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CEF-Fiber Coupling Efficiency

The Fiber Coupling Efficiency (CEF) option computes the coupling efficiency of a diffraction image into a single fiber mode. The fiber mode can be Gaussian, defined by the fiber's step index profile, or user-defined. Effects of misalignments and cleavage angles are also taken into account. Sensitivity of the coupling efficiency to variations in one or two alignment parameters can be computed and graphed. Polarization-dependent loss and additional energy loss factors can be automatically computed if polarization ray tracing is enabled. Output can be in coupling percentage or insertion loss (decibel scale).

When to Use the Fiber Coupling Efficiency (CEF) Option

The CEF option computes the percentage of the energy in a diffraction aerial image which is collected by a single optical fiber mode. The default behavior is to compute this using a ray traced beam definition, in which the overlap integral of the complex PSF and the (scalar) fiber mode is evaluated. Optionally, you can bypass the PSF calculation and instead use user-defined input to determine the characteristics of the beam incident on the fiber; see "Creating the Beam Definition" on page 19-183 for information on how to do this.

Use the CEF option for any of the following purposes:

- To compute the coupling efficiency from a lens system into a single-mode optical fiber or into a single mode of a multi-mode optical fiber. The fiber can be decentered or tilted with respect to the chief ray, and can have a cleavage angle on the tip.
- To investigate the sensitivity of the coupling efficiency to misalignments of the fiber with respect to the diffraction image.
- To investigate the sensitivity of the coupling efficiency to tilts of the fiber.
- To investigate the sensitivity of the coupling efficiency to changes in the cleavage angle of the tip of the fiber.
- To determine the polarization sensitivity of the coupling lens by calculating the polarization-dependent loss.

Energy Loss Factors that Impact Fiber Coupling Efficiency

The primary purpose of the CEF option is to compute the percentage of energy in a diffraction aerial image that is collected by a single optical fiber mode. This percentage is relative to the energy in the beam **exiting** the optical system. Sometimes it is desirable to include energy loss factors due to light passing through the optical system. These additional factors fall into three categories:

1. Energy from the input fiber or light source that is blocked by various apertures or truncated by apodization (*beam clipping*).
2. Energy that is lost through reflection or absorption at glass-air interfaces through the system (i.e., *surface losses*).
3. Energy that is absorbed by the optical materials in the system (i.e., *absorption losses*).

If you are using the *Ray trace lens system* beam definition, beam clipping is automatically included in the computation of fiber coupling efficiency whenever Gaussian pupil apodization is defined for the lens. This reduces the CEF by the beam-clipping factor. If Polarization Ray Tracing (POL Y) is enabled, the computation will also include surface losses; see "Default Assumptions" on page 19-189 for more details.

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Note: If Gaussian pupil apodization (PUI) is used, the degree of truncation is known and is applied to the CEF calculation. If an INT file is used, however, the degree of truncation is unknown and is omitted from the CEF calculation. Therefore, the two methods yield different values of CEF; PUI yielding the lower value.

Absorption losses typically have very little impact on a free-space photonic system. However, this factor can be determined using the **Transmission Analysis** feature of CODE V (**Analysis** > **System** menu). This feature also lists the surface losses. Transmission Analysis (TRA) must be used to determine surface losses and/or absorption losses when using either the Gaussian beam or (complex field) Buffer Input beam definitions in CEF (see "Creating the Beam Definition" on page 19-183 and "Beam Definition" on page 19-190 for details about these beam definitions).

The method for the computation of *beam clipping* varies depending on the beam definition used in CODE V:

- For the *Ray trace lens system*, this factor is automatically included if Gaussian pupil apodization is defined, regardless of whether polarization ray tracing is enabled or not.
- The *Gaussian beam* option always treats the Gaussian beam as being untruncated. This means that no beam clipping factor is included.
- The *Intensity and Phase Files* option assumes that the intensity and phase are defined at the output fiber, so no beam clipping factor is included.
- Using the *Buffer Input* option to input complex field data into CEF (**Analysis > Diffraction > Beam Synthesis Propagation** or **Analysis > Diffraction > FFT Beam Propagation**) does not automatically include energy loss from beam clipping in the computation. With FFT Beam Propagation, however, this loss is included in the BPR output as the *Energy Fraction* (after surface) listed for the image, or final, surface.

The table below summarizes how to determine each of the energy loss factors (beam clipping, surface losses, and absorption losses) based on what type of beam definition is used.

	Energy Loss Factors		
Beam Definition	**Beam Clipping Losses**	**Surface Losses**	**Absorption Losses**
Ray Trace – POL N	Included in CEF*	Use TRA	Use TRA
Ray Trace – POL Y	Included in CEF*	Included in CEF	Use TRA
Gaussian beam	Not applicable	Use TRA	Use TRA
Intensity and Phase file	Not applicable	Not applicable	Not applicable
Buffer Input (complex field)	Use BPR Energy Fraction	Use TRA	Use TRA

*If Gaussian pupil apodization is defined.

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Default Operation

Using the GUI, a Gaussian fiber mode radius of 0.0052 mm (or system units equivalent; corresponds with SMF 28 fiber at 1550 nm) is used for the output fiber, the fiber location is considered fixed at the image surface vertex and aligned along the image surface Z-axis, and a ray traced beam definition is used. There is no default operation when you use the command line, since a fiber mode profile must be specified before any calculations can be done.

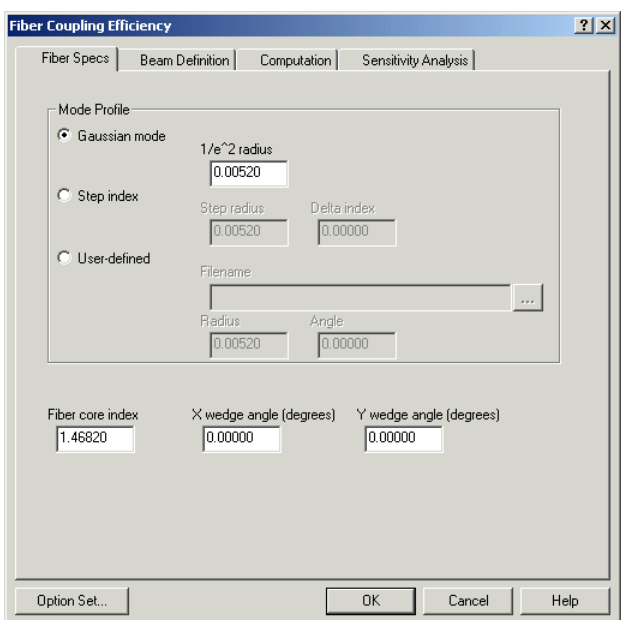
Command Mnemonics
(alphabetical)

ADE	AZI	BDE	BIN	CIN	BPH
GRI	INB	LIS	MPR	NRD	PLO
RCX	RCY	SN1	SN2	TGR	WDX
WDY	WRX	WRY	XDE	XSC	YDE

Defining Fiber Specifications

To define the fiber mode profile for the Fiber Coupling Efficiency option, choose the **Analysis** > **Diffraction** > **Fiber Coupling Efficiency** menu. The **Fiber Coupling Efficiency** dialog box displays, with the **Fiber Specs** tab automatically displayed. Define the controls on this tab as described in the table below.

Note: The output fiber location is defined in the LDM, in the **System Data** window (**Lens** menu). See “Defining Output Fiber Location” on page 3-56 for details.



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Command Syntax		
Screen Control	**Explanation**	**Default**
MPR GAU gaussian_radius or **MPR** STE core_radius delta_n or **MPR** FIL filename radius [angle]		
Mode profile	**Required.** Specifies one of three forms of mode profile: **Gaussian mode.** The first form selects a Gaussian mode profile with a radius specified at an intensity value which is $1/e^2$ times the peak intensity (in lens units). **Step index.** The second form selects a step index profile, with specified step radius (in lens units) and specified change in index across the step. **User-defined.** The third form selects a user-defined profile specified in a .INT file. The file normalization radius is specified (in lens units), as is the rotation angle of the .INT file (in degrees, default for rotation angle is 0). The rotation angle of the .INT file around the Z axis is similar to how IRO rotates the orientation of surface .INT file data. Note that this data represents field amplitude.	On the command line, none. This is a required input. In the GUI, the default is Gaussian mode, radius of 0.0052 mm (corresponds to SMF-28 fiber at 1550 nm).
CIN index_of_fiber_core		
Fiber core index	Specifies the refractive index of the fiber core. This is used when MPR STE is used or whenever nonzero values of WDX or WDY are used.	1.4682 (corresponds to SMF-28 fiber at 1550 nm)
WDX x_wedge_angle_degr		
X wedge angle	Specifies the wedge angle (cleavage angle) of the front face of the fiber in the X direction. See “Fiber Specification” on page 19-189 for more details about how the wedge angle is defined. Wedge errors in the X and Y directions are assumed to be independent; this is valid for small wedge angles. Use only if WDX is not specified with SN1 or SN2.	0.0
WDY y_wedge_angle_degr		
Y wedge angle	Specifies the wedge angle (cleavage angle) of the front face of the fiber in the Y direction. See “Fiber Specification” on page 19-189 for more details about how the wedge angle is defined. Wedge errors in the X and Y directions are assumed to be independent; this is valid for small wedge angles. Use only if WDY is not used with SN1 or SN2.	0.0

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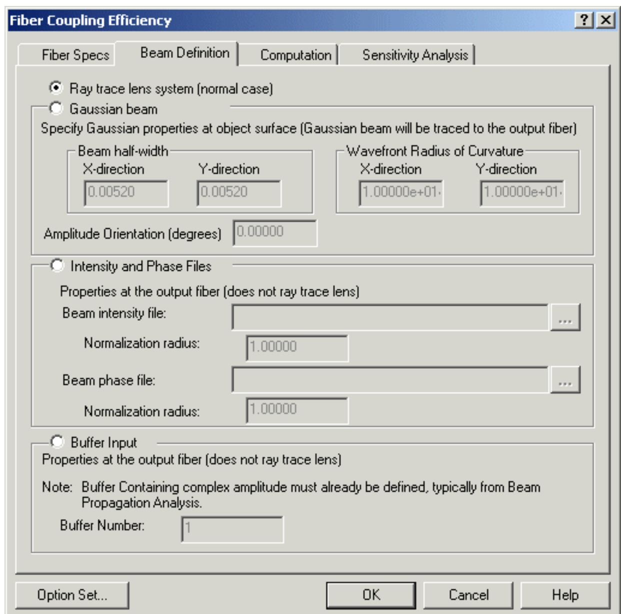
Defining the Output Fiber Position

The output fiber location is defined in the LDM, in the **System Data** window (**Lens** menu). See "Defining Output Fiber Location" on page 3-56 for details.

Creating the Beam Definition

The beam definition commands allow you to define how the wavefront at the output fiber is computed. To define the beam, choose the **Analysis** > **Diffraction** > **Fiber Coupling Efficiency** menu. Click the **Beam Definition** tab in the **Fiber Coupling Efficiency** dialog box, and define the controls as described in the table below.



Command Syntax		
Screen Prompt	**Explanation**	**Default**
GUI command only.		
Ray trace lens system	(Default beam definition mode.) When this setting is selected, the CEF option uses its internal PSF calculation to determine the characteristics of the beam incident on the fiber. See "Sensitivity Analysis" on page 19-193 for details.	
WRX x_beam_half_width...z		
Gaussian Beam/ Beam half-width: X-direction	X beam radius at the $1/e^2$ intensity point in the X meridian for specifying a Gaussian beam at the object surface of the lens. If only WRX or WRY is entered, both are set to the same value (circular beam).	

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Command Syntax		
Screen Prompt	**Explanation**	**Default**
WRY y_beam_half_width...z		
Gaussian Beam/ Beam half width: Y-direction	Y beam radius at the $1/e^2$ intensity point in the Y meridian for specifying a Gaussian beam at the object surface of the lens. If only WRX or WRY is entered, both are set to the same value (circular beam).	
RCX x_wave_radius...z		
Gaussian Beam/ Wavefront Radius of Curvature: X-direction	X radius of curvature of Gaussian wavefront in X meridian. Value of 0 is interpreted as infinity. If only RCX or RCY is entered, both are set to the same value (spherical wavefront).	Infinity.
RCY y_wave_radius...z		
Gaussian Beam/ Wavefront Radius of Curvature: Y-direction	Y radius of curvature of Gaussian wavefront in Y meridian. Value of 0 is interpreted as infinity. If only RCX or RCY is entered, both are set to the same value (spherical wavefront).	Infinity.
AZI starting_orientation_degr...z		
Amplitude Orientation	Orientation (in degrees) of amplitude function of Gaussian beam about the optical (z) axis. Allows rotation of beam intensity definition from default x-y orientation.	0.0
BIN filename normalization_radius...z		
Intensity and Phase Files/ Beam intensity file/ Normalization radius	Input INT file containing intensity data for the beam incident on the fiber. The interferogram file must be of the FIL type, with the units being relative intensity and the SSZ value being equivalent to unit intensity. Normalization radius defines the size of the beam incident on the fiber and is required. To assure all of the energy in the INT file falls within the computation grid, TGR * GRI should equal or exceed 2 * the normalization radius.	
BPH filename normalization_radius...z		
Intensity and Phase Files/ Beam phase file/ Normalization radius	Input INT file containing phase data for the beam incident on the fiber. The interferogram file must be of the WFR type, with the units in waves and the SSZ value being equivalent to one wave at the wavelength of propagation. Normalization radius defines the size of the beam incident on the fiber and is required. To assure all of the energy in the INT file falls within the computation grid, TGR * GRI should equal or exceed 2 * the normalization radius.	

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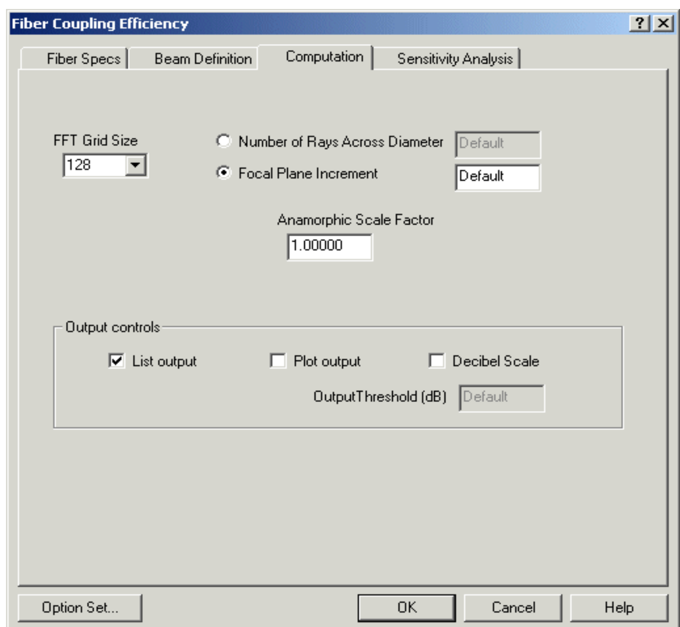
Command Syntax		
Screen Prompt	**Explanation**	**Default**
INB Bi		
Buffer Input/ Buffer Number	Use data in a worksheet buffer to define a grid of points that represents the beam incident on the fiber. The location, orientation, and grid dimensions [obtained from the Beam Propagation (BPR), Beam Synthesis Propagation (BSP), or Point Spread Function (PSF) options, or user generated] are included in the buffer. If you are generating your own data, use the BUF LIS command to view BPR or BSP output for the required data format.	

Defining Computation Controls

To define computation controls for the Fiber Coupling Efficiency option, choose the **Analysis** > **Diffraction** > **Fiber Coupling Efficiency** menu. The **Fiber Coupling Efficiency** dialog box displays. Click the **Computation** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
TGR num_fft_grid_pow_of_two		
FFT grid size	Transforms grid size. **Range**: 16 or more, must be a power of 2. Unless overridden by NRD or GRI, also determines the number of rays traced in proportion to TGR**2. Use to improve accuracy for systems with large or unusual obscurations, or to increase the size of the image area analyzed relative to the Airy disc. Only used for ray traced beam definition.	128

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Command Syntax		
Screen Control	**Explanation**	**Default**
NRD num_rays_across_diameter....z		
Number of rays across diameter	Specifies number of rays traced across the pupil diameter for the shortest wavelength; other wavelengths are proportionately smaller to make image plane grids match. See GRI command, also. **Range**: Recommended - no more than 2 times up or down from the default; look out for artifacts of extreme choices. Use either NRD or GRI, if desired, not both. Only used for ray traced beam definition.	TGR/2 at short wavelength.
GRI image_surface_spacing....z		
Focal plane grid increment	Specifies grid spacing measured on the image surface - alternative to NRD. Use to choose a more convenient number than the default. **Range**: Recommended - no more than 2 times up or down from the default; look out for artifacts of extreme choices. Use either NRD or GRI, if desired, not both. Only used for ray traced beam definition.	Shortest wavelength ∗ fnumber/2. (Airy disc diameter for shortest wavelength spans 4.88 grid increments regardless of TGR value.
XSC scale_x_psf_by_factor....z		
Anamorphic scale factor	Scales X dimension of image by this factor. Used to handle highly anamorphic exit pupils. The largest (X or Y) numerical aperture of the exit pupil is used in establishing default values for GRI/NRD; this may lead to insufficient sampling in either the X or Y dimension, depending on which was largest; check this with the PMA option. Use XSC to scale up the X dimension of the image, which correspondingly reduces the number of pupil sampling points in the X direction, and vice versa. **Ex**: XSC 2 scales the X dimension of the image by 2, the GRI or NRD by 0.5. Only used for ray traced beam definition.	1.0
LIS Yes | No....z		
List output	Provides tabular output.	Yes.
PLO Yes | No		
Plot output	Provides plots of the coupling efficiency as a function of the parameter entered with the SN1 command. For each value taken on by the parameter specified with SN2, a separate curve is generated with different line styles (up to a maximum of 20 curves).	Yes, if the number of values designated in the SN1 command is greater than one.
DB Yes | No [threshold]		
Decibel Scale/ Output Threshold (dB)	Scale output to be insertion loss (in units of decibels) subject to the threshold value. The default threshold is -50 decibels.	No.

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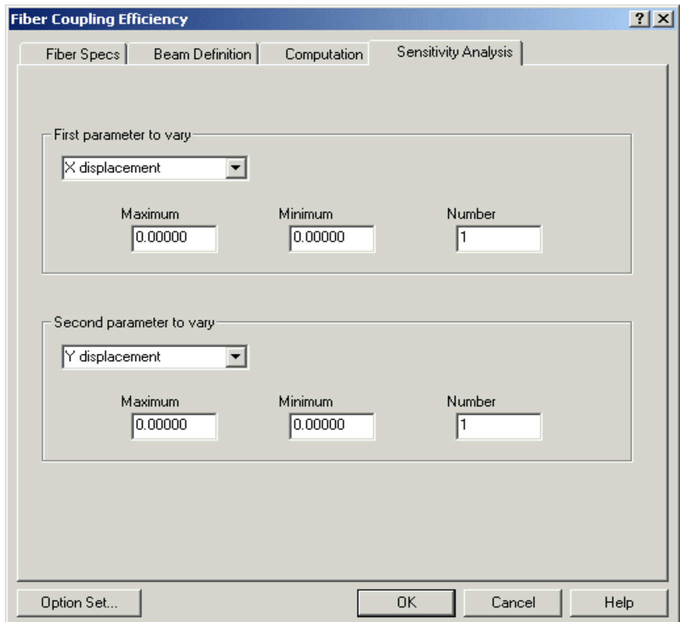
Defining Analysis Selection Settings

To define analysis selection settings for the Fiber Coupling Efficiency option, choose the **Analysis** > **Diffraction** > **Fiber Coupling Efficiency** menu. The **Fiber Coupling Efficiency** dialog box displays. Click the **Analysis** tab, and define the controls on this tab as described in the table below.



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Command Syntax		
Screen Control	**Explanation**	**Default**
SN1 XDE | YDE | ADE | BDE | WDX | WDY [max_value [min_value [num_values]]]		
First parameter to vary	Computes the sensitivity of the coupling efficiency to changes in the specified alignment parameter. Allowed alignment parameters are: X-displacement (in lens units) of output fiber (XDE), Y-displacement of output fiber (YDE), alpha tilt (in degrees) of output fiber (ADE), beta tilt of output fiber (BDE), X-wedge (in degrees) on fiber face (WDX), and Y-wedge on fiber face (WDY). The range of values of the parameter are specified (**Maximum** and **Minimum** fields), and the number of values spanning the range is specified (**Number** field). The default for **Maximum** (max_value) is 0.0, the default for **Minimum** (min_value) is 0.0, and the default for number of values is 1. **Note**: The specified alignment parameter cannot be the same as specified with SN2. If it is the same, the SN1 entry takes precedence and SN2 will be set to XDE or YDE, whichever is not used by SN1.	XDE 0.0 0.0 1
SN2 XDE | YDE | ADE | BDE | WDX | WDY [max_value [min_value [num_values]]]		
Second parameter to vary	Computes the sensitivity of the coupling efficiency to changes in the specified alignment parameter. Allowed alignment parameters are: X-displacement (in lens units) of output fiber (XDE), Y-displacement of output fiber (YDE), alpha tilt (in degrees) of output fiber (ADE), beta tilt of output fiber (BDE), X-wedge (in degrees) on fiber face (WDX), and Y-wedge on fiber face (WDY). The range of values of the parameter are specified (**Maximum** and **Minimum** fields), and the number of values spanning the range is specified (**Number**). The default for **Maximum** (max_value) is 0.0, the default for **Minimum** (min_value) is 0.0, and the default for number of values is 1. **Note**: The specified alignment parameter cannot be the same as specified with SN1. If it is the same, the SN2 entry takes precedence and SN1 will be set to XDE or YDE, whichever is not used by SN2.	YDE 0.0 0.0 1

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Discussion of Input and Computations

What to Include in the LDM Data

The output fiber location, which can be in either a fixed or compensated position, is defined in the LDM, in the **System Data** window (**Lens** menu). For details, see "Defining Output Fiber Location" on page 3-56; both GUI and command-line instructions are provided.

If you wish to compute the coupling efficiencies through-focus, enter the LDM data for depth of focus (NFO, FFO, IFO). If you wish to perform polarization ray tracing, enter POL Y (**Lens** > **System Data** menu, **Activate Polarization Ray Tracing** checkbox on the **Polarization** page in the **System Data** window).

Default Assumptions

- The CEF option works only for a single fiber mode. If you wish to know the coupling efficiency into a fiber which supports multiple modes, you can run CEF separately on each of the modes which are present in the fiber and sum the results.
- There are no polarization variations within the fiber mode. Essentially, this means that the fiber is a modeled by a low order mode whose E-field is linearly polarized and oriented to match the polarization state of the entering beam.
- The fibers are not tapered.
- When polarization ray tracing is not enabled (POL N), surface and absorption losses are not considered in computing the percent energy coupled (beam clipping losses are included if Gaussian pupil apodization has been defined).
- When polarization ray tracing is enabled, polarization, apodization, and surface losses (including aperture clipping, Fresnel reflection losses, and diffraction-efficiency losses from thick-volume holograms) are considered in computing the percent energy coupled. Polarization losses between the exit pupil and the output fiber, as well as the transmittance losses from the entrance pupil to the exit pupil are computed. Note that this calculation is only done when the ray traced beam definition is used; it does not apply when Gaussian beam, intensity/phase files, or buffer input beam definitions are used to determine the characteristics of the beam incident on the fiber.

Fiber Specification

On the command line, the fiber mode profile must be specified with **MPR** before any computations can be done; there is no default. In the GUI, the default is Gaussian mode, with a radius of 0.0052 (SMF 28 fiber at 1550 nm). There are three choices for the mode profile:

GAU	–	The fiber has a Gaussian mode profile. Many fibers, including step index fibers, can be approximated as a Gaussian mode fiber. The $1/e^2$ radius of the Gaussian must be specified. Note that the $1/e^2$ radius does **not** correspond to the physical radius of the fiber (see "Technical Notes" on page 19-205).
STE	–	The fiber is a step index fiber. The fiber core radius (in lens units) and the index difference across the step must be specified. The index step can be to a clad or to air. The index of the fiber core is assumed to be 1.4682; this can be changed (**CIN**).
FIL	–	The field amplitude of fiber mode profile is user-defined and described in an .INT file. Any form of the .INT file can be used (grid, radial grid, Zernike, or Fringe Zernike). The normalization radius of the .INT file must be specified, as well as the rotation angle of the file with respect to the x-axis.

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The fiber location can be either fixed or compensated, as specified with the **FLO** command. In the GUI, this is defined in the **System Data** window (**Lens** menu), on the **Fiber Location** page. For complete details about defining the output fiber location in both the GUI and on the command line, go to "Defining Output Fiber Location" on page 3-56.

By default, the front face of the fiber is perpendicular to the fiber. On the **Fiber Specs** tab, a wedge, or cleavage, angle can be specified (**X** and **Y wedge angle** fields or **WDX**, **WDY** commands). The wedge angle is specified as the angle between the fiber face and the plane perpendicular to the fiber orientation. If the fiber lies in either the X-Z or Y-Z plane of the image surface, the WDX and WDY represent a beta and alpha tilt respectively of the fiber face relative to the fiber direction. The sign convention for WDX and WDY is the same as for CODE V tilts, where WDX represents a beta tilt that is left-handed about the +Y axis, and WDY represents an alpha tilt that is left-handed about the +X axis. If the fiber is not oriented in the X-Z or Y-Z plane of the image surface, a cross-product calculation is used to define a local fiber X and Y axis and the wedge is applied in that coordinate system.

The wedge angles in x and y are assumed to be independent and can be given in any order; this is valid for small values of the wedge angles. The wedge is modeled as a small prism added to the front of the fiber, and therefore you must specify the **Fiber core index** (**CIN** command). Note that for FLO CMP, the fiber orientation takes into account wedge on the fiber face.

Beam Definition

There are four ways to define the beam incident on the fiber:

- **Ray traced beam definition** (default). Rays are traced to the exit pupil and an internal PSF calculation is used to determine the characteristics of the beam incident on the fiber.
- **Gaussian beam**. Specifies an untruncated Gaussian beam that is traced through the system to determine the characteristics of the beam incident on the fiber.
- **Intensity and Phase Files**. One or two INT files are imported that contain intensity and/or phase data to define the incident beam at the output fiber.
- **Buffer Input**. Complex amplitude data representing the incident beam at the output fiber is obtained either from the BSP option or from user-defined data.

In the GUI, you can define these methods on the **Beam Definition** tab in the **Fiber Coupling Efficiency** dialog box.

Ray Traced Lens System

With the ray trace lens system method, the coupling efficiency can be computed by evaluating the overlap integral of the complex PSF and the mode profile, appropriately normalized. The equation used is

$$CE = \frac{\left|\iint (\mathrm{PSF} \bullet \mathrm{mode})\right|^2}{\iint \mathrm{PSF}\ \ \mathrm{PSF}^* \bullet \iint \mathrm{mode}^2}$$

Note that the PSF is a complex quantity and the mode profile is a scalar quantity. To use the ray trace method, select the **Ray trace lens system** button on the **Beam Definition** tab. On the command line, this is the default method, and you do not need to enter a specific command.

For a compensated fiber location (defined in the **System Data** window, **Fiber Location** page or with FLO CMP on the command line), using the ray traced method means that:

- The fiber will be repositioned at the X, Y, Z position of the chief ray intercept on the image surface for each zoom and field position and at each wavelength.

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- The fiber is aligned along the chief ray.
- If the angle of incidence of the chief ray at the image surface is not normal, CEF takes into account the effect of the phase differences between the tilted beam and the computed PSF on the image surface.
- CEF assumes that the optical field data is centered on the fiber. However, the lateral position of the data on the fiber can be controlled using the **X** and **Y Offset** fields (XOF, YOF commands) and the **Sensitivity Analysis** controls (SN1/SN2 XDE and SN1/SN2 YDE commands).

Gaussian Beam

Rather than using ray trace data to define the beam incident on the fiber, you can define the beam using Gaussian beam parameters. This bypasses CEF's internal PSF calculation. To use this method, select the **Gaussian beam** button on the **Beam Definition** tab. This activates the beam parameter fields: Beam half-width in X and Y directions, wavefront radius of curvature in the X and Y directions, and amplitude orientation. From the command line, use **WRX**, **WRY**, **RCX**, **RCY**, and **AZA**.

Note that the focal plane grid increment (GRI) and transform grid size (TGR) have an impact on the Gaussian beam calculation. Use GRI to define adequate sampling across the MPR dimension (e.g., GRI = MPR/5). Make sure that the TGR x GRI value is at least twice as large as the Gaussian spot size at the output fiber.

The Gaussian input commands provide a way to use beam data calculated in a manner similar to the Gaussian Beam trace (BEA) option as input to CEF. The user-defined input data corresponds to the object surface, and the CEF-generated output at the image surface is computed orthogonal to the beam direction.

For a compensated fiber location (defined in the **System Data** window, **Fiber Location** page or with FLO CMP on the command line), using the Gaussian beam method means that:

- The fiber will be repositioned at the X, Y, Z position of the chief ray intercept on the image surface for each zoom, field, and wavelength combination.
- The fiber is aligned along the chief ray.
- CEF assumes that the optical field data is centered on the fiber. However, the lateral position of the data on the fiber can be controlled using the **X** and **Y Offset** fields (FBX, FBY commands) and the **Sensitivity Analysis** controls (SN1/SN2 XDE and SN1/SN2 YDE commands).

Intensity and Phase Files

As another alternative to the CEF option's internal PSF calculation, you can use phase and intensity data from INT files to define the input wavefront to the fiber. To use this method, select the **Intensity and Phase Files** button on the **Beam Definition** tab. This activates fields where you can select beam intensity and beam phase files to import. For both file types, you are required to specify the normalization radius, which defines the size of the beam. From the command line, use **BIN** and **BPH**.

Note that intensity and phase files are always assumed to be centered on the image surface vertex, perpendicular to the image surface Z-axis. Thus, the calculation is always done with FLO CMP regardless of the user-specified FLO setting.

Buffer Input

The final method for defining the beam incident on the fiber is to import complex amplitude data from the worksheet buffer. To use this method, select the **Buffer Input** button on the **Beam Definition** tab. This activates the **Buffer Number** field, where you specify the worksheet buffer number where the input data is stored. On the command line, use **INB**.

This method allows you to define the beam incident on the fiber using data produced by other CODE V options such as Beam Propagation (BPR), Beam Synthesis Propagation (BSP), and Point Spread Function (PSF). For scalar fields, the complex amplitude data from these options can be written to the worksheet buffer

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using the **WBF CMP** command. For vector fields, the data can be written from BSP using either the **WBF VEC** or **WBF VFD** command. The data can then be used as input to CEF using the **INB** command.

For a compensated fiber location (defined in the **System Data** window, **Fiber Location** page or with FLO CMP on the command line), using buffer input means that:

- The fiber will be repositioned at the X, Y, Z position of the beam centroid on the image surface for each zoom, field, and wavelength combination.
- The fiber is aligned along the beam direction.
- CEF assumes that the optical field data is centered on the fiber, regardless as to its position on the surface when generated in BPR or other option. However, the lateral position of the data on the fiber can be controlled using the **X** and **Y Offset** fields (FBX, FBY commands) and the **Sensitivity Analysis** controls (SN1/SN2 XDE and SN1/SN2 YDE commands). For a fixed fiber location, the field data from BPR is computed on a plane that is normal to the direction of propagation, with the center at the point of intersection of the direction of propagation with the surface. The center of the fixed fiber can be specified with respect to the image surface vertex with the FBX and FBY commands.
- CEF assumes that the optical field data is measured on a plane. Therefore, when using BPR data as input to CEF, the near field propagator (NFP) or the far field propagator (FFP) must be used as the final propagator because the output for these propagators is on a plane. The sphere to sphere propagator (SSP) outputs data on a sphere and will therefore introduce defocus if used in CEF.

You can perform full vector calculations (including polarization-dependent properties) using BSP data by means of the following procedure:

1. Specify an initial polarization state, run BSP (with polarization ray tracing enabled).
2. Write the vector result to a buffer by going to the **Output Controls** tab in the BSP dialog box. In the **Worksheet Buffer Output** spreadsheet, choose either **Vector Field** format (2d-grid or rows of field numbers) for the **Output Quantity** parameter . You can also use the **WBF** command with either the **VEC** or **VFD** keyword.
3. Change the polarization state to be orthogonal to the initial state, run BSP again (with polarization ray tracing enabled), and write (append) the new set of vector data to the same buffer.
4. Use the two data sets in this buffer as input to CEF by going to the **Beam Definition** tab in the CEF dialog box, clicking the **Buffer Input** radio button, and entering the buffer number. You can also use the **INB** command.

   CODE V then computes the coupling efficiency for both input states and the polarization dependent loss (PDL), and identifies the input states having maximum and minimum transmission.

If only one set of BSP vector data is passed to CEF, the PDL cannot be computed. Only the coupling efficiency for that particular polarization state will be computed and the following warning message will be displayed:

```
"The buffer contains data for a single polarization state. Only the coupling
efficiency for that polarization state can be computed."
```

If two sets of BSP vector data are submitted but do not have orthogonal polarization states, the coupling efficiency will be computed for the first state only, and the following warning will be displayed:

```
"The data sets do not have orthogonal polarization states. Polarization
dependent coupling efficiency cannot be computed. Coupling efficiency will only
be computed for the first polarization state."
```

The command syntax for calculating the polarization-dependent coupling efficiency from buffer-resident data is described on page 19-185.

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Sensitivity Analysis

The coupling efficiency is computed for a range of variations of any two of the fiber alignment parameters: X-displacement (in lens units) of output fiber (XDE), Y-displacement of output fiber (YDE), alpha tilt (in degrees) of output fiber (ADE), beta tilt of output fiber (BDE), X-wedge (in degrees) on fiber face (WDX), and Y-wedge on fiber face (WDY). The choice of which two parameters to vary are made in the **First Parameter to Vary** and **Second Parameter to Vary** areas (**SN1** and **SN2**) on the **Sensitivity Analysis** tab in the **Fiber Coupling Efficiency** dialog box; the default is XDE and YDE. They cannot both be the same; if they are entered to be the same, the first one entered is changed to be either XDE or YDE, depending on which is not used by the other. For any parameter selected, the range of parameter values can be specified, and the number of values spanning the range can be specified. The default is to compute the coupling efficiency for only one value of the parameter (0.0).

Parameters selected to be varied with **SN1** and **SN2** should not also have values explicitly specified by the corresponding command.

The output is a table of coupling efficiencies for the specified values of the selected alignment parameters. This table can be listed (**LIS**) or plotted (**PLO**). An additional command requests the output data to be in units of decibels, subject to a threshold value (**DB**).

Computational Controls

Conceptually, the CEF option with the ray traced beam definition is internally computing a point spread function (PSF) prior to computing the overlap integral. As such, the considerations for controlling the FFT process for the PSF option apply to CEF as well. Refer to the PSF option for additional detail on these considerations.

The default grid interval in the image may not be a convenient size, or may not give sufficient image detail. It can be increased up to a factor of two to shrink the relative size of the image (**GRI** or **NRD**). The lens wavefront will be represented by more data, which will take longer to calculate by the square of the scale change. The grid interval can also be decreased to expand the relative size of the image. It is unwise to do this beyond a factor of two (unless **TGR** is also increased) because the lens will be represented by very few points in the wavefront.

The default size of the FFT transform grid is 128. This may be modified (**TGR**), but the value must be a power of 2 (minimum value is 16). If any other value is entered, it will be rounded up to the next allowable value. For example, **TGR** 45 will result in a 64x64 transform grid. The default physical spacing in the image plane is selected so that the pupil grid of the shortest wavelength fills up half the transform grid. Use **TGR** to improve accuracy for systems with large or unusual obscurations, or to increase the size of the image area analyzed relative to the Airy disc.

The formula relating the FFT parameters is

$$\mathrm{GRI} = \frac{\lambda_s \bullet f/no \bullet \mathrm{NRD}}{\mathrm{TGR}} \quad .$$

The f/no is the f/number in the image space for the axial beam (or 2X the largest half-beam at any field if it is larger than the axial beam).

By default, fiber coupling efficiency is listed as a percentage. Optionally, insertion loss output (in decibels) can be requested. The formula relating the two quantities is

$$\mathrm{InsertionLoss\ (dB)} = 10 * \log_{10} [\mathrm{coupling\ efficiency}]$$

For more details about grid computation controls, see the following discussion in the Point Spread Function (PSF) option documentation: “Grid Considerations for Diffraction Calculations in CODE V” on page 19-358.

Description of Output

The output can be listed (**LIS**), plotted (**PLO**), or both. The default is to get listed output but not plotted output.

The listed output comprises header information and a table of coupling efficiencies or insertion loss (perfect coupling of 100% of the energy is represented by a coupling efficiency of 1.0, or insertion loss at 0.0 dB). The header information includes computational information, information about the output fiber and location/orientation information about the beam and the output fiber.

The parameter across the top of the table is the parameter specified with **SN1**, and the parameter down the table is the parameter specified with **SN2**. A separate table is generated for each field, through-focus position, wavelength, and zoom position.

For plotted output, a graph is made of the coupling efficiency against variations of the alignment parameter specified with **SN1**. For each separate value of the alignment parameter specified with **SN2** a separate curve is made in the plot. Up to 20 curves can be plotted on the same graph. More than 20 curves, corresponding to more than 20 separate values of the **SN2** alignment parameter, are not plotted, but will appear in the listed output. A separate graph is made for each field, through-focus position, and zoom position.

If the fiber mode is a step index, the fiber may be multi-mode. This is checked for, and a warning message is printed if the mode is multi-mode. See "Technical Notes" on page 19-205 for further details.

Polarization-Dependent Energy Loss Calculation

When polarization ray tracing is enabled (POL Y), the CEF option considers polarization, apodization, aperture clipping, Fresnel reflections at surfaces, and diffraction-efficiency of volume HOEs when computing the coupling efficiency. Bulk absorption from optical glasses is not included. The polarization losses between the exit pupil and the output fiber, as well as the transmittance losses from the entrance pupil to the exit pupil and the output fiber, as well as the transmittance losses from the entrance pupil to the exit pupil, are output. Note that this calculation is only done when the PSF calculation is used; it does not apply when user-defined input is used to determine the characteristics of the beam incident on the fiber.

Both listed and plotted CEF output will contain data for any polarization-dependent energy loss (in the listed output, this data appears at the end). An additional table is generated that displays the polarization-dependent loss for each pair of parameters in the sensitivity matrix (see Example 5, page 19-202). In general, there will be an input polarization state that results in maximum coupling efficiency, and an orthogonal state that results in minimum coupling efficiency. The polarization-dependent loss ratio is given by the CEF_{min}/CEF_{max}. The polarization-dependent contrast is given by the $(CEF_{max}-CEF_{min})/(CEF_{max}+CEF_{min})$. The quantities are always computed using CEF and converted to insertion loss if **DB Yes** is specified. CODE V also lists the input states that result in maximum and minimum coupling efficiency.

The calculation of the CEF occurs in three parts:

- from the source to the entrance pupil
- from the entrance pupil to the exit pupil
- from the exit pupil to the fiber

The CEF calculation also considers two orthogonally polarized states. From these two states, all possible polarization states can be constructed.

The following quantities are listed in the output:

- **Fraction of input energy accepted:** This represents the energy coupling between the source and the entrance pupil. For a non-Gaussian input, this is assumed to be 1. If the input is a Gaussian beam, this represents the fraction of the Gaussian beam power that is intercepted by the entrance pupil.

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- **Energy transmitted by optical system:** This is the coupling efficiency between the entrance and exit pupils. It accounts for losses due to clipping by the apertures, but does not include transmission losses.
- **Total coupling efficiency:** This represents how much of the starting energy is coupled into the fiber. This includes the two previous quantities plus the overlap integral of the PSF and the fiber mode profile.
- **Maximum/Minimum CEF for all input states:** CODE V calculates what polarization states will have the best (maximum) and worst (minimum) coupling efficiencies. It reports the CEF values for both extremes, as well as the description of the polarization states that achieve these CEF extremes.
- **Polarization dependent loss:** This gives an indication of how sensitive the coupling efficiency is to polarization effects. The PDL contrast and ratio are defined mathematically as:

$$\text{Contrast} = \frac{CEF_{max} - CEF_{min}}{CEF_{max} + CEF_{min}}$$

$$\text{Ratio} = \frac{CEF_{min}}{CEF_{max}}$$

  When calculating the Polarization dependent loss, note that it is defined in terms of the CEF, not the loss (dB). Since output in dB is a logarithmic scale, the ratio is calculated as:

$$\text{Ratio} = CEF_{min}(dB) - CEF_{max}(dB)$$

- The **polarization states** that produce the maximum and minimum coupling efficiency.

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Examples

A perfect 50 mm diameter f/2 lens module will be used in the following examples. The lens data are as follows.

```
LENS
TIT  "50 MM DIA F/2 LENS"
DIM  MM
EPD  50
WL  500
S  0  0
MOD
MFL  100
MED  50
MFD  1
S  0  0
PIM
GO
```

Example 1. Coupling into an uncladded fiber

In this example, we will use a step index fiber with a core diameter of two microns (i.e., a core radius of one micron, or .001 mm). We will use a fiber core index of 1.51. Since the fiber is uncladded, the step in the index to the outside of the fiber is 0.51.

Note that this fiber is in actuality a multi-mode fiber. Since CEF only computes the coupling efficiency into the HE11 mode of a step index fiber, this results in an efficiency less than 1.0, with the rest of the energy either being not coupled into the fiber or coupled into the higher modes.

The output lists the standard output for all diffraction-based options followed by the specific output for the coupling efficiency.

```
Command Inputs:
  CEF
  MPR  STE  0.001  0.51
  CIN 1.51
  GO
```

```
APERTURE STOP
             SEMI-DIAMETER =     25.000000
               (Based on the maximum reference ray height at the stop.)

   X and Y focal lengths for each field angle

      X        0.100000E+03
      Y        0.100000E+03

   X and Y F-numbers for each field angle

      X            2.000000
      Y            2.000000

   Reference sphere radius for each field angle

               0.100000E+03

   Optimum increment in image plane is  0.0005000 units.
   Actual  increment in image plane is  0.0005000 units.
   Transform grid size is  128 x  128
```

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```
CEF option:  Computes the coupling efficiency of the lens into a single
             mode fiber, or into a single mode of a multimode fiber.

   The fiber is a step-index fiber.
             Core radius (lens units): 0.001000
             Core index:                1.51000
             Cladding index:            1.00000

   The fiber parameter, V, has a value of:  14.218
   Single mode operation is limited to values of V between 0.0 and 2.405.
   This fiber supports multiple modes.  Only the coupling into the
   fundamental (HE11) mode is considered.

                  POSITION:              1
      RELATIVE FIELD (X,Y):   (   0.000   0.000  ) mm.
                WAVELENGTH:          500.0        nm.
                   DEFOCUS:            0.00000    mm.

 The center position of the front face of the fiber, and the fiber
 orientation vector in image space coordinates are given by:

    FIBER POSITION (X,Y,Z): (   0.000000E+00   0.000000E+00   0.000000E+00  ) mm.
 FIBER ORIENTATION (L,M,N): (   0.000000E+00   0.000000E+00   0.100000E+01  )


 The coordinates of the center of the beam, and the beam
 orientation vector in image space are given by:

     BEAM POSITION (X,Y,Z): (   0.000000E+00   0.000000E+00   0.000000E+00  ) mm.
  BEAM ORIENTATION (L,M,N): (   0.000000E+00   0.000000E+00   0.100000E+01  )

 Coupling Efficiency
  YDE:          0.00
_______________________
  XDE
 0.00      |   .82122
```

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Example 2. Coupling of a Gaussian mode PSF into a Gaussian mode fiber

If the fiber mode matches the PSF mode, then perfect or near perfect coupling can take place. In this example, we will apodize the pupil with Gaussian apodization which goes to 0.001 intensity at the edge of the pupil. We will then specify a Gaussian mode fiber whose sigma matches that of the PSF output. The coupling efficiency is then nearly 100%. The PER CENT OF UNAPODIZED ENERGY value indicates that the Gaussian beam contains 14.5% of the energy relative to a uniformly illuminated pupil. The PER CENT OF GAUSSIAN USED value indicates that 99.9% of the energy under the Gaussian curve is being coupled into the fiber. The coupling efficiency includes this factor.

```
Command Inputs:
   PUI 0.001       ! Specify Gaussian apodization
   CEF
   MPR GAU 0.00119
   GO
```

```
APODIZED APERTURE ENERGY

        FIELD POSITION               PER CENT OF              PER CENT OF
      RELATIVE    DEGREES        UNAPODIZED ENERGY          GAUSSIAN USED

         0.00       0.00              14.50                     99.90


CEF option:  Computes the coupling efficiency of the lens into a single
             mode fiber, or into a single mode of a multimode fiber.

   The fiber mode has a Gaussian shape with a radius of 0.00119 mm.
   (This radius is the distance at which the field is 1/e times its peak.)


                  POSITION:               1
      RELATIVE FIELD (X,Y):    (   0.000    0.000  ) mm.
                WAVELENGTH:            500.0         nm.
                   DEFOCUS:              0.00000     mm.

 The center position of the front face of the fiber, and the fiber
 orientation vector in image space coordinates are given by:

    FIBER POSITION (X,Y,Z): (   0.000000E+00   0.000000E+00   0.000000E+00  ) mm.
 FIBER ORIENTATION (L,M,N): (   0.000000E+00   0.000000E+00   0.100000E+01  )


 The coordinates of the center of the beam, and the beam
 orientation vector in image space are given by:

     BEAM POSITION (X,Y,Z): (   0.000000E+00   0.000000E+00   0.000000E+00  ) mm.
  BEAM ORIENTATION (L,M,N): (   0.000000E+00   0.000000E+00   0.100000E+01  )


 Coupling Efficiency
  YDE:          0.00
_______________________
  XDE
 0.00      |  .99801
```

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Example 3. Variation of coupling efficiency to changes in fiber alignment

We will take the same lens and fiber mode as example 2 and look at the variation of insertion loss as the fiber is shifted in the Y direction and tilted in the YZ plane. The output is a table of the efficiency vs. the parameter values. The table can also be plotted. Only the final coupling efficiency table and plot is shown.

```
Command Inputs:
  CEF
  MPR  GAU  0.00119
  SN1  YDE  0  0.001  11
  SN2  ADE  0  5  6
  STL  1  2  3  4  5  6      ! Specify line styles
  DB Y
  GO
```

Coupling Efficiency (dB.)

ADE:	0.0000	1.0000	2.0000	3.0000	4.0000	5.0000
YDE						
.00000	-0.009	-0.082	-0.304	-0.674	-1.192	-1.857
.00010	-0.086	-0.160	-0.382	-0.751	-1.269	-1.933
.00020	-0.198	-0.272	-0.493	-0.863	-1.380	-2.044
.00030	-0.348	-0.421	-0.643	-1.012	-1.528	-2.191
.00040	-0.538	-0.612	-0.833	-1.202	-1.718	-2.380
.00050	-0.775	-0.849	-1.070	-1.438	-1.953	-2.615
.00060	-1.173	-1.247	-1.468	-1.835	-2.349	-3.009
.00070	-1.598	-1.672	-1.893	-2.259	-2.772	-3.430
.00080	-2.054	-2.128	-2.348	-2.714	-3.225	-3.881
.00090	-2.545	-2.620	-2.840	-3.204	-3.714	-4.369
.00100	-3.081	-3.155	-3.375	-3.739	-4.247	-4.900

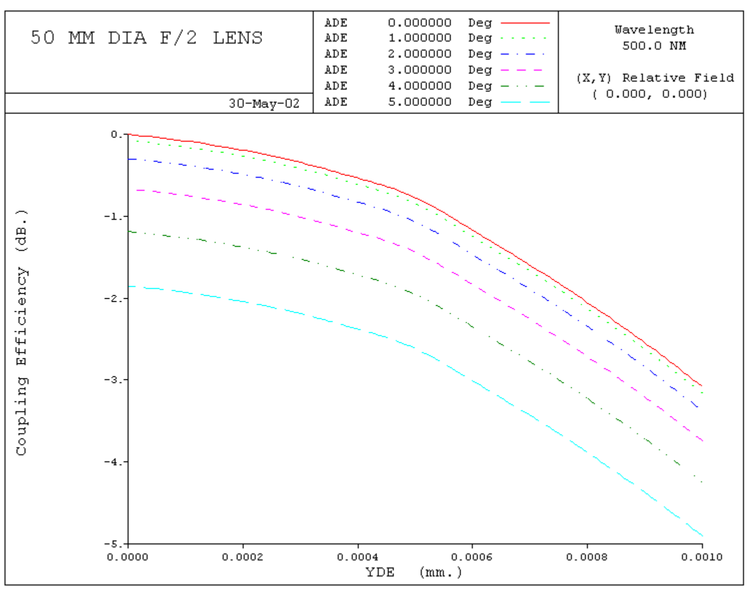

Figure 1. Plot of coupling efficiency as a function of decenter and tilt angle

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Example 4. BPR output used as input to CEF

This example defines a singlet to focus the 5 micron waist radius output of a laser. The BPR option is used to propagate the beam from the laser output to the paraxial image. The complex field data at the image is written to the worksheet buffer and is used as input to the CEF option.

Command Inputs:

```
RDM;LEN
TIT "Melles Griot LSF"
EPD    9.0
DIM    M
WL     587.56
SO     0.0 43.8467377172
S      12.9 3.19 BK7_SCHOTT
  STO
  CIR 4.5
  CIR EDG 5.0
S      -85.25 0.0
  CIR 4.5
  CIR EDG 5.0
S      0.0 41.7235946725
  PIM
SI     0.0 0.0
GO

BPR
wrx .005
dbp sa
!  CEF requires field defined on plane.
!  Therefore FFP or NFP must be used for final
!  propagation space if used for CEF input.
dbp ffp si-1..i
plo int si n
!  Direct BPR output to buffer for input to CEF
wbf cmp si b2
go

cef
! Define Gaussian Beam
mpr gau .00600
inb b2
go

buf del b2
```

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```
Actual  increment in image plane is  0.0006874 units.


 CEF option:  Computes the coupling efficiency of the lens into a single
              mode fiber, or into a single mode of a multimode fiber.

    The fiber mode has a Gaussian shape with a radius of 0.00600 mm.
    (This radius is the distance at which the field is 1/e times its peak.)


                   POSITION:              1
       RELATIVE FIELD (X,Y):    (   0.000   0.000  ) mm.
                 WAVELENGTH:           587.6        nm.
                    DEFOCUS:             0.00000    mm.

  The center position of the front face of the fiber, and the fiber
  orientation vector in image space coordinates are given by:

     FIBER POSITION (X,Y,Z): (   0.000000E+00   0.000000E+00   0.000000E+00  ) mm.
  FIBER ORIENTATION (L,M,N): (   0.000000E+00   0.000000E+00   0.100000E+01  )


  The coordinates of the center of the beam, and the beam
  orientation vector in image space are given by:

      BEAM POSITION (X,Y,Z): (   0.000000E+00   0.000000E+00   0.000000E+00  ) mm.
   BEAM ORIENTATION (L,M,N): (   0.000000E+00   0.000000E+00   0.100000E+01  )


  Coupling Efficiency
   YDE:         0.00
_______________________
   XDE
  0.00      |   .48811
```

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Example 5. Fiber coupling with a ball lens

This example shows the CEF output for a ball lens. Polarization ray tracing is enabled (POL Y), which automatically includes polarization effects and surface losses in the CEF calculation.

Command Inputs:

```
RDM N;LEN
TITLE 'Ball lens fiber coupler'
NAO   0.144
PUX   0.66
PUY   0.66
PUI   0.135
DIM   M
WL    1550.0
REF   1
WTW   1
INI   ' '
XOB   0.0
YOB   0.0
WTF   1.0
VUY   0.0
VLY   0.0
CA APE
SO    0.0 2.99609283716
  RED 1.0
S     0.666666666667 3.0 BK7_SCHOTT
  STO
  CIR EDG 1.5
S     -0.666666666667 2.99609283716
  CIR EDG 1.5
  PIM
SI    0.0 -0.155824321685
  THC 0
! Delete coatings
DEL COA SA
! Activate polarization ray tracing
POL Y
GO

cef
! Define Gaussian Beam
mpr gau .0052
go
```

```
        APERTURE STOP
        SEMI-DIAMETER =      0.445846
          (Based on the maximum reference ray height at the stop.)



 X and Y reduction ratios for each field angle

    X        0.918707E+00
    Y        0.918707E+00
```

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```
  X and Y F-numbers for each field angle

     X            3.189954
     Y            3.189954


  Reference sphere radius for each field angle

                  0.884810E+01



  Optimum increment in image plane is  0.0024722 units.
  Actual  increment in image plane is  0.0024722 units.
  Transform grid size is  128 x  128


  APODIZED APERTURE ENERGY

       FIELD POSITION             PER CENT OF               PER CENT OF
     RELATIVE    DEGREES       UNAPODIZED ENERGY           GAUSSIAN USED

        0.00       0.00             20.53                      99.00


CEF option:  Computes the coupling efficiency of the lens into a single
             mode fiber, or into a single mode of a multimode fiber.

  The fiber mode has a Gaussian shape with a radius of 0.00520 mm.
  (This radius is the distance at which the field is 1/e times its peak.)



                 POSITION:              1
     RELATIVE FIELD (X,Y):    (    0.000    0.000   )  mm.
               WAVELENGTH:           1550.0          nm.
                  DEFOCUS:               0.00000     mm.

 The center position of the front face of the fiber, and the fiber
 orientation vector in image space coordinates are given by:

    FIBER POSITION (X,Y,Z): (    0.000000E+00    0.000000E+00    0.000000E+00    ) mm.
 FIBER ORIENTATION (L,M,N): (    0.000000E+00    0.000000E+00    0.100000E+01    )


 The coordinates of the center of the beam, and the beam
 orientation vector in image space are given by:

     BEAM POSITION (X,Y,Z): (    0.000000E+00    0.000000E+00    0.000000E+00    ) mm.
  BEAM ORIENTATION (L,M,N): (    0.000000E+00    0.000000E+00    0.100000E+01    )


 Coupling Efficiency
  YDE:          0.00
_______________________
  XDE
 0.00      |   .72997
```

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```
Coupling efficiency for input polarization state at the nominal
fiber position:

   Fraction of input energy accepted        0.9900! Beam clipping factor
   Energy transmitted by optical system*    0.9213! Surface losses factor
   Total coupling efficiency (CEF)          0.7300! Total CEF for
                                              current polarization state
   Maximum CEF for all input states         0.7301
   Minimum CEF for all input states         0.7298
   Polarization dependent loss:
         Contrast                           0.0002! (.7301-.7298)/(.7301+.7298)
         Ratio                              0.9996! .7293/.7301

 * Excludes bulk transmission losses

   Input polarization states that produce the maximum and
   minimum CEF:
                                      MAXIMUM       MINIMUM
                                      -------       -------
   Polarized fraction (PFR):           1.0000        1.0000
   Minor/major axis ratio (PTP):       0.0000        0.0000
   Orientation in degrees (POR):     -90.0000        0.0000
   Handedness (PRO):                   Right         Right

Polarization Dependent Contrast
   YDE:          0.00
_______________________
   XDE
  0.00      |  .000187

Polarization Dependent Loss Ratio
   YDE:          0.00
_______________________
   XDE
  0.00      |  0.9996
```

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Technical Notes

Gaussian Approximation to a Step Index

A Gaussian mode approximation to a step index profile can be found from the following formulae (derived from *Optical Waveguide Theory*, by Snyder & Love, Chapman and Hall, 1983).

Define the following terms:

Fiber core index n_{co}

Clad index n_{cl}

Profile height parameter $\Delta = (n_{co}^2 - n_{cl}^2)/(2n_{co}^2)$

Fiber radius ρ

A fiber parameter V is computed from

$$V = (2\pi/\lambda)\ \rho\ n_{co}\ (2\Delta)^{1/2}\ .$$

If V > 2.4, then the fiber is probably a multi-mode fiber, and the actual coupling efficiency may be greater than that calculated by CEF. The Gaussian mode radius r_0 is calculated from

$$r_0 = \rho\ /\ [\ln (V)]^{1/2}$$

or, for r_0 that can be used at smaller values of V:

$$r_0 = 0.65 + 1.619\ /\ V^{1.5} + 2.879/V^6 \qquad \text{for } 0.8 < V < 2.5.^*$$

The mode profile of the approximating Gaussian is then given by

$$E(r) = \exp\ [-r^2\ /\ (r_0^2)]\ .$$

*From Marcuse: “Loss Analysis of Single Mode Fiber Splices,” *Bell Syst. Tech. J.* 56, 703, 1977.

Isoplanatism and OSC

Any calculation that deals with extended objects depends upon isoplanatism - constancy of the point image patch as the field changes over the width of the object, e.g. over enough cycles of the MTF target to integrate properly. Isoplanatism is connected with Offense Against Sine Condition (OSC) and is destroyed by significant OSC residuals. OSC can also lead to invalid distribution of rays over the exit pupil, if not properly compensated.

In all CODE V options that deal with diffraction or accurate intensity calculations (ALI, CEF, LSF, MTF, PAR, PMA, PSF, TOR, and WAV), special programming has been incorporated to represent the local intensity and magnification changes that occur with OSC, so that any wavefront and point image is correctly apodized and calculated, even in the presence of large OSC; for example, an f/0.3 parabola would have massive OSC. This special process is valid in all forms of calculation (convolution, FFT, etc.) and has little effect on compute time.

Even though the calculation is accurate, the lack of isoplanatism will still cast doubt on the usefulness of any option results dealing with extended objects, when the image is changing so rapidly across the target. In these options (CEF, LSF, MTF, PAR, PMA, PSF), a test is made to see if OSC is sufficient to affect results. If so, a warning is issued to alert you that the system is not isoplanatic at the field in question.

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F-Numbers, Focal Lengths and Reduction Ratios

In some of the CODE V options that deal with diffraction calculations (CEF, LSF, MTF, PAR, PMA, and PSF), the listed output includes focal lengths (or reduction ratios if the object distance is finite) and f-numbers based on the references rays at each field. A value for both the X and Y directions is given. These numbers vary with field and are useful for relating image dimensions to object dimensions and for simple relative illumination calculations. Also included are the reference sphere radii for each field. Diffraction is assumed to take place at the reference sphere.

The f-numbers (fno) are based on a calculation of the image intensity. Thus, if the pupils are approximately elliptical, an estimate of the relative illumination can be obtained from the product of the X and Y numerical apertures. (The numerical aperture is given by NA = 1/(2*fno).) This calculation assumes a Lambertian object and a uniformly illuminated exit pupil and ignores transmission losses in the lens. It includes the effect of a non-flat image surface. Note that, for a perfect thin lens with stop in contact and the object at infinity, the X numerical aperture is proportional to the cosine of the field angle while the Y numerical aperture is proportional to the 3rd power of the cosine, thus giving the cosine 4th law.

The reduction ratio, which is listed for a system with a finite object distance, is the ratio of an incremental distance on the image to the corresponding distance on the object, measured in a coordinate system normal to the surface. In general, a square patch on the image can represent a parallelogram shaped patch on the object, with the X and Y reduction ratios used to calculate the sides. The angle of the parallelogram is not listed although it is included in the internal calculation.

The focal length, which is listed for a system with an infinite object distance, relates the image patch size to an angle in object space. It can be thought of as the product of the f-number and pupil diameter, similar to the paraxial definition. Consistent with the other calculations, it assumes a measurement normal to the object surface which is typically flat for an object at infinity. Thus, dividing the image patch size by the focal length gives the change in the sine of the field angle. To get the change in angle, divide this number by the cosine of the field angle.

The reference sphere radius is also listed for each field. It is used to calculate the wave aberrations and is also used in the calculation of the focal lengths and f-numbers although it normally has very little influence on these numbers. It can be used to identify potential problems when the radius is so short that the reference sphere is within the caustic of the image.