ASAP

Technical Guide

POLARIZATION IN ASAP

Breault Research Organization, Inc.

This technical publication is for use with ASAP®.

Comments on this manual are welcome at: **support@breault.com**

For technical support or information about other BRO products, contact:

US/Canada:1-800-882-5085

Outside US/Canada:+1-520-721-0500

Fax:+1-520-721-9630

E-Mail:

Technical Customer Service:support@breault.com

General Information:info@breault.com

Web Site:http://www.breault.com

Breault Research Organization, Inc.

6400 East Grant Road, Suite 350

Tucson, AZ 85715

brotg0923_polar (June 22, 2010)

Contents

POLARIZATION ANALYSIS

In this technical guide, the techniques and commands used to perform polarization analysis in ASAP® (Advanced Systems Analysis Program) from Breault Research Organization, Inc., are described. In ASAP, you can include the effects of polarization in your analysis. This polarization analysis can be performed in either of the ASAP modes, **`BEAMS INCOHERENT GEOMETRIC`** or **`BEAMS COHERENT DIFFRACT`**.

This technical guide is structured in the same order that is commonly used to perform any ASAP analysis:

- **Setting up the system**: system commands, coatings, polarization components
- **Creating** polarized **sources**
- **Ray tracing** polarized light
- **Analyzing** polarized light

The content of this document was written with the assumption that the reader has an understanding of polarized light. For those interested in the fundamental concepts of polarized light, please see "List of References" on page 31.

Specific ASAP commands are capitalized when referred to inside this document. Examples of ASAP scripts presented in this document were created in the ASAP Editor. The Editor document window is shown once in the first example. Subsequent examples show only the script.

This technical guide is complemented by the technical publication bro4310, "Polarization: Improved simulation of real-world devices in ASAP", which describes polarization features added in ASAP 2008 and later. This and any other BRO technical publication referenced in this document may be viewed or downloaded from the BRO Knowledge Base, http://www.breault.com/k-base.php.

POLARIZATION COMMANDS

Most of the commands used in polarization analysis are the same as those used in scalar analysis. This document discusses performing polarization analysis in ASAP using 12 commands. Some of these 12 commands are used for only polarization analysis, while others are also used in scalar analysis; but, to some extent, they are used differently in polarization analysis. While there are some more advanced or specialized ASAP polarization techniques not discussed within this document, the techniques covered here allow you to handle the vast majority of polarization issues.

The table below lists the 12 commands organized into five command types.

TABLE 1. ASAP Commands for Polarization Analysis

Command Type	Command Name
System	**FRESNEL BOTH** **XMEMORY**
Coating	**INTERFACE** **COATING LAYERS** **COATING MODELS**
Polarization component	**IDEAL** **CRYSTAL**
Source creation	**POLARIZ**[1]
Analysis	**PLOT POLARIZATION** **LIST ELLIPSE** **FIELD** **FIELD...DELTA** **POLARIZ**[1]

[1]The **POLARIZ** command is used as both a source creation and an analysis command.

SETTING UP THE SYSTEM

Initial system commands

We must issue two general commands to perform ASAP analysis with polarized light. These commands are **FRESNEL BOTH** and **XMEMORY** (either **NORM** or **FULL**). If you are interested in modeling birefringent crystals or total internal reflections, you must also issue the **SPLIT** command.

The **FRESNEL BOTH** command instructs ASAP to apply the Fresnel equations at media boundaries to obtain the appropriate amounts of reflected and transmitted light. **BOTH** refers to calculating the **S** and **P** polarization components separately for both reflection and polarization, leading to two reflection and two transmission coefficients. In the default form, **FRESNEL AVE**, the **S** and **P** polarization components are averaged together, thus leaving only one reflection and one transmission coefficient. The application of polarization-sensitive coatings to media boundaries is discussed in "Polarization-sensitive coatings" on page 9.

The **XMEMORY** command determines the amount of information that accompanies each ray. It is always set at one of three levels: **MIN**, **NORM**, or **FULL**. **XMEMORY MIN** stores the least amount of ray data. To perform polarization analysis in the **BEAMS INCOHERENT GEOMETRIC** mode, we must issue the **XMEMORY NORM** command, which is the default setting. This command instructs ASAP to include additional information with each ray that describes its polarization state. It is not necessary to explicitly issue an **XMEMORY** command when working in the **BEAMS COHERENT DIFFRACT** mode, because issuing the **PARABASAL** command automatically sets the **XMEMORY** to **FULL**.

Polarization-sensitive coatings

Three ways exist to assign a polarization-sensitive coating to an **OBJECT** in ASAP. The simplest method is to use the **INTERFACE** command and choose numerical reflection and transmission values for normal incidence. ASAP determines a quarter-wave layer that achieves these values at normal incidence. At all other angles of incidence, ASAP calculates the correct Fresnel reflection and transmission coefficients for the incident polarization and angle of incidence based on the quarter-wave layer it determined. Although this method is not based on the users actual system, it is simple and at times may be adequate.

The most precise method for specifying a polarization-sensitive coating in ASAP is with the **COATING LAYERS** command. Two basic ways to use the **COATING LAYERS** command exist. You can enter the layer thicknesses as either the physical thickness in **WAVELENGTH** units, or as the optical thickness (the product of the index and the physical thickness) in units of the reference vacuum wavelength. The syntax for **COATING LAYERS** is:

```
COATING LAYERS [W]
d  m  [ d'  m'  d''  m'' ... ] ['name']
```

NOTES:

`W`	reference wavelength in vacuum
`d`	layer thickness—either (1) physical thickness in wavelength units, or (2) optical waves of reference wavelength
`m`	names (or numbers) of previously defined media

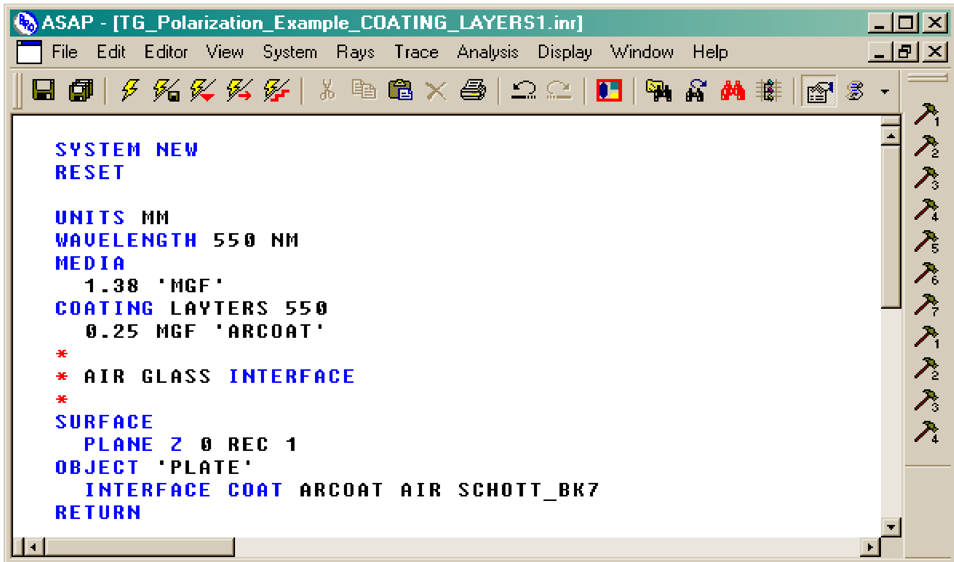
(1) If `W` is entered, the layer thicknesses are optical thicknesses in units of the reference wavelength in a vacuum. If `W` is absent, the layer thicknesses are physical thicknesses specified in wavelength units.

(2) Layers are defined starting from the low-index side of the interface and ending on the high-index side of the interface. This order is usually the opposite of the order in which the real layers are applied to a substrate.

(3) Groups of `d` layers can be replicated `m` times by placing a `-d` and a positive `m` after a group of layers.

Two examples of a **`COATING LAYERS`** input, which were created in the ASAP Editor, are shown below. The first is a simple quarter-wave magnesium fluoride (MGF) coating, using the form with a reference wavelength (**`W`**) specified. The second example describes physical layer thicknesses in wavelength units, and uses the layer group replication method described in Note (3) above.

The first example shows a script with the **`COATING LAYERS`** command, and specifies the layer as fractional optical waves of the reference wavelength (550 nm in this case). In other words, the product of the physical thickness of the layer times the MGF index (1.38) is equal to 0.25 × 550 nm.



Example 1 of **COATING LAYERS** *command (shown in the ASAP Editor document window)*

The second example of script with the **COATING LAYERS** command specifies the layer as physical thicknesses in **WAVELENGTH** units (**NM**, in this case). It uses the group replication feature to replicate the group of two layers (**MGF** and **FICT**) five times.

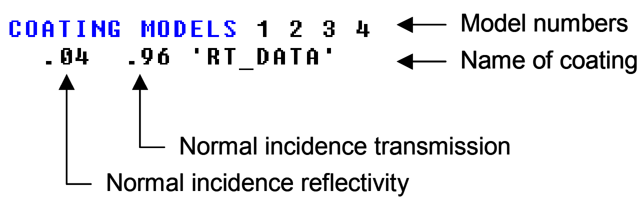
```
SYSTEM NEW
RESET

WAVELENGTH 550 NM
MEDIA
  1.38 'MGF'
  1.83 'FICT'
COATING LAYERS
  99.638 MGF 75.137 FICT -2 5 'DEMO_COAT'
*
* AIR GLASS INTERFACE
*
SURFACE
  PLANE Z 0 REC 1
OBJECT 'PLATE'
  INTERFACE COAT DEMO_COAT AIR SCHOTT_BK7
RETURN
```

Example 2 of script for **COATING LAYERS** *command*

The final method for defining a polarization-sensitive coating uses the **COATING MODELS** command. With this command, you can assign specific reflection and transmission values to an **OBJECT** as a function of incident angle and polarization. These values are supplied in the form of a look-up table, which is called by the **BSDFDATA** command and the ...**ANGLES** command argument. This command is often useful if the exact coating prescription is not known, but measured reflection and transmission values are available. It can also be useful to model more realistic coating behavior than the ideal prescription due to errors in layer thicknesses and indices.

COATING MODELS has two syntax forms. These two forms are similar, except that the more complex form allows for the use of different models for different wavelengths. This document addresses the simpler form. The slightly different syntax for the other form can be found in either ASAP online Help or the *ASAP Reference Manual* (see the Command Output window for a link to the manual, or look in <install dir>\asapxx\doc\manual.txt or manual.pdf).

The syntax for the simpler (without wavelength dependence) **COATING MODELS** command is given below.



Example of script for **COATING MODELS** *command*

The numbers shown as **1 2 3 4** in the example above refer to the **MODELS** corresponding to the S-polarization reflection, P-polarization reflection, S-polarization transmission, and P-polarization transmission, respectively. We can refer to the same **MODEL** for more than one of the four categories, such as

```
COATING MODELS 1 1 2 2
```

or even,

```
COATING MODELS 1 1 1 1
```

The two numbers on the next line of the command give the normal incidence reflectance and transmittance coefficients. These numbers are followed by the name assigned to the coating.

The form of the entry for the **BSDFDATA** table is shown below.

```
MODELS
  BSDFDATA ANGLES
     0   0   1
    10   0   .95
    20   0   .90
    30   0   .85
    40   0   .80
    50   0   .75
    60   0   .70
    70   0   .65
    80   0   .60
    90   0   .55
```

Example of a **BSDFDATA** *table, to which the* **COATING MODELS** *command refers*

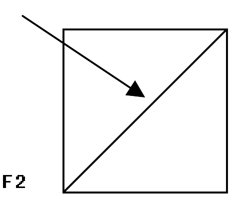
The first column of numbers on the left of the **BSDFDATA** table lists angle of incidence values. For use in **COATING MODELS**, the entries in the middle column of numbers are always 0's. The last column of numbers on the right contains the flux values. Once constructed, this **MODEL** can be referred to in any of the four positions in the **COATING MODELS** command. The given flux values represent only one of the two components of the actual ray reflection and transmission values. The reflection and transmission amounts for a ray at a given angle are obtained by multiplying the flux values from the **BSDFDATA** table by the appropriate (**r** or **t**) normal incidence value given in the second line of the **COATING MODELS** command.

***NOTE*: Several peculiarities exist with this command, which are due to its original purpose for defining scatter models. The zero degree angle of incidence value is always normalized to a value of one. The other values are then scaled by the same factor. Values for angles intermediate to those listed explicitly in the table are interpolated linearly in logarithmic space. Therefore, to get more accurate interpolation for intermediate values, you need to explicitly specify many table values at close increments, rather than having large gaps between angle entries. Also, because logarithms are involved, you need to specify zero flux values with very small numbers, such as 1E-9, rather than exactly zero.**

An example of ASAP script that defines **MODELS** and **COATING MODELS** is shown below.

```
SYSTEM NEW
RESET

MODELS
 BSDFDATA ANGLES !! R(s-pol)
   0    0    1
  35    0    .85
  40    0    .93
  45    0    .97
  50    0    .93
  55    0    .85
  90    0    1

 BSDFDATA ANGLES !! R(p-pol)
   0    0    1
  35    0    0.2
  40    0    0.1
  45    0    0.005
  50    0    0.1
  55    0    0.2
  90    0    1

 BSDFDATA ANGLES !! T(s-pol)
   0    0    1
  35    0    .15
  40    0    .07
  45    0    .03
  50    0    .07
  55    0    .15
  90    0    1

 BSDFDATA ANGLES !! T(p-pol)
   0    0    1
  35    0    0.2
  40    0    0.9
  45    0    .995
  50    0    0.9
  55    0    0.8
  90    0    1

COATING MODELS 1 2 3 4
 1 1 'POL_BS'  !! The behavior at
               !! normal incidence

SURFACE
 PLANE  Z   0  RECT 20 90
    ROTATE  Y   135.0  0  0
OBJECT 'CUBE_HYPOTENUSE'
  INTERFACE COATING   POL_BS  NCaF2  NCaF2
```

Name of interface coating for hypotenuse



Example of **MODELS** and **COATING MODELS**, and applying **COATING MODEL** to an **OBJECT**

Polarization components

Two commands exist in ASAP for describing polarization components: **`IDEAL`** (a **`LENS`** type) and **`CRYSTAL`** (a **`MEDIA`** type). The **`IDEAL`** command describes the polarization properties of the component in the form of a Jones operator (a 2×2 matrix). The **`CRYSTAL`** command describes a uniaxial birefringent medium. These commands are described in more detail below.

IDEAL

The **`IDEAL`** command is a type of **`LENS`** entity. For polarizing elements, the values in the row following the **`IDEAL`** command are always set to **`1 0 0 1`**. The next row is the Jones operator in a row format rather than the conventional 2×2 format.

TABLE 2. Examples of equivalent Jones operators in their conventional 2x2 format, and in the ASAP four-value row format

Polarizing Element	Jones Matrix	ASAP Representation
Vertical linear polarizer	$\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$	`0 0 0 1`
Horizontal linear polarizer	$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$	`1 0 0 0`
45° linear polarizer	$\frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$	`0.5 0.5 0.5 0.5`
-45° linear polarizer	$\frac{1}{2}\begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}$	`0.5 -0.5 -0.5 0.5`
Quarter-wave plate (fast axis vertical)	$e^{i\frac{\pi}{4}}\begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix}$	`COS[45] 'SIN[45] 0 0 SIN[45] '-COS[45]`
Quarter-wave plate (fast axis horizontal)	$e^{i\frac{\pi}{4}}\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$	`COS[45] 'SIN[45] 0 0 -SIN[45] 'COS[45]`
Half-wave plate (fast axis vertical or horizontal)	$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$	`1 0 0 -1`
Half-wave plate (fast axis ±45°)	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	`0 1 1 0`

Polarizing Element	Jones Matrix	ASAP Representation
Right circular polarizer	$\frac{1}{2}\begin{pmatrix} 1 & i \\ -i & 1 \end{pmatrix}$	`0.5 0`-0.5 0`-0.5 0.5`
Left circular polarizer	$\frac{1}{2}\begin{pmatrix} 1 & -i \\ i & 1 \end{pmatrix}$	`0.5 0`-0.5 0`0.5 0.5`

Case 1

```
LENS
IDEAL Z 0 10
  1 0 0 1      <-- "a b c d" matrix elements
  1 0 0 0      <-- Horizontal polarizer Jones matrix elements
OBJECT 'POLARIZER'
INTERFACE 0 1 AIR AIR
ROTATE Z 45 0 0      <-- Rotate polarizer 45°
```

Case 2

```
LENS
IDEAL Z 0 10
  1 0 0 1
  .5 .5 .5 .5      <-- 45° polarizer Jones matrix elements
OBJECT 'POLARIZER'
INTERFACE 0 1 AIR AIR
```

Two ways to generate the same polarizing element with the **IDEAL** *command*

CRYSTAL

One of the media supported in ASAP is crystal. The **MEDIA CRYSTAL** command establishes a uniaxial birefringent medium. Within the command, we must specify the following information:

- Index of refraction for rays polarized along the crystal (or optic) axis.
- X, Y, and Z component values for any vector-oriented parallel to the crystal axis (or, equivalently, the direction cosines).
- Medium that describes the ordinary index (polarized perpendicular to the crystal axis). This entry references a medium that had to be defined prior to the **MEDIA CRYSTAL** command.
- Name of the crystal.

```
MEDIA
  1.655 'CALCITE_ORD'
  1.485 CRYSTAL 0 .7071 .7071 CALCITE_ORD 'CALCITE_MEDIUM'
```

Example of a birefringement crystal constructed with the **MEDIA CRYSTAL** *command*

Note that the incident ray is split into an ordinary ray and an extraordinary ray. The ordinary ray is considered the parent ray in ASAP, while the extraordinary ray is the child ray. In general, the **SPLIT** command must be set high enough to allow for one increase in generation for every time the ray propagates through the crystal. Issues related to calculating the correct field energy and polarization state for beams after propagation through crystals are addressed in the section, “Analyzing Polarized Light” on page 24.

BRO recommends defining a separate CRYSTAL for each component in a system. The reason is that, if an object that references a CRYSTAL is moved, the coordinate transformation is applied to the medium and therefore changes all OBJECTS that reference that medium.

CREATING POLARIZED SOURCES

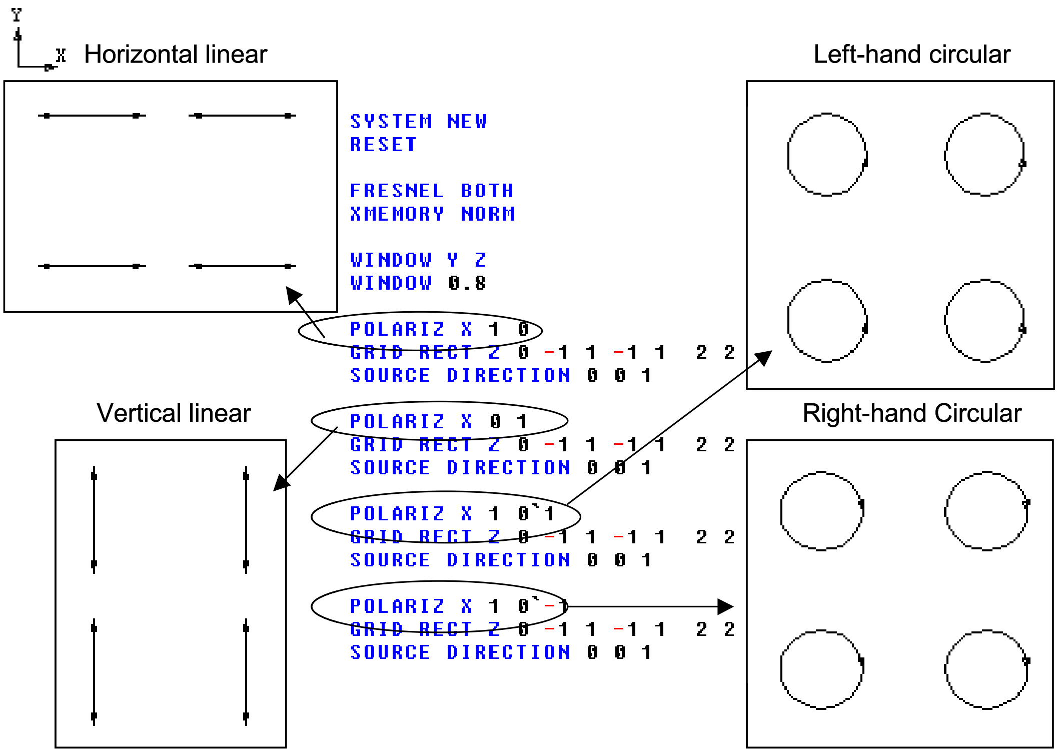
The **POLARIZ** command must be issued *prior to* polarized source creation. This command sets the polarization for all future source creation. The polarization state given in the **POLARIZ** command stays in effect until a different **POLARIZ** command is issued. The **POLARIZ** command is also used to examine the properties of the individual X, Y, or Z field components. This second type of application of the **POLARIZ** command is described later in this guide in the analysis section.

Similar to the common Jones vector representation, the **POLARIZ** command describes the polarization state of the light by specifying the complex amplitude of two orthogonal polarization states. The ASAP syntax for creating the intended state of polarization is shown below.

```
POLARIZ X  [a  a']
        Y
        Z
```

Example of a **POLARIZ** *source*

The first entry after the word **POLARIZ** is one of the global X, Y, or Z axes. The value of the **a** entry specifies the complex amplitude of the polarization component in this specified global axis direction. The **a′** term that follows the **a** term gives the complex amplitude of the polarization component orthogonal to both the **a** component and the ray direction. **ROTATE** or **SOURCE DIRECTION** is applied after ray creation, and gives rise to polarization directions that remain orthogonal to the ray propagation direction. Examples using the **POLARIZ** command to specify various polarization states are given below.



Examples of **POLARIZ** *command to specify four polarization states*

You can specify a linear polarization state that is polarized along any of the three global axes without explicitly specifying **a** and **a′** values. An example of this is given below.

```
POLARIZ X
```

Several other ways exist for specifying the same polarization state. For example, the three **POLARIZ** commands shown below all specify the same X-polarization state.

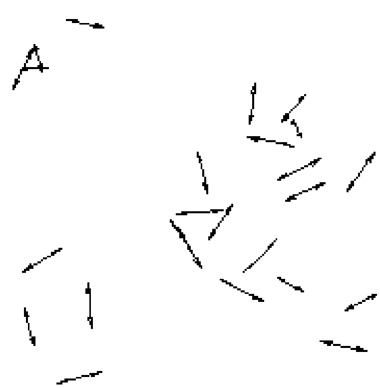
```
POLARIZ X
POLARIZ X 1 0
POLARIZ Y 0 1
```

The ASAP source-creation commands, **GRID**, **GAUSSIAN**, **RAYSET**, and **DECOMPOSE**, create totally polarized light. As stated previously, the polarization state is input through the **POLARIZ** command in a form similar to Jones vectors. States of partial polarization can be created only through the incoherent summing of combinations of differently polarized sources. In ASAP, it is not possible to input polarization states directly in the form of Stokes vectors. When a **POLARIZ** command is issued prior to an **EMITTING** command, the chosen polarization state is applied to all the rays prior to the randomizing of their directions. Next, the directions of the rays get randomly perturbed. Because of this, the user should be careful when using **POLARIZ** in conjunction with **EMITTING**.

Two examples of sources generated by **EMITTING** and **POLARIZ** and are shown below. Each example shows the script and the plot output.

```
SYSTEM NEW
RESET

FRESNEL BOTH
XMEMORY NORM

POLARIZ X
EMITTING RECT Z 0 1 1 25

WINDOW Y X
PLOT POLARIZ
```

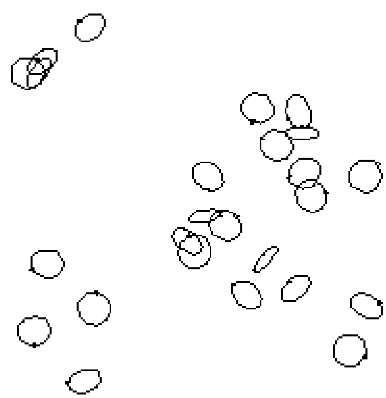
Example #1 of script using **EMITTING** *and* **POLARIZ** *linear horizontal*



Example #1 of plot generated from **EMITTING** *and* **POLARIZ** *linear horizontal*

```
SYSTEM NEW
RESET

FRESNEL BOTH
XMEMORY NORM

POLARIZ X 1 0`1
EMITTING RECT Z 0 1 1 25

WINDOW Y X
PLOT POLARIZ
```

Example #2 of script using **EMITTING** *and* **POLARIZ** *left-hand circular*



Example #2 of plot generated from **EMITTING** *and* **POLARIZ** *left-hand circular*

The **DECOMPOSE** command creates a set of beams that correspond to the field within the current BRO029.dat file. It is one of the four commands, along with **GRID**, **RAYSET**, and **GAUSSIAN**, that allow for the creation of **COHERENT** sources. As such, if polarization analysis is being performed, a **POLARIZ** command must be issued prior to the **DECOMPOSE** command. Also, if the field to be decomposed has significant amounts of orthogonal polarization components, a **POLARIZ** and **DECOMPOSE** pair must be issued for each component.

An example is shown below.

```
POLARIZ X
DECOMPOSE POSITION
POLARIZ Y
DECOMPOSE POSITION
POLARIZ Z
DECOMPOSE POSITION
```

***NOTE*: Because of the method employed in ASAP, the results are sometimes more accurate when you skip one of the polarization components if the amount of energy in that component is several orders of magnitude less than the other components. In other words, if the field is polarized primarily in X and Y with only a tiny Z component, it may be more accurate to just decompose the X and Y components and skip the Z decomposition. To determine whether the component with the small amount of energy should be decomposed or not, we must examine how well the total fields match before and after `DECOMPOSE`.**

RAY TRACING POLARIZED LIGHT

When tracing polarized light, ASAP carries additional information for each ray. Even so, ray tracing with the **`TRACE`** command is exactly the same for polarized light as it is for scalar light, provided that the commands described in the previous two sections that relate to setting up the system and creating polarized sources have been done correctly.

ANALYZING POLARIZED LIGHT

Some of the commands used to analyze polarized light are most appropriate for use in the **`BEAMS INCOHERENT GEOMETRIC`** mode. These commands can still be used in the **`BEAMS COHERENT DIFFRACT`** mode, but portions of their output should be ignored. Also, some commands used to analyze polarized light can be used only in the **`BEAMS COHERENT DIFFRACT`** mode. These distinctions are addressed below.

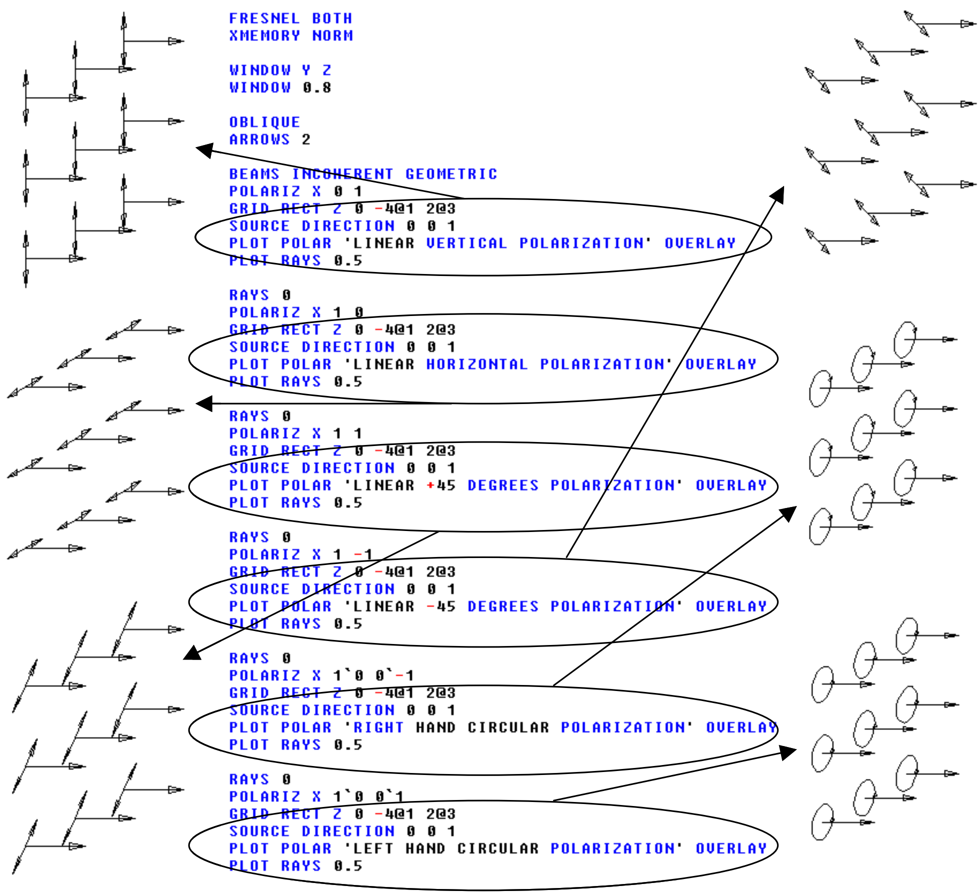
Polarization analysis in the BEAMS INCOHERENT GEOMETRIC mode

In ASAP, all the incoherent flux commands work the same in the analysis of polarized light as they do for analysis without polarization. Two additional commands are available for polarization analysis in the **BEAMS INCOHERENT GEOMETRIC** mode. Those commands are **PLOT POLARIZATION** and **LIST ELLIPSE**.

PLOT POLARIZATION

PLOT POLARIZATION (also referred to in its simpler form as **PLOT POLAR**) plots the polarization ellipses of all the **CONSIDER**ed and **SELECT**ed rays that are inside the current **WINDOW** on a ray-by-ray basis. The size of the individual ellipse is related to the amount of ray flux. Arrows indicate the handedness of the polarization state. When used in conjunction with a **MEDIA CRYSTAL** command, it plots the ordinary and extraordinary rays separately, without information as to their relative phases. For this reason, we must use the **FIELD...DELTA** command to get the correct polarization state after propagation through **MEDIA CRYSTAL**. The **FIELD** command can be used only in **BEAMS COHERENT DIFFRACT** mode, and is discussed in “Polarization analysis in the BEAMS COHERENT DIFFRACT mode” on page 28.

A script example of the **PLOT POLAR** command is shown below.



Examples of the **PLOT POLAR** *command with* **PLOT RAYS** *and corresponding polarization plots*

LIST ELLIPSE

LIST ELLIPSE lists the polarization parameters of all the **CONSIDER**ed and **SELECT**ed rays on a ray-by-ray basis in the ASAP command output window. The three parameters listed are:

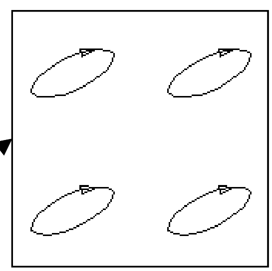
1 The orientation is described by listing the components of a unit vector (direction cosines) in the direction of the major axis of the polarization ellipse.

2 The ellipticity is described as the ratio of the length of the minor axis divided by the length of the major axis. This has a value of zero for linearly polarized light, one for circularly polarized light, and a value between zero and one for all other polarization states.

3 The handedness is described by the sign of the ellipticity. If the sign is positive, the polarization state is right-handed; if it is negative, the polarization state is left-handed. Right-handed is defined as the polarization direction rotating clockwise in time for light approaching the observer.

Similar to the **PLOT POLAR** command, the **LIST ELLIPSE** command lists the ordinary and extraordinary rays separately, without any relative phase information. For this reason, it is necessary to use the **FIELD...DELTA** command to get the correct polarization state after propagation through **MEDIA CRYSTAL**.

```
SYSTEM NEW
RESET

SEGMENTS 2
ARROWS 2

LENS
  IDEAL Z 0 1
  1 0 0 1
  COS[45]`SIN[45] 0 0 SIN[45]`-COS[45]
  ROTATE Z 25
OBJECT  'QUARTER_WAVE'
  INTERFACE 0 1 AIR AIR

SURFACE
  PLANE Z 1 RECTANGLE  1 1
OBJECT 'DETECTOR'
  INTERFACE 0 0 AIR AIR

POLARIZ X .707 .707
GRID RECT Z -1 -4@1  2 2
SOURCE DIRECTION 0 0 1

PROFILES OVERLAY
TRACE PLOT

CONSIDER ONLY DETECTOR
WINDOW Y X
PLOT POLAR
LIST ELLIPSE
```



```
Total of  200.20 millisec (   0.00 microsec CPU) to trace 4
 --- CONSIDER ONLY DETECTOR
 --- WINDOW Y X
 --- PLOT POLAR

 Distribution of data within:
     Window Vertical: Y = -2.00000    to  2.00000      ( 4.00000   )
          Horizontal: X = -2.00000    to  2.00000      ( 4.00000   )
[10] Click here to view - ASAP Plot  1

 --- LIST ELLIPSE
               Major Axis Orientation                                     Minor/Major
     Ray      X            Y            Z           Flux      Object        Ratio
        1  0.9063078    0.4226183    0.0000000    1.00            2     0.3639703
        2  0.9063078    0.4226183    0.0000000    1.00            2     0.3639703
        3  0.9063078    0.4226183    0.0000000    1.00            2     0.3639703
        4  0.9063078    0.4226183    0.0000000    1.00            2     0.3639703
```

Example of the **LIST ELLIPSE** *command*

Polarization analysis in the BEAMS COHERENT DIFFRACT mode

FIELD AND THE DELTA OPTION

The **FIELD** command is used in the **COHERENT** mode to calculate the complex field, regardless of whether we are examining a scalar field or a vector field including polarization. In the scalar case, ASAP calculates one complex field value per pixel; whereas, in the polarized case, it calculates three complex field values per pixel, one for each of the global X, Y, Z polarization components. Because of this, the maximum number of pixels available in **COHERENT** polarization analysis goes down by the square root of three in each dimension. The **SPREAD NORMAL** command can be used to calculate the field energy for **COHERENT** scalar fields, but it does not account for polarization, and therefore gives incorrect results when used for polarized fields. Use the **FIELD ENERGY** command to calculate the energy for polarized fields. This command correctly sums the squared moduli of the X, Y, and Z components to obtain the total field energy.

To examine the various field components of the field for a given polarization in ASAP, we must first issue a **POLARIZ** command, which specifies the component of interest. (A different usage of this command was described earlier to set the polarization state for future source creation.) This step applies for any of the field parameters except **FIELD ENERGY**, which as stated above, sums all the components together in quadrature. The example below shows the commands we must use to examine the phase of each component after issuing a **FIELD** command in any form.

```
POLARIZ X
DISPLAY 29 PHASE  !! displays x-pol phase
POLARIZ Y
DISPLAY 29 PHASE  !! displays y-pol phase
POLARIZ Z
DISPLAY 29 PHASE  !! displays z-pol phase
```

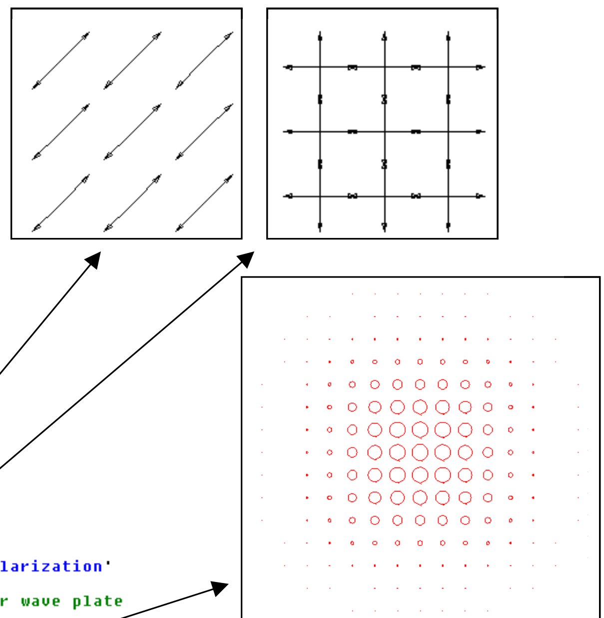
The **POLARIZ** command can also be used to determine the amount of energy in each component. When used in conjunction with the **FORM 2** command to square the amplitude (or modulus) values on a pixel-by-pixel basis, we obtain an energy map for a given polarization component.

An example is given below.

```
POLARIZ X
DISPLAY 29 AMPLITUDE
FORM 2 !! generates array of x-pol energy values
POLARIZ Y
DISPLAY 29 AMPLITUDE
FORM 2 !! generates array of y-pol energy values
POLARIZ Z
DISPLAY 29 AMPLITUDE
FORM 2 !! generates array of z-pol energy values
```

The **FIELD** command used with the **DELTA** option creates a plot of the polarization ellipses. Unlike the **PLOT POLAR** command, the plots created by **FIELD...DELTA** sum the overlapping beam fields with the appropriate relative phases. This process allows for the correct plotting of the polarization ellipses, even after the beams have split into ordinary and extraordinary beams. An example is shown below.

```
UNITS MM
FRESNEL BOTH

MEDIA
 1.5 'ORD'
 1.501 CRYSTAL 1 0 0 ORD 'QWP'

SURFACE
 PLANE Z 1 RECT 2
OBJECT 'QWP.FRONT'
INTERFACE 0 1 AIR QWP

SURFACE
 PLANE Z 1.25 RECT 2
OBJECT 'QWP.BACK'
INTERFACE 0 1 AIR QWP

SURFACE
 PLANE Z 2 RECT 2
OBJECT 'DET'

PARABASAL 4
BEAMS COHERENT DIFFRACT
WIDTHS 1.6
WAVELENGTH 1 UM

POLARIZ X 1 1
GRID ELLIPTIC Z 0 -4@1 3 3
SOURCE DIRECTION 0 0 1

PIXELS 15
WINDOW Y X
PLOT POLARIZATION 'Intitial polarization'

TRACE  !! trace through quarter wave plate

WINDOW Y X
PLOT POLARIZATION 'PLOT POLAR plots each extraordinary and ordinary ray separately '

TITLE 'FIELD...DELTA sums the extraordinary and ordinary rays coherently'
FIELD ENERGY DELTA
DISPLAY
```



Example of the same field examined with both the **PLOT POLAR** *command and the* **FIELD...DELTA** *command*

LIST OF REFERENCES

- *Optics*, Eugene Hecht, 4th Edition. Pearson Education, 2001, ISBN 0805385665. This is a general book about optics, presented at a basic level of understanding, and is a good place to start.
- *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*. Max Born and Emil Wolf. Cambridge University Press, 1999, ISBN 0521642221. This is a general book about optics, presented at an advanced level of understanding.
- *Fundamentals of Polarized Light: A Statistical Approach*, Christian Brosseau, John Wiley & Sons, Inc., 1998, ISBN 0471143022.
- *Polarized Light: Production and Use*, William A. Shurcliff. Umi Research Pr, 1980, ASIN 0317080512. Out of print, but may be available on the Internet.
- *Optical Waves in Crystals: Propagation and Control of Laser Radiation*, Amnon Yariv and Pochi Yeh. John Wiley & Sons, Inc., 2002, ISBN 0471430811.
- Polarized Light in Optics and Spectroscopy, D. S. Kliger, J. W. Lewis, C. E. Randall. Academic Press, 1997, ISBN 0124149758. This book is a comprehensive introduction to polarized light. Out of print, but may be available on the Internet.

SCRIPT EXAMPLES FOR POLARIZATION

A

The following scripts are examples of polarization in ASAP. You can copy and paste the script into an editor, such as the ASAP Editor, and run the file to see the results.

Crystal Interference Pattern

Creates a birefringent medium with the **CRYSTAL** command and polarizer with the **IDEAL** command to create an interference pattern from a diverging beam.

```
!!ASAP EXAMPLE OF INTERFERENCE FROM A BIREFRINGENT
!!UNIAXIAL CRYSTAL
SYSTEM NEW
RESET

UNITS MM
WAVELENGTH 0.0001

MEDIA
  1.6 'ORD'
  1.5 CRYSTAL 0 0 1 ORD 'CRYSTAL'

FRESNEL BOTH

SURFACE
  PLANE Z 1 RECT 1.5
OBJECT 'SIDE_1'
  INTERFACE COAT +BARE AIR CRYSTAL

SURFACE
  PLANE Z 2 RECT 1.5
OBJECT 'SIDE_2'
  INTERFACE COAT +BARE AIR CRYSTAL

LENS
  IDEAL Z 3 2
    1 0 0 1 define a no lens
    0 0 0 1 turn it into a vertical linear polarizer
OBJECT 'LINEAR_POLARIZER'

SURFACE
```

```
  PLANE Z 4 RECT 2.5
OBJECT 'DETECTOR'

BEAMS COHERENT DIFFRACT
PARABASAL 4
WIDTHS 1.6

POLARIZ X 1 0
GRID POLAR Z 0 0 1 0 360 5 6
SOURCE POSITION 0 0 -5

TITLE 'BIREFRINGENT PLATE WITH LINEAR POLARIZER'

WINDOW Y Z

PROFILES OVERLAY

TRACE PLOT

CONSIDER ONLY DETECTOR
WINDOW Y -2@2 X -2@2
PIXELS 301

FIELD ENERGY 4

DISPLAY
PICTURE

RETURN
```

Double Refraction Ray Trace

Generates a plot of double refraction for a ray trace through a calcite crystal.

```
!!ASAP FILE OF ORDINARY AND EXTRAORDINARY RAY
!!SPLITTING IN CALCITE
SYSTEM NEW
RESET

UNITS MM
WAVELENGTH 630 NM

FRESNEL BOTH
```

```
MEDIA
  1.655 'CALCITE_ORD'
  1.485 CRYSTAL COS[30] 0 SIN[30] CALCITE_ORD 'CALCITE_EXT'

SURFACE
  PLANE Z 0 RECT 10
OBJECT 'CALCITE_FRONT'
  INTERFACE COATING +BARE AIR CALCITE_EXT

SURFACE
  PLANE Z 10 RECT 10
OBJECT 'CALCITE_BACK'
  INTERFACE COATING +BARE AIR CALCITE_EXT

BEAMS INCOHERENT GEOMETRIC

POLARIZ X 1 1
RAYSET Z -5
0 0 1
SOURCE DIR 0 0 1

WINDOW X Z
TITLE 'ORDINARY AND EXTRAORDINARY RAY TRACES THROUGH CALCITE'
PLOT FACETS OVERLAY
TRACE PLOT
```

Birefringent Sapphire Dome

Creates sapphire dome with the **CRYSTAL** command, traces rays through dome, and calculates polarization map of field.

```
!! Polarization Effects of a Sapphire Dome
SYSTEM NEW
RESET

WAVELENGTH 4250 UNITS 1.E-6

MEDIA
  1.664 'ORDSAP' !ordinary indices for following extraordinary
  1.656 CRYSTAL 0 0 1 ORDSAP 'SAPPHIRE'

FRESNEL BOTH
```

```
SPLIT 1

SURFACE
  OPTICAL Z 0 37.5 ELLIPSE 37.5
OBJECT 'DOME_OUTER'
  INTERFACE COATING +BARE AIR SAPPHIRE

SURFACE
  OPTICAL Z 0 35.214 ELLIPSE 35.214
OBJECT 'DOME_INNER'
  INTERFACE COATING +BARE AIR SAPPHIRE
  SHIFT Z 2.286

SURFACE
  PLANE Z 0 ELLIPSE 40
OBJECT 'IMAGE'
  SHIFT Z 45

BEAMS INCOHERENT GEOMETRIC

GRID ELLIPTIC Z -1 -1 1 -30 30 1 5
SOURCE DIRECTION Z

PROFILES OVERLAY 'SAPPHIRE DOME & RAY TRACE'
TRACE PLOT

RAYS 0
BEAMS COHERENT DIFFRACT
PARABASAL 8
WIDTHS 1.6

POLARIZ X 1 1'90
GRID ELLIPTIC Z -5 -4@30 2@25
SOURCE DIRECTION Z

WINDOW Y X
ARROWS 1
SEGMENTS 2
PLOT POL 'INPUT POLARIZATION'

TRACE
PLOT POLAR 'OUTPUT POLARIZATION VIA PLOT POLAR'

TITLE 'ACTUAL ELECTRIC FIELD BEHAVIOUR'
PIXELS 15 set pixels for field real points
FIELD REAL 45 DELTA
```

```
$DO 1 4
FIELD REAL 45 DELTA +?/8 OVERLAY COLOR ?

RETURN
```

Crystal Quarter-Wave Plate

Constructs a quarter-wave plate using the **CRYSTAL** command, traces rays, and generates polarization map of beam with both **PLOT POLARIZ** and **FIELD...DELTA**.

```
!!ASAP FILE OF A CALCITE QUARTER WAVE PLATE
!!FAST AXIS VERTICAL
SYSTEM NEW
RESET

UNITS MM
FRESNEL BOTH

MEDIA
(NO=1.655) 'CALCITE_ORD'
(NE=1.485) CRYSTAL 0 1 0 CALCITE_ORD 'CALCITE_EXT'

!!FIRST CALCULATE THE REQUIRED THICKNESS OF QUARTER WAVE PLATE
!!PHASE=2PI/LAMBDA*D*(NO-NE)=PI/2 FOR QUARTER WAVE PLATE

LAMBDA=0.6328E-3
D=LAMBDA/(4*ABS(NO-NE))

!!SOME OTHER VARIABLES TO DEFINE THE LASER
W0=0.5 !!LASER WAIST SIZE 1/e^2 RADIUS
PI=4*ATAN(1)

SURFACE
  PLANE Z 0 RECT 10
OBJECT 'Q_WAVE_FRONT'
  INTERFACE COATING +BARE AIR CALCITE_EXT

SURFACE
  PLANE Z (D) RECT 10
OBJECT 'Q_WAVE_BACK'
  INTERFACE COATING +BARE AIR CALCITE_EXT

SURFACE
  PLANE Z 1 RECT 10
OBJECT 'DETECTOR'

!!Macro to create Polarized GRID POLAR
```

```
POLAR_RAY { 3
BEAMS COHERENT
WAVELENGTH 632.8 NM
PARABASAL 4
WIDTH 1.6

POLARIZ X #1 #2
USERAPOD POS 2@(W0*SQRT(PI/2)) W0*SQRT(PI/2)^2
GRID POLAR Z -1 0 4.6*W0/2 0 360 11 6
SOURCE DIR SIN[#3] 0 COS[#3]
}
ENTER POLARIZ X a POLARIZATION COMPONENT>
ENTER POLARIZ X a' POLARIZATION COMPONENT>
ENTER INCIDENT ANGLE>

!!Macro to do the polarization analysis
ANALYSIS {
$POLAR_RAY 1 1 0

WINDOW Y -2@(4.6*W0/2) X -2@(4.6*W0/2)
WINDOW 1.25
PIXELS 51

FIELD ENERGY -1
DISPLAY
ISOMETRIC 'INPUT LASER BEAM'
RETURN

PLOT POLAR 'PLOT POLAR ILLUSTRATION OF INPUT'
PIXELS 15

FIELD REAL -1 DELTA 'POLARIZATION ELLIPSES WITH FIELD...DELTA'

$DO 1 4
FIELD REAL -1 DELTA +?/8 OVERLAY 'ELECTRIC FIELD VECTORS WITH FIELD...DELTA!'
RETURN

WINDOW Y Z
TITLE 'RAY TRACE THROUGH CALCITE'
PROFILES OVERLAY
TRACE PLOT 10 TEXT OVERLAY
0 3 -5, 0 0 0.25, 0 0.25 0 'QUARTER WAVE PLATE'
0 2 2, 0 0 0.25, 0 0.25 0 'DETECTOR'
RETURN
RETURN
```

```
CONSIDER ONLY DETECTOR
WINDOW Y -2@(4.6*W0/2) X -2@(4.6*W0/2)
WINDOW 1.25
PIXELS 51

FIELD ENERGY 1
DISPLAY
ISOMETRIC 'LASER BEAM AFTER QUARTER WAVE PLATE'
RETURN

PLOT POLAR 'PLOT POLAR ILLUSTRATION OF OUTPUT'
PIXELS 15

FIELD REAL 1 DELTA 'OUTPUT POLARIZATION ELLIPSES WITH FIELD...DELTA'
$DO 1 4
FIELD REAL 1 DELTA +?/8 OVERLAY 'OUTPUT ELECTRIC FIELD VECTORS WITH FIELD...DELTA' COLOR ?
}

$ANALYSIS
RETURN
```

Dichroic Polarizer

Uses the **CRYSTAL** command to create dichroic polarizer, traces rays, and calculates transmitted polarization.

```
!!ASAP FILE TO DEMONSTRATE A DICHROIC POLARIZER
SYSTEM NEW
RESET

UNITS MM
FRESNEL BOTH
BEAMS INCOHERENT GEOMETRIC

CUTOFF (C=1E-9)

A=-LOG(C)/10 !!ABSORPTION COEFFCIENT
MEDIA
  1.6 ABSORB (A) 'ORDINARY'
  1.5 CRYSTAL COS[30] 0 SIN[30] ORDINARY 'DICHROIC'

SURFACE
  PLANE Z 0 RECT 10
```

```
OBJECT 'FRONT'
  INTERFACE COATING +BARE AIR DICHROIC

SURFACE
  PLANE Z 10 RECT 10
OBJECT 'BACK'
  INTERFACE COATING +BARE AIR DICHROIC

POLARIZ X 1 1
RAYSET Z -5
0 0 1
SOURCE DIRECTION 0 0 1

WINDOW Y -2@2 X -2@2
PLOT POLAR 'POLARIZATION STATE BEFORE DICHROIC POLARIZER'
LIST ELLIPSE

TITLE 'DICHROIC POLARIZER: EXTINGUISHING THE EXTRAORDINARY RAY'
WINDOW X Z
PLOT FACETS OVERLAY
TRACE PLOT

WINDOW Y -2@2 X -2@2
PLOT POLAR 'POLARIZATION STATE AFTER DICHROIC POLARIZER'
LIST ELLIPSE
```

Glan Prism Polarizer

Constructs a Glan polarizing prism using the **CRYSTAL** command, traces ray through polarizer, and examines the polarization states of the beams emerging from the top and back of the prism. The polarization of the top beam, which should be a mixed polarization state, is simplified by assigning a **+BARE INTERFACE** on the diagonal surfaces of the prism. Therefore, the reflected beam through the prism top is only the TIR beam of the single polarization component.

```
!!ASAP FILE OF GLAN FOUCAULT PRISM
SYSTEM NEW
RESET

UNITS MM
WAVELENGTH 630 NM
FRESNEL BOTH
SPLIT 2
BEAMS INCOHERENT GEOMETRIC
```

```
MISSED ARROWS 5

MEDIA
  1.655 'CALCITE_ORD'
  1.485 CRYSTAL 1 0 0 CALCITE_ORD 'CALCITE_EXT'

AIR_GAP=0.25

SURFACE
  PLANE Z 0 RECT  5 ((5-(AIR_GAP/2))/TAN[38.5])
OBJECT 'CALCITE_FRONT'
  INTERFACE COATING +BARE AIR CALCITE_EXT

SURFACE
  PLANE Y (5-(AIR_GAP/2))/TAN[38.5]
  PLANE Z 0
  PLANE Z 5-(AIR_GAP/2) RECT 5 25
  ROTATE X 38.5 0 5-(AIR_GAP/2)
OBJECT 'CALCITE_MID1'
  INTERFACE COATING +BARE AIR CALCITE_EXT
  BOUNDS 0.2 -0.3

SURFACE
  PLANE Y -(5-(AIR_GAP/2))/TAN[38.5]
  PLANE Z 10
  PLANE Z 5+(AIR_GAP/2) RECT  5 25
  ROTATE X 38.5 0 5+(AIR_GAP/2)
OBJECT 'CALCITE_MID2'
  INTERFACE COATING +BARE AIR CALCITE_EXT
  BOUNDS -0.2 0.3

SURFACE
  PLANE Y -(5-(AIR_GAP/2))/TAN[38.5]
  PLANE Z 5+(AIR_GAP/2)
    ROTATE X 38.5 0 5+(AIR_GAP/2)
  PLANE Z 10  RECT  5 25
OBJECT 'CALCITE_BACK'
  INTERFACE COATING +BARE AIR CALCITE_EXT
  BOUNDS 0.2 0.3

SURFACE
  PLANE Z 0
  PLANE Z 5-(AIR_GAP/2)
    ROTATE X 38.5 0 5-(AIR_GAP/2)
  PLANE Y (5-(AIR_GAP/2))/TAN[38.5]  RECT  25 5
OBJECT 'CALCITE_TOP'
```

```
  INTERFACE COATING +BARE AIR CALCITE_EXT
  BOUNDS -0.2 0.3

SURFACE
  PLANE Z 10
  PLANE Z 5+(AIR_GAP/2)
    ROTATE X 38.5 0 5+(AIR_GAP/2)
  PLANE Y -(5-(AIR_GAP/2))/TAN[38.5] RECT  25 5
OBJECT 'CALCITE_BOTTOM'
  INTERFACE COATING +BARE AIR CALCITE_EXT
  BOUNDS 0.2 -0.3

POLARIZ X 1 1 !!.37 .6`.2
RAYSET Z -5
0 0 1
SOURCE DIRECTION 0 0 1

WINDOW Y -2@1 X -2@1
PLOT POLAR  '+45 DEGREE POLARIZED BEAM BEFORE TRACE'
LIST ELLIPSE

WINDOW Y Z
TITLE '+45 DEGREE POLARIZED BEAM TRACED THROUGH A GLAN FOUCAULT PRISM'
PLOT FACETS OVERLAY
TRACE PLOT

CONSIDER ONLY CALCITE_TOP
LIST ELLIPSE
WINDOW Z 3 4 X -2@.5
PLOT POLAR 'ORDINARY RAY'

CONSIDER ONLY CALCITE_BACK
LIST ELLIPSE
WINDOW Y -2@1 X -2@1
PLOT POLAR 'EXTRAORDINARY RAY'
```

Ideal Quarter-Wave Plate

Uses the **IDEAL** command to construct a quarter-wave plate, traces rays, and generates a polarization map of transmitted beam. Because the **IDEAL** command was used, there is no ray spitting and the **PLOT POLAR** command gives the same result for the transmitted polarization map as the **FIELD... DELTA** command.

```
!!Conversion of Linear to Circular Polarized Light with IDEAL Lens (ASAP Example)
SYSTEM NEW
RESET

UNITS MM
FRESNEL BOTH

WAVELENGTH 0.6328 UM
BEAMS COHERENT DIFFRACT
PARABASAL 4
WIDTHS 1.6

LENSES
  IDEAL Z 1 5
  1 0 0 1
  COS(45]`SIN(45] 0 0 SIN(45]`(-1*COS(45])
OBJECT 'QUARTER_WAVE_PLATE'

SURFACE
  PLANE Z 5 RECT 10
OBJECT 'DETECTOR'

POLARIZ X 1 1
GRID ELLIPTIC Z 0 -4@4.6 2@10
SOURCE DIRECTION 0 0 1

TITLE 'INPUT POLARIZATION STATE'
WINDOW Y X
PLOT POLAR

TRACE

SEGMENTS 2
ARROWS 1
TITLE 'POLARIZATION STATE AFTER QUARTER WAVE PLATE'
PLOT POLAR

PIXELS 15
TITLE 'ELECTRIC FIELD VECTOR'
FIELD REAL 5 DELTA

$DO 1 4
FIELD REAL 5 DELTA ?/8 OVERLAY  COLOR ?
RETURN
```

Wollaston Prism

Uses the **CRYSTAL** command to construct a Wollaston prism, ray traces, and shows a polarization map of the split rays.

```
!!ASAP FILE OF A WOLLASTON POLARIZING BEAM SPLITTER
SYSTEM NEW
RESET

TITLE 'BIREFRINGENT RAY SPLITTING IN A WOLLASTON PRISM'

MEDIA
  1.66
  1.49 CRYSTAL 1 0 0 1 'X_CALCITE'
  1.49 CRYSTAL 0 1 0 1 'Y_CALCITE'

BEAMS INCOHERENT GEOMETRIC
FRESNEL BOTH
SPLIT 2

SURFACE
  PLANE Z 0 RECT 1/TAN[15]
OBJECT 'FRONT'
  INTERFACE COAT +BARE AIR Y_CALCITE

SURFACE
  PLANE Z 1 RECT 1/SIN[15]; ROTATE X 15
OBJECT 'MIDDLE'
  INTERFACE COAT +BARE Y_CALCITE X_CALCITE

SURFACE
  PLANE Z 2 RECT 1/TAN[15]
OBJECT 'BACK'
  INTERFACE COAT +BARE X_CALCITE AIR

POLARIZ Y 1 1'90
RAYSET Z -1
0 0 1
SOURCE DIRECTION 0 0 1

WINDOW Y -2@1 X -2@1
PLOT POLAR 'INPUT POLARIZATION STATE'

WINDOW Y -1 1 Z -1 3
```

```
PROFILES OVERLAY
TRACE PLOT

CONSIDER ONLY 0.1

WINDOW Y X
WINDOW 1.5
PLOT POLARIZATION
```

Rhomb

Demonstrates the conversion of linear-to-circular polarization due to phase shifts on reflection from the surfaces of a Fresnel rhomb.

```
!!ASAP EXAMPLE OF FRESNEL RHOMB TO DEMONSRATE
!!POLARIZATION BY REFLECTION
SYSTEM NEW
RESET

BEAMS INCOHERENT GEOMETRIC
FRESNEL BOTH !!CONFIGURE POLARIZATION RAY TRACE
SPLIT 1

MEDIA
  1.517 'GLASS'

EDGES
  RECT Z 0 .5 .5 4
  REPEAT
  SHIFT Z 2
  SKEW Y 90-54.62 Z 0
OBJECT
  0.1 0.2 'PRISM_SIDES'
INTERFACE COATING BARE AIR GLASS

EDGES
  REPEAT 1
OBJECT 'FRONT_FACE'
  INTERFACE COATING BARE AIR GLASS

EDGES
  REPEAT
  SHIFT Z 2
```

```
  SKEW Y 90-54.62 Z 0
OBJECT 'BACK_FACE'
INTERFACE COATING BARE AIR GLASS

EDGES
  REPEAT 0.1
  SHIFT Z 1
OBJECT 'EXIT_PLANE'

!!SET UP +45 DEGREE LINEARLY POLARIZED SOURCE
POLARIZ X 1 1
GRID POLAR Z -.5 0 .5 0 360 1 4 1
SOURCE DIRECTION 0 0 1

WINDOW Y X
WINDOW .5
ARROWS 3
SEGMENTS 3
PLOT POLAR 'INPUT 45 DEGREE LINEAR POLARIZATION'

WINDOW Y -0.5 2 Z -0.5 3
ARROWS 1
TITLE 'TOTAL INTERNAL REFLECTION FRESNEL RHOMB'
PLOT FACETS 1 1 OVERLAY
TRACE PLOT

SELECT ONLY 0 C !!SELECT ONLY THOSE RAYS IN +Z DIRECTION
WINDOW Y X
WINDOW 0.5
ARROWS 3
PLOT POLAR 'OUTPUT CIRCULAR POLARIZATION'
$VIEW
```

Polarizer Rotator

Uses the **IDEAL** command to construct a polarization rotator, and traces rays through rotator— reflecting from mirror, back through the rotator, and to a detector. It uses the **LIST ELLIPSE** command to examine the starting polarization and the polarization after each pass through the rotator. It shows that this type of rotator behaves like a Faraday rotator, in that two passes through the device double the effect rather than cancel it.

```
!! POLARIZATION ROTATOR
SYSTEM NEW
```

```
RESET

FRESNEL BOTH
SPLIT 2

ALPHA=180 !! OPTICAL ROTARY POWER IN DEGREES/MM
THICKNESS=.125 !! ROTATOR THICKNESS IN MM
THETA=ALPHA*THICKNESS

LENSES
  IDEAL Z 1 1
  1 0 0 1
  COS[THETA] SIN[THETA] -SIN[THETA] COS[THETA] !!FLIP
OBJECT 'ROTATOR'

SURFACE
  PLANE Z 2 RECT 1
OBJECT 'MIRROR'
  INTERFACE 1 0 AIR AIR

SURFACE
  PLANE Z -1 RECT 1.5
OBJECT 'DET'

POLARIZ X 1 0
GRID RECT Z .5 -4@1 1 2
SOURCE DIRECTION 0 0 1
!!SOURCE DIRECTION 0 SIN[5] COS[5]

LIST ELLIPSE

WINDOW Y Z
PLOT POLAR OVERLAY
PLOT FACETS OVERLAY
TRACE 0 MIRROR PLOT
PLOT POLAR
LIST ELLIPSE

WINDOW Y Z
TRACE PLOT
PLOT POLAR
$VIEW

LIST ELLIPSE
```

Calculating Stokes Parameters

We can use the **IDEAL** lens to compute the Stokes vector. Recall that the Stokes vector defines a vector space that spans polarized, unpolarized, and partially polarized light. The Stokes vector is determined by measuring four polarization parameters of the light. All four polarization parameters are determined by individually inserting a filter into the beam and measuring the transmitted irradiance. The four filters are:

1 Isotropic filter (passes all polarization states equally)

2 Horizontal linear polarizer

3 Linear polarizer at 45 degrees

4 Right hand circular polarizer

The Stokes vector elements are computed from the irradiances as follows:

5 $S0 = I_H + I_V$

6 $S1 = I_H - I_V$

7 $S2 = I_{45} - I_{135}$

8 $S3 = I_R - I_C$

The Stokes filters are inserted (and rotated if required) separately into a ray of polarized light with the aid of a **$DO** loop. The **$DO** loop also traces the rays once through each filter. All the filters exist in the object database, but are turned off and on with the **CONSIDER** command. The flux of each ray is grabbed after propagating through each filter, and the Stokes parameters and degree of polarization are computed with the above equations.

```
!!FILE FOR CALCULATING STOKES PARAMETERS
SYSTEM NEW
RESET

UNITS MM
FRESNEL BOTH

COATING
  0 1   'TRANS_50'

!!ISOTROPIC FILTER
LENS
```

```
  IDEAL Z 0 10
  1 0 0 1
OBJECT 'ISOTROPIC'
  INTERFACE COATING TRANS_50 AIR AIR

!!HORIZONTAL LINEAR POLARIZER
LENS
  IDEAL Z 1 10
  1 0 0 1
  1 0 0 0
OBJECT 'HOR_LIN_POL'
  INTERFACE COATING TRANS_50 AIR AIR

!!VERTICAL LINEAR POLARIZER
LENS
  IDEAL Z 2 10
  1 0 0 1
  0 0 0 1
OBJECT 'VER_LIN_POL'
  INTERFACE COATING TRANS_50 AIR AIR

!!+45 DEGREE LINEAR POLARIZER
LENS
  IDEAL Z 3 10
  1 0 0 1
  1 0 0 0
OBJECT '45D_LIN_POL'
  INTERFACE COATING TRANS_50 AIR AIR
  ROTATE Z 45 0 0

!!+135 DEGREE LINEAR POLARIZER
LENS
  IDEAL Z 4 10
  1 0 0 1
  1 0 0 0
OBJECT '135D_LIN_POL'
  INTERFACE COATING TRANS_50 AIR AIR
  ROTATE Z 135 0 0

!!RIGHT CIRCULAR POLARIZER
LENS
  IDEAL Z 5 10
  1 0 0 1
  1/2 0`1/2 0`-1/2 1/2
OBJECT 'RC_POL'
  INTERFACE COATING TRANS_50 AIR AIR

!!LEFT CIRCULAR POLARIZER
LENS
```

```
  IDEAL Z 6 10
  1 0 0 1
  1/2 0`-1/2 0`1/2 1/2
OBJECT 'LC_POL'
  INTERFACE COATING TRANS_50 AIR AIR

SURFACE
 PLANE Z 7 RECT 10
OBJECT 'DETECTOR'

EMIT_SOURCE { 3
POLAR X #1 #2
EMITTING DISK Z 0 2@1 #3 10 10
 FLUX TOTAL 100
}
ENTER POLARIZ X a  COMPONENT>
ENTER POLARIZ X a' COMPONENT>
ENTER TOTAL NUMBER OF RAYS>

NRAYS=10000

$DO 2 7
{$EMIT_SOURCE 1 1 (NRAYS)
!!$EMIT_SOURCE 1 0`1 (NRAYS)
!!INSERT THE ACTUAL SOURCE ABOVE
WINDOW X Z
CONSIDER ONLY 0 ? 8
!!PLOT FACETS OVERLAY
TRACE !!PLOT (NRAYS)/10
CONSIDER ONLY 8
STATS
$GRAB 'TOTAL' 0 2 PFLUX?
$REG PFLUX?
RETURN
 }

IH=PFLUX2
IV=PFLUX3
I45=PFLUX4
I135=PFLUX5
IRC=PFLUX6
ILC=PFLUX7

S0=IH+IV
S1=IH-IV
S2=I45-I135
```

```
S3=IRC-ILC
$REG S0 S1 S2 S3

RETURN
```