating. In order to model an uncoated air/glass interface, you must delete the default coating from the surface (DEL COA command). Similarly, if a more sophisticated, multilayer coating is desired at a surface, then this must be explicitly assigned to that surface. Only those multilayer coatings that have been created and stored with the CODE V MUL option can be assigned to a surface. MUL must also be used to create the multilayer files that are used to model reflective surfaces. Notice that in CODE V, a bare metallic reflector must be modeled as a “multilayer” consisting of a single layer of the metal, sufficiently thick so that it does not transmit any light, that is deposited on a substrate. The optical properties of the substrate are unimportant if the metallic layer is sufficiently thick. See “MUL - Multilayer Coating Design and Analysis” on page 23-47 for more details and examples.

Modeling of Linear Polarizers, Retarders, Faraday Rotators and Generalized Polarization Devices: Coordinate Issues

Idealized linear polarizers, retarders and Faraday rotators can be assigned to surfaces in CODE V (only one per surface). Additionally, the effect of a surface on the polarization state can be described in terms of its Jones matrix. (Jones matrices can be specified either using a fixed Jones matrix that is identical for all rays, or

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through the USP interface that allows you to model a variation of Jones matrix with changes in incident ray properties or surface position.) Each of these devices can be modeled with a Jones matrix. This Jones matrix characterizes the transformation of the input polarization state to an output polarization state. However, the input ray and the output ray are not usually collinear. Thus, the polarization coordinate system in which the Jones vector for the input light is described and the coordinate system in which the Jones vector for the output light is described will usually differ. In addition to the standard and the collimated polarization coordinate systems that have already been described, there are different pairs of input and output polarization coordinate systems that are convenient for characterizing the behavior of a device that affects the polarization state. Some devices are described most simply by their behavior in intermediate coordinate systems. The next several paragraphs describe some useful coordinate systems and coordinate system pairs. After these coordinate systems are understood, the descriptions of the behavior for polarizers and retarders is simplified.

One particularly useful pair of coordinates is what we refer to as the INPUT_OUTPUT pair. This is best described by recognizing that the input ray vector and the output ray vector (incident and refracted/reflected/diffracted ray vectors) define a plane. A vector that is orthogonal to that plane can serve as a basis vector for describing *both* the input and the output polarization states, because it will be orthogonal to both the input and the output rays. If we call this the X_{pol} axis, then we can define a Y_{pol} axis that is perpendicular to X_{pol} and the incident ray, and defined so that the cross product of X_{pol} and Y_{pol} is in the direction of the incident ray (that is, X_{pol},Y_{pol}, and the incident ray form the basis vectors of a right-handed coordinate system). We can define a Y'_{pol} in a similar fashion for the output ray direction.

One particularly important use of this INPUT_OUTPUT coordinate system pair is to define an operation that we will refer to as idealized bending of a ray. If we imagine an input ray and an output ray, with the polarization state for each described in the appropriate INPUT_OUTPUT coordinate system, then a transformation between the input polarization state and the output polarization state that is represented by an identity Jones matrix has a unique geometrical significance. This transformation leaves the S component of the light unchanged. The P component of the input electric field is transformed into the P component of the output electric field by imagining that it is rigidly attached to the input ray. As the input ray is rotated to align to the output ray, the input P component is rotated through the same angle to become the output P component. This idealized bending was used earlier in the definition of the collimated coordinate system that is used to characterize the polarization state of light along a ray path. In the case of collimated coordinates, the Z axis plays the part of the output ray.

A second useful pair of coordinate systems is the S-P coordinate system pair. This pair is described in many optics texts. However, there is an ambiguity in the definition of the P direction. The S direction is perpendicular to the plane of incidence (the plane that contains the surface normal and the ray), and the P direction is within that plane, and orthogonal to the ray. This definition can be applied for both the incident and exiting rays. The ambiguity in the direction of the P direction is removed by requiring that the cross product, where **R** is the ray direction. That is, **S, P,** and **R** form the basis vectors for a right-handed coordinate system. Again, note that there is a different **P** vector for the input and output rays, though they share the same **S** vector. (In CODE V, when the S-P coordinate system is specified in a USP, the program assumes that the surface normal, the incident ray and the exiting ray all lie in the same plane. This is not necessarily true; the user should only specify use of these coordinates if this condition is met.[1])

While the INPUT_OUTPUT coordinate system pair may be useful for conical diffraction, another useful coordinate system pair is referred to as the GRATING_VECTOR_COORDINATES. The input grating vector coordinate system has its $\mathbf{X}_{gVec}$ coordinate axis formed by the normalized cross product of the surface normal and the incident ray. Thus it is equivalent to the S direction for the incident ray. $\mathbf{Y}_{gVec}$ is equal to the cross product of the incident ray with the $\mathbf{X}_{gVec}$ axis. Similarly, $\mathbf{X'}_{gVec}$ is the normalized cross product of the surface normal with the exiting ray vector, and $\mathbf{Y'}_{gVec}$ is the cross product of the exiting ray and $\mathbf{X'}_{gVec}$. That is, the GRATING_VECTOR_COORDINATES can be thought of as a pair of S-P coordinate systems, one for the input ray and one for the output ray.

1. This condition may be violated at diffractive surfaces if the local grating vector does not lie in the plane containing the surface normal and the incident ray. Also, for extraordinary rays in birefringent media, if the crystal axis does not lie in the plane containing the incident ray and the surface normal, the condition may be violated.

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Modeling of Linear Polarizers, Retarders, Faraday Rotators and Generalized Polarization Devices: Characterization

The polarizers, retarders and rotators in CODE V are ideal in the sense that they are not based on any physical model of how a polarizer or retarder works, and therefore they cannot predict those aspects of polarizer or retarder behavior that depend on the details of such a model. For example, the model used for retarders allows you to specify a component that retards the phase of one component (the component along the slow. axis) by a fixed amount with respect to the orthogonal component. However, the phase lag introduced is independent of wavelength because no physical model of the retarder, such as one that would account for dispersion of the ordinary and extraordinary indices of a birefringent plate, is used. Similarly, the ideal linear polarizer that is incorporated assumes that the polarizer passes all of the light in one component of the beam (the component along the transmitting axis) and some fraction of the light in the orthogonal component of the beam. In CODE V, such ideal components are called polarization operators, and they are entered with the POP command.

All polarization operators in CODE V act on the incoming electric field vector (i.e., the incoming ray direction cosines). For some polarization devices, it is important that the ray direction cosines be considered within a material, and not in air. For example, sheet polarizers are the most common type of polarizer. To properly model the attenuation of the electric field for a sheet polarizer, it should be defined so that the incident electric field is in a medium with a refractive index that matches the sheet material (approximately 1.5 for several different types). The POP LIN operator should be placed on the back surface of this material. For sheet polarizers, if you place the POP LIN on the front surface (or on a dummy surface in air), the attenuation will vary more quickly with angle of incidence compared to the physical behavior of a sheet polarizer.

The action of a polarizer or retarder is described in a 2D coordinate system. In the cases of a polarizer or Faraday rotator, these devices act in the standard polarization coordinate system that is associated with the output ray. That is, the output ray and the local Y axis of the surface define a plane. The X axis of the coordinate system is perpendicular to that plane and the Y axis of the coordinate system is chosen so that the cross product of the X axis with the Y axis gives the output ray direction. In this coordinate system, the action of a polarizer can be described as follows:[2] the component of the input electric field that is in the Y direction is passed without attenuation, while the orthogonal component has a user-specified amount of attenuation. Note that the transmitting axis of the polarizer device always lies in a plane that contains the local Y axis of the surface. Thus, to rotate the polarizer's transmitting axis, it is necessary to rotate the surface using a CDE command. For this reason, it is often useful to place idealized polarizer devices on dummy surfaces.

Similarly, for Faraday rotators, the action is described as a rotation in a coordinate system that is perpendicular to the ray after reflection or refraction from the surface. In that system, the plane of polarization is rotated by a specified amount.

The ideal retarder coordinate system is identical to the collimated coordinate system that was described earlier. The idealized bending model that was described earlier is used to convert the initial polarization state into a collimated coordinate system. The ideal retarder acts in this collimated coordinate system. Its fast axis is aligned with the Y axis of the collimated coordinate system. The final step, after the effect of the retarder is applied in the collimated coordinate system, is to use the idealized bending model to transform back to a coordinate system that is perpendicular to the output ray.

If the polarization characteristics of a surface are described by a (fixed) Jones matrix, then this Jones matrix will be represented in the standard polarization coordinate system associated with the output ray. Thus the coordinate considerations are identical to those that apply to polarizers and Faraday rotators. If a user-defined surface property (USP) to define a more general (perhaps varying) Jones matrix, then the USP will return a variable, COORD_TYP to specify which of 5 possible coordinate systems are used to represent the Jones matrix. The meaning of COORD_TYP is as follows:

2. In order to determine the polarization state in this standard polarization coordinate system that is incident on the polarizer, the program performs an idealized bending of the incident ray into the output ray. This bending was described in “Polarization Coordinate System” on page 9-20.

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COORD_TYP = 0:	The Jones matrix is applied in the standard coordinate system associated with the output ray.
COORD_TYP = 1:	The Jones matrix is applied in the collimated coordinate system
COORD_TYP = 2:	The Jones matrix is applied in the S-P coordinate system
COORD_TYP = 3:	The Jones matrix is represented in the grating-vector coordinate *systems*. That is, the input polarization state is represented in the input grating vector coordinate system, and the output polarization state is represented in the output grating vector coordinate system.
COORD_TYP = 4:	The Jones matrix is represented in the input-output coordinate system.

Notice that you can use multiple retarders and linear polarizers to construct more general polarizers; however, there can only be one device per surface. For instance, a right or left circular polarizer can be constructed by a quarter-wave retarder, followed by a linear polarizer (with transmitting axis oriented at +45° or -45° with respect to the fast axis of the first retarder), followed by a second retarder which has its fast axis rotated 90° relative to the fast axis of the first retarder. An example of a right-handed circular polarizer that is modeled in this way is given later.

The surface listing output (SUR Sk|Si..j) will list any polarizer or retarder data that has been assigned to a surface.

Assigning a Perfect Refractive Coating to a Surface

The command POP JMX replaces the current polarization properties of the interface with that of a perfect coating (i.e., one that does not change the amplitude or phase of the S or P component of the electric field). If a multilayer coating was defined on the selected surface, it is removed. If CODE V's default quarter-wave of magnesium fluoride was present, it is removed as well.

This feature is implemented by assigning an identity Jones matrix to a single surface. You can also specify how the polarization of a ray changes at any surface by explicitly specifying four complex numbers (eight real numbers) for the Jones matrix elements. The JR1-JR4 commands define the real components of the Jones matrix, and the JI1-JI4 commands define the imaginary components.

$$\begin{bmatrix} JR1,JI1 & JR2,JI2 \\ JR3,JI3 & JR4,JI4 \end{bmatrix}$$

It is important to note that the magnitudes of the elements of the Jones matrix that are entered in association with the POP JMX command are actually SQRT(*T*). Thus, before being used internally, they are converted to *t* by dividing by:

$$\sqrt{\frac{n'\cos\theta'}{n\cos\theta}}$$

To access the Jones matrix controls in the GUI, choose the **Lens** > **Surface Properties** menu, and click **Polarization Operator** in the **Surface Properties** window.s navigation tree. Choose **Jones Matrix** in the **Type** field, and click the **Commit Data** button to display the Jones matrix controls. Clicking the **Perfect Refractive Coating** button changes the Jones matrix values to be equivalent to a perfect refractive coating; note that selecting the **Polarization Operator** button in the **Cement/Coating** page in the **Surface Properties** window also defines a perfect refractive coating for the current surface.

Modeling of Birefringent Retarders

In addition to the idealized linear polarizers and retarders that can be assigned to a surface (POP LIN and POP RET), CODE V provides a more accurate model for retarders made from birefringent materials. The model is based on a pseudo-birefringent ray trace that simulates the dominant effects of ray propagation through a low-order wave plate (small retardance values) composed of birefringent material. When a ray is incident on birefringent material, depending on its angle of incidence and polarization state, it may split into two separate

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rays referred to as an ordinary ray (o-ray) and an extraordinary ray (e-ray). These two rays travel along different paths through the material, and each ray experiences a different index of refraction as it travels through the material.

However, for low-order wave plates, a reasonably good approximation of the true behavior can be obtained by assuming that the e-ray travels along the same path as the o-ray, but experiences a different index of refraction. This is the same model that CODE V employs when performing polarization ray tracing through birefringent material (BIR). The index of refraction for the e-ray is dependent on the direction of this ray through the material, and is computed by CODE V based on the values of the principal indices of refraction, N_e and N_o. This is a reasonable model if the retarder plate is not too thick. For example, the retardance error will be less than 0.01 waves for a quartz wave plate, which has an index difference ($N_e - N_o$) of 0.009, if the thickness is less than 5 mm.

To model a birefringent retarder, you must specify N_e, N_o, and the orientation of the crystal axis. These parameters are assigned to a material following a surface (Glass 2 for NSS surfaces). The ordinary index is designated by the material properties. The index difference ($N_e - N_o$) is specified with the **NEO** command. The crystal axis orientation is specified with the **CAO** or **CAD** command.

The index difference can have a positive or negative value. For positive values, the fast axis of the retarder is orthogonal to the crystal axis. For negative values, the fast axis of the retarder is along the crystal axis. The crystal axis is assumed to lie within the local X–Y plane of the surface preceding the material. The angle between the crystal axis and the local Y axis is specified (in degrees). The sign of this angle follows the same convention as a CDE rotation of a surface. Thus, for a crystal axis which lies in the second quadrant (positive Y component, negative X component), the angle value is positive.

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Use of Polarization Ray Trace Information by CODE V

Generally, polarization ray tracing does not alter the path of a ray through a system. The exception to this statement occurs if the system contains a birefringent material, and the user has specified that the extraordinary ray path is selected in the birefringent material. For this special case, if POL Yes has been specified, polarization ray tracing is used for all real (not paraxial) ray tracing performed by the program. In the more common case, the polarization ray trace generates amplitude and phase information that alters the polarization state along the ray, but does not alter the ray path. In these more common cases, only certain CODE V options utilize the additional information that is generated during the polarization ray trace. Because polarization ray tracing is slower than ordinary ray tracing, CODE V options that do not use polarization information do not perform polarization ray tracing. If polarization ray tracing can affect an option's output, and POL=Y, polarization ray tracing is performed. The following paragraphs list those CODE V options and analyses for which polarization can affect the output.

AUT – During optimization, the polarization state of the beam can have various effects on the results. Polarization effects can introduce phase changes to the beam that can impact OPD- and MTF-based error functions. Changes in the geometric optical path of the rays through birefringent materials can affect the transverse-ray-based error functions, as well as the calculation of ray based constraints. Polarization components or properties included in the definition of user-defined constraints can also affect results. Therefore, polarization ray tracing is performed in the AUT option whenever POL = Y. In order to save ray tracing time, you may want to de-activate polarization ray tracing (POL=N) before you run AUT unless one of these conditions exists in your lens model:

- You are performing an OPD optimization in which polarization-induced phase differences can affect results
- Polarization components or definitions are included in user-defined constraints
- Birefringent ray tracing is active

MTF – The polarization state of the beam in the exit pupil is used in order to decompose the field into orthogonal vector components. Each of these orthogonal field components yields an independent optical transfer function (OTF). These individual OTFs are summed with appropriate weighting in order to give the overall OTF which then readily yields the resultant MTF. This is entirely analogous to the summation process that is used to determine a polychromatic MTF from the monochromatic OTFs. Not applicable to geometrical MTF.

PSF, LSF, PAR – The polarization state of the beam in the exit pupil is used in order to decompose the field into components. Each of these components acts independently in the formation of the image, so the resultant PSF, LSF, or aerial image intensity (in PAR) can be computed as the sum of the results for each component.

FIE, SPO, TOR, VIE – The effect of birefringent material on the geometrical optical path of the extraordinary ray through the optical system is taken into account in these options if the **BIR** EXT command is issued. The ray trace is performed for the ordinary ray if the **BIR** ORD command is issued. Amplitude and phase data normally generated during polarization ray tracing is not computed since these options do not utilize this information. In addition, TOR will calculate changes to the MTF or coupling efficiency (CEF) assuming a polarized input beam when polarization ray tracing is enabled. TOR's polarization dependent loss (PDL) calculation always assumes a polarized input beam.

PMA – Polarization ray tracing is active only if PPH or PIN requests are made. If the PIN request has been made, then the pupil intensity map includes polarization dependent effects such as reflection losses that occur at coated or uncoated surfaces. The PPH request causes the program to print maps of wavefront phase in the exit pupil. (The values listed on the map are all modulo 1 wave, i.e., they range from -0.5 waves to + 0.5 waves.) There are four maps possible for each field, wavelength and zoom combination. If you imagine that the input light is totally polarized, with the polarization state described by the ellipse parameters specified in the LDM, then one map gives the phase of the wavefront that would result if a linear polarizer with its transmitting axis parallel to the Y axis was placed after the last surface. A second map gives the phase that would be seen if the same input beam was used but the transmitting axis of the polarizer was parallel to the X axis. The third and fourth maps are analogous to the previous two; the difference is that the maps

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correspond to those that would be obtained with a different input polarization state – the elliptical state that is orthogonal to the state specified in the LDM.

TRA – Polarization ray tracing is always used in order to compute the reflection or transmission losses with accurate physical modeling. This is true whether or not you have activated polarization ray tracing in other options with the POL Y command; the POL command has no effect on TRA. Thus, transmission of the system will be dependent on the polarization state of the input beam. The program will use an unpolarized input beam as the default input beam. This can be modified by you by using the appropriate LDM commands (PFR, PTP, POR and PRO). The effect of any polarizers and retarders in the lens is also included.

LUM, TRA, RSI, SIN, RAYRSI, RAYSIN, RAYTRA – The normal way to set up your optical system is to have the sources at the object and the receiver at the image. You may set up your optical system to model the sources at the image and the receiver at the object. For optical systems set up in this reverse orientation, reverse polarization ray tracing (RVT Yes) allows you to determine the transmission characteristics of the optical components as the polarized propagates from the image surface to the object surface, as they are designated in the CODE V model. This represents the actual use of the optical system in its intended application. The input polarization state associated with a particular field point is used as input at the image surface. Depending on the complexity of the optical system, and the inclusion of polarizing elements in the optical system, there can be variations between the transmission characteristics determined from the forward and reverse ray traces.

RSI, SIN – The intensity transmittance along the ray (including all Fresnel and multilayer calculations when polarization ray tracing is active, but excluding attenuation losses due to transmission through the thicknesses of glass elements) is listed. In addition, if POL Y has been issued, then the OPD output is suppressed, and four phase values are listed instead. These are analogous to the four phase maps that are listed in PMA with the PPH request, i.e., they represent the phase values (with respect to the chief ray) of the ray as if it passed through an X or Y analyzer for an input beam whose polarization is either identical to or orthogonal to the elliptical state specified in the LDM. Finally, the polarization properties of the ray path are listed in terms of the diattenuation and retardance of the ray path. Additional polarization related quantities can be output for each surface if the proper ROF requests have been made. These ROF requests are listed here:

PXI	–	The relative intensity of the ray, as if it passed through a linear polarizer with transmitting axis parallel to the X' axis.
PYI	–	The relative intensity of the ray, as if the polarizer axis is parallel to the Y' axis.
PFR	–	The degree of polarization of the ray (fraction of light polarized).
PTP	–	The ratio of the intensity of the minor axis component to the major axis component for polarized portion of the field associated with the ray.
POR	–	The orientation of the major axis of the polarization ellipse with respect to the Y' axis. (The X'-Y' coordinate system is defined such that the X' axis is orthogonal to the plane that contains the ray and the Y axis of the local surface. Y' is chosen such that the cross product of X' x Y' is a unit vector in the direction of the ray.) Positive angles are angles that rotate the X' axis toward the Y' axis.
PRO	–	The direction of rotation of the field vector for the polarized component of the field (i.e., its “handedness”). The rotation is right-handed if the field vector rotates in a clockwise direction when viewed from the direction in which the ray is approaching the observer.
POL	–	Equivalent to asking for all of the polarization-related output, i.e., it causes PXI, PYI, PFR, PTP, POR, and PRO output to be listed.
JR1, JR2, JR3, JR4	–	The four real components of the Jones matrix (the matrix relating input Jones vector to output Jones vector).
JI1, JI2, JI3, JI4	–	The four imaginary components of the Jones matrix.
MGS, MGP	–	Magnitude of the transmittance (or reflectance) factor for the s or p component of the electric field.

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PHS, PHP	–	Phase (in degrees) of the transmittance (or reflectance) factor for the s or p component of the electric field.
JNS	–	Equivalent of asking for all the Jones matrix components JR1, JI1,..., JR4, JI4 plus MGS, MGP, PHS, and PHP output to be listed. These are listed in two rows per surface.
Macros	–	There are several macros for output of Jones vectors, Stokes parameters, Mueller matrices, etc., after ray tracing. Refer to “Polarization Analysis Macros” on page 25D-40 for further description.

When polarization ray tracing is enabled, RSI output also includes information about the polarization properties for the ray path, including a beam projection calculation. This is labeled as the **Product of beam projection factors along ray**. This quantity is given by

$$\frac{|n' \cos\theta'|}{|n \cos\theta|}$$

where n' is the index of refraction after reflection or refraction, and theta' is the angle the exiting ray makes with the surface normal. n is in the index of refraction before the surface, and theta (θ) is the angle that the incident ray makes with the surface normal. This quantity is computed for each ray/surface intersection, and the beam projection factor is the product of all of these factors.

The Jones matrix describes the relationship between the output electric field vector and the input electric field vector. It is important to realize that the electric field is a quantity that is not conserved across refractive interfaces. For example, at a refractive interface, the Jones matrix, represented in a coordinate system aligned with the s/p coordinate axes of the interface will look like:

$$\begin{bmatrix} \boldsymbol{t}_s & 0 \\ 0 & \boldsymbol{t}_p \end{bmatrix}$$

where $\boldsymbol{t}_s$ and $\boldsymbol{t}_p$ are the transmittance values computed from the Fresnel equations. If the light is going from a medium of high index to a medium of lower index, these values may exceed one. However, the energy transmittance across the interface for the p or s component is proportional to the quantity:

$$T = \frac{n' \cos\theta'}{n \cos\theta} \boldsymbol{t}_{p,s}^2$$

where θ is the angle of incidence, θ' is the angle of refraction, $\boldsymbol{t}_{p,s}$ is the field amplitude transmittance for the s or p component of the field, n is the index of refraction for the incident medium and n' is the index of refraction for the output medium.

The output of the Jones matrix data for the raytrace is given in terms of the true Jones matrix at an interface. Thus, as explained, the magnitude of its components may exceed one, or may be less than one at an interface that transmits all of the energy. However, it is important to note that the magnitudes of the elements of the Jones matrix that are entered in association with the POP JMX command are actually $\sqrt{T}$. Thus, before being used internally, they are converted to $\boldsymbol{t}$ by dividing by:

$$\sqrt{\frac{n' \cos\theta'}{n \cos\theta}}$$

Note: The normalization scheme used to specify the magnitude of the elements of this matrix is different from the scheme used for output of Jones matrix data using the ROF JNS command in association with RSI or SIN (single ray trace).

The polarization properties of an optical system along a particular ray path can be characterized by a Jones matrix describing that ray path. It is possible to decompose the Jones matrix so that it consists of a partial polarizer, followed by a retarder. The polarizer is characterized by the diattenuation which is the ratio:

$$\frac{T_{max} - T_{min}}{T_{max} + T_{min}}$$

where T_{max} is the maximum transmittance for the polarizer, and T_{min} is the minimum transmittance for the polarizer. Similarly, the retarder is characterized by the retardance, which is defined as $Phase_{max}$ - $Phase_{min}$. Diattenuation and retardance across a pupil diameter can both be plotted for a lens by means of the POLDSP.SEQ macro, included with CODE V. See “POLDSP.SEQ Macro” on page 9-33 for examples of output.

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Examples of Polarization Output

Example 1. Fresnel rhomb

The Fresnel Rhomb is a device that uses the phase lag between s and p components that occurs at total internal reflection to produce circularly polarized light from an input beam that is linearly polarized. Two successive total-internal reflections, each of which contributes a 45° phase difference between s and p components, will cause a net phase difference of 90°.

Sequence to create the Rhomb:

```
!
!  Sequence file to create a Fresnel Rhomb
!
RDM N;LEN
EPD 2.
WL  500.
!
PRV                   ! Define 'GLASS' with an index of 1.51
PWL 500.
'GLASS' 1.51
END
!
SO     0. 0.1E+11
S      0. 3.
STO
S      0. 5. 'GLASS'
S      0. -9. TIRO
BEN
ADE 54.6231
S      0. 5. TIRO
BEN
ADE -54.6231
S      0. 10.
SI     0. 0.
GO
DEL COA SA            ! Delete default coatings
PFR 1.                ! Specify totally polarized input
                      !  (the default PTP is 0.0, so this
                      !  command specifies linearly polarized
                      !  light.)
POR -45               ! Specify the field to be oriented
                      !  at -45 deg.
POL Y                 ! Activate the polarization ray tracing
ROF POL               ! Request Polarization output from RSI.
                      ! Note the ROF POL command is equivalent
                      !  to ROF PXI PYI PFR PTP POR PRO.
RSI F1 R1
```

RSI output:

Note that the PFR (polarization fraction) column indicates that the light remains totally polarized. However, the “I ratio” column which gives the ratio of the minor axis intensity to the major axis intensity starts out at 0.0, linear polarization, and changes to 1.0, circular polarization.

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```
Position  1, Wavelength =   500.0 NM
          X INT       Y INT      POL FR      I RATIO     POL ANG     POL ROT
OBJ      0.50000     0.50000    1.00000     0.00000   -45.00000    LINEAR
STO      0.50000     0.50000    1.00000     0.00000   -45.00000    LINEAR
  2      0.47936     0.47936    1.00000     0.00000   -45.00000    LINEAR
  3      0.47936     0.47936    1.00000     0.17157   -45.00000    RIGHT
  4      0.47936     0.47936    1.00000     1.00000     0.00000    RIGHT
  5      0.45957     0.45957    1.00000     1.00000     0.00000    RIGHT
IMG      0.45957     0.45957    1.00000     1.00000     0.00000    RIGHT
  Phase with respect to the chief ray (Waves):
             Yphase:     0.000     Xphase:     0.000
             Yphase2:    0.000     Xphase2:    0.000
                        Intensity transmission: 0.9191

  Polarization properties for the ray path:
                          Magnitude        Orientation      Ellipticity
         Diattenuation:     0.0000000         0.0000           0.0000
         Retardance:        90.000003(deg)    0.0000           0.0000
         Polarization coordinate system rotation angle:    0.0000 (deg.)
         Product of beam projection factors along ray:    1.00000
```

Example 2. A right-circular polarizer

Surface listing showing polarizers and retarders. This listing shows how a group of 3 polarization operators, 2 quarter-wave retarders and 1 linear polarizer, are combined to produce a right-circular polarizer. This group will pass right-handed circularly polarized light with no attenuation. Linearly polarized light that is input to this group will be changed to right-handed circularly polarized light and it will have its intensity reduced to half of its input value. If left-handed, circularly polarized light is input to this group, it is completely attenuated. Note that the surface listing indicates whether the polarization operator is a polarizer, retarder, or other type. When it is a retarder, then the amount of retardation of the slow-axis component relative to the fast-axis component is listed, (e.g., 0.25, a quarter wave for the retarders at surfaces 2 and 4). If it is a linear polarizer, then the attenuation factor for light polarized along the local X axis (e.g., 1.00 at surface 3; this is total attenuation of the X-polarized light) is given.

```
              RDY                THI       RMD           GLA
2:         INFINITY            0.000000
 POP RET:    0.2500
3:         INFINITY            0.000000
 XDE:     0.000000    YDE:     0.000000    ZDE:     0.000000    DAR
 ADE:     0.000000    BDE:     0.000000    CDE:    45.000000
 POP LIN:   1.0000

4:         INFINITY            0.000000
 XDE:     0.000000    YDE:     0.000000    ZDE:     0.000000    DAR
 ADE:     0.000000    BDE:     0.000000    CDE:    90.000000
 POP RET:    0.2500
```

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Example 3. POLDSP.SEQ Macro

This macro produces a plot of the polarization state, diattenuation, or retardance across the pupil. A separate plot is produced for each field and zoom position. The example output is for the reference wavelength, using 11 rays across the pupil diameter. Plots are shown for zoom position 1 only, to provide comparison between output types. See “POLDSP.SEQ” on page 25D-42 for more information on the macro.

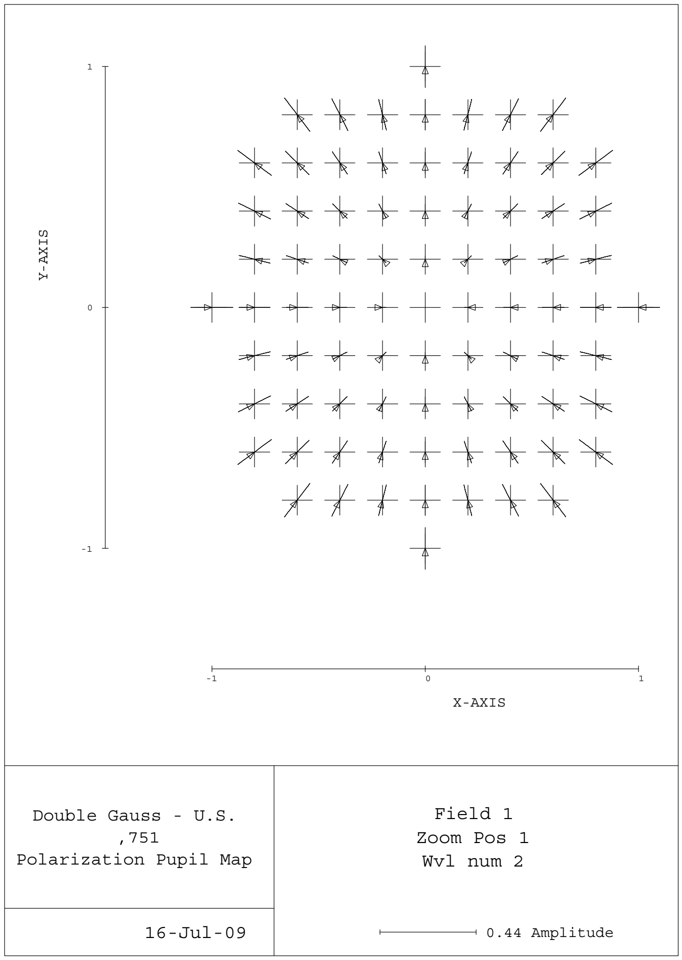

Figure 2. Polarization Pupil Map for Zoom Position 1

```
Summary - Pupil Averaged Stokes Vector
=======================================

Filename => C:\CODEV\lens\dbgauss.len
Title    => Double Gauss - U.S. Patent 2,532,751
```

Field	Zoom	S0	S1	S2	S3	Degree of Polarization
1	1	0.94137	0.00000	0.00000	0.00000	0.00000
2	1	0.94342	0.00043	0.00000	0.00000	0.00046
3	1	0.94376	0.00004	0.00000	0.00000	0.00004

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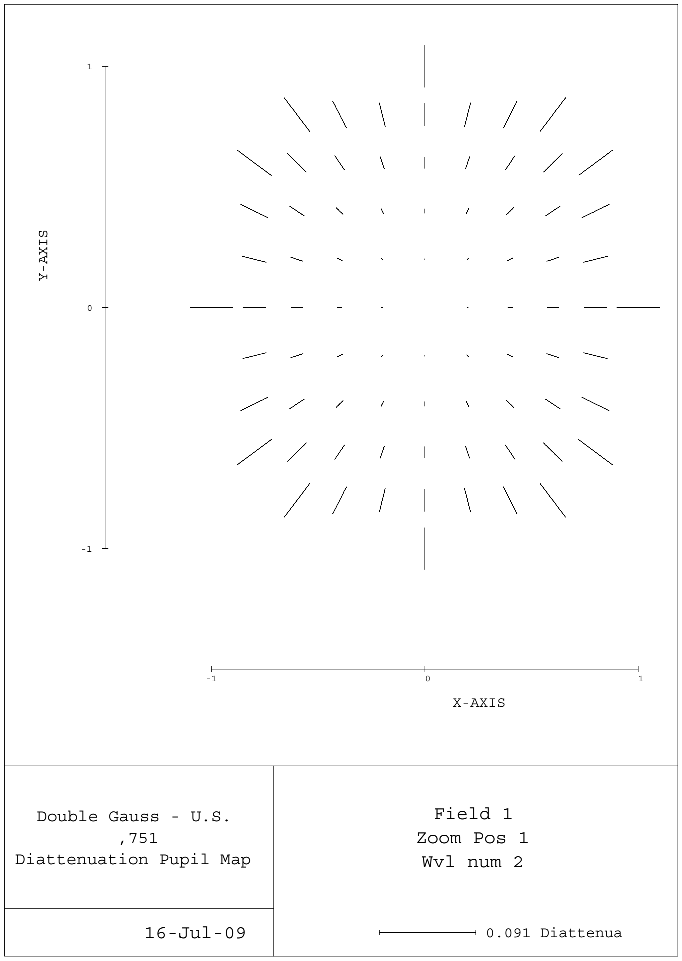

Figure 3. Diattenuation Pupil Map for Zoom Position 1

```
Summary - Diattenuation
=======================================

Filename => C:\CODEV\lens\dbgauss.len
Title    => Double Gauss - U.S. Patent 2,532,751


Field          Zoom          Maximum        RMS
                             Magnitude
===============================================
  1              1           0.04016      0.01245
  2              1           0.03018      0.00758
  3              1           0.02212      0.00544
```

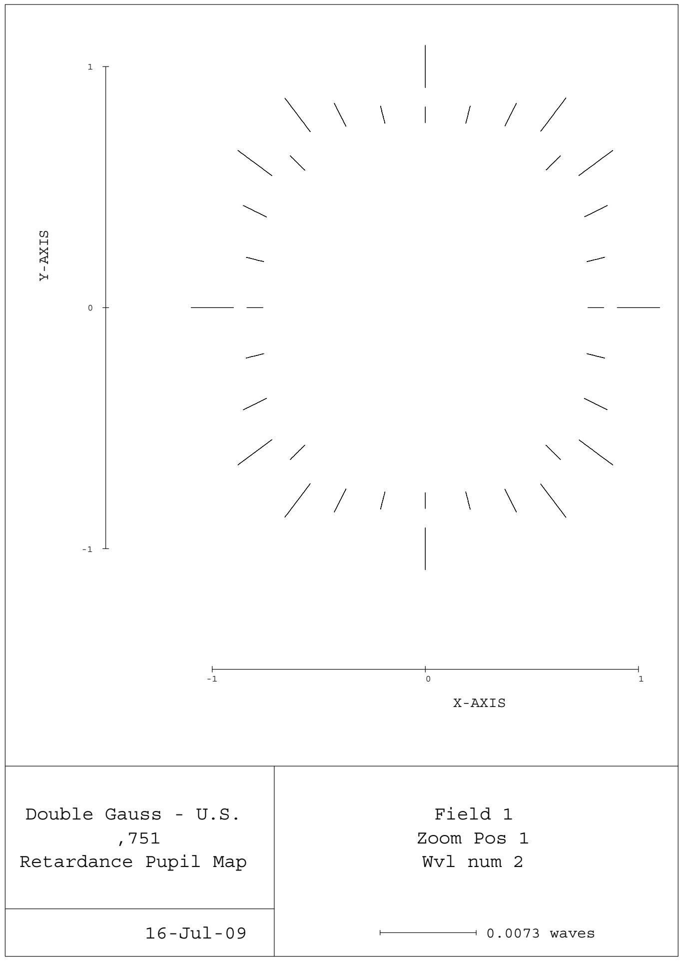

Figure 4. Retardance Pupil Map for Zoom Position 1

```
Summary - Retardance (waves)
=======================================

Filename => C:\CODEV\lens\dbgauss.len
Title    => Double Gauss - U.S. Patent 2,532,751


Field          Zoom         Maximum        RMS
                            Magnitude
===============================================
  1              1          0.00323      0.00108
  2              1          0.00219      0.00055
  3              1          0.00150      0.00039
```

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Example 4. A TIR cube-corner reflector

This last example, which is rather long, illustrates some of the PMA and PSF output. It should be noted that the output format for PSF data is unchanged when polarization ray tracing is active, but the computations do account for the polarization effects in the point spread listings or plots. To illustrate this fact, the example uses a cube-corner reflector with no angle errors to reflect a plane wave. The reflected wavefront is brought to a focus using the AFI command which simulates a perfect lens. Ordinarily, one would expect that the PSF would have the shape of the Airy pattern; however, because of the polarization effects that occur at the TIR interfaces, the PSF is altered substantially. This is shown in the contour plots of Figure 5, Figure 6, and Figure 7. Here is the sequence file that produces all of the listed or plotted output that is shown for this example:

```
LEN
WL 632.8
AFI -5
EPD 1
S 0 0                                 ! Aperture stop
CCR 2 SILICA TIR                      ! Input the corner cube
S 0 0
S 0 -5                                ! Afocal perfect lens
DEL COA SA                            ! Delete coatings
PFR 1.0                               ! Specify completely polarized beam
!
POL Y  ! Activate polarization ray tracing
!
! Compute a PSF
PSF; tgr 256
TIT '      Total PSF        TIR Corner Cube '
GRI 0.00005
pgr 24
lis n; plo n
con sup; lev num 6
go
!
!  Insert a polarizer prior to the image plane to obtain
!  the PSF due to the "Y-polarized component" only.
!
ins si-1
pop lin si-2
psf; tgr 256
TIT '  Y-component PSF     TIR Corner Cube   '
gri 0.00005
lis n; plo n
pgr 24
con sup; lev num 6
go
!
!  Show the intensity of the Y component of the beam
!  in the exit pupil.
!
PMA; tgr 32; com; PIN ; plo n; go
!
! Now rotate the polarizer to view the "X-component PSF"
!
si-2
cde 90; dar
psf; tgr 256
TIT '  X-component PSF     TIR Corner Cube   '
gri 0.00005
pgr 32
lis n; plo n
con sup; lev num 6
```

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```
go
!
!  Show the intensity of the X component of the beam in the exit pupil.
!
PMA; tgr 32; com; PIN ; plo n; go
!
!
!  Show the phase map in the exit pupil when the
!  incident beam is linearly polarized. (A phase
!  map is produced for both components, X and Y)
DEL POP SA
PMA
PPH YP1 XP1
TGR 32
COM; PLO N
GO
```

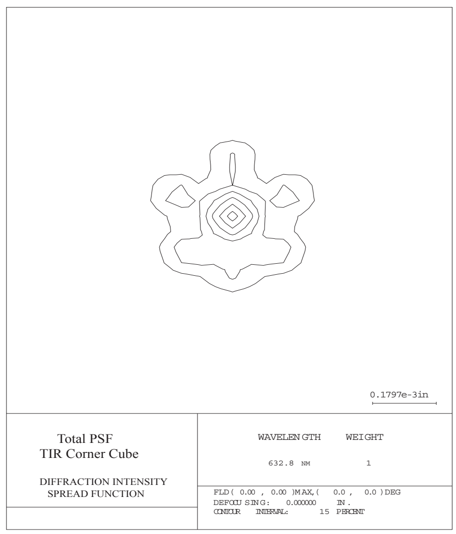

Figure 5. Total PSF for Linearly Polarized Light (Y Direction)

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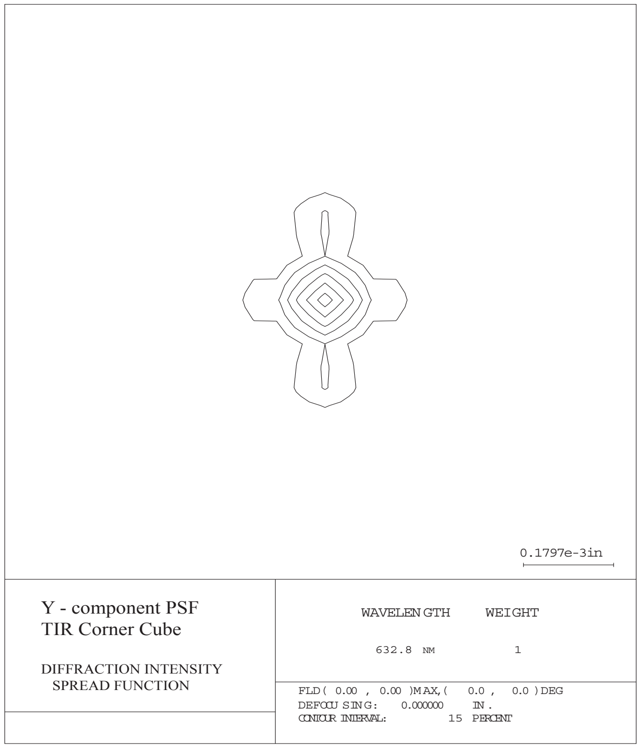

Figure 6. Y-component PSF for linearly polarized light (Y direction)

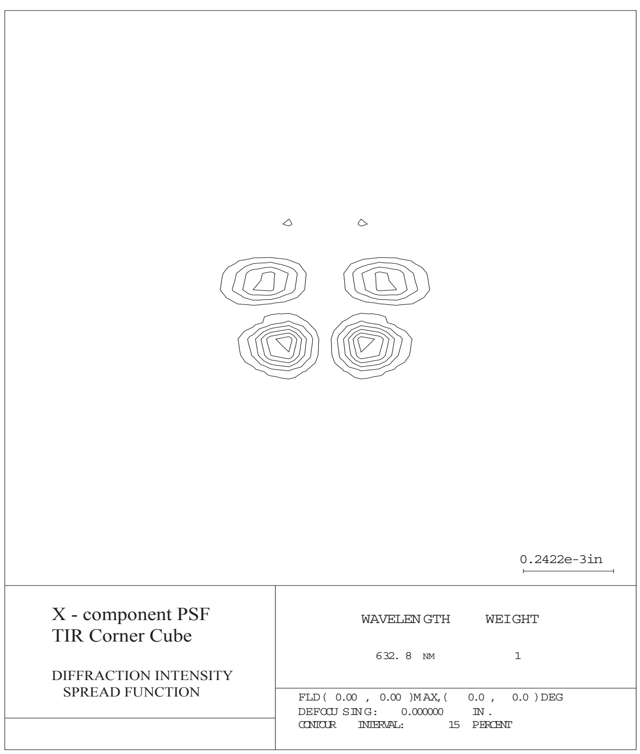

Figure 7. X-component PSF for linearly polarized light (Y direction)

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The next two pupil maps show the intensity in the exit pupil of the system for the Y polarized component and the X polarized of the output beam:

```
          POSITION  1       WAVE OPTICS PUPIL INTENSITY                               02-May-07


                                                      WAVELENGTH   WEIGHT  NO. OF RAYS   PUPIL GRID
  FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,   0.00)DEG    632.8 NM       1       197         17 x   17
  DEFOCUS =   0.000000 MM.

  AVERAGE INCREMENTS ON ENTRANCE PUPIL (LENS UNITS)
        DX = ( -0.062500,  0.000000)
        DY = (  0.000000, -0.062500)
WAVELENGTH  =      632.8 NM
 SUM OF VALUES =  10856.
 THROUGHPUT =   55.1 PERCENT
         7     8     9    10    11    12    13    14    15    16    17    18    19    20    21    22    23    24    25    26    27


   9                                                                40
  10                                                    40    40    40    40    40    40    40
  11                                        40    40    40    40    40    40    40    40    40    40    40
  12                                  40    40    40    40    40    40    40    40    40    40    40    40    40
  13                                  40    40    40    40    40    40    40    40    40    40    40    40    40
  14                            86    86    40    40    40    40    40    40    40    40    40    40    40    86    86
  15                            86    86    86    86    40    40    40    40    40    40    40    86    86    86    86
  16                            86    86    86    86    86    86    40    40    40    86    86    86    86    86    86
  17                      86    86    86    86    86    86    86    86    40    86    86    86    86    86    86    86    86
  18                            86    86    86    86    86    86    40    40    40    86    86    86    86    86    86
  19                            86    86    86    86    40    40    40    40    40    40    40    86    86    86    86
  20                            86    86    40    40    40    40    40    40    40    40    40    40    40    86    86
  21                                  40    40    40    40    40    40    40    40    40    40    40    40    40
  22                                  40    40    40    40    40    40    40    40    40    40    40    40    40
  23                                        40    40    40    40    40    40    40    40    40    40    40
  24                                                    40    40    40    40    40    40    40
  25                                                                40
```

```
      POSITION 1        WAVE OPTICS PUPIL INTENSITY
                                                      WAVELENGTH   WEIGHT  NO. OF RAYS   PUPIL GRID
  FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,  0.00)DEG    632.8 NM       1       197        17 x  17
  DEFOCUS =   0.000000 INCHES

  AVERAGE INCREMENTS ON ENTRANCE PUPIL (LENS UNITS)
        DX = ( -0.062500,  0.000000)
        DY = (  0.000000, -0.062500)
 WAVELENGTH  =      632.8 NM
SUM OF VALUES =   7506.
THROUGHPUT =   38.1 PERCENT
         7     8     9    10    11    12    13    14    15    16    17    18    19    20    21    22    23    24    25    26    27


   9                                                                53
  10                                                    53    53    53    53    53    53    53
  11                                        53    53    53    53    53    53    53    53    53    53    53
  12                                  53    53    53    53    53    53    53    53    53    53    53    53    53
  13                                  53    53    53    53    53    53    53    53    53    53    53    53    53
  14                             7     7    53    53    53    53    53    53    53    53    53    53    53     7     7
  15                             7     7     7     7    53    53    53    53    53    53    53     7     7     7     7
  16                             7     7     7     7     7     7    53    53    53     7     7     7     7     7     7
  17                       7     7     7     7     7     7     7     7    53     7     7     7     7     7     7     7     7
  18                             7     7     7     7     7     7    53    53    53     7     7     7     7     7     7
  19                             7     7     7     7    53    53    53    53    53    53    53     7     7     7     7
  20                             7     7    53    53    53    53    53    53    53    53    53    53    53     7     7
  21                                  53    53    53    53    53    53    53    53    53    53    53    53    53
  22                                  53    53    53    53    53    53    53    53    53    53    53    53    53
  23                                        53    53    53    53    53    53    53    53    53    53    53
  24                                                    53    53    53    53    53    53    53
  25                                                                53
```

The next two pupil maps show the wavefront phase maps for the Y-polarized components of the beam. These phase maps show the phase of the fields whose intensities were shown in the previous two pupil maps.

```
      POSITION  1       WAVE OPTICS WAVE ABERRATION                              02-May-07
               Wavefront viewed through Y-analyzer; (YP1 output)
```

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```
                                                            WAVELENGTH   WEIGHT  NO. OF RAYS  PUPIL GRID
     FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,   0.00)DEG     632.8 NM       1        197        17 x   17
     DEFOCUS =    0.000000 MM.

    AVERAGE INCREMENTS ON ENTRANCE PUPIL (LENS UNITS)
          DX = ( -0.062500,  0.000000)
          DY = (  0.000000, -0.062500)
    Wave aberrations in hundredths of wavelength     632.8NM
         RMS =    0.125 waves        P-V =     0.267 waves
 SUM OF VALUES =    1710.
        7    8    9   10   11   12   13   14   15   16   17   18   19   20   21   22   23   24   25   26   27


    9                                                      0
   10                                       0    0    0    0    0    0    0
   11                             0    0    0    0    0    0    0    0    0    0    0
   12                        0    0    0    0    0    0    0    0    0    0    0    0    0
   13                        0    0    0    0    0    0    0    0    0    0    0    0    0
   14                  27   27    0    0    0    0    0    0    0    0    0    0    0   27   27
   15                  27   27   27   27    0    0    0    0    0    0    0   27   27   27   27
   16                  27   27   27   27   27   27    0    0    0   27   27   27   27   27   27
   17             27   27   27   27   27   27   27   27    0   27   27   27   27   27   27   27   27
   18                  27   27   27   27   27   27    0    0    0   27   27   27   27   27   27
   19                  27   27   27   27    0    0    0    0    0    0    0   27   27   27   27
   20                  27   27    0    0    0    0    0    0    0    0    0    0    0   27   27
   21                        0    0    0    0    0    0    0    0    0    0    0    0    0
   22                        0    0    0    0    0    0    0    0    0    0    0    0    0
   23                             0    0    0    0    0    0    0    0    0    0    0
   24                                       0    0    0    0    0    0    0
   25                                                      0

               RMS Wave aberration           Shift of nominal image
                    (waves)                         point (mm)
  ( FIT )                                  X              Y            Focus
    None             0.125 (P-V = 0.267)
    Tilt             0.125            0.000000       0.000000
Tilt/Focus           0.125            0.000000       0.000000      -0.001361


         POSITION  1        WAVE OPTICS WAVE ABERRATION                              02-May-07
                  Wavefront viewed through X-analyzer; (XP1 output)

                                                            WAVELENGTH   WEIGHT  NO. OF RAYS  PUPIL GRID
     FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,   0.00)DEG     632.8 NM       1        197        17 x   17
     DEFOCUS =    0.000000 MM.

    AVERAGE INCREMENTS ON ENTRANCE PUPIL (LENS UNITS)
          DX = ( -0.062500,  0.000000)
          DY = (  0.000000, -0.062500)
    Wave aberrations in hundredths of wavelength     632.8NM
         RMS =    0.301 waves        P-V =     1.000 waves
 SUM OF VALUES = -50808.
        7    8    9   10   11   12   13   14   15   16   17   18   19   20   21   22   23   24   25   26   27


    9                                                    -38
   10                                     -88  -88  -88  -38  -38  -38  -38
   11                           -88  -88  -88  -88  -88  -38  -38  -38  -38  -38  -38
   12                      -88  -88  -88  -88  -88  -88  -38  -38  -38  -38  -38  -38  -38
   13                      -88  -88  -88  -88  -88  -88  -38  -38  -38  -38  -38  -38  -38
   14                 -19  -19  -88  -88  -88  -88  -88  -38  -38  -38  -38  -38  -38  -69  -69
   15                 -19  -19  -19  -19  -88  -88  -88  -38  -38  -38  -38  -69  -69  -69  -69
   16                 -19  -19  -19  -19  -19  -19  -88  -38  -38  -69  -69  -69  -69  -69  -69
   17            -19  -19  -19  -19  -19  -19  -19  -19    0  -69  -69  -69  -69  -69  -69  -69  -69
   18                 -19  -19  -19  -19  -19  -19  -50    0 -100  -69  -69  -69  -69  -69  -69
   19                 -19  -19  -19  -19  -50  -50  -50    0 -100    0    0  -69  -69  -69  -69
   20                 -19  -19  -50  -50  -50  -50  -50    0    0 -100    0    0    0  -69  -69
   21                      -50  -50  -50  -50  -50  -50    0    0 -100 -100    0 -100    0
   22                      -50  -50  -50  -50  -50  -50    0    0 -100    0    0 -100 -100
   23                           -50  -50  -50  -50  -50    0    0 -100    0    0    0
   24                                     -50  -50  -50  -50    0    0 -100
   25                                                    -50

               RMS Wave aberration           Shift of nominal image
                    (waves)                         point (mm)
  ( FIT )                                  X              Y            Focus
    None             0.301 (P-V = 1.000)
    Tilt             0.290            0.000442       0.000945
Tilt/Focus           0.290            0.000442       0.000945      -0.007605
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