Gaussian Beam and Fiber Coupling Tutorial Using OSLO

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INTRODUCTION

This tutorial demonstrates how to choose and insert a simple catalog lens in OSLO and then perform three different Gaussian beam analyses on the resulting system:

    1) ABCD (paraxial) Gaussian beam propagation,
    2) Skew (astigmatic) Gaussian beam propagation,
    3) Fiber coupling calculations using real ray tracing and a Gaussian apodized pupil.

Even if you are only interested in understanding how to perform fiber coupling calculations in OSLO, it is advised that you DO NOT skip the first two sections of this tutorial. The tutorial is relatively short and it is important that you see how the different calculations relate to each other. This tutorial is written so that it can be performed using all editions of OSLO (including OSLO LT).

OUTLINE

The steps in the exercise are as follows:

- **Lens entry** - Enter a "ball" lens from one of the vendor catalogs in OSLO.

    o Use Melles Griot part number MGLMS202

    o Set up the conjugates of the lens so that it is used at -5 magnification

    o Set the lens Drawing Conditions so that the object and image surfaces can be seen in the drawings and multiple rays are traced across the aperture in side views.

- **ABCD (paraxial) Gaussian beam propagation calculation** - Use the interactive spreadsheet and Gaussian beam plotting options

    o Set the beam waist to be 1 micron at the object surface in the interactive spreadsheet.

    o While keeping the beam waist at 1 micron, change the beam spot size to be 20 microns at the object surface. Note that multiple solutions to the Gaussian Beam calculation are generated.

    o Observe both solutions using the interactive Gaussian beam plotting capability

- **Skew (astigmatic) Gaussian beam propagation calculation** - Calculate the propagation of an Gaussian beam that is astigmatic (different beam widths in the two orthogonal cross sections of the beam).

    o Change the Y and X spot sizes of the beam to be 0.5 and 1.5 microns at the object surface.
    o Observe the calculation results.

- **Fiber coupling calculations using real ray tracing and a Gaussian apodized pupil** - Couple the astigmatic Gaussian beam to a gradient index fiber which has a Gaussian shaped refractive index across its cross section.

    o Calculate the power coupling efficiency

    o Note the increase in coupling efficiency that is obtained when the image plane is moved 300 microns closer to the lens

    o Observe the Point Spread Function of the beam at the fiber coupling plane (the image plane).

DETAIL

In the following detailed steps, many of the words you need to type and actions you need to perform will be highlighted with "quotes" so they stand out from the rest of the tutorial text. The quotes are only used to increase readability of this document. Do not type the quotes themselves.

Lens entry

This first part of the Detail section of the tutorial deals with entering the basic elements of a new lens. This lens will be used in later sections so follow along with these step-by-step instructions..

1) Choose "File>>New Lens…" from the OSLO menu
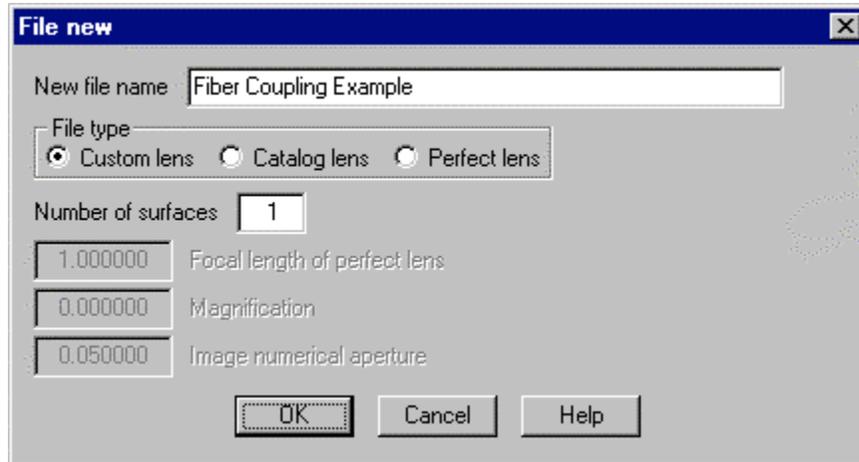
2) In the resulting "File new" dialog box, enter the file name "Fiber Coupling Example", select Custom lens and enter 1 surfaces, then click on the OK button.

*A new spreadsheet will appear where you can enter data in almost all the spreadsheet cells. Note that at the top of the spreadsheet, permanent text and user editable text can exist in the same cell. **For example:** note the static text "Ent beam radius" and the editable value of 1.000000 is contained in the same cell.*
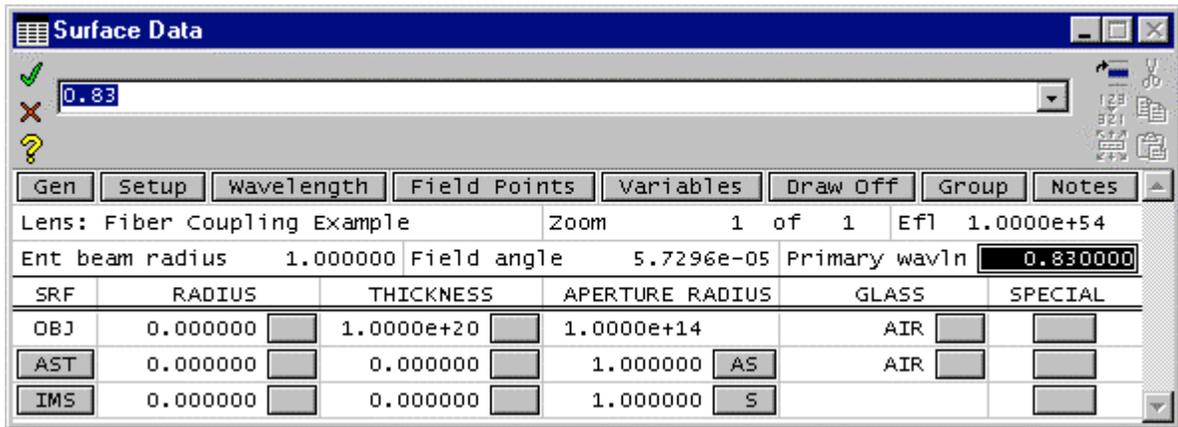
**Note that the user can edit the right side of all these**
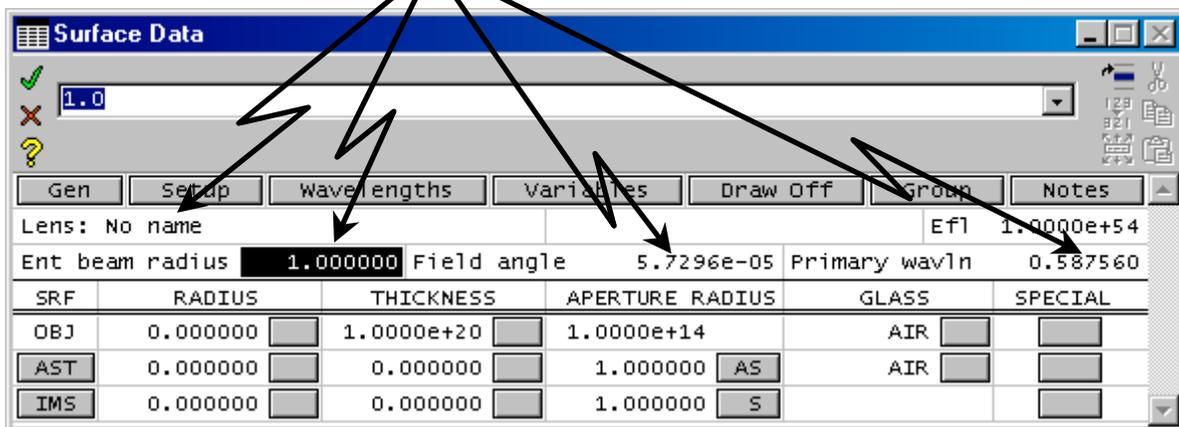
1-3   Gaussian Beam and Fiber Coupling Tutorial Using OSLO

3) Enter the text "Fiber Coupling Example" in the "Lens:" cell
4) Enter the wavelength "0.83" in the "Primary wavln" cell

NOTE:

If at any time while working with OSLO, you find that have closed the Surface Data window (this can be done by clicking on the "Green Check" or "Red X"), the resulting window will just look like this "Command" window.
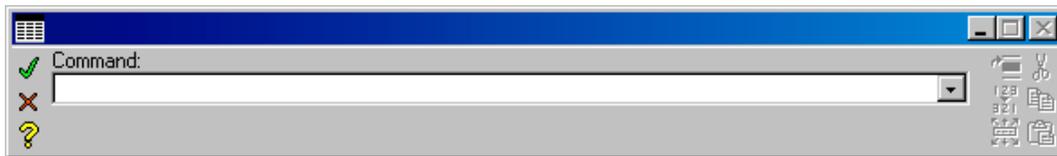
To get the Surface Data spreadsheet back, choose "Lens>>Update Lens Data" from the OSLO menu.

5) Now is a good time to save the current state of your lens by choosing File>>Save Lens from the OSLO menu, and then clicking on the "Save" button.
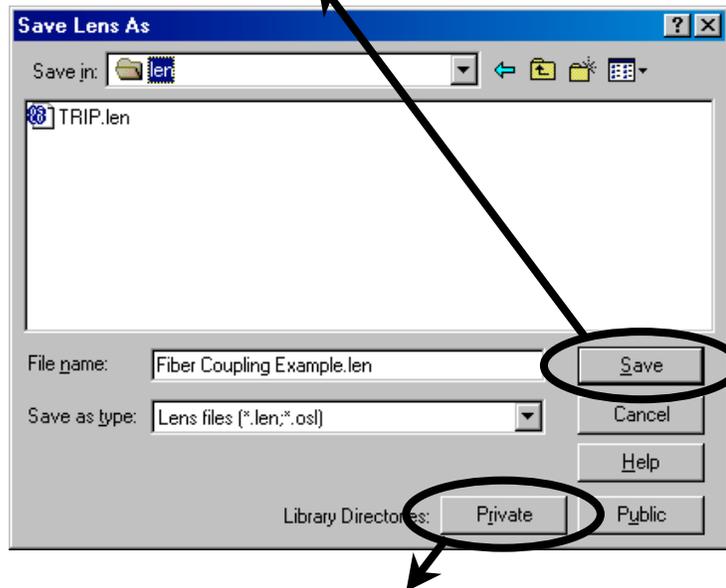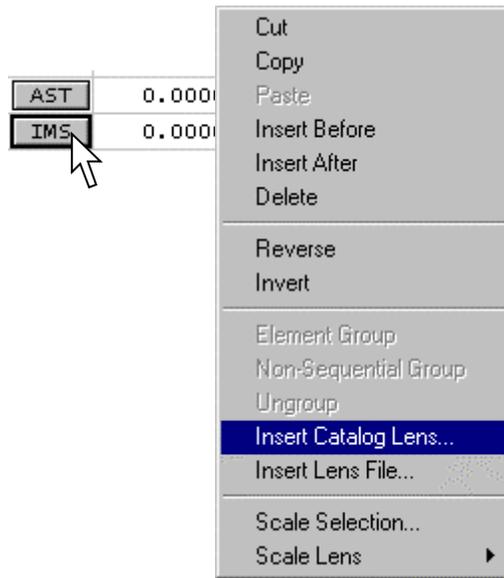

Before you save the lens, make sure that you click on the "Private" button to ensure that the lens is stored in your "...\private\len" lens directory. This directory is for all the lens files that you will create. No program files will be written to the private directory during future OSLO upgrades. Putting all your lenses in this directory (or sub directories of it) will ensure that your files do not get overwritten by future OSLO release files.

Note that the object surface (which is always surface number "0") is labeled "OBJ" and the image surface (currently this is surface number "2") is labeled "IMS". In any system that you create in OSLO, there is always an object and an image surface. Since you chose one ("1") surface when you started this lens, there is an additional surface listed that is labeled "AST" because it is currently the Aperture Stop surface.

Gen	Setup	Wavelengths	Variables	Draw Off	Group	Notes

Lens: Fiber Coupling Example   Efl   1.0000e+54

Ent beam radius   1.000000   Field angle   5.7296e-05   Primary wavln   **0.830000**

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	.000000	1.0000e+20	1.0000e+14	AIR	
AST	.000000	0.000000	1.000000 AS	AIR	
IMS	0.000000	0.000000	1.000000 S		

AST	0.000
IMS	0.000

- Cut
- Copy
- Paste
- Insert Before
- Insert After
- Delete
- Reverse
- Invert
- Element Group
- Non-Sequential Group
- Ungroup
- **Insert Catalog Lens...**
- Insert Lens File...
- Scale Selection...
- Scale Lens ▶

6) To insert a catalog lens just before the image surface, click the right mouse button on the gray box containing the "IMS" in the surface ("SRF") column, and choose "Insert Catalog Lens…" from the resulting list.

Catalog Lens Database

MGLMP059
MGLMP061
MGLMP063
MGLMS002
MGLMS003
MGLMS005
MGLMS102
MGLMS103
MGLMS105
MGLMS202
MGLMS203
MGLMS205
MGLMS302
MGLMS303
MGLMS305
MGLMS402

Part: MGLMS202   Diameter: 1.440
EFL: 1.100   Thickness: 2.000

This opens up the Catalog Lens Database dialog window which by default shows the positive lenses from the Melles Griot Catalog (Catalog = "MG_POS").
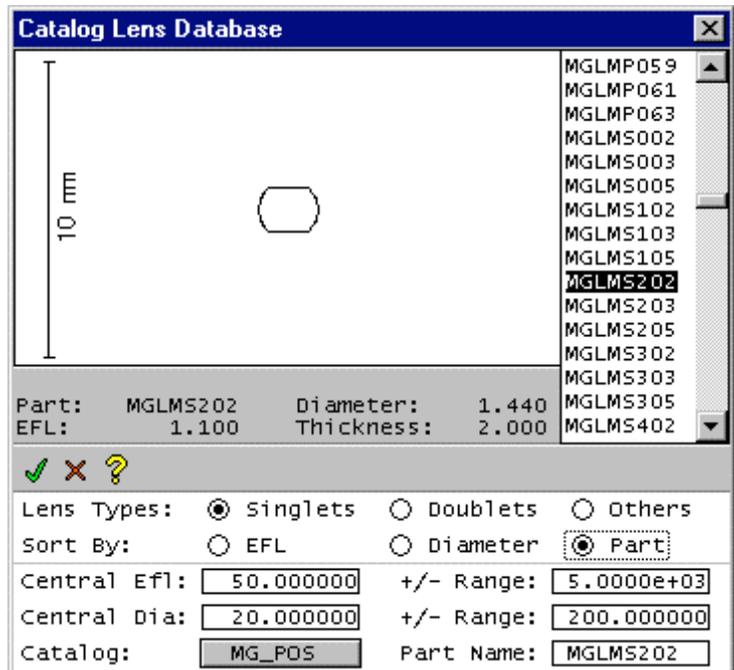
7) Choose "Lens Types:" to be "Singlets" and "Sort By:" to be "Part" number, and then choose "MGLMS202" from the resulting list.

Lens Types:	⦿ Singlets	○ Doublets	○ Others
Sort By:	○ EFL	○ Diameter	⦿ Part

Central Efl: 50.000000   +/- Range: 5.0000e+03
Central Dia: 20.000000   +/- Range: 200.000000
Catalog: MG_POS   Part Name: MGLMS202

8) To accept this catalog part as a lens to be inserted into your system, click on the green check on the left hand side of the window.

Note that the MGLMS202 lens has now been inserted into your Surface Data spreadsheet starting at surface 2.

Gen	Setup	Wavelength	Field Points	Variables	Draw Off	Group	Notes ▲

Lens: Fiber Coupling Example		Zoom	1 of 1	Efl	1.101696

Ent beam radius	1.000000	Field angle	5.7296e-05	Primary wavln	0.830000

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	1.0000e+20	1.0000e+14	AIR	
AST	0.000000	0.000000	1.000000 AS	AIR	
2	MGLMS202	2.000000 F	0.720000 F	FIXED F	
3		0.000000	0.720000 F	AIR	
IMS	0.000000	0.000000	0.092310 S		

9) If you want to see the lens in a simple graphic window, click on the "Draw Off" button at the top of the Surface Data spreadsheet window. This button will toggle the Autodraw window on and off.
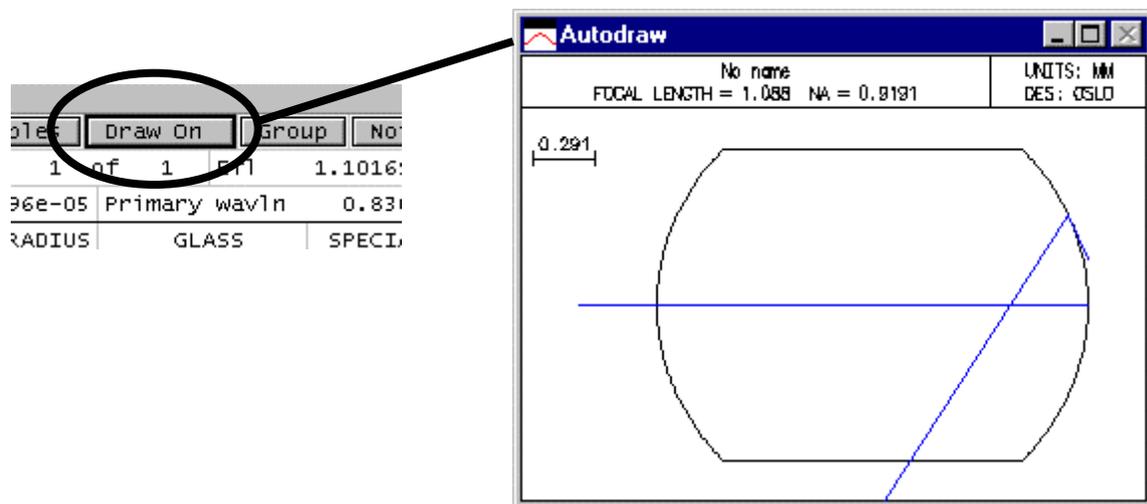
10) If you want to see the surface radii of curvature and the glass type of this lens, click on the "Group" button at the top of the Surface Data spreadsheet window so that the button now indicates "Surfs". This button will toggle between showing surface groups and individual surfaces in your Surface Data spreadsheet.

11) Note that the thickness of the catalog lens is 2x the radii of the surfaces of the lens. This results in a simple ball lens although the complete spherical shape of the ball cannot be seen because the physical aperture radii on the lens have been set to 0.72.

12) Set the thickness of surface 1 to be "-1". In the sequential order of the surface spreadsheet, this will cause surface 2 (the beginning surface of the catalog lens) to always be 1 mm to the left of surface 1. And since surface 1 is the aperture stop, for this tutorial the system aperture stop will always be in the center of the thickness of the catalog lens (1 mm to the right of surface 2 places it in the middle of a 2 mm diameter lens.

Gen	Setup	Wavelengths	Variables	Draw On	Surfs	Notes
Lens: Fiber Coupling Example					Efl	1.101696
Ent beam radius	1.000000	Field angle	5.7296e-05	Primary wavln		0.830000

SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		1.0000e+20		1.0000e+14		AIR		
AST	0.000000		-1.000000		1.000000	AS	AIR		
2	1.000000	F	2.000000	F	0.720000	F	LASFN9	F	
3	-1.000000	F	0.000000		0.720000	F	AIR		
IMS	0.000000		0.000000		0.092310	S			

Now using some very simple numbers as an example, lets assume that we want to use this catalog lens to image a Gaussian beam source (or" object") of 1 micron to an "image" of 5 microns. Since we are using a single lens, we know that the orientation of the object to image must be inverted and the resulting magnification would be -5. Forcing the object and image distances (conjugates) of our system to create a -5x imaging system is easy…

10) Click on the "Setup" button at the top of the Surface Data Spreadsheet and enter "-5" in the "Magnification" field of the resulting Paraxial Data Editor spreadsheet. Note that a number of other fields in the "Conjugates" will be recalculated.

Gen	Setup	Wavelength	Field Points	Variables	Draw Off	Surfs	Notes

Conjugates	
Object dist	1.322036
Object to PP1	1.322036
Gaus img dist	5.610179
PP2 to image	6.610179
Magnification	-5.000000
	17.030000
1.000000 sdgy	1.000000

11) Remember to click on the Green check in the upper left corner of the window to save your changes.

Your spreadsheet should now look like this:

Gen	Setup	Wavelengths	Variables	Draw On	Surfs	Notes
Lens: Fiber Coupling Example					Efl	1.101696
Ent beam radius	1.000000	Field angle	5.7296e-05	Primary wavln		0.830000

SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		1.322036		1.3220e-06		AIR		
AST	0.000000		-1.000000		1.000000	AS	AIR		
2	1.000000	F	2.000000	F	0.720000	F	LASFN9	F	
3	-1.000000	F	5.610179		0.720000	F	AIR		
IMS	0.000000		0.000000		6.6102e-06	S			

With the object and image conjugates of the lens now changed, we should be able to view the effect of the new conjugates on the lens drawing. To get a little better view of the lens in the Autodraw window, we will now change the drawing parameters to display the object and image surfaces and also to show more rays:

12) To force the drawing of the object surface (along with the drawing of the rays going to it), click in the gray box in the special column of the object surface, and choose "Surface Control (F)>>General" from the resulting popup menu.
13) In the resulting Surface Control Data dialog box, choose "Surface appearance in lens drawing" to be "Drawn".
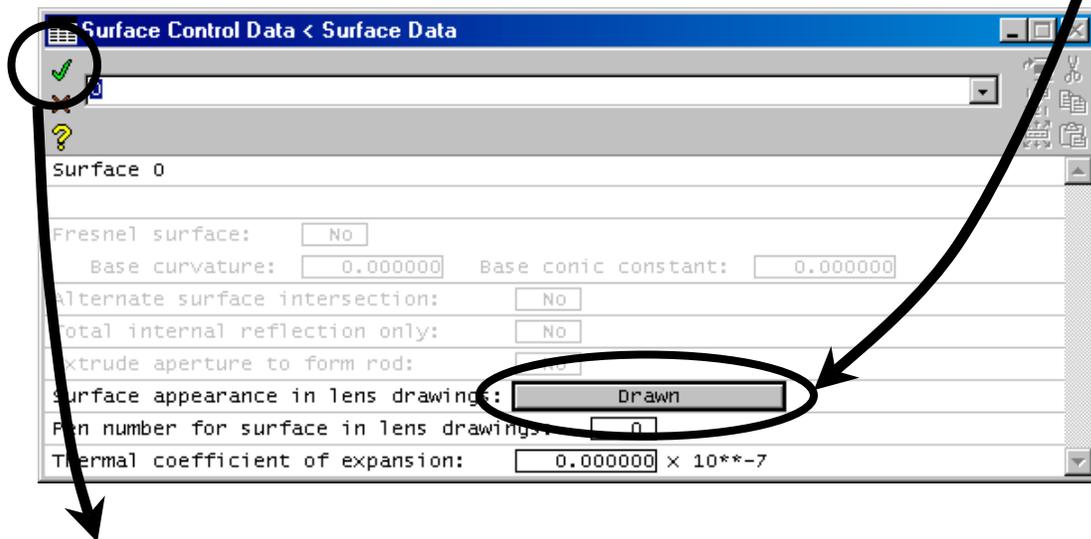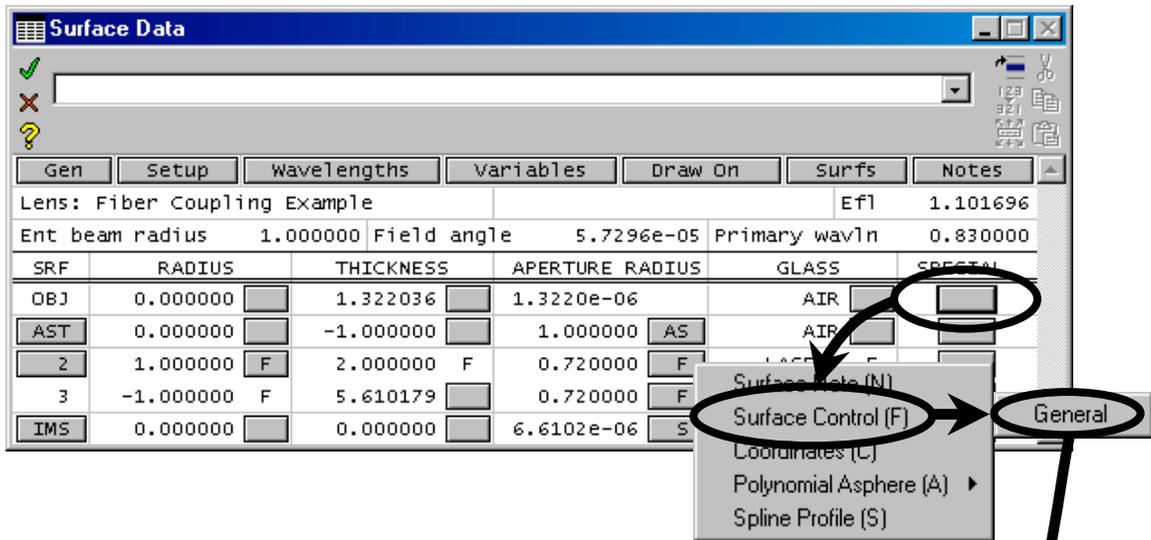
14) Click the green check to save the changes in the Surface Control Data Window.

15) To force the image surface (IMS) to be drawn, perform the same tasks (steps 12-14) on the image surface. The resulting spreadsheet will have an "F" in the SPECIAL column for the Object (OBJ) and Image (IMS) surfaces.

16) To draw more rays, choose "Lens>>Lens Drawing Conditions…" from the OSLO menu. Near the bottom of the resulting Lens Drawing Conditions spreadsheet, set the number of "Rays" to be drawn for the "Frac Y Obj" = 0 and "Frac X Obj" = 0 to be "11". Click the green check to accept your changes.

Now with the Autodraw window open, you should be able to see a good side view representation of your current lens with -5x magnification and 11 rays across the aperture. Note that the performance of the lens is not very good and a few of the drawn rays do not converge at the image plane.
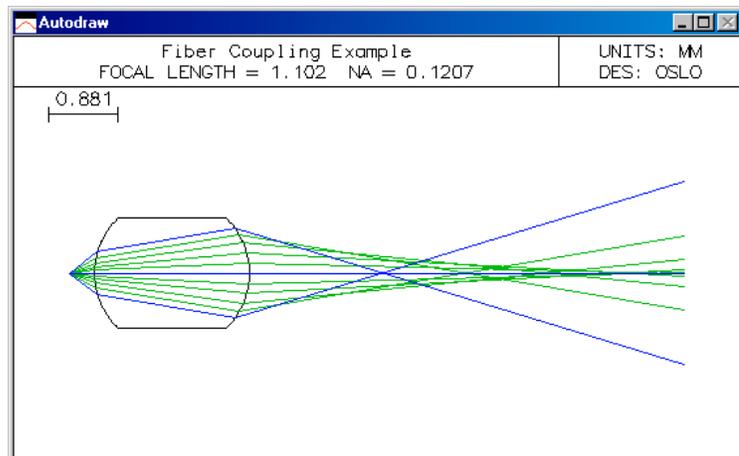
Before moving on, you should save your lens by choosing "File>>Save Lens" from the OSLO menu.

ABCD (paraxial) Gaussian beam propagation calculation
The tutorial continues with the first analysis option:
17) Choose Source>>Paraxial Gaussian Beam (ABCD) from the OSLO menu. The resulting Gaussian Beam Tracing spreadsheet calculates a Gaussian beam as it passes through your lens using the paraxial "ABCD" law (see the OSLO Optics Reference for more information).
18) Note that on the left side of the spreadsheet you can define the setup of the Gaussian beam and on the right side of the spreadsheet you can evaluate the Gaussian beam. Try experimenting with values entered into cells on the left side and note the changes to values on the right.
19) Note that of the four values shown (w,w0,z,R) on the left side, only two are required and the others will be calculated from the initial two. The last two values you change on the left side are noted with an asterisk.

If you ever want to "reset" this Gaussian Beam Tracing spreadsheet, simply close the spreadsheet by clicking on the red X in the upper left, and reopen the spreadsheet from the OSLO menu as in step 17.

Try the following parameter values in the spreadsheet:
20) On the left side of the window,
20a) Set the "Beam Specification Surface" to "0"
20b) Set w0=0.001 (beam waist spot size = 1 micron)
20c) Set z=0 (waist distance = 0mm)

You have now effectively placed the beam waist exactly at the position of the object surface with a size of 1 micron.

21) Look at the right side of the window and note that the resulting waist size in image space (surface 4) is 5 microns with a very small defocus error of -3.282 microns.

Note that if you specify a different beam size at the object surface but keep the size of the beam waist the same (0.001), OSLO determines that you must intend to displace the beam waist position from the object surface. However, since you didn't specify which direction to displace the beam waist (in front or behind) there would be two possible solutions to the problem:

22) Enter w=0.02 and w0=0.001 and you will find that there are now two solutions for when the beam waist falls both in front of (Solution II) and behind (Solution I) the object surface. Remember that a negative distance means the distance is to the left or "in front of" the object as light travels from left to right.
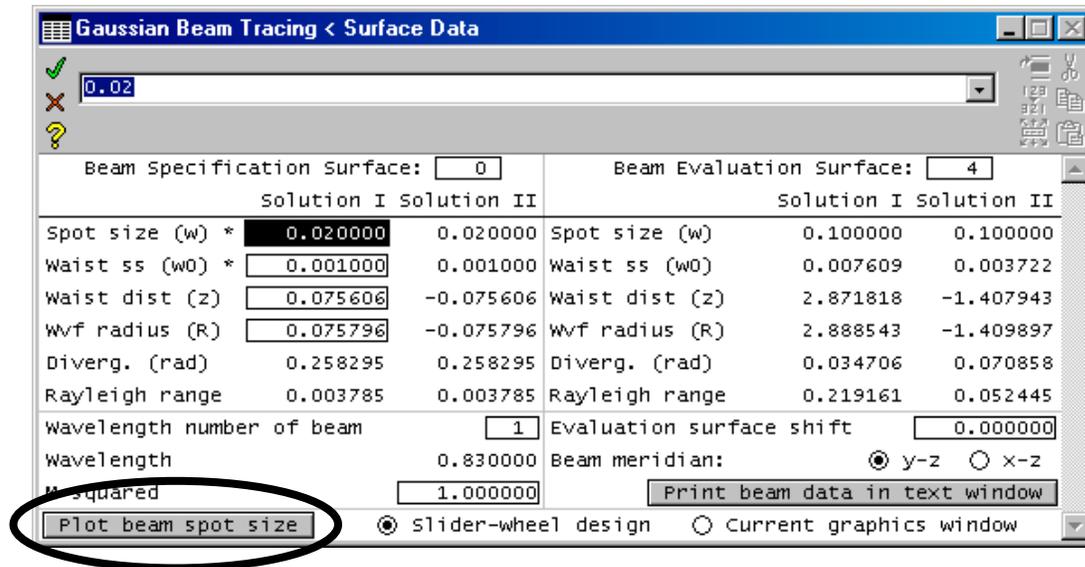
23) Note that now there are also two solutions in image space (look at the right side of the Gaussian Beam Tracing dialog window).

24) Click on the "Plot Beam Spot Size" button at the bottom of the spreadsheet to watch an interactive visual display of the beam spot size (beam width profile).


The semi-diameter of the Gaussian beam cross section (i.e. 1/2 of the beam width profile) is shown in the resulting graphics window. In a paraxial system the optical system and the resulting Gaussian beam are both rotationally symmetric about the optical axis. This means that only one half of the beam profile needs to be displayed and the two solutions (I & II) can be super imposed on top of each other. Solution I is graphed above the optical axis and Solution 2 is graphed below.

By looking at the two solutions, you can see that each solution starts with the same sized beam at the object surface (the left most point of the graph). But in Solution I the beam waist happens to the right of the object surface and in Solution II the beam waist is situated to the left - but it is not shown: it is just to the left of the edge of the graph.

The three vertical lines in the resulting graphics window correspond to the optical surfaces 1, 2 and 3 in the optical system. Since this is a paraxial analysis, each of the surfaces is illustrated as a straight vertical line even though surfaces 2 and 3 have curvatures. Also, note that surface 1 is shown to the left of surface 2. For this analysis, negative thicknesses are shown as positive so that the surfaces can be shown in surface order from left to right. The analysis values of the beam sizes are still calculated correctly.

25) Note that there is a separate slider bar that is attached to this graphic window. When you plot the Gaussian beam spot size for the first time, your slider bar may be so small that some of the features are obscured. Stretch the slider bar sideways so that the slider button is fully accessible.
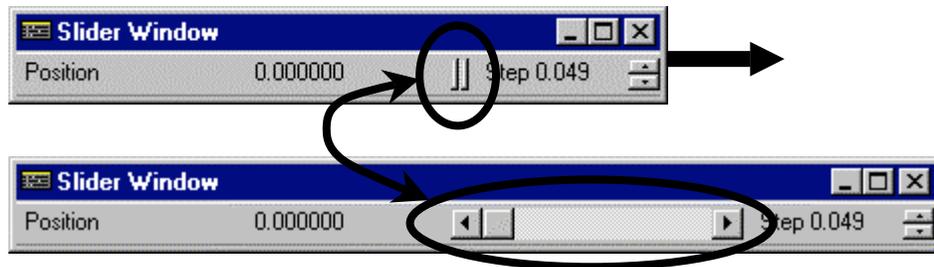
26) Try moving the slider bar and observe the associated graphics window. As the vertical line that represents the analysis plane of the system moves back and forth, the spot size values at the bottom of the window will be continually updated.
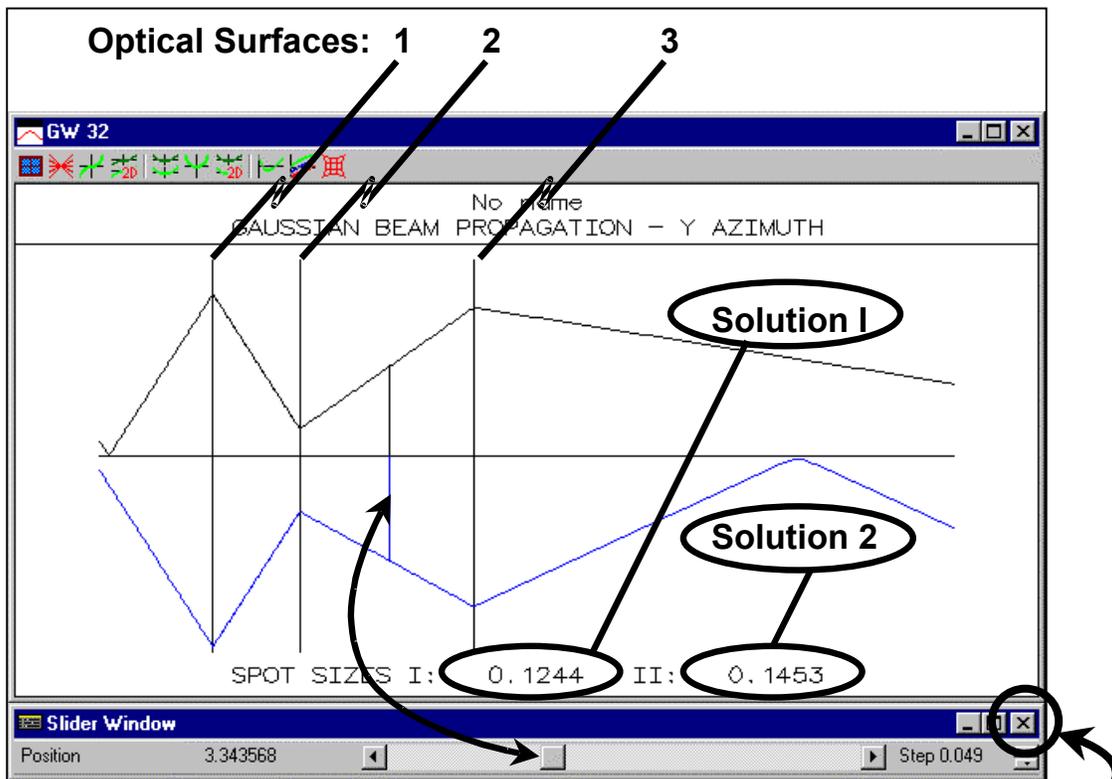
*To close the slider window, click on the close box in the upper right corner of the slider.*
To close the Gaussian Beam Tracing window, click on the green check in the upper left corner.

Skew (astigmatic) Gaussian beam propagation calculation

Now we change the object so that it mimics an astigmatic Gaussian beam. For purposes of this example, we will work in round numbers, we assume that the beam has a vertical (y) spot size of 0.5 microns, and a horizontal (x) spot size of 1.5 microns.

27) Choose Source>>Skew Gaussian Beam… from the OSLO menu
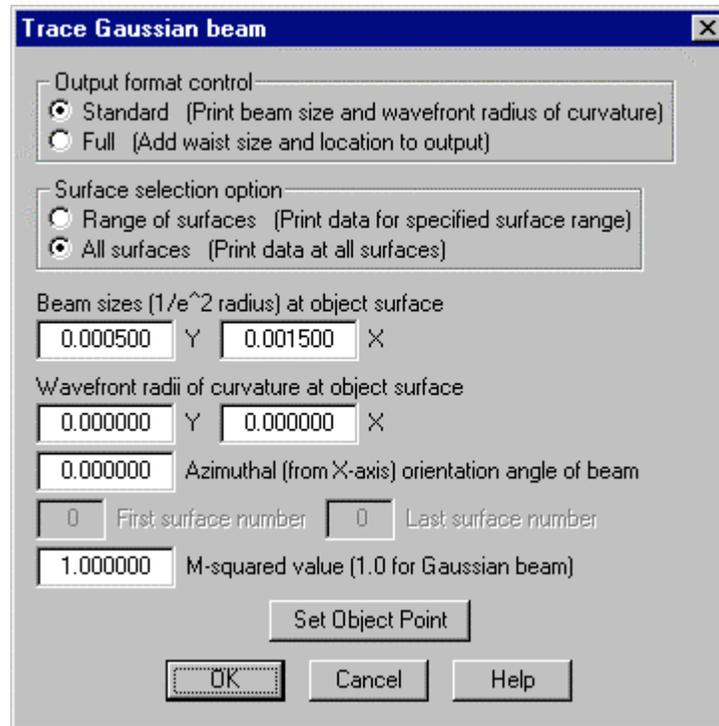
28) In the resulting dialog box, enter the Y and X 1/e^2 radii at the object surface.
29) Click on the OK button to accept the changes you made and perform the analysis.

For this example, we will assume that the beam waist occurs exactly at the object surface. If this was not the case, you would enter a value for the wavefront radii at the object surface, which would specify that the beam waist occurs elsewhere.

Note that if the beam deviated from a Gaussian cross section, you could adjust the M-squared parameter (M^2) for a better modeling fit. A brief discussion about the M^2 parameter can be found in the Optics Reference with reference to other literature for a more in depth treatment of the subject of M^2 (1).

Note that the analysis you just performed uses the same ABCD algorithm described in the previous section, except now it is applied using different parameters in the two orthogonal cross sections of the Gaussian beam (Y & X).

30) Due to the complexity of the data output, the data gets written to the text window but it reports basically the same information that was available in the symmetric ABCD analysis.

Fiber Coupling Calculations

Up until now, we have discussed the propagation of Gaussian beams using paraxial calculations. However aside from utilizing the M^2 parameter, paraxial calculations do no take into account aberrations of the propagating beam. OSLO also allows the user to approximate Gaussian beam propagation using real ray tracing. Please note that the concept of describing beam waists is probably no longer applicable for beams that are severely aberrated (i.e. if they deviate significantly from a Gaussian cross section). Therefore the OSLO implementation of ray traced Gaussian propagation does not attempt to calculate these typical Gaussian parameters (beam waist, beam divergence ...etc.).

31) In the previous analysis, note that the 1/e^2 beam size on surface 1 was 0.698556 and 0.232857 respectively.

32) To propagate the Gaussian beam properly, we apply a Gaussian apodized cross section to the ray tracing calculations. We do this by opening up the "Setup" editor from the surface data spreadsheet and propagating beam.
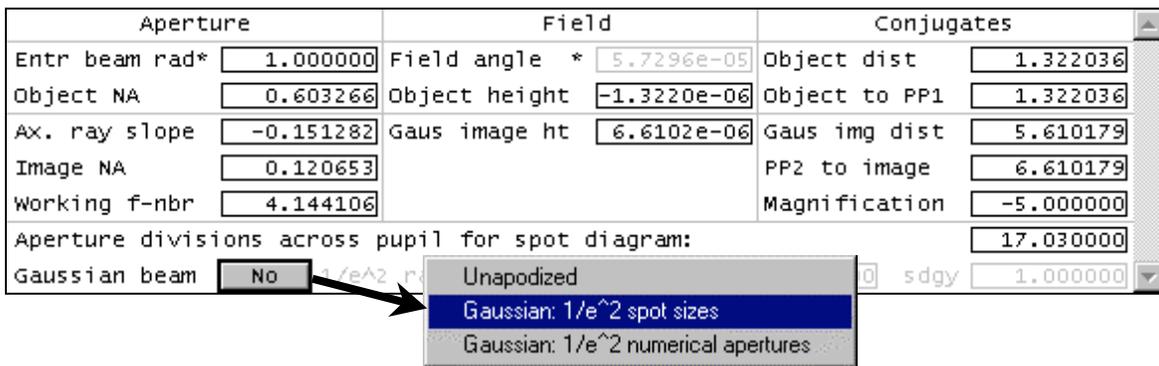
33) Once in the Paraxial Setup Editor, choose Gaussian 1/e^2 spot sizes and enter 0.698556 and 0.232857 into the resulting "sdgx" and "sdgy" cells (it defines the semi-diameter of the Gaussian cross-section in both the X and Y directions).
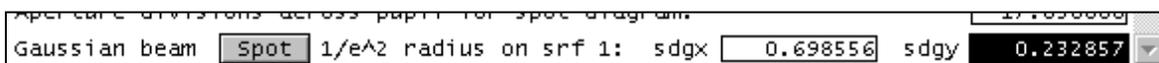
34) Close this dialog by choosing the green check from the upper left of the window.

Additionally, if the average of the Y and X wavefront radius (Y RFR RAD and XRFR RAD) from the analysis performed in step #29 was significantly different from the object thickness of the lens, you should change the object thickness to be the average of these two values.

35) To perform the fiber coupling calculation itself, we choose "Source>>Fiber Coupling…" from the OSLO menu.
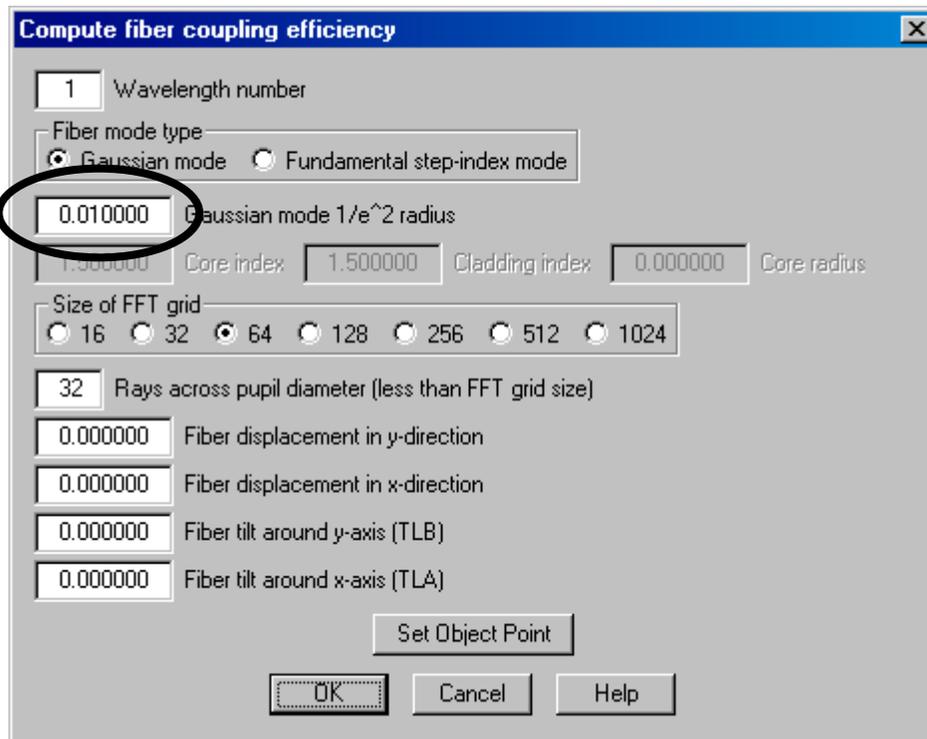
36) In the resulting dialog, we choose to investigate our beam being coupled into a single mode fiber that has a Gaussian mode 1/e^2 radius of 10 microns. Enter 0.01 mm into the Gaussian mode cell of the dialog box.

*Note that from this dialog box, you can control the tilt and translation of the coupling fiber with respect to the optical beam. Note that the tilt (TLA and TLB) of the fiber is relative to the coordinate system of the image surface, while the displacement (x and y directions) are relative to the intersection of the chief ray at the image plane. To change to a different field position (a different chief ray) click on the "Set Object Point" button and choose a different field point.*
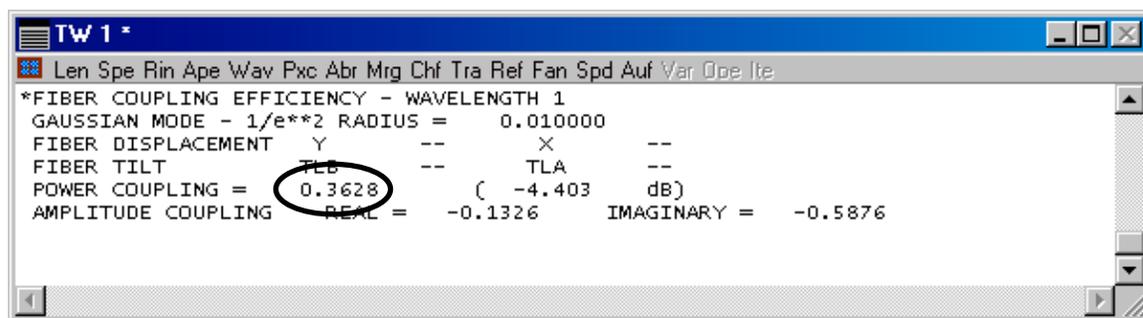
37) Keeping all the other defaults in the dialog box as they are, choose OK accept your entry and perform the fiber coupling calculation.

38) You can observe that the resulting analysis that gets printed to the text window reveals that the Fiber Coupling Efficiency is 36.28%.
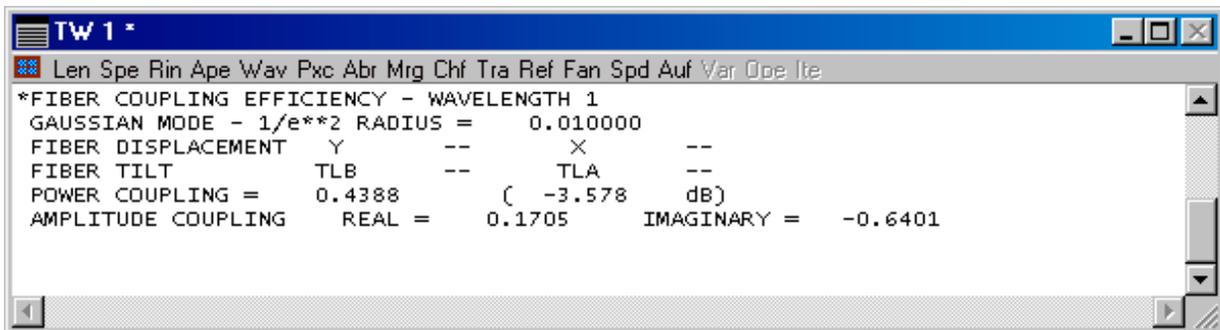
39) The above efficiency was calculated at paraxial focus (as calculated when we performed the magnification calculation). It is well known that in the presence of spherical aberration, best focus is not at the paraxial focus. Introduction of a focus shift can also be used to increase the coupling efficiency. For example, try shifting the end of the fiber (the image plane itself) by 300 microns towards the lens (make the distance to the image surface 0.3mm less). You can do this by entering the number -0.3 as the thickness of the image surface.

Gen	Setup	Wavelengths	Variables	Draw On	Surfs	Notes
Lens: Fiber Coupling Example					Efl	1.101696
Ent beam radius		1.000000	Field angle	5.7296e-05	Primary wavln	0.830000

SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		1.322036		1.3220e-06		AIR		F
AST	0.000000		-1.000000		1.000000	AS	AIR		
2	1.000000	F		F	0.720000	F	LASFN9	F	
3	-1.000000	F	5.610179		0.720000	F	AIR		
IMS	0.000000		-0.300000		0.045391	S			F

Note that in OSLO, the distance of from the second to last surface (here surface #3) to the image surface (here surface #4) is actually the sum of the thicknesses of surfaces #3 and #4. This helps the user add and subtract small defocus values by adjusting the thickness of the image surface (here surface #4 or IMS). Putting a value of -0.3 as the thickness of the image surface, effectively moves the image surface -0.3 mm to the left (a negative thickness means that the distance is to the left).

40) Note that this defocus change results in the increasing the fiber coupling efficiency to almost 44% if you perform the fiber coupling analysis again.

```
TW 1 *                                                              _ □ ×
Len Spe Rin Ape Wav Pxc Abr Mrg Chf Tra Ref Fan Spd Auf Var Ooe Ite
*FIBER COUPLING EFFICIENCY - WAVELENGTH 1
 GAUSSIAN MODE - 1/e**2 RADIUS =     0.010000
 FIBER DISPLACEMENT    Y       --       X       --
 FIBER TILT         TLB       --     TLA       --
 POWER COUPLING =     0.4388     ( -3.578    dB)
 AMPLITUDE COUPLING    REAL =    0.1705    IMAGINARY =   -0.6401
```

In order to calculate the fiber coupling efficiency, OSLO performs an overlap integral of the beam compared with the fiber cross sections at the image plane and calculated the percentage of light coupled into the fundamental mode of the fiber. In other words, the calculated "Power Coupling" value only represents the efficiency of the coupling itself. For example, it does not take into account light lost through Fresnel reflections prior to the image surface. For this information, you must perform separate analyses in OSLO and then manually combine the results of those efficiency calculations with the fiber coupling efficiency calculated here.

In the Premium edition of OSLO, users can choose to couple into a specialized fiber by attaching a user created CCL function to the fiber coupling efficiency calculation (see the dialog associated with step #36 above). OSLO will use the user created CCL function during the fiber coupling efficiency calculation.

41) Another way to observe the performance of the Gaussian beam at the image plane without specifically measuring fiber coupling efficiency, is to calculate the diffraction point spread function (PSF) by choosing "Source>>Truncated Gaussian Beam" from the OSLO menu (you can also choose PSF options from the graphic window toolbars).
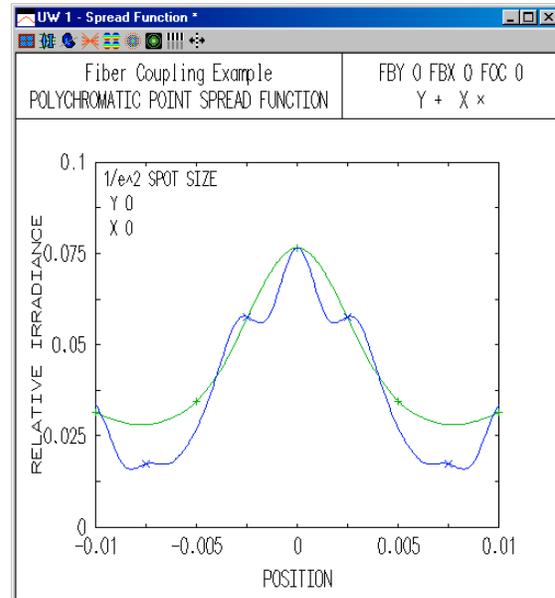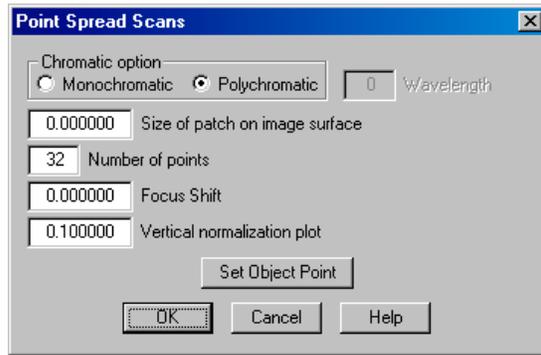
Please note that the PSF calculation in OSLO is a far field diffraction calculation and as a result, is not valid if the imaging optics of your model are placed within the Raleigh range of the beam waist in image space. This is also true of the Fiber Coupling Efficiency calculations within OSLO. Placement of optics (such as field lenses) close to the coupling plane of your model may potentially invalidate the approximation of this modeling approach. For a general discussion of the calculation of fiber coupling efficiency, the interested reader is referred to Wagner and Tomlinson (2).

References:

1. A. E. Siegman, Proc. SPIE **1224**, 2, 1990.

2. R. E. Wagner and W. J. Tomlinson, "Coupling efficiency of optics in single-mode fiber components," Appl. Opt. **21**, 2671-2688 (1982).