



*Photonics
Modeling Guide*

**CODE V 10.2
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OPTICAL RESEARCH ASSOCIATES

3280 East Foothill Boulevard, Suite 300

Pasadena, California 91107

Phone: (626) 795-9101

Fax: (626) 795-0184

E-mail: service@opticalres.com

<http://www.opticalres.com>

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Chapter 1

Introduction

CODE V is a general-purpose optical design and analysis program that can be used for many types of optical systems. In recent years, there has been an interest in the design and analysis of discrete components for fiber optical telecommunication systems, including devices such as isolators, couplers, and wavelength-division multiplex (WDM) filters. CODE V is an excellent tool for designing such systems, whether they contain basic components such as lenses, mirrors, prisms, and gratings (including micro-optical components), or additional features such as coatings and polarizing elements.

This introductory guide describes the detailed steps necessary to define, optimize, and analyze a ball lens coupler and a grating-based WDM de-multiplexor system. It also provides examples of additional telecom components. These examples serve as a starting point for working with these types of components.

Check the Optical Research Associates Web site <http://www.opticalres.com> for additional example macros or later editions of this guide. You can also obtain information on these features via e-mail by addressing requests to service@opticalres.com.

Questions and Answers About CODE V and Photonics Systems

What do you mean by photonics systems?

In this guide, the term *photonics systems* is used more or less interchangeably with *optical telecommunication systems*. This includes a number of optical devices that typically interface with fiber optics, such as connectors, multiplexors, isolators, couplers, and filters.

Where does CODE V fit in with photonics systems?

CODE V was originally developed as a tool for designing and analyzing image-forming optical systems such as microscopes, cameras, laser scanners, and scientific instruments. Many photonics systems have components that are fundamentally similar to conventional image-forming optics. CODE V is a powerful tool for working at the optical component level, but it does not have features related to complete systems, networks, etc.

What are the advantages of using CODE V for this type of design work?

CODE V can model an extremely broad range of system types. It also provides powerful optimization and analysis capabilities, as well as a robust macro language for extending its calculations.

CODE V can handle systems with many surface types, diverse materials (including gradient index), general diffraction gratings, multi-wavelength systems, polarization properties (including birefringence), multi-layer coatings, and even user-defined properties. It provides analysis options such as diffraction beam propagation (BPR), diffraction-based evaluations including polarization effects (e.g., point spread function and encircled energy), and many types of geometrical optics-based calculations.

CODE V also provides a special feature for calculating diffraction-based coupling efficiency (also known as insertion loss). This calculation is normally based on the standard diffraction point spread function, which includes the effects of polarization and coatings. It is also possible to calculate coupling efficiency by importing data from the more rigorous beam propagation option (BPR), although, in this case, polarization and coating effects are not included.

How do you model optical fibers in CODE V?

In most cases, the optical fibers themselves are not modeled in CODE V, and usually do not need to be modeled, because CODE V is typically used to design components that interface to or from optical fibers. For this, you need a way to define properties of the light emerging from a fiber that is then processed by the device you are modeling. For certain analyses, such as coupling efficiency, you also need to define the input properties of a fiber. CODE V has these capabilities.

CODE V also has a feature called non-sequential surface modeling that can be used to model straight segments of certain types of fibers. This type of model is useful for some special purposes, but is not normally used in the design of typical photonics components.

Can CODE V model integrated optics or waveguide-type systems?

Not directly. CODE V is used to model discrete components consisting of such devices as lenses, prisms, mirrors, filters, gratings, gradient index rods, and polarizing elements. Integrated optics is the domain of other software packages, although it is possible to take the output of an integrated device (in the form of the complex amplitude distribution) and use this as the input to the beam propagation calculation in CODE V. There is a feature available in Beam Propagation (BPR) for importing a complex amplitude file in a special format, and a macro is supplied for exporting complex field data from CODE V. Optiwave (<http://www.optiwave.com>) is the first company to support this feature in their guided wave software, although the format is documented and may be usable with other software.

What about optical coatings?

CODE V includes a coating design and analysis module that can be used to define and even optimize multi-layer coatings. Although it is a powerful utility, its design features are not as extensive as those of certain dedicated coating design programs, because CODE V is intended to be used primarily for optical system design, not coating design. After a coating prescription is defined and saved in a file, the coating can be attached to any surface, where it will properly affect the polarization state and transmission of rays traced through it. Polarization can be very important in certain diffraction analyses, including point spread function and insertion loss calculations.

What analyses can CODE V perform that apply to photonics systems?

CODE V can perform geometrical calculations such as simple ray tracing, spot diagrams, and encircled energy, which are useful in the early stages of component design. To evaluate system performance, CODE V uses the diffraction point spread function (PSF) or, more often, the coupling efficiency (CEF), which is derived from the PSF. CODE V macros allow you to study CEF vs. wavelength, which is important for WDM systems. You can also use the beam propagation feature (BPR) to examine the amplitude and phase of a beam anywhere in the system. BPR is a powerful feature, but it requires careful attention to issues of sampling to get the most accurate results. Tolerance analysis is also available.

What is tolerance analysis, and why is it important?

Tolerance analysis refers to the study of how a system performs when it is constructed with manufacturing errors within a specified range; these are the tolerances. Simulating how a system performs with errors in construction is essential for evaluating whether or not the design is truly practical. CODE V has a number of tolerance methods available, including the ability to tolerance on coupling efficiency, on user-defined quality measures, and even with user-defined tolerance parameters. The effects of assembly-time adjustments (known as compensators) can also be simulated.

Tolerance sensitivity is a major driver on the cost of manufacturing any optical device. As photonics systems become more complex and handle more closely spaced channels, the ability to perform tolerance analysis becomes even more important.

What can CODE V do to optimize photonics systems?

CODE V has a powerful optimization engine called AUTO (for automatic design). This feature systematically varies system parameters to reduce the size of a specified “error function” that correlates with image quality. Default error functions based on spot size or RMS wavefront area are normally used at first, but user-defined error functions are also possible, and a single mode-profile command can be added to AUTO input to define a coupling efficiency error function. You can optionally account for Gaussian beam spreading in coupling efficiency optimization by selecting an additional command. CODE V’s ability to precisely control boundary conditions (i.e., constraints) is unmatched in the industry.

Chapter 2

Fiber Coupling with a Ball Lens

This chapter uses a very simple pre-defined optical system to quickly demonstrate the photonics modeling features of CODE V, including coupling efficiency, optimization, and beam propagation.

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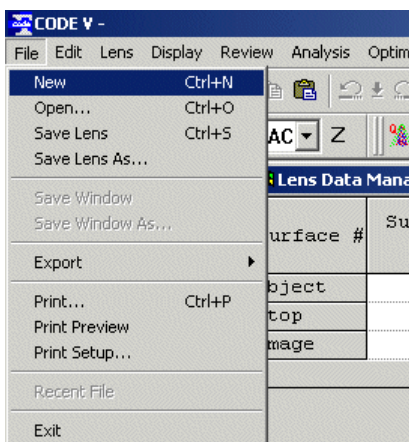
Using the New Lens Wizard

The New Lens Wizard helps you set up new optical system models, starting with sample lenses, a patent database, your own collected “favorites,” or a blank lens. In this procedure, you will start with one of the supplied sample lenses: a ball lens. A ball lens is a small glass sphere that can be used to couple the output of one optical fiber into another. Although this is a very simple lens, it provides a useful demonstration of various design techniques for optical telecom systems, which you can apply to more complex systems.

Defining the Ball Lens with the New Lens Wizard

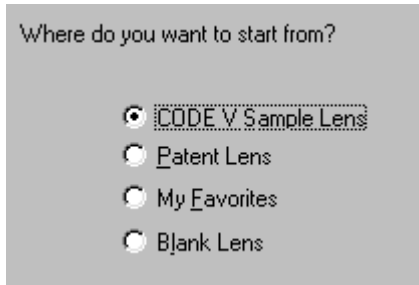
Before you can try this example, you need to install and start CODE V. We assume that CODE V is already correctly installed and that you know how to launch the program from the Windows **Start** menu.

1. Start CODE V.
2. Choose the **File > New** menu to launch the New Lens Wizard.



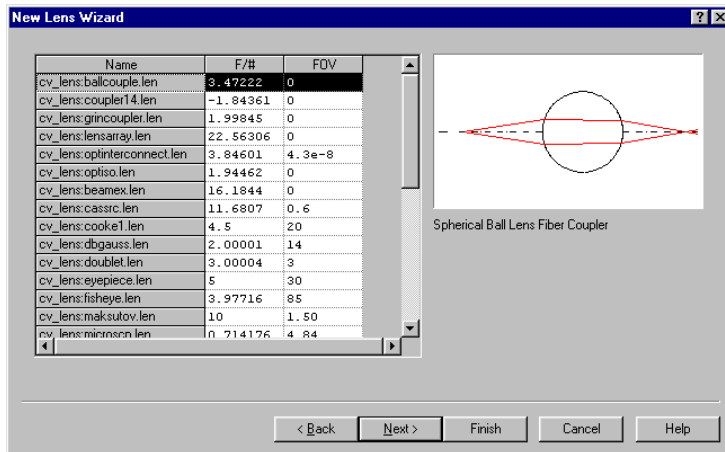
If the New Lens Wizard does not launch, choose the **Tools > Preferences** menu, and be sure the **Use Wizards** checkbox is checked on the **UI** tab.

3. Click the **Next** button to bypass the first screen in the New Lens Wizard.
4. In the second screen in the New Lens Wizard, click the **CODE V Sample Lens** button (the default), and click **Next**.

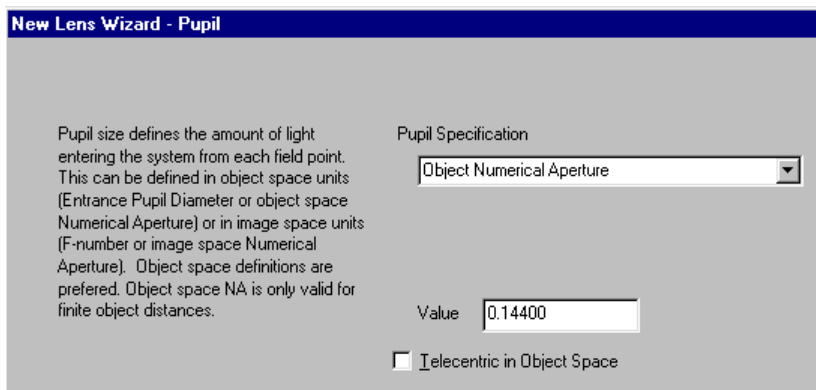


- Click on the first line of the spreadsheet to select the following lens: **cv_lens:ballcouple.len**

The New Lens Wizard will show you a picture of the selected lens.



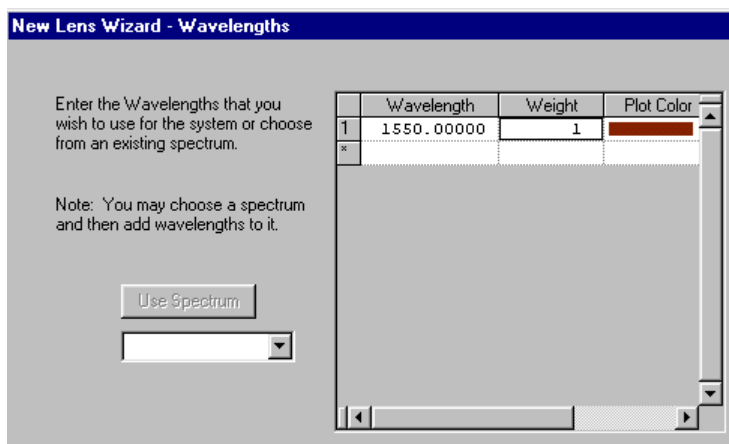
- Click **Next** to go to the **Pupil** screen in the New Lens Wizard.



The pupil type and size determine how much light is accepted by the optical system. In photonics systems, this is normally specified as numerical aperture, which is the size of the cone of light emitted by the input fiber or other source. There is additional data that defines the intensity distribution or apodization of the pupil. This is a Gaussian profile whose properties are set by the output characteristics of single mode fibers used as input (lasers are also approximately Gaussian).

7. Click **Next** to accept the displayed data.

The **Wavelengths** screen in the New Lens Wizard is displayed.

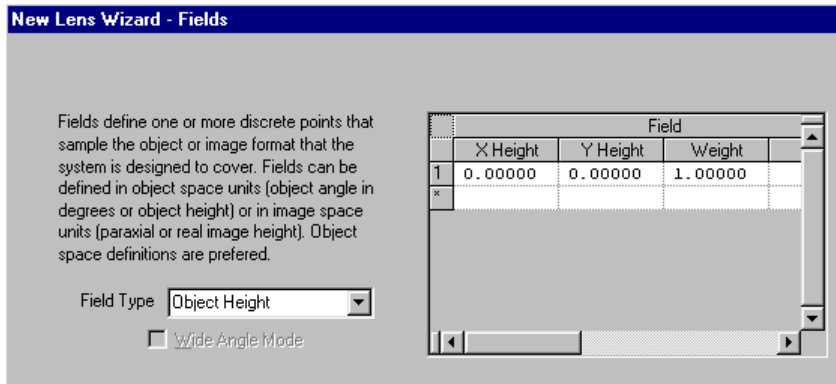


The Wavelengths screen has only a single value: 1550 nm. Wavelengths are always expressed in nanometers (nm) in CODE V (1550 nm = 1.55 microns).

8. Click **Next** to accept the single wavelength definition and go to the **Reference Wavelength** screen.

The *reference wavelength* is used to trace the reference rays, a special set of rays used for defining default apertures, first order calculations, lens drawings, etc. In this case, there is only one wavelength anyway, but many systems use multiple wavelengths.

9. Click **Next** to accept 1550 as the reference wavelength and go to the **Fields** screen.



The term *field* refers to the field of view of an optical system. For systems with a finite object distance like this one, field is usually expressed as object height. The *object* in a fiber system is essentially a point source that is nominally on the axis of the input fiber. This defines the lateral (x,y) positioning of the input fiber with respect to the optics. The longitudinal (z) position is defined by the object distance.

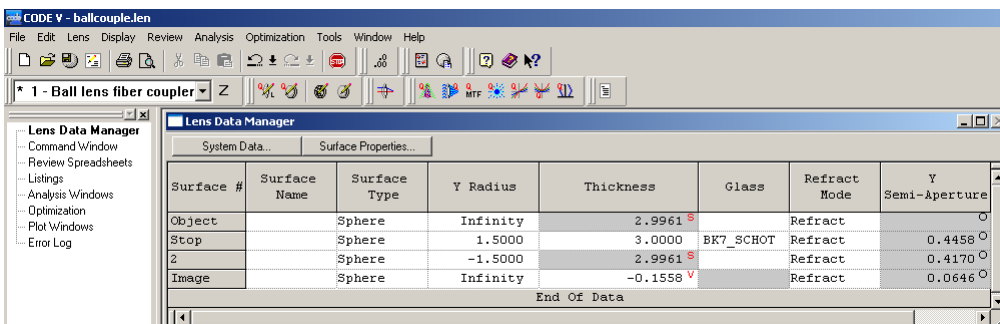
10. Click **Next** to accept (0,0) as the object coordinate.
11. Click **Done** on the final (“Congratulations...”) screen of the New Lens Wizard.

This lens is now ready for lens pictures, analysis, optimization, and more.

Looking at the Lens Data

The lens data is made up of two major parts, *System Data* and *Surface Data*. You have seen some of the System Data in the New Lens Wizard (pupil, wavelength, and fields). Another important System Data entry is pupil apodization. For the ball lens, a Gaussian intensity distribution is applied to the pupil, which simulates the output from an SMF-28 fiber. You will learn more about this, and other System Data entries, later. Surface Data is displayed in the **Lens Data Manager (LDM)**

spreadsheet window and in the **Surface Properties** window (**Lens > Surface Properties** menu). The LDM spreadsheet is shown below, along with the menu bar and toolbars that are used to run the various program features (your toolbar may not look exactly like this one, which has been customized through the **Tools > Customize** menu).



The screenshot shows the CODE V software interface with the Lens Data Manager window open. The window title is 'CODE V - ballcouple.len'. The menu bar includes File, Edit, Lens, Display, Review, Analysis, Optimization, Tools, Window, and Help. The toolbar contains various icons for file operations and analysis. The Lens Data Manager window has a 'System Data...' tab selected, showing a spreadsheet with the following data:

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	2.9961 S		Refract	0
Stop		Sphere	1.5000	3.0000	BK7_SCHOT	Refract	0.4458 0
2		Sphere	-1.5000	2.9961 S		Refract	0.4170 0
Image		Sphere	Infinity	-0.1558 V		Refract	0.0646 0

The spreadsheet ends with 'End Of Data'.

Surface data consists of curvature or radius of curvature, thickness to the next surface, glass or material, apertures, and a few other parameters. Still other parameters are available in the Surface Properties window. One thing to notice in the LDM spreadsheet is that some numbers have small letters next to them. These are called *status indicators* (see “Status indicators in spreadsheet cells” in the online help for details). Some status indicators are for solves (S); solves are values that are set automatically by CODE V to meet a specified condition (these cells are shaded gray because you cannot directly edit these solved values). The V status indicator on the image surface thickness (defocus) indicates a variable for optimization.

This numerical data is very useful and important, but a picture always makes things a bit more clear.

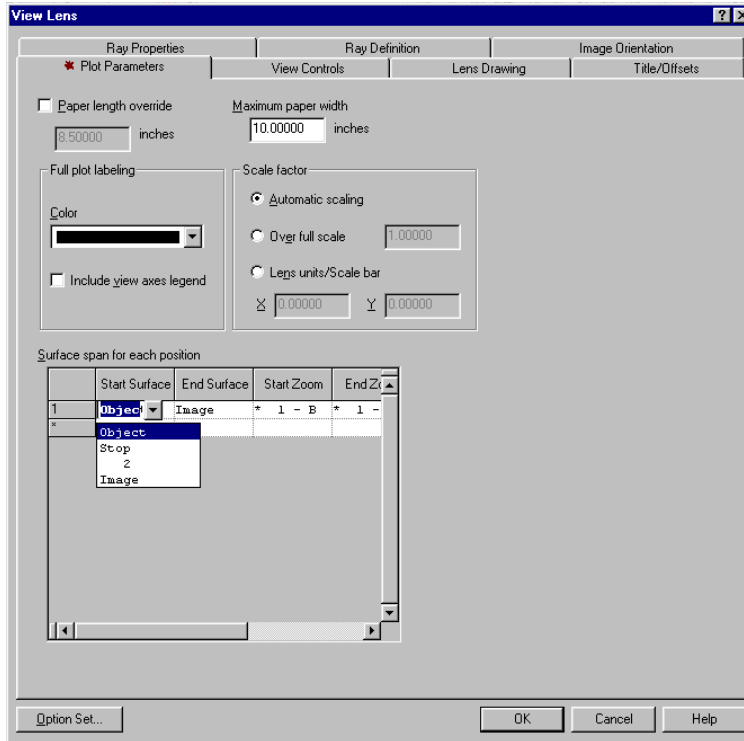
Generating a Lens Picture

There are a number of ways to make lens pictures in CODE V. The main lens drawing feature is called View Lens, and this is found on the Display menu. There are also several tools on the tool bar for making quick lens pictures, though these are set up to draw from the first surface to the image, and in most photonics examples, you will want to draw from the object surface. This is not a big problem.


1. Choose the **Display > View Lens** menu.

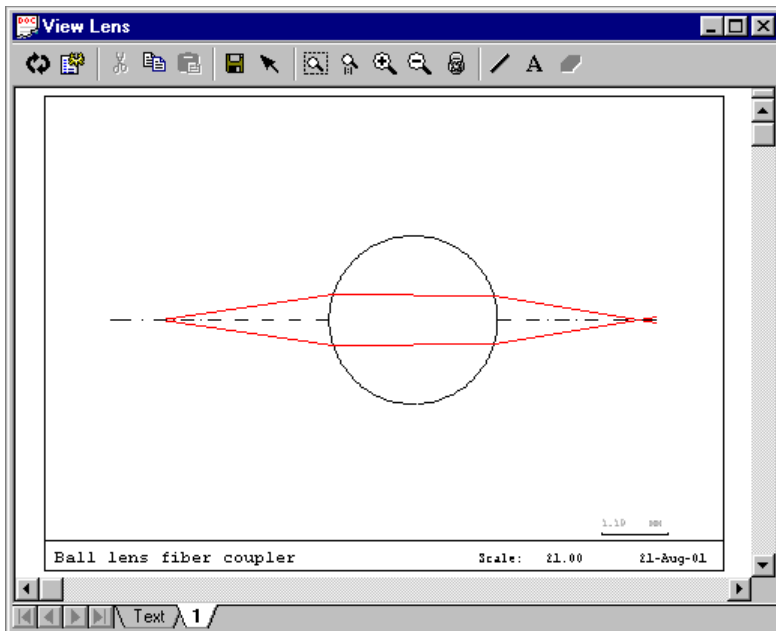
This displays the **View Lens** dialog box, where you can set up and run the VIEW option. There are multiple tabs for the many settings that are possible with the VIEW option. For now, you only need to change the surface range.


- Double-click the first cell in the first row of the **Surface span for each position** spreadsheet, and choose **Object**.



- Click **OK** to run the VIEW option.

The lens picture is displayed in a tabbed output window (TOW). These output windows always have a text tab and may have one or more graphics tabs, as this one does. Keep this window open (you can resize and move it if you like). If you change the lens, you can re-run the picture with the current settings by clicking the Execute/Recalculate button. 



You can also change the settings with the Modify Settings button , which appears on each option-generated TOW (macros can also display in TOW's, but these do not have a Modify Settings button, only the Execute/Recalculate button).

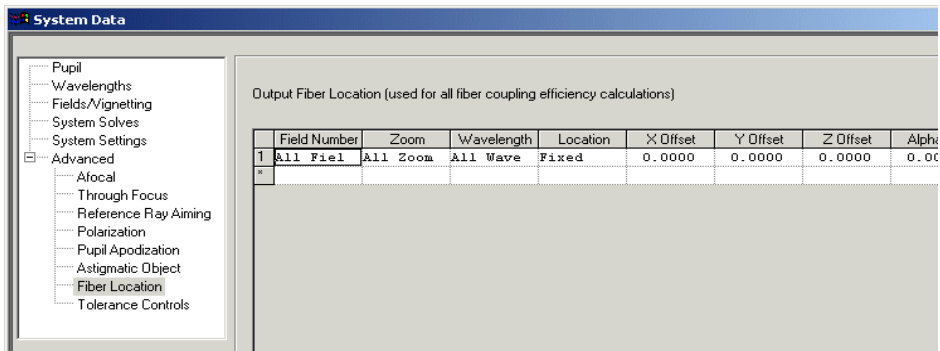
Calculating Coupling Efficiency

There is certainly more to learn about how a lens is defined in CODE V, and we will go into more details in the next few chapters. But since this simple lens is intended to couple light into a single-mode fiber, you may be curious about how well it can do this. CODE V has a feature called Fiber Coupling Efficiency (CEF) just for this purpose.

CEF is a diffraction-based calculation, meaning that it accounts for the wave nature of light, and not only geometrical aberrations (it can even include polarization effects). By default, CEF calculates the diffraction point spread function (PSF) and determines the overlap integral of the PSF with the mode profile of the output fiber. This can be defined in several ways, most commonly as a Gaussian function. There are several other ways to define the input to the CEF calculation, and you will use the Beam Propagation method at the end of this chapter.

Defining CEF Input

1. To define the fiber position, choose the **Lens > System Data** menu, and click **Fiber Location** in the **System Data** window's navigation tree.
2. Choose **Fixed** for the fiber position (**Location** field), as shown below.

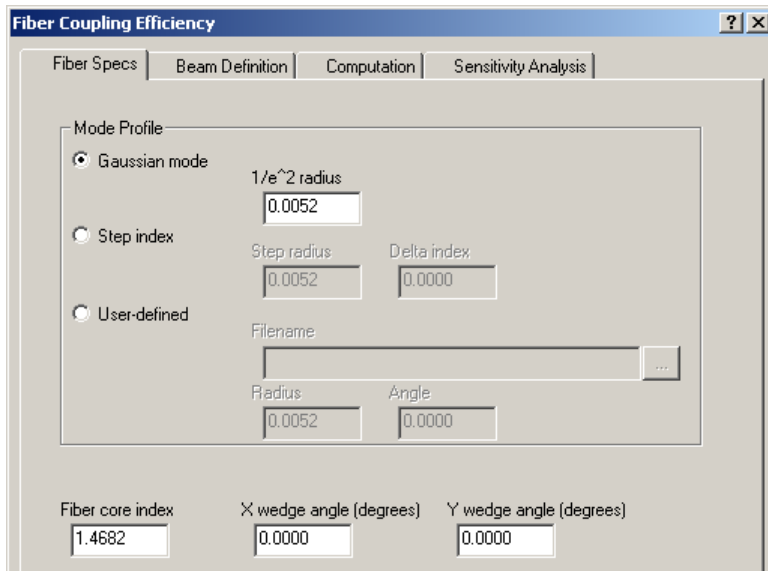


Fixed at $X=0$, $Y=0$ is actually the default, but it's good to check this. The other method, compensated, aligns the fiber with the chief ray, or center ray, for each field. This would not make a difference for an on-axis case like this, but in other systems, this can be an important choice.

3. Choose the **Analysis > Diffraction > Fiber Coupling Efficiency** menu.

This opens the **Fiber Coupling Efficiency** dialog box. You will change settings on most of the tabs in this dialog box before clicking **OK** to run it.

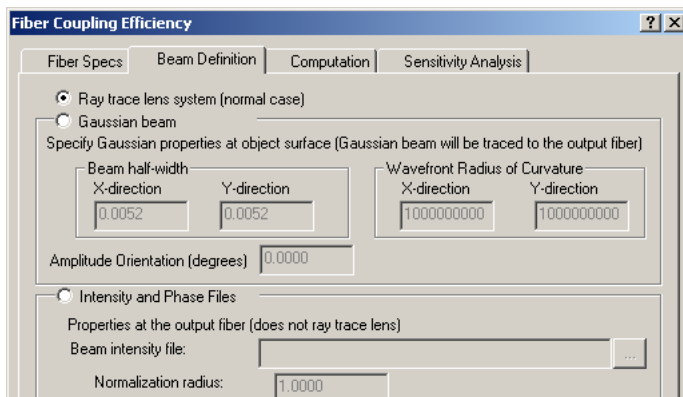
- On the **Fiber Specs** tab, make sure the value for the fiber Gaussian mode radius is **0.0052** mm. This is the default value for this field.



The fiber specification is for the output fiber (i.e., the fiber that light is going into). Remember that the input fiber characteristics were modeled using a point source with Gaussian apodization of the pupil.

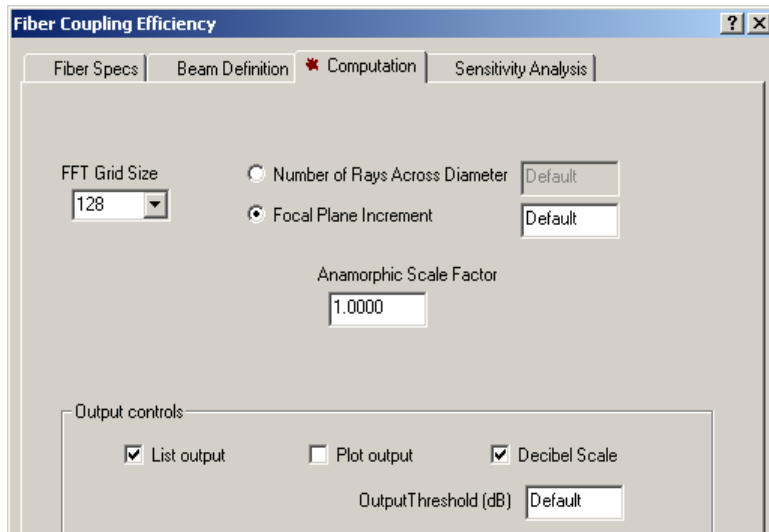
Note that there are other methods for defining the single mode for coupling calculations, but Gaussian is most typical, and 0.0052 mm is a value typical of common fibers such as SMF-28 at 1550 nm.

- Click the **Beam Definition** tab.



The default **ray trace** method is a good choice in many cases. This means that the program traces rays through the lens and calculates insertion loss based on this. Other choices on this tab involve Gaussian beam tracing or importing the data from another option (you will do this with beam propagation data at the end of this chapter). *For now, no changes are needed.*

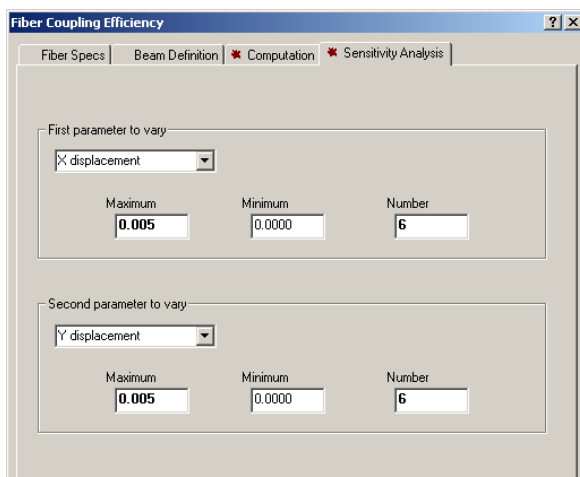
6. Click the **Computation** tab, and select the **Decibel Scale** checkbox in the **Output controls** area.



You may need to change the FFT grid size or focal plane increment for some systems to get good sampling, though the defaults are usually pretty good. You need to make a run first to see if changes are needed (e.g., if the focal plane increment is large compared to the mode radius, results will not be good).

Decibel units for insertion loss are most common in telecom applications, so this is a useful feature in CEF. The default is fractional coupling efficiency values unless you select the **Decibel Scale** checkbox.

7. Click the **Sensitivity Analysis** tab. Enter **0.005** for the maximum value for both X and Y displacement, and enter **6** for the number of values as shown below.

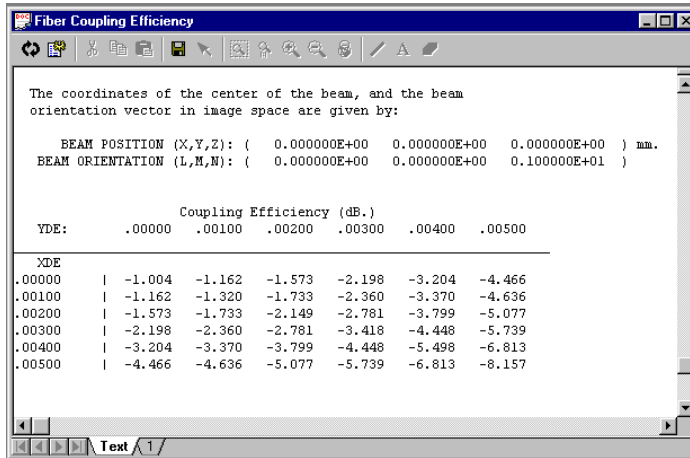


You don't really need to do sensitivity analysis now, but it's easy and instructive to do so. This tab allows you to analyze the effects of errors such as misalignment (this case), tilt, or wedge in the output fiber.

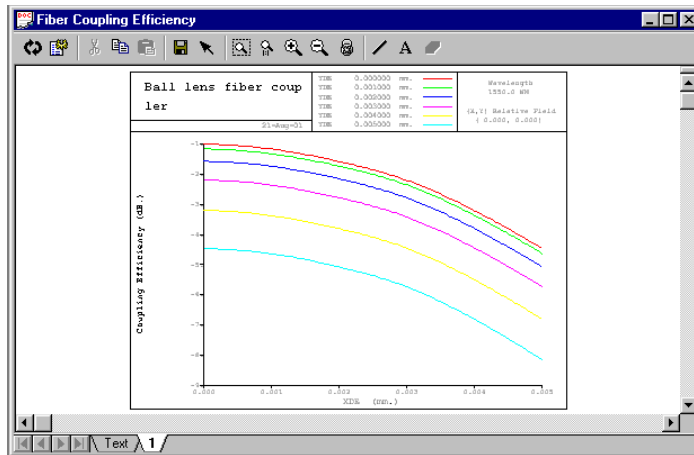
Note that this sensitivity or error analysis applies only to the placement and properties of the output fiber. Errors in the optics themselves are handled with tolerance analysis; see Chapter 5 in the *CODE V Introductory User's Guide* for more information about tolerancing.

8. Click **OK**.

The **Text** tab of the **Fiber Coupling Efficiency** output window always includes tabular data on the coupling efficiency as well as auxiliary information on the number of rays traced, the alignment of the fiber, etc.



If sensitivity analysis is specified, you can also get graphical output showing the coupling efficiency as a function of the error parameters, as shown below.



Coupling efficiency can also include polarization effects, which will then consider the effects of coatings on glass surfaces (CODE V assumes a $\frac{1}{4}$ -wave anti-reflective coating of MgF_2 on all glass surfaces, unless this is deleted or replaced with a multilayer coating). Although CEF is calculated only in the reference wavelength, there is a supplied macro (plotw1.seq) that allows you to plot CEF as a function of wavelength. This will be used in a later example.



Tip: Don't close the output window for coupling efficiency; you will need to re-run it and modify its settings later. However, you can move, resize, or minimize the window.

Optimizing the Lens

There is not a lot of optimization you can do with a ball lens of a particular size. Changing the radius and glass will make a difference, but once these are fixed, the only remaining variable is the longitudinal (z) position of the output fiber. This has already been optimized in this example, but that's easy to change. You can zero out the image surface thickness value, which is used as a defocus adjustment. You can then use Automatic Design (AUTO) to refocus it.

Looking at Variables

In the LDM spreadsheet window, do the following to create a variable:

- Change the thickness of the Image surface to 0 as shown below, then press the Tab or Enter key (or click in any other cell) to enter this data.

Notice the small **V** displayed next to this value. This indicates a variable, which is a parameter that is allowed to change for optimization purposes. (Note that this is the only variable in this lens—some lenses have many variables, but, in this case, you are only making a small adjustment to a finished design, albeit a simple one.) You can right-click on any cell to display a shortcut menu of settings that apply to the cell. Two common settings are **Vary** and **Freeze**.

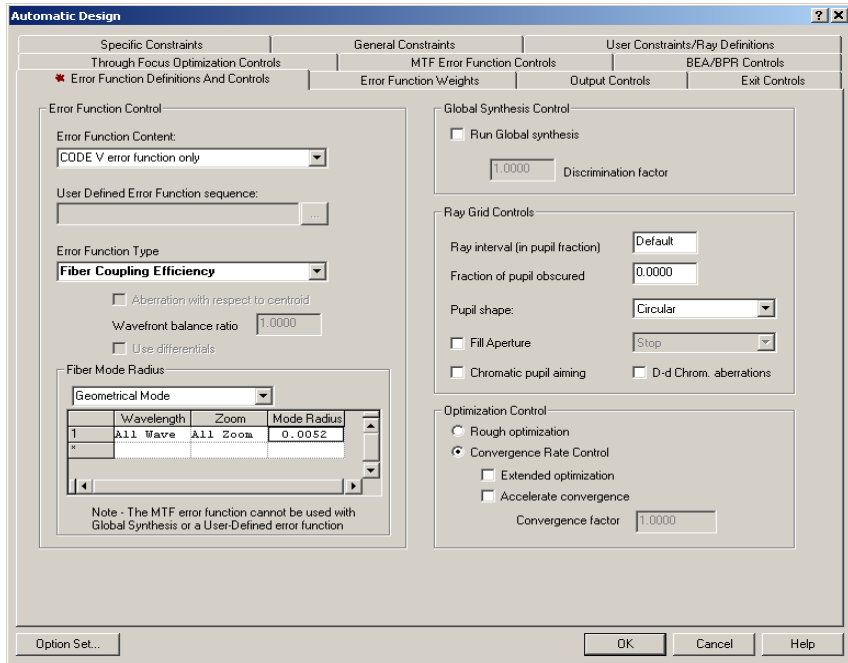
Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	2.9961 S		Refract	
Stop		Sphere	1.5000	3.0000 BK7_SCHOT		Refract	0.4458 O
2		Sphere	-1.5000	2.9961 S		Refract	0.4170 O
Image		Sphere	Infinity	0.0000 V		Refract	0.0646 O
End Of Data							

If you re-run the Fiber Coupling Efficiency now, you will find that the nominal value (i.e., no decentration errors) is about -3 dB, compared to about -1 dB when focused. You can get back to this value with optimization.

Defining Automatic Design Input

1. Choose the **Optimization > Automatic Design** menu.

The **Automatic Design** dialog box is displayed.



On the first tab, **Error Function Definition and Controls**, you can choose from several optimization quality criteria or “error functions” depending on your application. Transverse ray aberration is most common and works best when your design is very far from a reasonable solution. In this case, fiber coupling efficiency is the best choice, since the ball lens coupler is only out of focus.

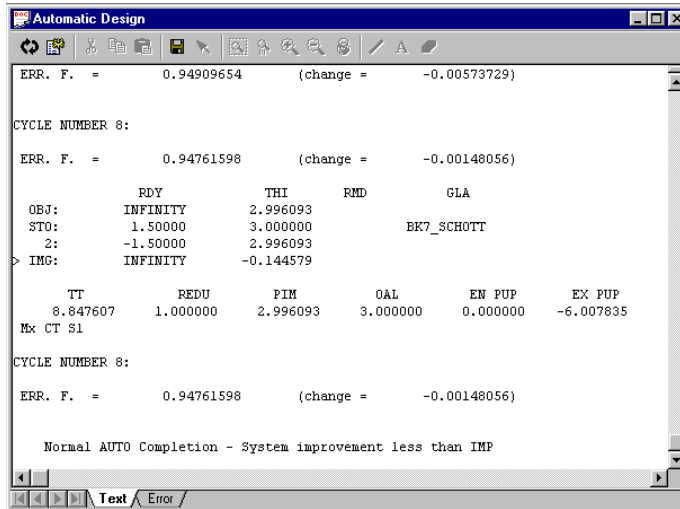
2. Choose **Fiber Coupling Efficiency** from the **Error Function Type** dropdown list.
3. Click in the first row of the **Fiber Mode Radius** spreadsheet.

This inserts a mode radius of **0.0052** (the default value). There are many other AUTO inputs that will be important for later examples, but in this case, this entry is all you need.

4. Click **OK** to run AUTO.

Optimization Output

When AUTO is run, a tabbed output window is displayed with a **Text** tab that contains the cycle-by-cycle report of AUTO's attempt to improve this lens by varying the defocus term that you set to zero. The Error tab, which can contain standard warnings as well as error messages, is also displayed (its contents are nothing to worry about for this example).



The final optimization cycle is shown. The defocus value (your only variable) is about -0.14 mm (THI for the IMG surface—the minus sign indicates a shift of the fiber towards the ball lens). The error function (ERR.F.) has improved (become smaller; zero is best). It started out around 2.4 when you deliberately defocused it, and got down to around 1.0 in 8 cycles. AUTO stops when the improvement between cycles gets too small (there are other ways to control AUTO as well).

If you re-run CEF now, you should find that the original value of -1 dB or slightly below this value for the nominal coupling efficiency has been restored. The defocus and CEF values may be a little different from the earlier values due to the likely use of a different DEL (ray grid spacing) in AUTO.

Using Beam Propagation Analysis

We are covering a lot of ground in this chapter! Beam propagation is one of the newest and in some ways most advanced features of CODE V. It is especially important in systems where the size of the beam is fairly close to the size of the optical elements, which is usually the case in fiber optical components.

Why BPR Is Different from Other Diffraction Analyses

Beam propagation (BPR) is different from other diffraction analysis methods in CODE V. In PSF and CEF (which uses PSF data by default), the program assumes that all diffraction takes place at the exit pupil of the system, with a pupil shape and position derived from ray tracing. BPR also uses ray tracing, but it converts back and forth between a wave and a ray representation of the beam. This means it can handle diffraction effects anywhere in the system, not only at the exit pupil. In some situations, BPR and PSF will give almost identical results, while in others, BPR is the only accurate calculation (e.g., with a diverging Gaussian beam in a long air space between optical elements and/or fibers).

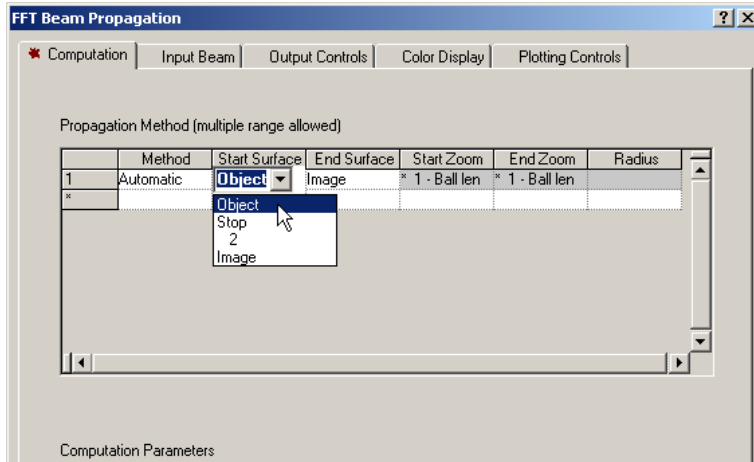
BPR has limitations, such as not including polarization effects (important in some systems). It also requires care to be sure there is enough sample resolution for accurate results at all surfaces. In spite of these points, BPR is the most accurate way to analyze many photonic systems. Please read the BPR section in Chapter 19 of the *Reference Manual*; it has a lot of useful advice as well as examples.

Defining BPR Input

1. Choose the **Analysis > Diffraction > FFT Beam Propagation** menu.

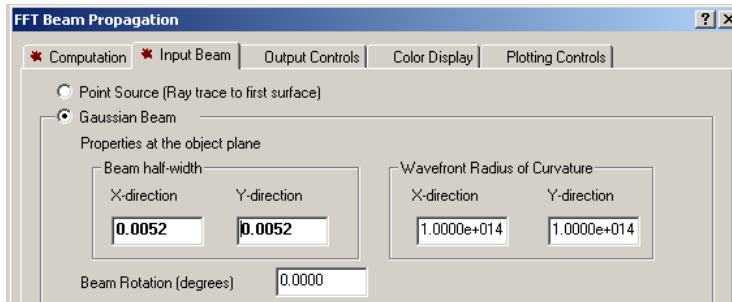
The **FFT Beam Propagation** dialog box is displayed with the **Computation** tab in the foreground. On the Computation tab, you can designate the range of surfaces to apply beam propagation methods (ray tracing is used for other surfaces, and is often accurate enough).

2. Click in the first row of the **Propagation Method** spreadsheet, and select **Object** as the **Start Surface**.



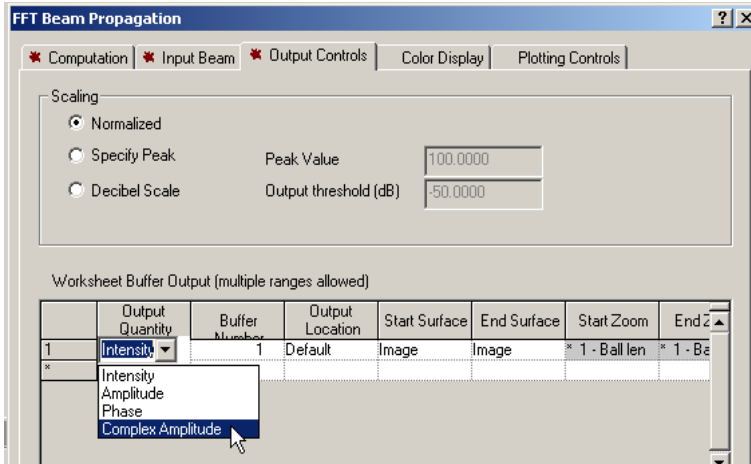
The **Automatic** method, which is inserted by default, means that BPR decides which propagation method to use for most accurate results based on beam size and other factors. Default computation parameters are acceptable for this example.

3. Click the **Input Beam** tab, select the **Gaussian Beam** button, and enter **0.0052** for the Gaussian beam half-width in both X and Y directions.



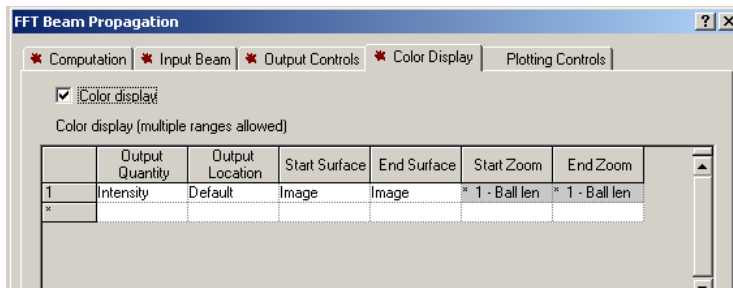
This defines a Gaussian beam for the input. BPR does not pick up Gaussian apodization from the LDM, when the beam is defined here. This is a special, pre-defined case of the more general amplitude and phase distributions that BPR uses to define starting beams.

4. Click the **Output Controls** tab and select **Complex Amplitude** in the first row of the **Worksheet Buffer Output** spreadsheet. Accept the defaults for other parameters such as buffer number (1).



This is the method used to export final BPR amplitude and phase data in a form that coupling efficiency (CEF) can import and use for more accurate CEF calculations. CEF can import the BPR data you are saving in buffer 1, which is essentially a tab-delimited text file.

5. Click the **Color Display** tab and select the **Color display** checkbox.



You can accept the defaults for other parameters including surface numbers (only on the image surface for input to CEF). This will add a color raster plot at the image surface to the default output.

6. Click **OK** to run BPR.

As with other options, graphical and text output displays in a tabbed output window (TOW).

BPR Output

BPR is unusual among CODE V options in that it can produce its output on any designated surface. Most options only produce final results on the image surface. In many cases, such as the current example, you only want data on the image surface, but you may sometimes want intermediate phase or amplitude data for diagnostic or other purposes.

The text output is reported for every surface. Diagnostic information tells you about the position and direction of the beam, as well as which propagation method is being used there. Beam radius information is determined by fitting to a Gaussian and displaying $1/e^2$ values. The summary table is most useful.

The screenshot shows the 'FFT Beam Propagation' window with the following data:

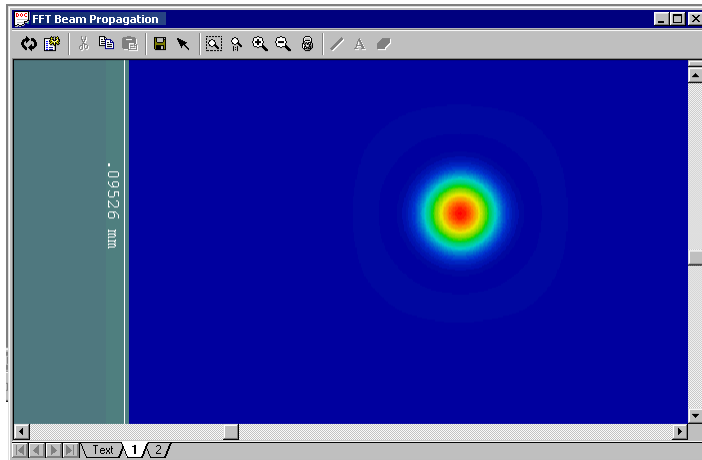
Surface #	FFT Grid Size	Grid Space Increment (mm)	Grid through Aperture X	Grid through Aperture Y	Samples through Aperture
OBJ	128	0.000742857	128	128	16384
STO	128	0.0504098	17	17	209
2	128	0.0458198	27	27	461
IMG	128	0.000753869	128	128	16384

Surface Summary Table 3*

Surface #	X-Gaussian Radius (mm) **	Y-Gaussian Radius (mm)	Orientation (degrees) ***	Center of Peak Gaussian X (mm)	Center of Peak Gaussian Y (mm)
OBJ	0.0052	0.0052	0	0	0
STO	0.285058	0.285058	0	0	0
2	0.290532	0.290532	0	0	0
IMG	0.00645296	0.00645296	0	-6.99728e-007	-6.99728e-007

* The intensity data is fit to a Gaussian function, and the $1/e^2$ radii are reported. The beam is projected onto the tangent plane of the surface.

DSP (raster display) graphics give you a visual impression of the beam intensity. Be sure to note the scale of the enclosing box.

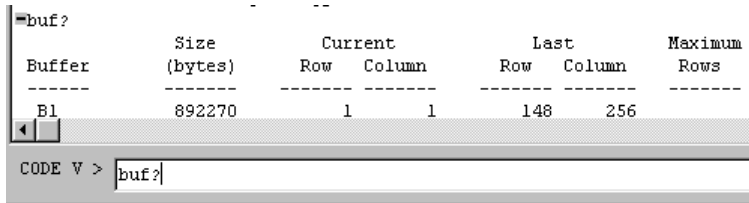


Calculating Coupling Efficiency from Beam Propagation

Now that you have done a beam propagation analysis and saved the complex amplitude in a Worksheet Buffer, you can run CEF and import the BPR data for a more accurate calculation of coupling efficiency. (If you closed the CEF output window, go back to the Coupling Efficiency section on page 13 and re-do the steps there to regenerate the output window).

In Beam Propagation (BPR), you directed output to buffer 1 (B1). Buffers are data structures used mainly by macros, but also used in some options to preserve grids of data for additional processing. There is currently no spreadsheet display of the Worksheet Buffers, but you can use a command to check buffer status.

- Type **BUF?** in the **Command Window** and press Enter.



Buffer	Size (bytes)	Current Row	Current Column	Last Row	Last Column	Maximum Rows
B1	892270	1	1	148	256	148

CODE V > buf?

This shows that the buffer exists and that it has 148 rows and 256 columns. The BPR grid was 128 x 128, but this is complex data, so each value has two components (hence 256 columns). The 148 rows come from 128 complex data value rows plus 20 header data rows.



Note: If you plan to run a second BPR run that writes to a buffer for export to CEF, **BE CAREFUL**. BPR appends the new data to the buffer so you must use the command **BUF DEL B1** (or B2, B3, etc. depending on what you used) to delete the buffer before export to CEF. If you do not, CEF will use the first valid data it finds in the buffer, which will be the “old” data. Another option is to direct the new calculation to a different buffer, such as 2.

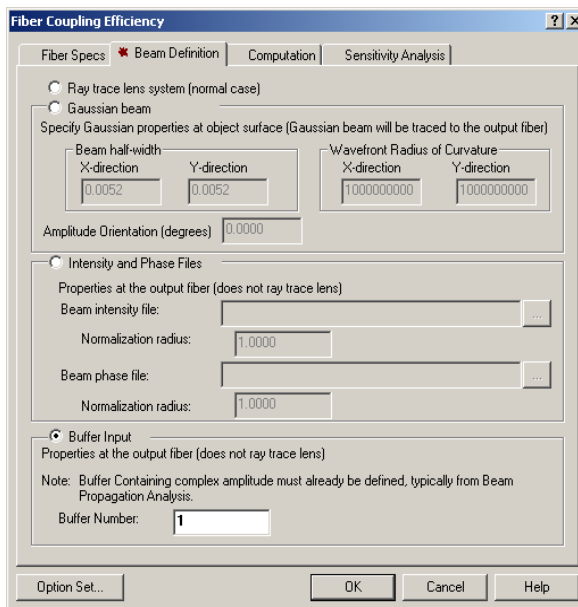
Importing BPR Data into CEF

Follow this procedure carefully and be sure that you have only one set of BPR data in buffer 1, as mentioned in the note above.

1. Click on the Modify Settings button  in the **Fiber Coupling Efficiency** output window.

All the settings will be the same as before, except for the source of the data.

2. Click the **Beam Definition** tab, and click the **Buffer Import** button. If necessary, enter **1** for the **Buffer Number** (this is the default).



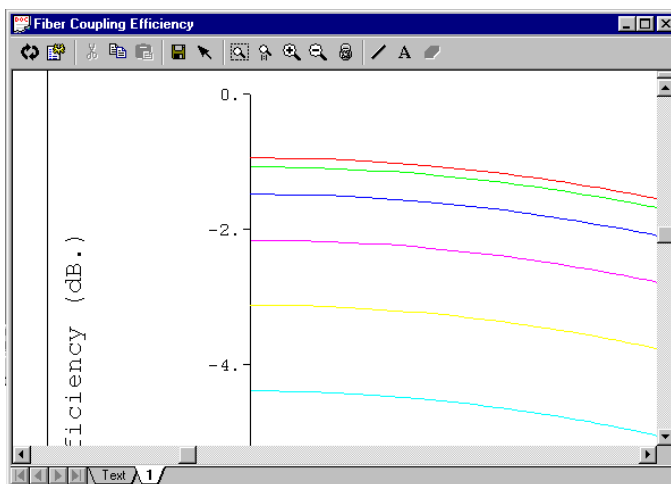
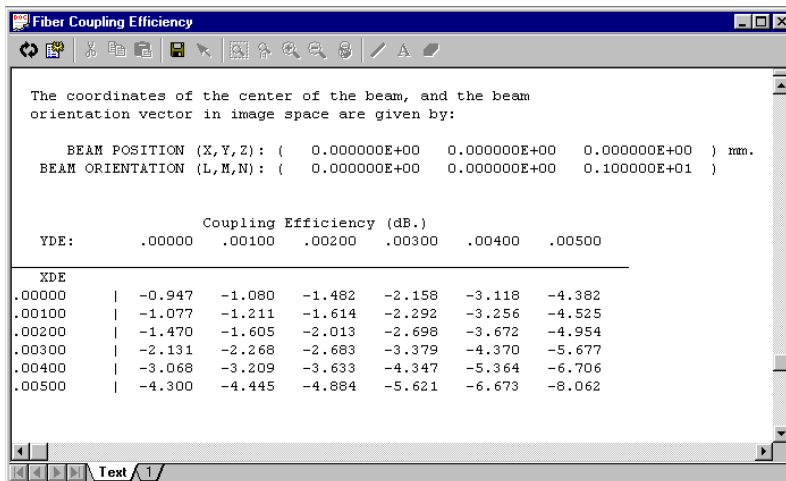
Also check the other tabs for correct values based on the earlier instructions (beam size 0.0052, decibel output, etc.)



Note: When you import BPR data into CEF, you must use the default grid settings on the **Computation** tab of the **Fiber Coupling Efficiency** dialog box; this allows CEF to set the grid according to the imported BPR data in the buffer. You can change the output controls to Decibels, but don't change the FFT Grid Size or other parameters at the top of the Computation tab.

3. Click **OK**.

The following output shows that the coupling efficiency is a little better than the value predicted by the default CEF calculation, which is about -0.95 dB for the nominal value.



Chapter 3

A Grating-Based WDM System

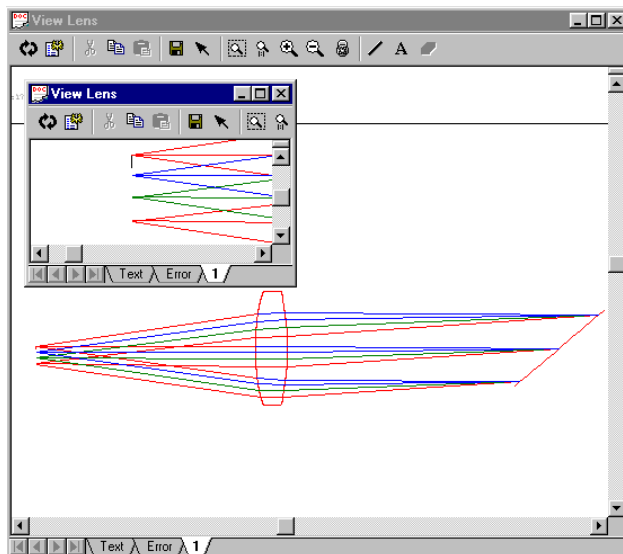
This chapter will describe the steps needed to set up a grating-based WDM demultiplexor, a device that takes a multi-wavelength input and feeds wavelength bands into output fibers. This system is closely related to grating spectrometers and monochromators used in various analysis instruments.

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Background on This Example

The grating demultiplexor system shown below is part of a WDM system that takes a multiple wavelength input beam from a fiber and uses a diffraction grating to split the wavelengths into separate output beams (the picture below uses two separate **View Lens** windows and represents the final design, including the multi-wavelength zoom optimization discussed at the end of this chapter).



This system is very similar to grating-based spectrometers and monochromators that have been used for many years in scientific instruments. The application of this particular “Littrow grating configuration” to fiber optics has been described in the literature since at least 1977¹. The numerical values are based on the assumption of a 20 mm focal length lens combined with typical optical fiber and diffraction grating parameters.

We will assume that the output beams are collected by separate fibers and will use the coupling efficiency into these fibers to measure the quality of the system. Note that while this model is similar to configurations used in some real WDM systems, properties such as the channel spacing between output fibers are not necessarily realistic. To keep the example relatively simple, no particular channel spacing was assumed. It works out to about 24 microns. In a real de-multiplexor, this spacing would be closer to 128 microns. The point of this example is not to design a

1. For example: Tomlinson, W.J., *Applied Optics*, Vol. 16, No. 8, August, 1977.

working system, but to show you the steps and techniques needed to model any similar system. Values for basic input specifications such as wavelengths and beam divergence (fiber NA) are realistic.

The Game Plan

This chapter has a lot of steps, but the problem we are trying to solve is not as complex as the number of steps might suggest. First of all, the basic configuration is one that is known to work for this problem, and we are assuming that the grating properties have been predefined. We will also assume that the goal is to use a single lens element to collimate and re-image the light, even if this means using an aspheric lens (multi-element solutions are also possible of course). The game plan for the rest of the chapter is this:

1. Describe how light from a single mode fiber is modeled in CODE V.
2. Use the New Lens Wizard to open a single lens (singlet) from the CODE V samples.
3. Scale and modify the lens for the desired use.
4. Duplicate the lens surfaces to allow a *double-pass* configuration, insert a mirror to fold the light path into the second copy of the lens, and use *pickups* to link together separate CODE V parameters that correspond to single physical parameters. This keeps the model physically realistic whenever such linked parameters changed.
5. Change the mirror into a diffraction grating and tilt it so the light again passes through the lens on the second pass.
6. Optimize to get the correct tilt angle, and then to improve the image quality on the image surface (output fiber) for a single wavelength.
7. Analyze the coupling efficiency at the design wavelength, then at multiple wavelengths (telecom C band).
8. Set up a zoom system to optimize multiple wavelengths simultaneously, for a more realistic physical configuration (i.e., make sure input and output beams do not conflict).

That's the plan. Now let's get started.

Modeling Fiber Input

CODE V does not explicitly model the optical fibers that provide input to this system, but instead requires that you specify the properties of a point source of light on the end of the fiber that is equivalent to the actual fiber's light output. These *object* properties include wavelengths, divergence (numerical aperture), beam location, and intensity profile. You could also specify polarization properties, but will not in this case.

More detailed properties and additional components can always be added later if you want to refine the design or analysis. For example, you will start with one wavelength, but later will define a range of wavelengths to evaluate the WDM performance of the system.

For a typical system using infrared lasers and Corning SMF-28 single-mode fiber, the basic properties are as follows:

Property	CODE V Equivalent	Typical Value
Wavelength in nanometers	Wavelength (WL)	1550 nm
Beam divergence	Numerical aperture (NAO)	0.144
Intensity profile	Gaussian apodization (PUI)	0.135 at 0.66 pupil fraction
Input fiber lateral offset	Object height (YOB)	0.15 mm

We will discuss the relationship between these specifications and the required CODE V input data. Some of these values will be entered in the New Lens Wizard during the initial definition of the lens, while others will be entered in the System Data window (discussed later).

Wavelength

The wavelength used in this example is 1550 nm, which is an infrared wavelength at the center of the telecom C wavelength band (about 1534 to 1566 nm). Although this WDM system is meant to work with multiple wavelengths, you can optimize and analyze it monochromatically first, then analyze its multi-wavelength performance using various techniques, including a special macro for plotting coupling efficiency vs. wavelength.

CODE V supports up to 21 simultaneous wavelengths. Many optical systems are polychromatic, using multiple wavelengths at the same time (e.g., camera lenses). With such systems, most CODE V calculations are polychromatic, considering all

wavelengths simultaneously, with the contribution of each wavelength determined by a wavelength weight. Optimization also considers all wavelengths simultaneously.

Telecom systems and many non-telecom grating-based systems, such as spectrometers, are multiple wavelength systems, but are not polychromatic. This means that the system must be designed to handle a specified range of wavelengths (e.g. the telecom C band), but each wavelength is handled separately for analysis purposes. In practice, some of the wavelength weights must be set to zero to turn off all wavelengths except the one desired for analysis. CODE V's zoom feature is a convenient way to do this that also allows “separate but simultaneous” optimization. This method will be introduced at the end of this chapter.

Numerical Aperture and Intensity Profile

Next we'll discuss the divergence or numerical aperture as well as the intensity profile (assumed Gaussian) of the input beam. These parameters can be derived from the mode radius of the fiber, which is a standard data sheet specification for single-mode fibers. For SMF-28, the mode radius for 1550 nm is 0.0052 mm (5.2 microns). You normally define the divergence of the beam in terms of the $1/e^2$ intensity radius. The $1/e^2$ far-field beam angle of a Gaussian beam of wavelength λ and mode radius w_0 is

$$\theta = \lambda / (\pi w_0)$$

You can substitute the wavelength 1.55 μm (1550 nm) and mode radius 5.2 μm and calculate a value of 0.09488 for the $1/e^2$ angle. However, you can avoid substantially truncating the beam by extending the numerical aperture out beyond the $1/e^2$ point—for instance, to the 1% point instead. In this case the $1/e^2$ point is only 0.66 of the numerical aperture, which is 0.144. ($0.09488/0.66 = 0.144$).

As described above, you want the intensity to drop to 0.135 ($1/e^2$) at 66% of the radius of the entrance pupil. Later you will choose the **Lens > System Data** menu, go to the **Pupil Apodization** page in the **System Data** window, and enter 0.135 for Intensity and 0.66 for both X and Y components of Relative Aperture Coordinates (these can be different in some systems, e.g., some laser diodes have anamorphic output). Since the $1/e^2$ point is at 66% of the pupil radius, there should be little beam clipping if you size the optics to match the NAO value, which is essentially how CODE V calculates default apertures. If you are modeling a system with known surface apertures, you should enter those on the appropriate surfaces. In this case, analysis options will honor the specified aperture sizes, even if these do not match the specified object (input fiber) numerical aperture.

Object or Field Definition

In this *double-pass* system, the light will pass through the lens, reflect from the grating, and pass again through the lens before being focused on the output fibers or detectors. The input fiber will need to be laterally offset to allow space for the output fibers. In CODE V, this lateral offset is defined by the object height, which is one of several ways to define the field of view of the system.

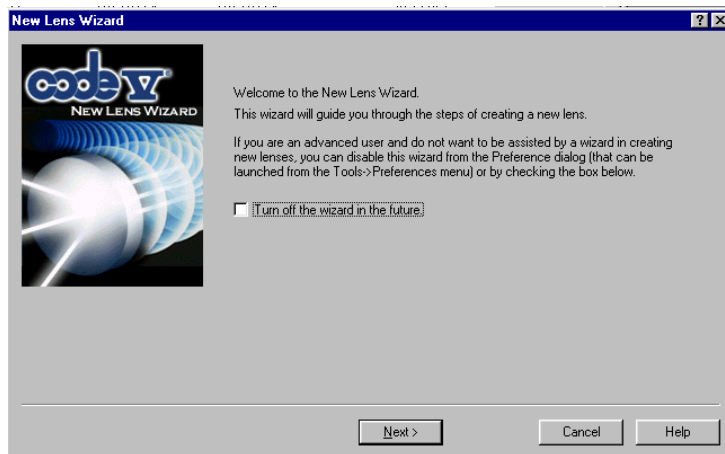
Although optimization will offset the image for the single design wavelength (1550 nm), you will also need to check the other wavelengths in this dispersive system to be sure that none of their output beams overlaps the input beam. This will actually turn out to be a problem, and it will be addressed at the end of this chapter, when zoom will be used to model three wavelengths.

The New Lens Wizard

You will be using an aspheric single lens in this example, setting it up as double pass. This means that the light from the input fiber will pass through the lens, reflect from the grating, pass a second time through the lens, and be collected in one or more fibers laterally displaced from the input fiber. This will require a few steps, but to begin, you need a single lens, and you can use the New Lens Wizard to get one.

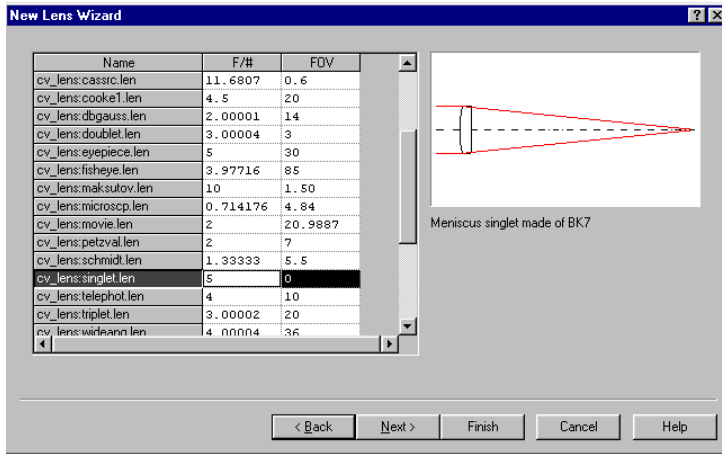
Getting Started

1. Start CODE V.
2. Choose the **File > New** menu to launch the New Lens Wizard.

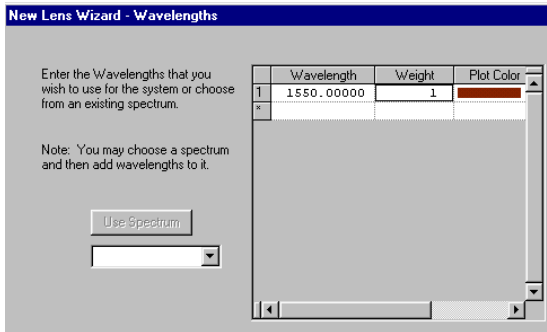


If the New Lens Wizard does not launch, choose the **Tools > Preferences** menu, and be sure the **Use Wizards** checkbox is checked on the **UI** tab.

3. Click **Next** to dismiss the Welcome screen.
4. Click the **CODE V Sample Lens** button (default) on the next screen. Click **Next**.
5. Scroll the list of sample lenses to find the file **cv_lens:singlet.len**, click on that file name, then click **Next**.

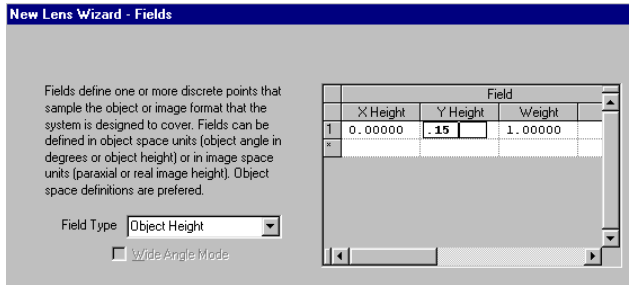


- On the **Pupil** screen, accept the default settings for now, and click **Next**.
Later you will change the pupil definition to Numerical Aperture - Object (NAO).
- On the **Wavelengths** screen, double-click the single wavelength value of 500 nm and change it to 1550 nm. Click **Next**.



- Click **Next** on the **Reference Wavelength** screen to accept the default value.

- On the **Fields** screen, change the type to **Object Height**, and change the Y Height of the single field point to 0.15, then click **Next**.



- Click the **Done** button on the New Lens Wizard's Congratulations screen to complete the initial setup.

The following figure shows how the LDM spreadsheet will look. More changes will be needed to use this lens for the demux example.

The screenshot shows the 'Lens Data Manager' window with a spreadsheet of lens parameters. The spreadsheet has the following data:

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	Infinity		Refract	0
Stop		Sphere	50.0000 V	5.0000	BK7_SCHOT	Refract	10.0000 0
2		Sphere	37110.2297 S	96.6638 S		Refract	9.7295 0
Image		Sphere	Infinity	0.0000 V		Refract	0.1192 0
End Of Data							

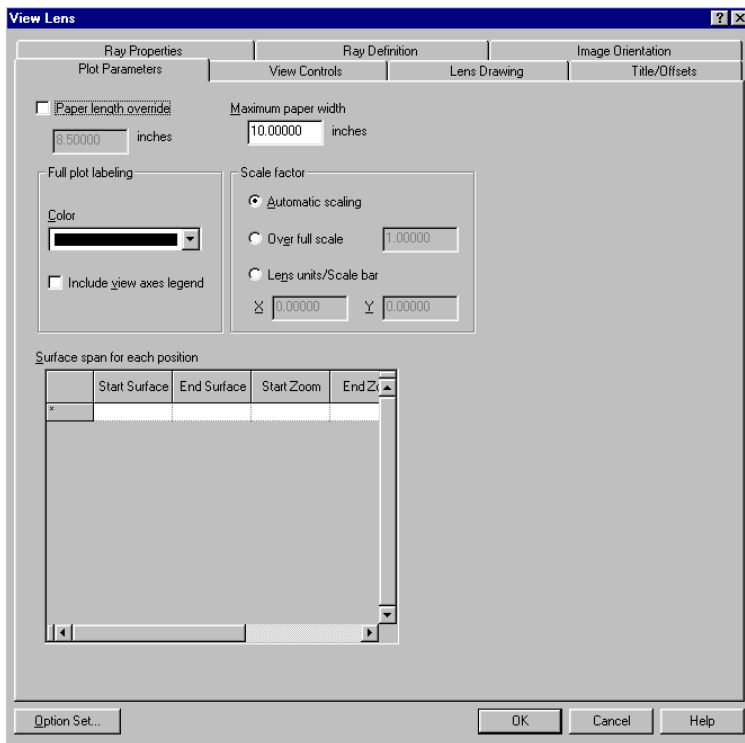
Making a Lens Picture

As you set up the system, it's a good idea to use a lens picture to be sure things are as you expect. It's often easier to catch errors by looking at a picture. You can then use **Edit > Undo** (perhaps multiple times) to reverse any unintended actions.

The View Lens feature is very flexible, and as you add surfaces and other properties, you will need to change its settings (e.g., surface range). But for now, you can use the default settings.

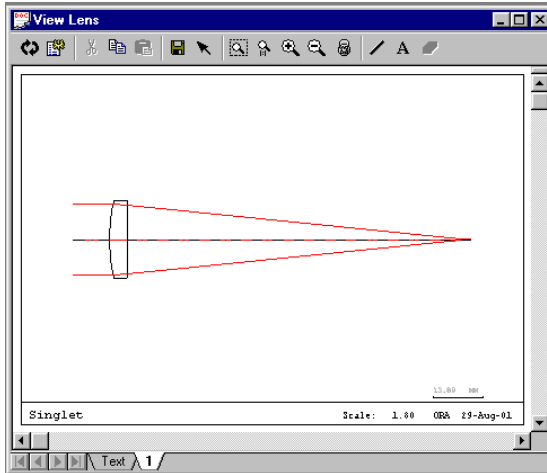
1. Choose the **Display > View Lens** menu.

The **View Lens** dialog box has a number of tabs and input controls.



2. Click the **OK** button.

The lens picture is shown below.



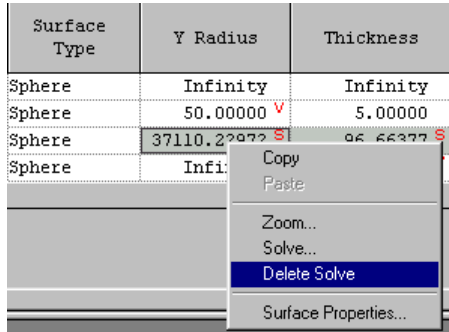
As you modify the lens through this chapter, you can update this picture at any time by clicking the Execute (re-calculate) button on the top left. When surface numbers or other features change, you will need to use the Modify Settings button to open the dialog box to change the input settings (currently default settings).

Solves, Scaling, and System Data

There are two solves in this lens: one for curvature, and one for paraxial image distance. Solves are used to set system data to values required to achieve certain specified properties, usually in terms of first order or paraxial ray trace data. Since you will be scaling and otherwise modifying this lens from its original purpose, solves may cause changes you don't want, so you should delete them now.

1. In the LDM spreadsheet window, right-click on the Y Radius of surface 2, and choose **Delete Solve** from the shortcut menu as shown below.

Surface Type	Y Radius	Thickness
Sphere	Infinity	Infinity
Sphere	50.00000 V	5.00000
Sphere	37110.22977 S	96.66377 S
Sphere	Infi:	



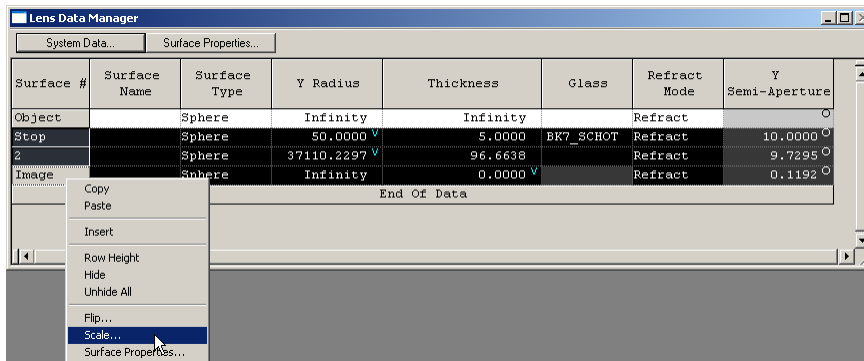
2. Right-click on the Thickness of surface 2, and choose **Delete Solve**.

This lens currently has an effective focal length (EFL) of 100 mm. How can you tell this? You can place EFL on the status bar at the bottom of the screen (choose the **Tools > Customize** menu and click on the **Status Bar** tab). You can also find the EFL from the **Display > List Lens Data > First Order Data** menu. For compact size, you will scale the lens to a focal length of 20 mm.

3. In the LDM spreadsheet, select surfaces (rows) 1 to 3.

Note that surface 1 is actually labeled as “Stop,” indicating the aperture stop surface, which is surface 1 by default. The aperture stop is the surface whose aperture limits the light-gathering ability of the system. We will eventually make the diffraction grating the stop for this system.

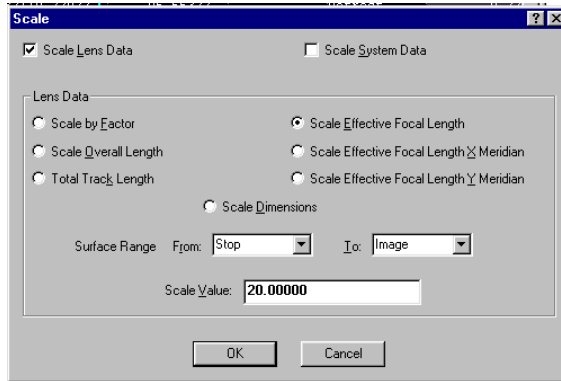
4. Right-click on any selected row and choose **Scale** from the shortcut menu.



Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	Infinity		Refract	
Stop		Sphere	50.0000 V	5.0000	BK7_SCHOT	Refract	10.0000
2		Sphere	37110.2297 V	96.6638		Refract	9.7295
Image		Sphere	Infinity	0.0000 V		Refract	0.1192

The **Scale** dialog displays. Note that the surface range matches the selected surfaces.

- In the **Scale** dialog box, click the **Scale Effective Focal Length** button, enter **20** in the **Scale Value** field, and click **OK**.



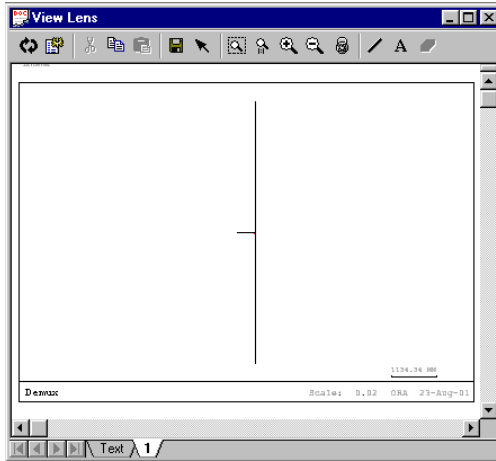
You want the output of this lens to be approximately collimated (rays parallel to the Z axis), so the object (fiber) should be about 20 mm from the lens (i.e., at the focal length distance, using the lens “backwards” to spread out a focused point into a parallel beam).

- Click in the thickness cell for the object surface (the value is currently Infinity) and enter **20**, then click or tab to another cell to enter the new value.

Y Radius	Thickness	Glass
Infinity	20.00000	
10.00000 ^v	1.00000	BK7_SCHOTT
7422.04594 ^v	19.33275	
Infinity	0.00000 ^v	
End Of Data		

Re-Drawing the Lens

You should re-draw the lens in the **View Lens** output window to see the effects of these changes. If you just click the Execute button, you will see something like this:



What's wrong? The lens is very small and the image surface (vertical line) is very big. VIEW uses the paraxial image height size for drawing the image surface. With the object distance set to 20 (object near the focal point), the paraxial image distance is long, and the paraxial image height very large (choose the **Display > List Lens Data > First Order Data** menu to see the numbers). The solution is to change the surface span for the drawing.

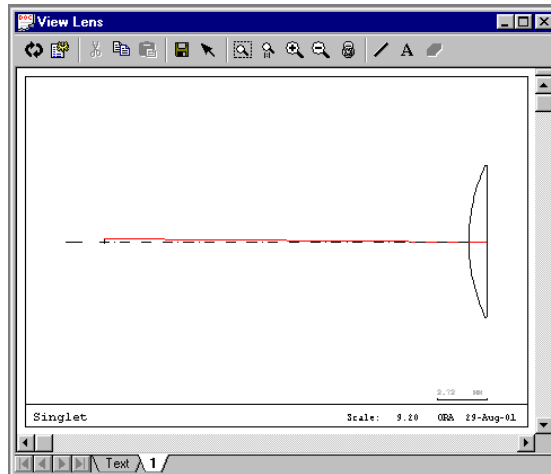
1. Click the Modify Settings button in the **View Lens** window.



The **View Lens** dialog box is displayed.

2. On the **Plot Parameters** tab, change the Surface span **Start Surface** value to **Object**, and the **End Surface** value to **2**, then click **OK**.

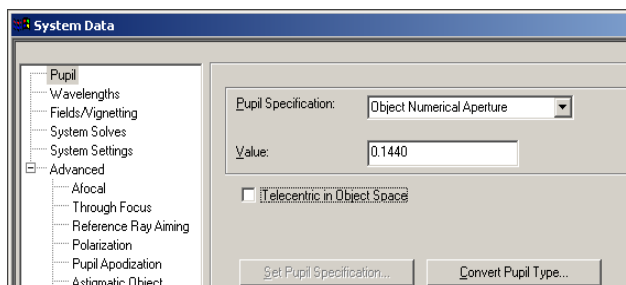
The picture looks better now, although only the chief ray is traced. Keep this window open so you can re-run or update it for later changes (it will remember the settings you have entered as long as you keep it open).



Completing the System Data

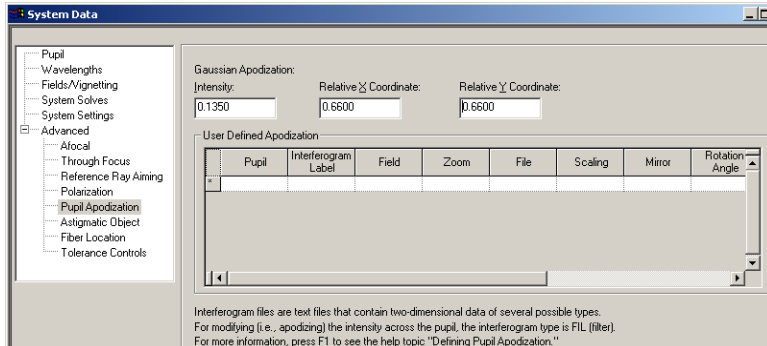
Now that the lens has a finite object distance, you can redefine the pupil size in terms of numerical aperture, based on the characteristics of the input fiber discussed earlier.

1. Choose the **Lens > System Data** menu. In the **System Data** window, click **Pupil** in the navigation tree to go to the Pupil page.
2. Change the **Pupil Specification** field from **Entrance Pupil Diameter** to **Object Numerical Aperture**.
3. Enter **0.144** in the **Value** field.



You can also define the pupil intensity in the System Data window, on the Pupil Apodization page. As discussed earlier, the intensity of a single mode fiber is well-approximated by a Gaussian.

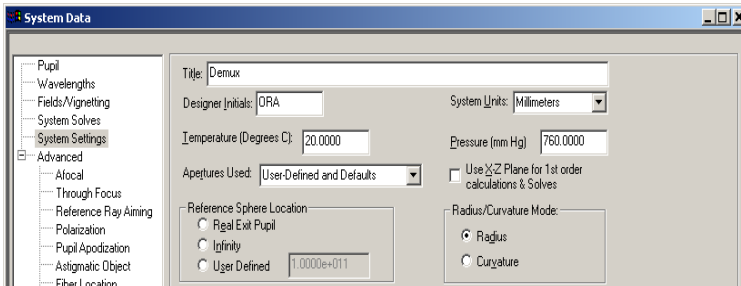
4. Click **Pupil Apodization** in the System Data window's navigation tree (found under **Advanced**) to open this page.
5. For Gaussian Pupil Intensity (**Intensity** field), enter **0.135**.



6. Enter **0.66** for both **Relative X** and **Y Coordinates**, then click or tab to another field.

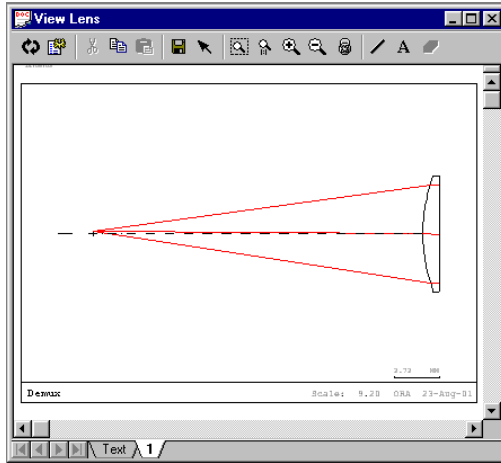
Finally, you can define a new title for this system.

7. Click **System Settings** in the navigation tree to open this page.
8. Enter a new title such as **Demux** in the **Title** field and click or tab to another cell to commit this data.



9. You can make a new picture by clicking the Execute button on the View Lens window.

The new output looks like this.



Double-Pass Setup

Physically, all you need now is to define the reflecting grating to complete the system, but in the sequential ray tracing model normally used by CODE V, it's necessary to define elements a second time if the light passes through them a second time (this is called a *double-pass* system). There is an alternate method called non-sequential surface modeling that doesn't require this, but such NSS systems have other complexities and are not needed in this case.

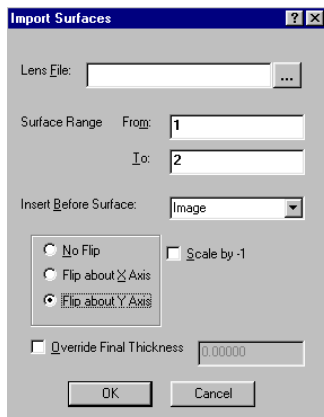
Importing Surfaces

Although you could insert surfaces and use copy and paste to define the second instance of the lens, there is an easier way. The **import surfaces** feature (CODE V command COP) is meant for duplicating ranges of surfaces from the current lens or from another saved lens file. It has several special settings for ordering the copied surfaces, based on the intended use. You can flip surfaces (reverse the order of the copied and inserted surfaces) for use in symmetric or double pass applications. You can also scale the properties by -1 to account for reflection, but in this example you will do that in a separate scaling step.

The **Import Surfaces** dialog box has a file name field that is used to select a saved.LEN file if you need to copy surfaces from another lens, but in this case, you are duplicating surfaces from the current lens. You can either leave the file name blank, or enter an asterisk (*).

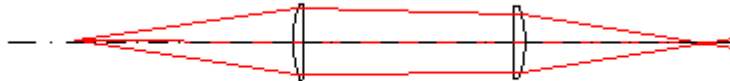
1. Click on the image surface in the LDM spreadsheet to set the insertion point (new surfaces will be inserted in front of the selected surface).
2. Choose the **Edit > Import Surfaces** menu.

The **Import Surfaces** dialog box is displayed.



3. Leave the lens file name blank, change the surface range (From **1** to **2**), and click the **Flip About Y Axis** button. Click **OK**.
4. In the **View Lens** window, click the Modify Settings button, set the **End Surface** value to **Image**, then click **OK**.

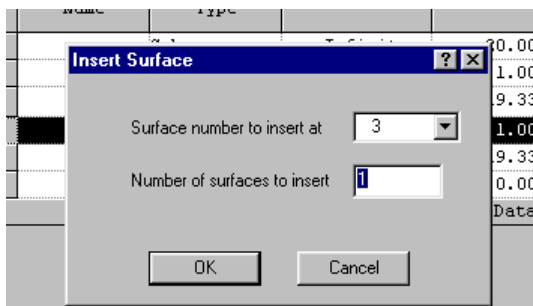
The following lens picture is generated.



Inserting the Mirror

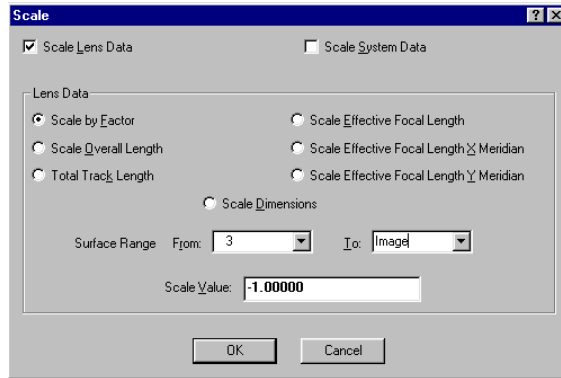
The lens element has been duplicated, as shown in the “unfolded” picture above, and will soon be aligned with its earlier representation. But first you need an additional surface to model the grating between the two copies of the lens. For now, we will approximate the grating surface with a mirror.

1. In the LDM spreadsheet, click on the surface number of surface 3 to select it, then right click and choose **Insert** from the shortcut menu.
2. In the **Insert Surface** dialog box, enter **1** for the number of surfaces to be inserted and click **OK**.



3. In the LDM spreadsheet, double-click the refract mode for surface 3 and choose **Reflect** from the shortcut menu.
4. Click the thickness cell for surface 2, choose the **Edit > Copy** menu, then use the **Edit > Paste** menu to duplicate this value for the thickness of surface 3.

5. Select surfaces **3** to the **Image**, right-click and choose **Scale**. In the **Scale** dialog box, be sure that **Scale by Factor** is selected and enter **-1** (negative one) for the **Scale Factor**.

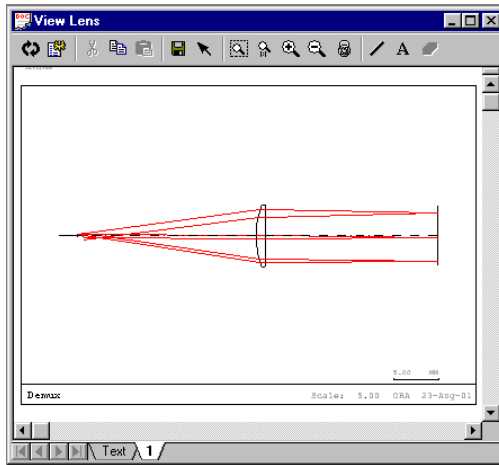


The LDM surface data should look like the following:

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	20.0000		Refract	
Stop		Sphere	10.0000 ✓	1.0000	BK7_SCHOT	Refract	2.9798 ○
2		Sphere	7422.0459 ✓	-19.3328		Refract	2.9767 ○
3		Sphere	Infinity	-19.3328		Reflect	2.8141 ○
4		Sphere	7422.0459 ✓	-1.0000	BK7_SCHOT	Refract	2.6514 ○
5		Sphere	10.0000 ✓	-19.3328		Refract	2.6479 ○
Image		Sphere	Infinity	0.0000 ✓		Refract	0.4863 ○
End Of Data							

6. Update your settings for the **View Lens** window by again clicking the **Modify Settings** button and changing the surface numbers on the **Plot Parameters** tab to start at **Object** and end at **Image**, since another surface has been inserted. Click **OK** in the **View Lens** dialog box.

The following lens picture is generated.



Notice that the two copies of the lens now overlay perfectly, so it appears to be only one lens element (which of course it physically is). The rays pass through the lens twice but do not overlay exactly due to the object offset and aberrations.

Using Pickups

Although the second pass surfaces are now properly defined and positioned, they will not stay that way if you vary them during optimization. AUTO would treat each variable as independent, and you could end up with a physically impossible solution in which a radius of curvature of the lens changes value after the reflection. To prevent this, you must couple the corresponding parameters together, or better yet, use pickups to keep the corresponding values identical through any change to the lens.

Pickups establish a relationship between two lens parameters of the same or even different type, with optional scaling and offset parameters. A very common scaling parameter is -1 which is used to duplicate a value with the opposite sign, a frequent need in double pass, reflecting systems.

Defining Pickups

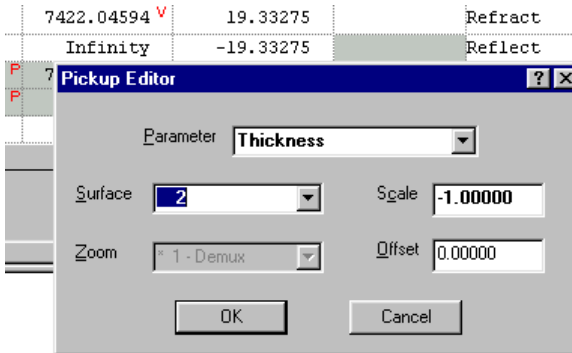
The procedure is done in the LDM spreadsheet window and is the same for any type of parameter.

1. Right-click on the cell for the item and surface number whose value you wish to “pick up” from an earlier value, and choose **Pickup** from the shortcut menu.

Surface Type	Y Radius	Thickness
Sphere	Infinity	20.00000
Sphere	10.00000 ▼	1.00000
Sphere	7422.04594 ▼	19.33275
Sphere	Infinity	-19.33275
Sphere	7422.04594 ▼	-1.00000
Sphere		-19.33275
Sphere		0.00000 ▼
		Of Data
		Surface Properties...

Note that the item you are picking up from (source value) need not be of the same type as the item you are defining, though it usually is, and this is the default.

2. In the **Pickup Editor** dialog box, choose the surface number whose value you are picking up.



You can also choose the Parameter type if it is different from the value you are defining (the default parameter is “same as dependent parameter,” but this was explicitly changed to Thickness in the example above). If there is a reflection between the source and picked-up surfaces, you may need to scale the range of surfaces after the reflection by entering -1 as shown.

The table below summarizes the needed pickups. Note that they are all of the same type in this example (i.e., thickness picked up from thickness). Note that the pickup of thickness 5 from the object thickness deliberately changes the value (from -19.3 to -20).

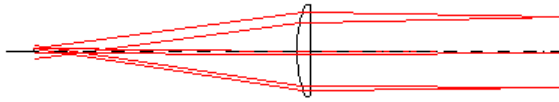
Right-click...	Surface	Pickup from	Scale
Surface type (profile)	4	2	
Surface type (profile)	5	1 (stop)	
Thickness	3	2	-1
Thickness	4	1 (stop)	-1
Thickness	5	Object	-1
Glass	4	1 (stop)	

Here is the LDM spreadsheet window showing all the pickups.

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	20.0000		Refract	
Stop		Sphere	10.0000 V	1.0000	BK7_SCHOT	Refract	2.9798 O
2		Sphere	7422.0459 V	19.3328		Refract	2.9767 O
3		Sphere	Infinity	-19.3328 P		Reflect	2.8141 O
4		Sphere	7422.0459 P	-1.0000 P	BK7_SCHOT P	Refract	2.6514 O
5		Sphere	10.0000 P	-20.0000 P		Refract	2.6479 O
Image		Sphere	Infinity	0.0000 V		Refract	0.5748 O

Since pickups will actually change lens data, a simple mistake such as an incorrect sign could change the lens form. It's best to check the numbers carefully and to make another lens picture.

3. In the **View Lens** window, click the Execute button to re-draw the lens.



The picture should not change from the previous step.

You have done quite a bit of work on this lens already, so it might be good to save the lens file if you have not already done so.

4. Choose the **File > Save Lens As** menu.
5. In the **Save As** dialog box, enter a name for the lens file, such as **DemuxStart.len**, and click the **Save** button.

You can change to a different directory before saving, as with any Windows application.

Modeling the Grating

The reflecting surface is in place, but you need to add grating parameters. Diffraction will change the ray angles from that of a simple reflector, so the grating will also need to be tilted to the correct angle to get the rays to pass through the lens on the way back. You can use trial and error to get the approximate tilt angle, then use optimization to refine it.

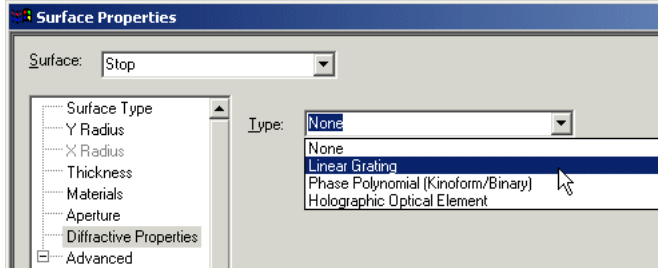
Creating the Grating

You are almost done defining the optical system, but you are missing some details, especially for the grating. The grating is what separates the wavelengths in the device, and its surface properties and tilt angle must be set to allow this. First you need to make the grating the size-limiting or “aperture stop” surface of the system.

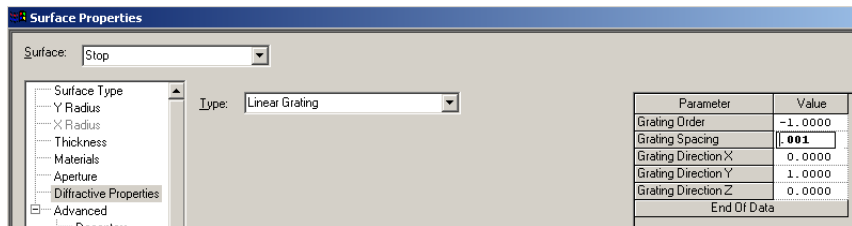
1. In the LDM spreadsheet, right-click on the surface number for surface 3 and choose **Set Stop Surface** to make the mirror the aperture stop surface.



2. Right-click on the surface type for surface 3 and choose **Surface Properties**. This will open the **Surface Properties** window.
3. Click **Diffractive Properties** in the Surface Properties window’s navigation tree to go to that page.
4. Choose **Linear Grating** in the **Type** field.



5. In the spreadsheet on the Diffractive Properties page, enter **-1** for the **Grating Order** and **0.001** for the **Grating Spacing**.



Gratings diffract light into multiple directions called orders, although they are usually designed to put most of the energy into one particular order, which we will assume to be -1 in this case. The Grating Spacing (in lens units, 0.001 mm; in this case, 1 micron) determines how dispersive the grating is—smaller values will diffract the light over larger angles, as a function of wavelength. This value represents a grating with 1/.001, or 1000 lines/mm. The Grating Direction values default to (X=0, Y=1, Z=0) which is correct for this case (rays will be diffracted in the +Y direction).



Note: CODE V estimates the scalar diffraction efficiency, or the amount of energy going into a given diffractive order, for a number of blazed grating profiles: kinoform, step approximation to a kinoform, or sinusoid. The grating profile determines only the diffraction efficiency of the rays; the direction and optical path lengths of the rays are determined by the grating order and spacing. For details about CODE V's scalar diffraction efficiency calculation, see page 4-116 in the *CODE V Reference Manual*.

Tilting the Grating

Now you must tilt the grating so the diffracted rays will re-enter the lens. You can use trial and error, changing the angle and updating a lens picture window to find the approximate value, which will be about -45° (this angle will be in the YZ plane, which is an alpha tilt, or ADE in CODE V terminology).

You can then use *constraint-only* optimization to find the value that places the output beam where you want it (at about -0.30 mm below the Z axis).

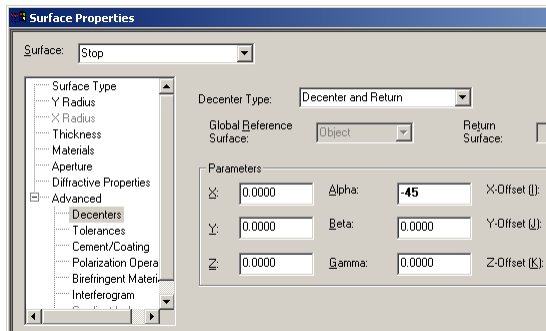
1. Click **Decenters** in the Surface Properties window's navigation tree (make sure you are working on surface 3, now called **Stop**).

The Decenters page is found under **Advanced** in the Surface Properties navigation tree. If you have closed the Surface Properties window, right-click on surface 3 and open it again.

2. Use the dropdown list to change the **Decenter Type** from **None** to **Decenter and Return**.

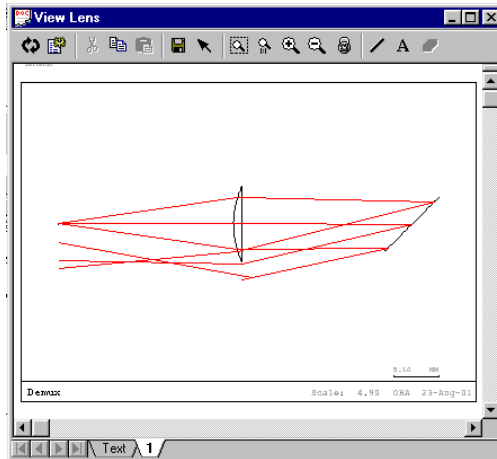
The decenter and return establishes a “temporary tilt” for the current surface only, re-aligning the exiting coordinate system with the entering coordinate system for the surface, which will keep the double pass configuration intact (i.e., the second copy of the lens element will still be aligned with the first, as you can tell from a lens drawing).

3. Enter **-45** in the **Alpha** field and press the Tab key.



4. Right-click on the Alpha value and choose **Vary** from the shortcut menu.

You will soon use AUTO to optimize this value for the correct output ray path. Right now the ray path is looking a bit ragged (re-run the still open **View Lens** window).



You can now use optimization to adjust the tilt angle to get the proper ray path, using a single variable. You will then set up additional variables and do additional optimization to improve the performance.



Note: You can also estimate a starting angle from the grating equation:

$$\sin I - \sin I' = m\lambda/d$$

where I is the incident angle, I' is the diffracted angle, m is the grating order (-1), λ the wavelength ($1.55 \mu\text{m}$), and d the grating spacing ($1 \mu\text{m}$). If you assume $I = I'$ (not quite true, but close) and solve $2 \sin I = m\lambda/d$ for I , you get -50.8° . This is very close to the optimized result. Not all problems have such a simple equation to solve, so trial-and-error followed by the constraint-only optimization approach is a very useful technique.

Optimizing the System

Although you could try running some analysis options now, it's clear from the lens picture that this system is grossly aberrated. You will use three steps to optimize this system:

1. Run AUTO in *constraints-only* mode to vary the grating alpha tilt angle to satisfy a single specific constraint: the chief ray height on the image surface.
2. Define aspheric and other variables to use for improving the image quality.

3. Run AUTO with a wavefront error function and additional constraints to improve the image quality.

Constraints Only for Tilt Solution

Although you could use trial and error to refine the value of the grating alpha tilt, AUTO provides a convenient way to solve such problems. Note that it does generally require a starting point that at least traces the reference rays. If this is not the case, AUTO tries reducing the field and pupil size temporarily, but this often does not work. For this case, the estimated value of -45° is close enough to optimize. First you need to freeze any variables other than the tilt angle.

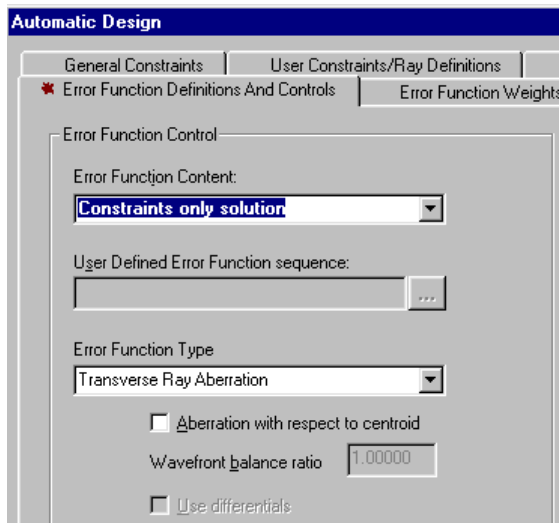
1. In the LDM spreadsheet, click and drag to select the Y radius cells for surfaces 1 and 2, then right click and choose **Freeze** from the shortcut menu.

Note that the V (variable) symbol disappears from these cells when you do this.

2. Right-click on the image surface thickness and choose **Freeze**.
3. Choose the **Review > Variables and Couplings** menu to display the **Variables and Couplings** spreadsheet. Make sure that the only parameter listed is the Alpha tilt of the Stop (grating) surface.
4. Choose the **Optimization > Automatic Design** menu.

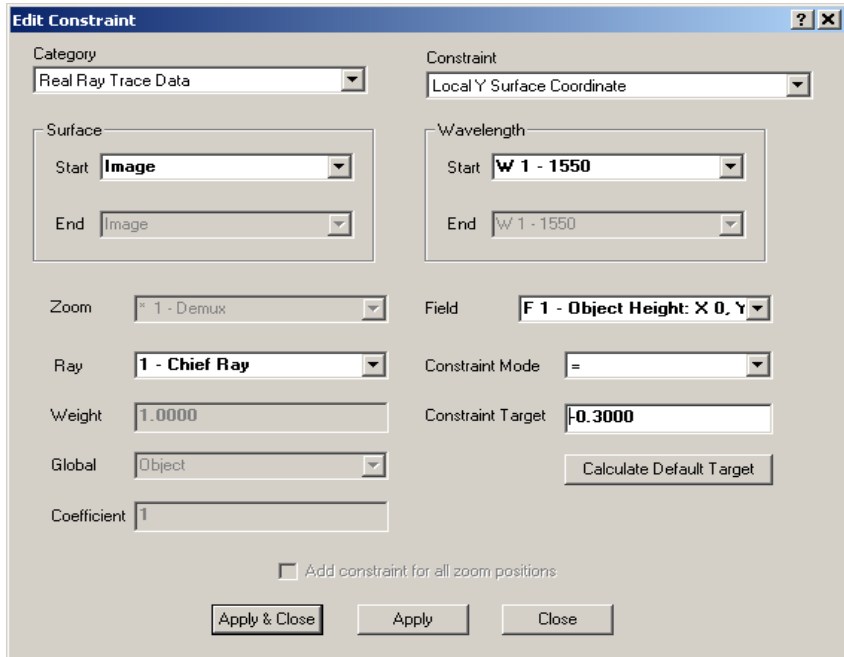
The **Automatic Design** dialog box is displayed.

5. On the **Error Function Definition and Controls** tab, choose **Constraints Only Solution** from the **Error Function Content** dropdown list.

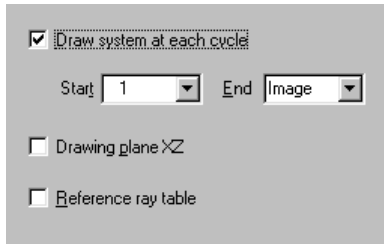


- On the **Specific Constraints** tab, click the **Insert Specific Constraint** button. The **Edit Constraint** dialog box is displayed.
- In the Edit Constraint dialog box, choose **Real Ray Trace Data** in the **Category** field, choose **Local Y Surface Coordinate** in the **Constraint** field, and click in any non-gray field.

This allows the program to update the available data fields for the chosen constraint (different constraint types require different combinations of parameters). In this case, the defaults are right except for the target (Image surface, field F1, chief ray, wavelength W1, constraint mode equality). Click the **Calculate Default Target** button to see the current value of this target, which is the real-ray image height.

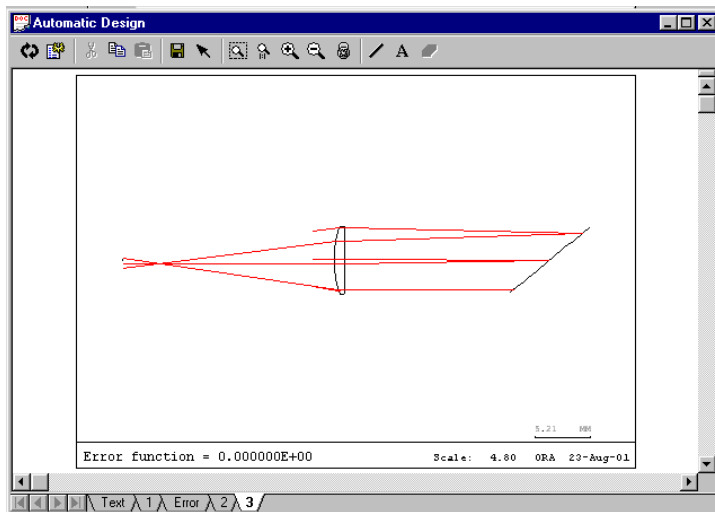


- Enter **-0.30** as the **Constraint Target** and click **Apply & Close**.
- Click the **Output Controls** tab, then click the **Draw system at each cycle** checkbox.



10. Click **OK** to run this optimization.

The **Automatic Design** tabbed output window is generated.



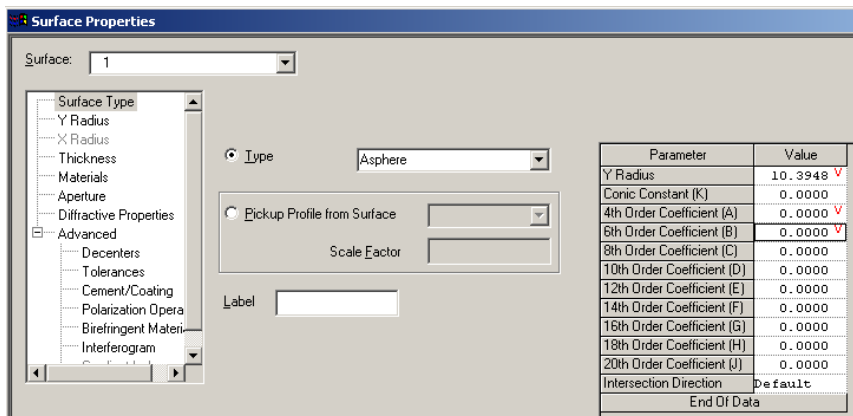
The solution is just what was requested—solving only the single real-ray constraint, but still with very poor image quality. If you scroll down to the end of the **Text** tab you will find that the final alpha tilt value is about -50.6° (ADE S3). **Keep this tabbed output window for AUTO** (you can resize, move or minimize it). You will next add aspherics and variables in the LDM and modify the AUTO inputs for image quality optimization.

Aspherics and Variables

Optimization requires appropriate variables and an error function to represent the system quality. Variables are designated by you by right-clicking and choosing **Vary** from the shortcut menu, as you have seen in previous procedures. You can start out with CODE V's default error function for wavefront error, but you will

impose a constraint on the airspace length to prevent the system from getting too long (this is usually determined by trial and error). You will also constrain a ray on the output (image surface) to lie at least 0.3 mm below the input fiber (for mechanical spacing). To get additional degrees of freedom to correct aberrations, you will make both surfaces of the lens aspheric and vary the aspheric coefficients to get the best performance. The profile pickups that you entered earlier will automatically make the pickup surfaces identical aspheres as well. Aspherics are more expensive to manufacture than spherical lenses, but there are now various production methods that can make aspheres a cost effective alternative to multiple spherical elements for many systems.

1. In the LDM spreadsheet, right-click on the surface type for surface 1 and choose **Surface Properties** from the shortcut menu.
2. On the Surface Type page of the Surface Properties window, change the Type to **Asphere** (choose from dropdown list), then click another field.
3. Right-click in the value cells for the 4th and 6th order coefficients (A and B) and choose **Vary Parameter** for both.



4. Change the surface selector (upper left) to surface 2, and make surface 2 an **Asphere** with 4th and 6th order coefficients (A and B) variable.
5. Back in the LDM spreadsheet, right-click and choose **Vary** for the Y radius values for surface 1 and surface 2.
6. Right-click and **Vary** the thickness for the object surface and surface 2.
7. Right-click and **Vary** the glass of surface 1.

Note that the glass BK7 will be changed into a *fictitious glass* designated 516800.641673 (index of 1.5168, V-value of 64.1673). Fictitious glass is a model that allows the glass properties to vary for optimization (catalog glasses

such as BK7 have fixed properties and thus cannot be variables). Optimized fictitious glasses must be converted to real glasses for final analysis and manufacture (the supplied macro **glassfit.seq** can help you with this task).



Note: Varying glass is not really necessary for a monochromatic system, but it is included here to show the techniques. The fictitious glass model is really intended for visual wavelengths, so any fictitious glass should eventually be replaced by a real glass, followed by a final optimization to be sure its performance in the infrared is as expected.

8. Choose the **Review > Variables & Couplings** menu, and verify the 10 variables shown below in the **Variables and Couplings** spreadsheet.

	Surface #	Parameter	Glass Sub-Parameter	Coupling Code
1	Object	Thickness		0
2	1	Curvature		0
3	1	Glass 1	Index and Dispersi	0
4	1	4th Order		0
5	1	6th Order		0
6	2	Curvature		0
7	2	Thickness		0
8	2	4th Order		0
9	2	6th Order		0
10	Stop	Alpha Tilt		0
End Of Data				

The **Coupling Code** value of zero indicates a variable, which will also be indicated by the **V** symbol in the LDM spreadsheet or Surface Properties window.

9. Choose the **File > Save Lens** menu to update the saved copy of this lens data.

Optimizing the Lens

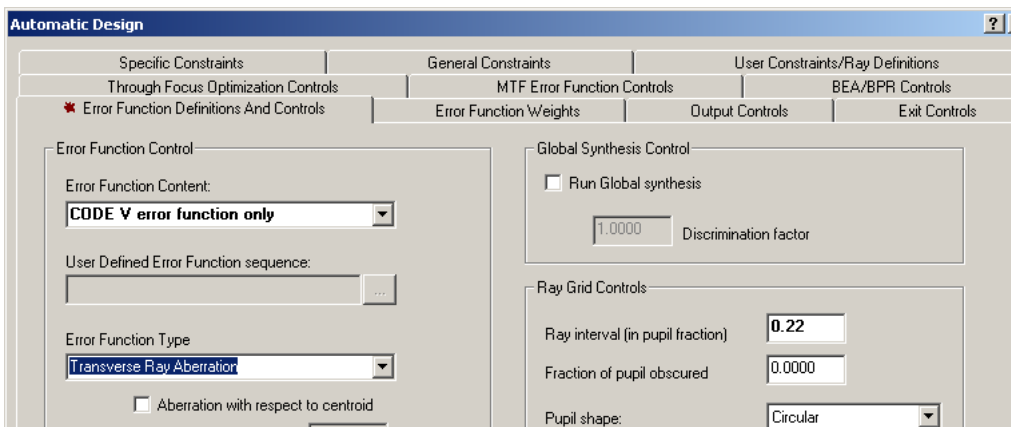
Now that you have defined aspherics and other variables, you should have enough degrees of freedom to improve the image quality with AUTO.

1. Click the Modify Settings button in the Automatic Design window used previously.

The settings made earlier will still be in place, but you will need to change some of them and add some others.

2. On the **Error Function Definitions And Controls** tab, change the Error Function Content to **CODE V error function only**.
3. Change the Ray Interval to **0.22** (under Ray Grid Controls).

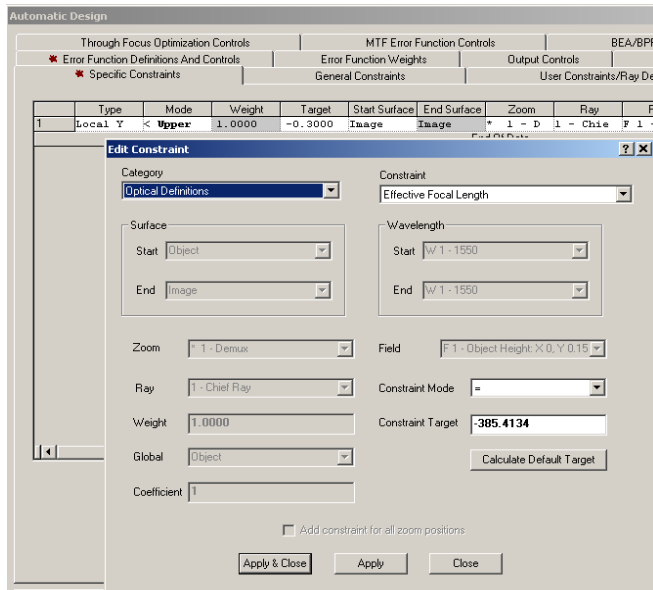
Note that this step is not required, since CODE V sets the ray interval to 0.22 whenever non-spherical surfaces are in the lens. However, it's good to be aware that you can change this ray spacing, since it can greatly affect the solution.



4. On the **Specific Constraints** tab, change the Mode for the previously entered Y ray constraint to **< Upper Bound**.

It's acceptable if the output beam is displaced below -0.30 mm.

5. Click the **Insert Specific Constraint** button to display the **Edit Constraint** dialog box.



6. In the **Edit Constraint** dialog box, choose the following:

- Category: **Manufacturing and Packaging**
- Constraint: **Center Thickness**
- Start Surface: **2**
- Constraint Mode: **> Lower Bound**
- Constraint Target: **10**

Click **Apply**.

7. With the **Edit Constraint** dialog box still open, repeat the above step exactly, with the following exceptions: make the mode **< Upper Bound** and the target **25**. Click **Apply & Close**.

The combined effect is to hold the air space between the lens and the mirror to between 10 and 25 mm. It is often necessary to enter the same constraint twice to establish lower and upper bounds. The command language allows a shortcut for this (CT S2 > 10 < 25), but this is still entered as two separate constraints.

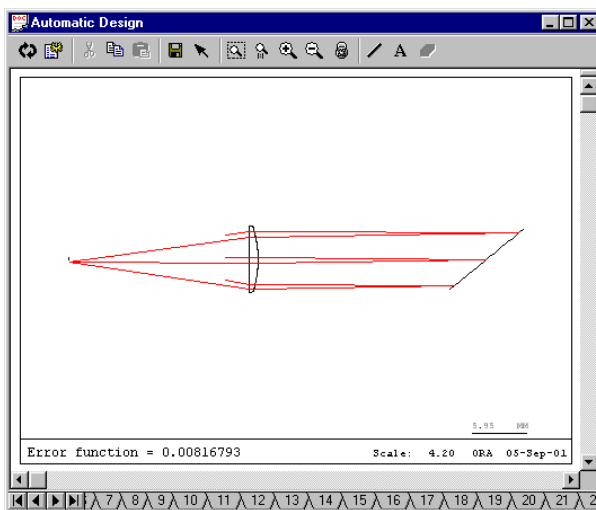
8. Check the **Specific Constraints** tab to be sure your constraints match the ones below.

Type	Mode	Weight	Target	Start Surface	End Surface	Zoom
1	Local Y Surface Coord < Upper Bound	0.00000	-0.30000	Image	Image	* 1 - D
2	Center Thickness > Lower Bound	0.00000	10.00000	2	Image	* 1 - D
3	Center Thickness < Upper Bound	0.00000	25.00000	2	Image	* 1 - D

End Of Data

9. Click **OK** to run the optimization.

Your final screen should look something like this (rays start just before surface 1, not at the object surface). Note that the beam is well focused and the final error function is a small number (zero is considered perfect for optimization purposes, but the true performance must be determined by analysis).



10. Choose the **File > Save Lens As** menu and give the optimized lens a new name (for example, **DemuxOpt.len**).

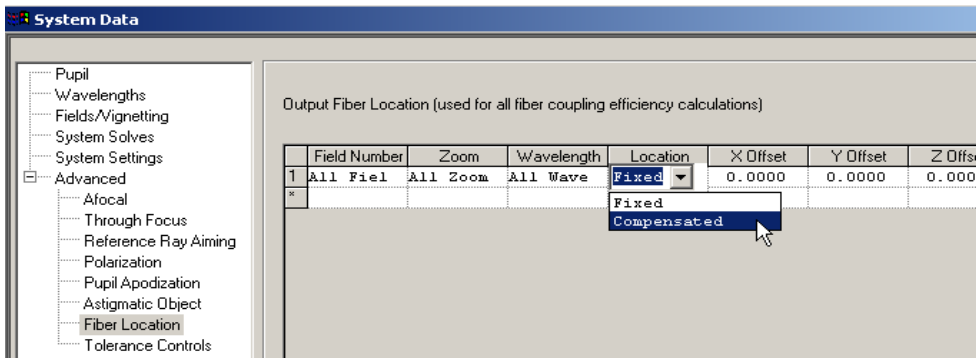
Analyzing the Performance

This system is intended for multiple wavelength use (WDM) over the telecom C band, but to start with, you should analyze the coupling efficiency at the design wavelength, 1550 nm. You can then use a macro to analyze the coupling efficiency over multiple single wavelengths. Other analysis or optimization will require special techniques, including zooming the wavelength weights and reference wavelength. This is because the system is not polychromatic, but instead is a multiple wavelength system, where each wavelength must be analyzed and optimized with reference to its own chief ray.

Coupling Efficiency

Coupling efficiency (CEF) was discussed in detail in Chapter 2, where it was used to analyze a simple ball lens coupler. The same inputs will apply here, so we will present only the steps, and show the fiber location setting in the **System Data** window that is used differently from the ball lens examples. Only non-default settings are noted.

1. In the **System Data** window (**Lens** menu), on the **Fiber Location** page, double-click the cell for Location, and choose **Compensated**.



2. Choose the **Analysis > Diffraction > Fiber Coupling Efficiency** menu.

The **Fiber Coupling Efficiency** dialog box is displayed.

3. On the **Fiber Specs** tab, choose **Gaussian** mode, and enter **0.0052** for the radius.

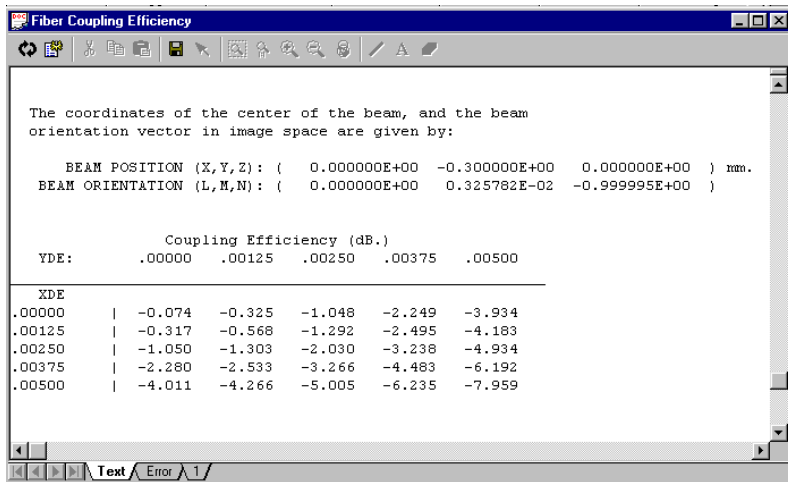
Recall that the Gaussian mode profile is a good approximation to SMF-28 fiber, with a mode radius of 0.0052 mm (5.2 μm) at 1550 nm.

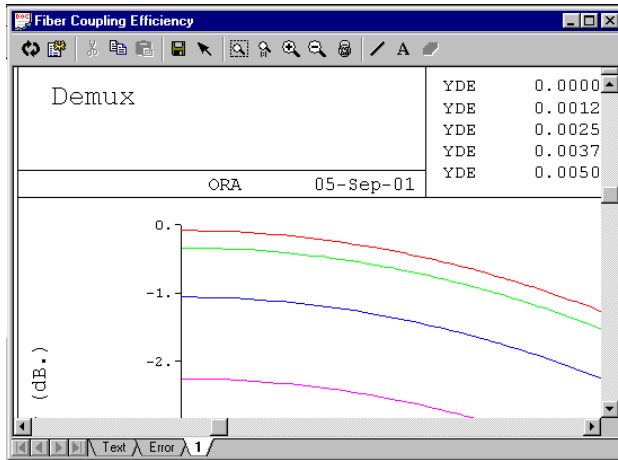
4. On the **Computation** tab, enter **0.001** as the **Focal Plane Increment**, and select the **Decibel Scale** checkbox (**Output Controls** area). The 0.001 increment ensures that at least 10 samples across the mode diameter and is a good default for fiber coupling systems. Often it is not necessary to select a focal plane increment, but if you want to ensure adequate sampling you can explicitly set this parameter.
5. On the **Sensitivity Analysis** tab, keep the defaults of X and Y displacement (output fiber decentering), but change the maximum values to **0.005** and the **Number** to **5**.

This defines the calculation, but you also need to specify the location of the fiber. The default is to fix the fiber on the axis (at X=0, Y=0 on the image surface). For centered systems, this is a good choice (and you may also choose to move or tilt the fiber from this position). But in this case, with a tilted system, you can choose the second option and have CEF “compensate” for the position of the fiber with respect to the chief ray.

6. Click **OK**.

The output shows that the nominal (centered on chief ray) coupling efficiency is good, with an insertion loss of about -0.08 dB. It drops off rapidly with decentering as you might expect. The plot shows this quite clearly.

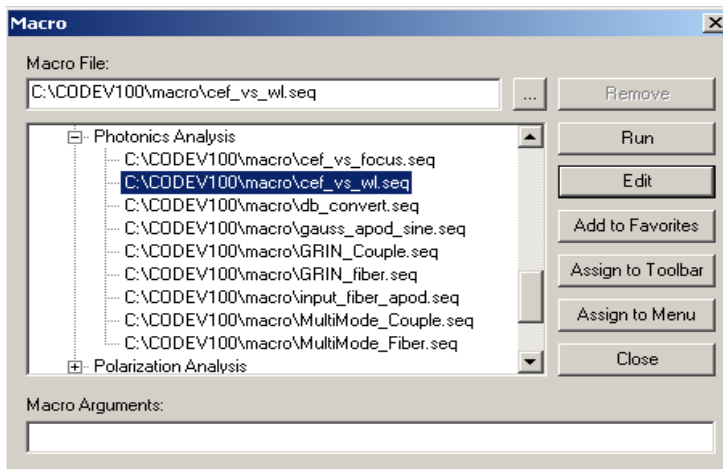




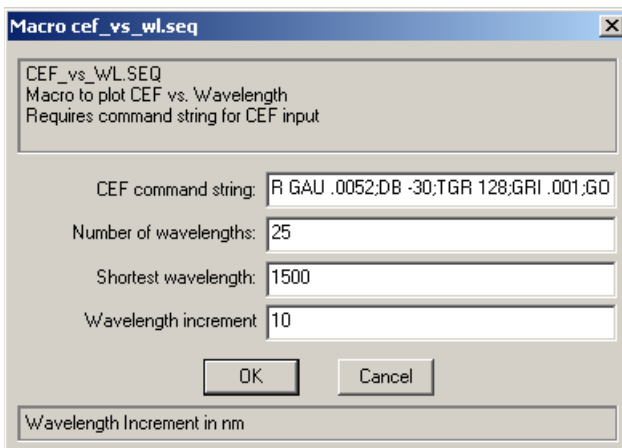
Coupling Efficiency vs. Wavelength

CEF itself only calculates the coupling efficiency for the reference (primary) wavelength of the optical system, but for WDM applications, coupling efficiency vs. wavelength is obviously important. ORA has written a macro for the common case of evaluating CEF over a series of wavelengths. This macro is called **CEF_VS_WL.seq**, and is available as a sample macro in the **Macro** dialog box. **CEF_VS_WL** has a GUI input dialog box, making it very easy to use.

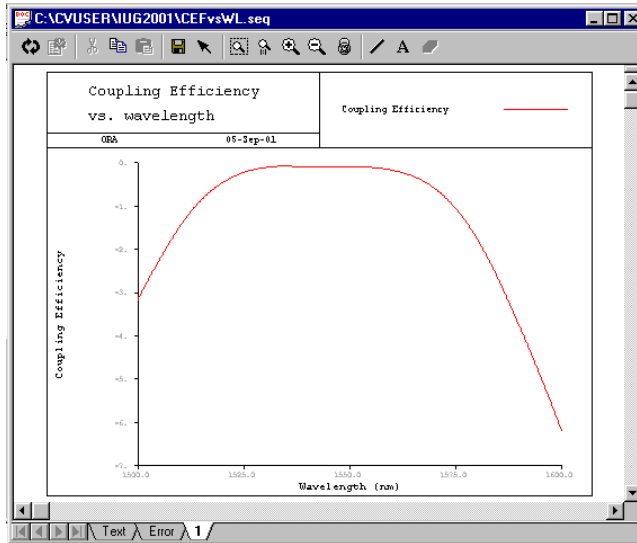
1. Choose the **Tools > Macro Manager** menu.
2. In the **Sample Macros** list, click **Photonics Analysis**.
3. Click **cef_vs_wl.seq**.



4. Click **Run** to run the selected macro.
5. Enter the parameters in the macro input dialog box as shown below. For the CEF command string (only partially shown below), enter:
CEF;MPR GAU .0052;DB -30;TGR 128;GRI .001;GO
6. Click **OK**.



The following output is generated.



You can see that even though you have optimized the system at only a single wavelength, that the coupling efficiency is better than -2 dB from 1500 to 1600 nm. In fact, over the C-band range of 1534.25 to 1566.31 nm, the worst insertion loss value is about -0.30 dB. This looks pretty good unless there are problems with getting to all of the output wavelengths.

Zooming Wavelength Weights

What is not evident from the `CEF_WL_PLOT` macro output is the position of the output beam for various wavelengths. You could investigate this by changing the single wavelength to various values and making a View plot or tracing single rays. If you do this, you will find bad news at the short end of the C-band spectrum (around 1534 nm). In optimizing to place the 1550 nm wavelength at -0.30 mm, the shorter wavelengths are displaced by a smaller distance, and they overlap the position of the input beam.

One thing you could do for this is simply optimize at the shortest wavelength in the desired band. This could work, since the longer wavelengths will all be displaced more than the shortest. But you may not get good performance across the whole band this way.

What Is Meant by *Zoom*?

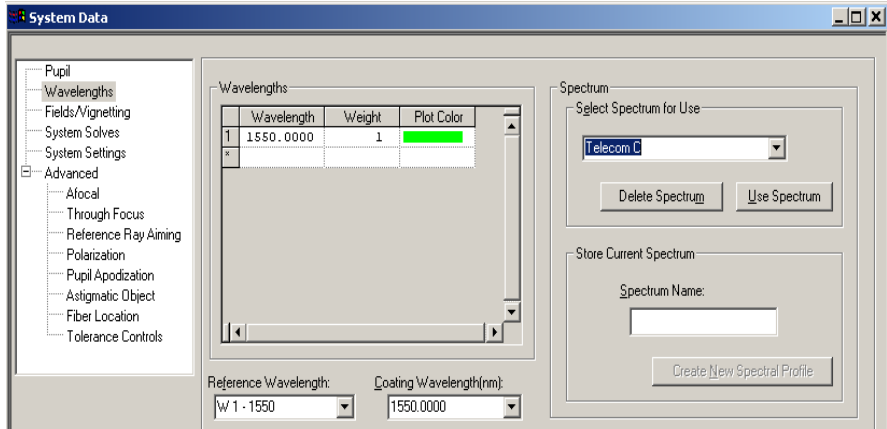
The general solution is to optimize over multiple wavelengths, but while this is a simple matter for polychromatic systems, it's a little more complicated for multi-wavelength grating systems such as this. It can be done by zooming the reference wavelengths and the wavelength weights. *Zoom* in CODE V really means multi-configuration, although the method can be used for true zoom lens design. In this case, we only need to make a way for each wavelength to optimize to a separate point on the image surface. Polychromatic systems try to place all wavelengths at the same image point, and any deviation from this is chromatic aberration (a defect). In this case, placing each wavelength at a separate point is the goal of the system.

The basic idea of *Zoom* is to specify a number of positions (up to 99), then to *zoom* one or more parameters that can take on different values across zoom positions. Any parameter that is *not* zoomed uses the same value for all zoom positions, so input for zoom systems can be fairly brief, depending on the complexity of what is changing. If you want to learn more about zoom methods, please read [Chapter 9](#) of the *CODE V Introductory User's Guide*.

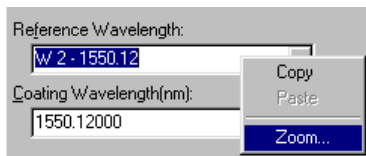
A Slightly Shorthand Procedure

Since this chapter is already pretty long, we will adopt a slightly different format in this section, providing the step-by-step instructions, and briefly summarizing expected results, but using fewer screen shots and shorter explanations than in the rest of this guide. The good news is that very little change is required in the inputs for optimization and analysis to handle the zoomed system. Most of the work is in setting it up in the LDM.

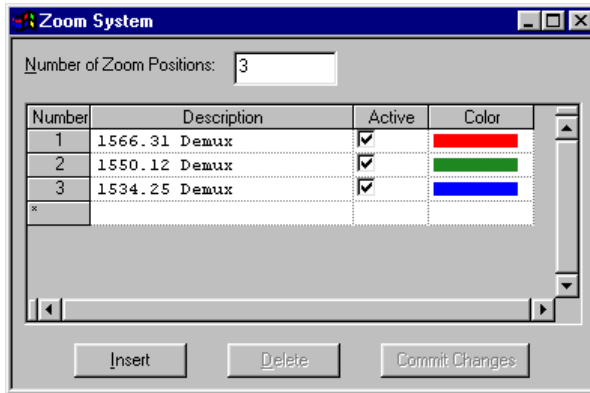
1. Choose the **Lens > System Data** menu, go to the **Wavelengths** page, then select the predefined **Telecom C** spectrum from the dropdown list and click the **Use Spectrum** button.



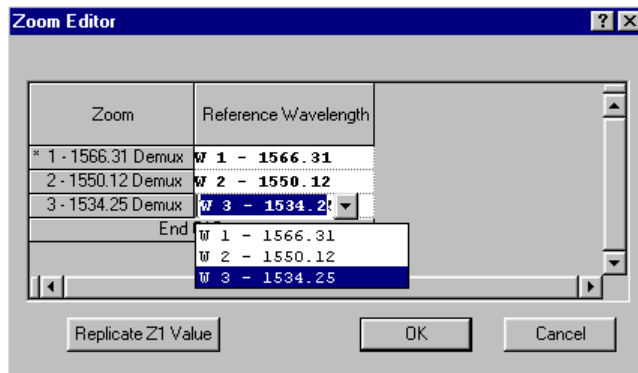
2. To zoom the reference wavelength, right-click the **Reference Wavelength** field, and choose **Zoom** from the shortcut menu. Click **Yes** in the dialog box that asks if you want to zoom the system.



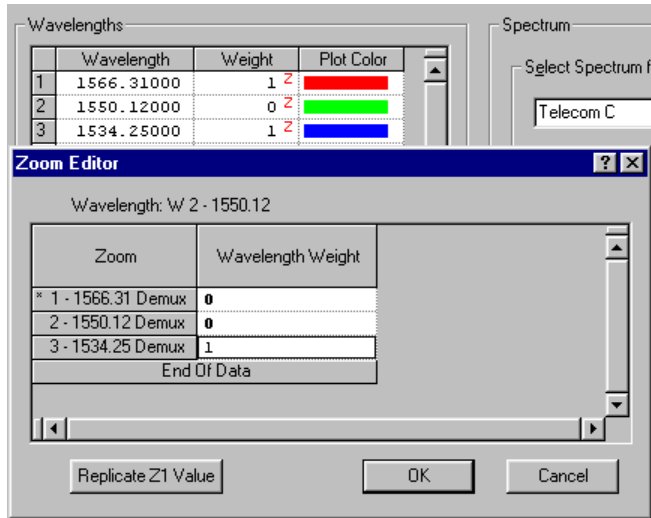
3. In the **Zoom System** dialog box, change the description to **1566.31 Demux**, change the number of zoom positions to **3** and press Enter. Edit the titles for z2 (**1550.12 Demux**) and z3 (**1534.25 Demux**). Choose a plotting color for each zoom position, then close the **Zoom System** dialog box.



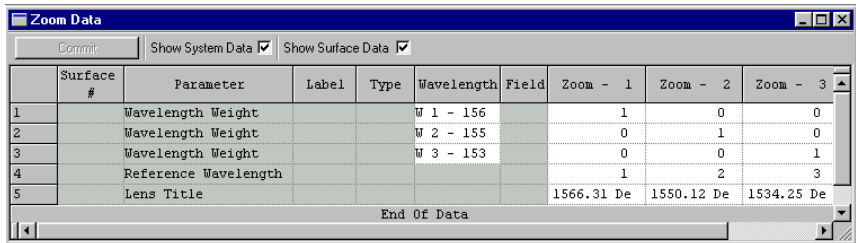
- Right-click again on the **Reference Wavelength** field, and choose **Zoom**. Since the system is zoomed, the **Zoom Editor** dialog box displays. Change the reference wavelength to W1 for Z1, W2 for Z2, and W3 for Z3 (as shown below). Then click **OK**.



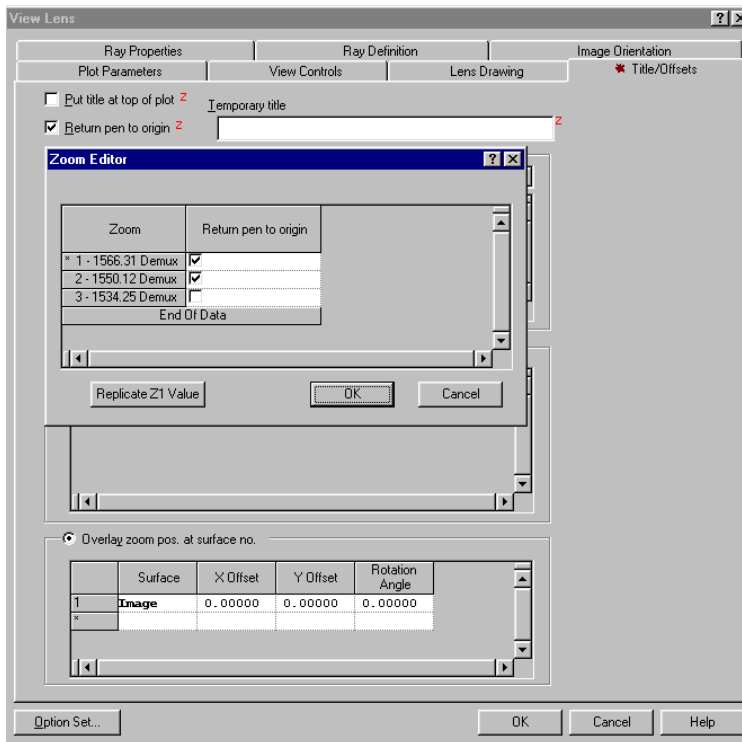
- To zoom the wavelength weights, right-click on the Weight for W1 and choose **Zoom**, and in the **Zoom Editor** dialog box, change the weights to 0 for Z2 and 0 for Z3 (1 for Z1, default value). Click **OK**.
- Right-click on the Weight for W2 and choose **Zoom**, and in the **Zoom Editor** dialog box change the weights to 0 for Z1 and 0 for Z3 (1 for Z2, default value). Click **OK**.
- Right-click the Weight for W3 and choose **Zoom** from the shortcut menu. In the **Zoom Editor**, change weights to 0 for Z1 and 0 for Z2 (1 for Z3, default value). Click **OK**.



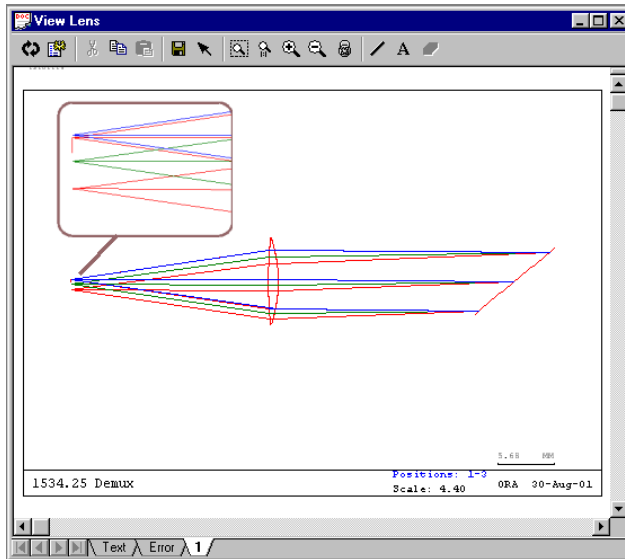
8. Choose the **Review > Zoom Data** menu and use the **Zoom Data** spreadsheet to confirm that weight is non-zero only for the reference wavelength in each position.



9. Choose the **Display > View Lens** menu, and:
 - In the **View Lens** dialog box on the **Plot Parameters** tab, make sure the surface span is object to image (zoom will not matter here since you will make a single overlay plot with all zooms).
 - On the **Title/Offsets** tab, right-click the **Return Pen to Origin** checkbox and choose **Zoom**. In the **Zoom Editor**, check the boxes for Z1 and Z2 but leave Z3 blank (as shown) and click **OK**.



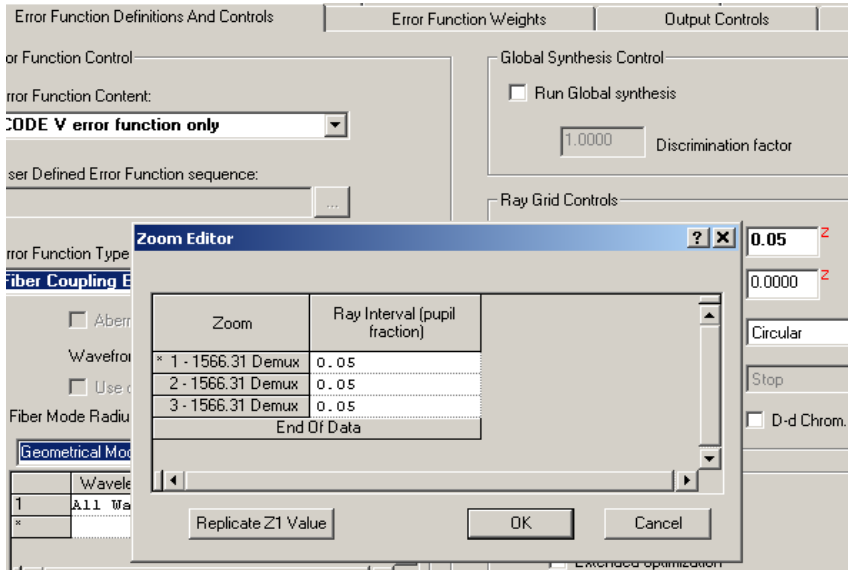
- On the same tab, click **Overlay zoom pos. at surface no.** and choose **Image** as the overlay surface with no offsets (both return and overlay steps are shown above).
- On the **Ray Properties** tab, in the **All rays** spreadsheet, insert 2 lines, and make them Z1, Z2, and Z3 with colors red, forest green, and blue.
- Click **OK**, and note that the shortest wavelength (blue) image beam overlaps the object beam (picture with detail inset below produced with copy/paste in graphics program).



10. Choose **File > Save Lens As**, and specify the file name **demuxZoomStart.len** or another name of your choice.
11. In the saved (still open) **Automatic Design** window used previously, click the **Modify Settings** button and do the following:
 - On the **Specific Constraints** tab in the **Automatic Design** dialog box, modify the already defined Specific Constraint ($Y < -0.3$) to change to **Z3** and **W3** (shortest wavelength - you must change **both** zoom and wavelength, and you may have to scroll horizontally to find the wavelength column)
 - On the **Error Function Definitions and Controls** tab, change the Error Function Type to **Fiber Coupling Efficiency**, and the mode radius (all zooms, all wavelengths as shown) to **0.0052**.
 - Right-click the **Ray Interval** field, choose **Zoom**, and enter **0.05** for Z1; click the **Replicate Z1** button, and click **OK**. Remember from Chapter 2 (ball lens example) that a smaller ray interval is often necessary for optimizing on fiber coupling efficiency (0.05 is the default value for fiber coupling optimization, but since you changed this value earlier, you need to re-enter the default value in this step). This allows more rays to be entered into the optimization error function.

- You may want to save these settings for later use by clicking the **Option Set** button, then the **Save As** button, and assigning a descriptive name to this set of inputs.

You don't need this as long as you keep the AUTO window open in this session, but if you close the window or end the session, you can restore all the settings by clicking **Option Set** and then **Load** to view the list of saved settings.



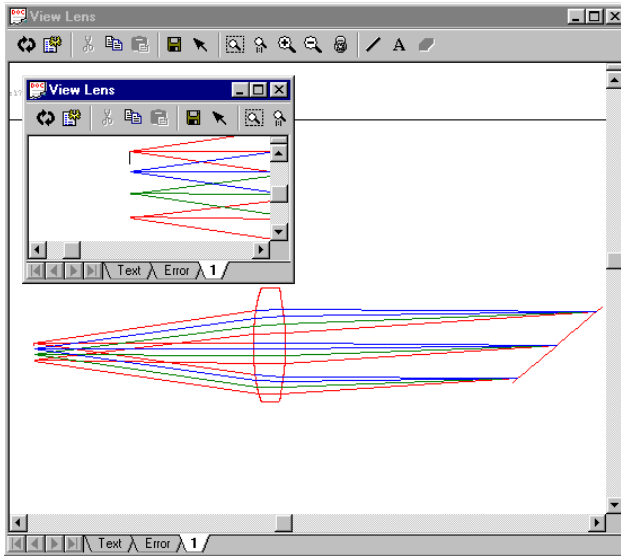
12. Click **OK** in the **Automatic Design** dialog box to re-run optimization.

The system improves but the lens is thin. You can vary the thickness of the lens (THI S1) to allow CODE V to fix this.

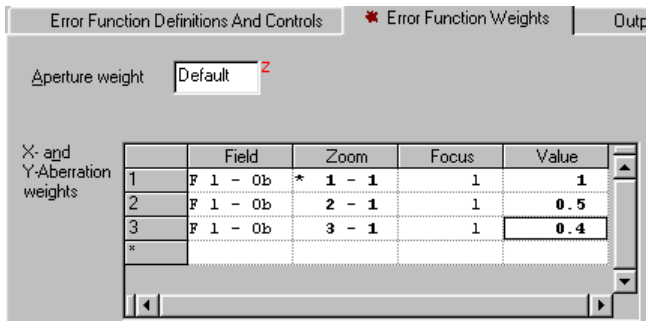
13. Choose the **Edit > Undo** menu to get the starting lens back, right-click on the LDM thickness of S1 and choose **Vary**. Right-click on Asphere S1 and choose **Surface Properties**. Make the 8th-order coefficient variable; do the same for S2 (right-click on the 8th-order coefficient and choose **Vary**).
14. Rerun AUTO by clicking the Execute button in the **Automatic Design** tabbed output window.
15. Click the Modify Settings button in the **Fiber Coupling Efficiency** tabbed output window. Go to the **Computation** tab in the CEF dialog box; then, right-click the **Focal Plane Increment** field, choose **Zoom**, and set the Focal Plane Increment for Z1..3 to **0.001**. Click **OK**.

The coupling efficiency should be around -0.2 dB for Z1, -0.16 dB for Z2, -0.09 dB for Z3, which is not perfectly balanced (look at the Text tab of the output window, scrolling to find output for each zoom position). Optimization WTF (field weights) for each zoom position may help by giving less emphasis to the “good” zoom positions.

16. Re-run VIEW (the former overlap of wavelengths is OK now; note that two separate View Lens windows are shown below).

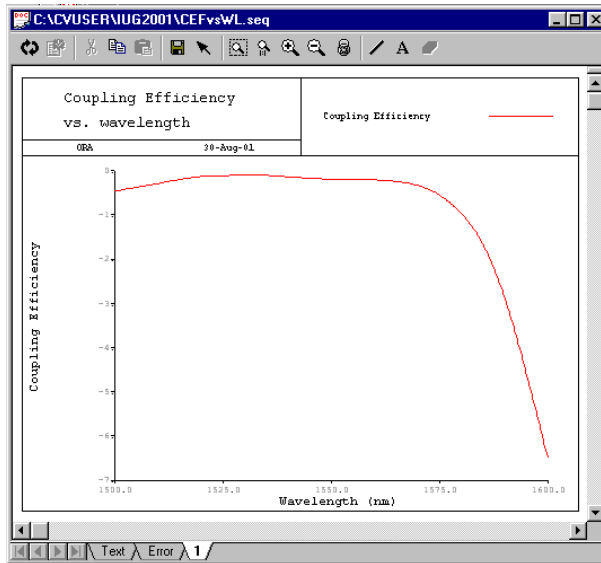


17. Rerun AUTO, changing WTF values (X- and Y-Aberration Weights) to **1.0** for Z1, **0.5** for Z2, **0.4** for Z3 (trial and error to balance CEF across colors better).



You may have to re-run the **Automatic Design** dialog box several times to get the best performance. AUTO stops when it sees little improvement, but re-running with the same settings five or six times will continue to improve the lens slightly. You can also change the settings on the **Exit Controls** tab to accept smaller improvement per cycle and to force more cycles (increase min and max cycles).

18. Re-run the **CEF_VS_WL.seq** macro (**Tools > Macro Manager** menu, or just click the Execute button if the output window is still open).



The coupling efficiency is within -0.2 dB in the 1534-1566 nm range. Further improvement may be possible, although convergence gets slow, and the dispersion properties of a single glass element will always produce chromatic aberration. Adding another glass element would likely be necessary to attain improved chromatic performance.

19. Choose the **File > Save Lens As** menu and save the optimized system under a new file name such as **DemuxZoomOpt.len**.

Chapter 4

Coupling Efficiency Calculations

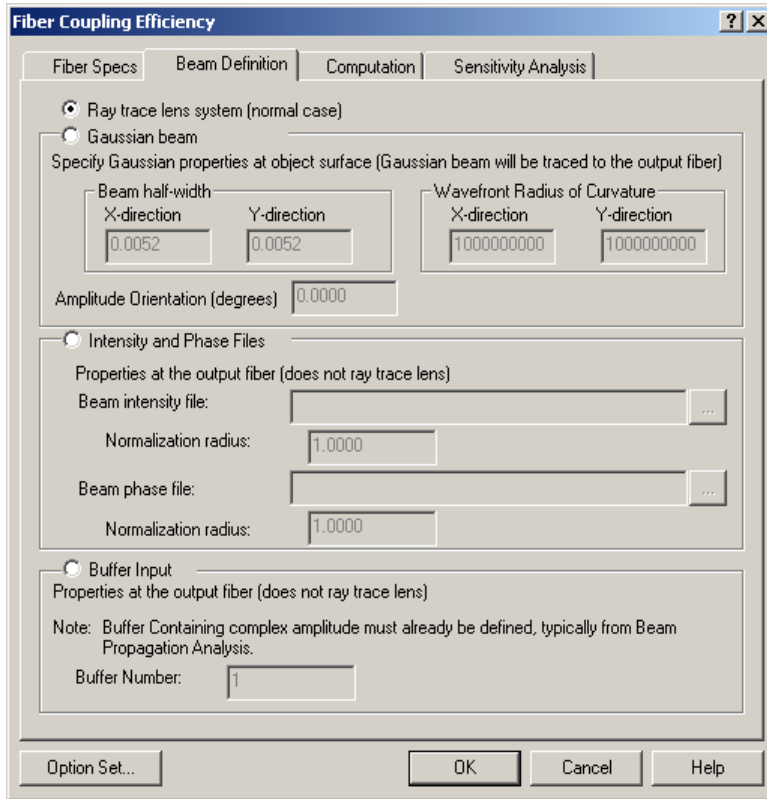
This chapter shows you how to set up a fiber optic coupler using off-the-shelf aspheric lens elements made for this purpose by Geltech. It then shows you how to compare the results of several coupling efficiency calculation methods, including beam propagation.

Contents

Methods of Calculating Coupling Efficiency	80
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Ray Trace Method: CEF Default Results.....	90
Gaussian Beam Trace Method	91
Coupling Efficiency from Beam Propagation Method	97
Conclusions	100

Methods of Calculating Coupling Efficiency

CODE V's Coupling Efficiency option (CEF) can calculate the coupling efficiency in several different ways. In each case, an amplitude and phase distribution function is placed at the image point, and the coupling efficiency is calculated as the overlap integral between this function and the mode profile of the output fiber (which is also specified in CEF and is most often a Gaussian). The method is specified on the **Beam Definition** tab of the CEF option dialog box (**Analysis > Diffraction > Fiber Coupling Efficiency** menu).



The four amplitude and phase distribution methods are as follows:

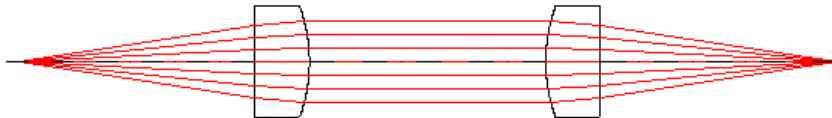
1. Ray trace the lens and determine the point spread function (PSF) at the image. This default method considers all aberrations in the system as well as the diffraction effects of apertures as mapped by ray tracing to the exit pupil of the system (the pupil function). This method can optionally include polarization effects, which may be important in some systems, especially when there are multilayer coatings.
2. Specify Gaussian beam parameters at the object surface. CEF then traces a Gaussian beam through the system to the image surface. The Gaussian beam trace is the same as that done by the BEA option (**Analysis > Diagnostics > Gaussian Beam Trace** menu), or by the supplied macro function GAUSSBEAM. These use a ray-based quasi-paraxial method to calculate beam parameters. This method considers Gaussian beam-spreading effects, but ignores all apertures as well as any aberrations other than astigmatism (see the BEA option section of the *Reference Manual* for technical notes on this calculation).
3. Specify the amplitude and phase directly as CODE V *.int* files, calculated somehow by the user (e.g., by a macro or external program of some sort). Again, CEF does not ray trace the lens itself if this method is used.
4. Calculate the amplitude and phase distribution by diffraction beam propagation (BPR option, **Analysis > Diffraction > FFT Beam Propagation** menu), and place the complex data in a *worksheet buffer* (a kind of data structure or file often used in macro programming). The CEF option can then import the beam propagation data at the image surface; this method can include the effects of diffraction at all internal surfaces and is the most accurate method for scalar calculations (BPR currently does not support polarization calculations).

We will show the ray trace, Gaussian beam, and beam propagation methods in this chapter, and see the effects of changing the air space in a nominally collimated space. But first you need to have a lens to work with.

Defining an Aspheric Coupler System

There are various ways to construct fiber optic couplers, including the simple ball lens presented in an earlier chapter. When additional components such as filters must be included, you will typically want a design that includes a collimated air space between the elements. One common solution to this design is gradient index (GRIN) elements (the final chapter of this document briefly discusses such a design, provided as a sample lens). Another approach is to use conventional spherical-surface singlets, although aspheric singlets can give much better performance.

In this section, you will construct a two-element coupler based on a Geltech catalog lens designed specifically for this purpose (completed design shown below). The Geltech catalog is not yet provided with CODE V (we plan to supply it in a future release, adding it to catalogs from Melles Griot, Newport, Edmund Scientific, and several others available through the **Edit > Insert Catalog Lens** menu). You can request more information about the Geltech catalog from LightPath Technologies (www.lightpath.com). The information needed for this particular Geltech catalog lens is provided in this section.



It's a useful exercise to set up a lens from scratch with data found in a Web or other catalog source. You can still use the New Lens Wizard for this purpose, using the steps in this section. As with the zoom section of the demux chapter, we will present the procedure in a slightly abbreviated form, without much explanation. If you did the earlier examples and follow the instructions carefully, you should have no trouble setting up this lens.



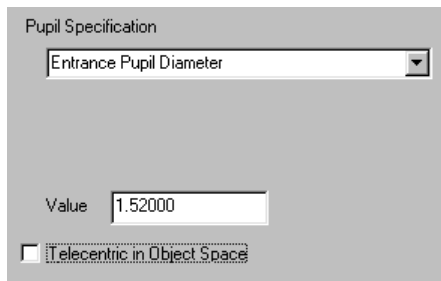
Note: This lens model is also available as a macro (.seq) file on the ORA Customer Support Web site, <http://www.oraservice.com>. Click the **CODE V Support** link on the main page, click **Macro and User-Defined Features Downloads**, and click **Photonics Macros**. The macro is called **asph_coupler.seq** and it includes the analysis results discussed in this chapter.

Lens Data

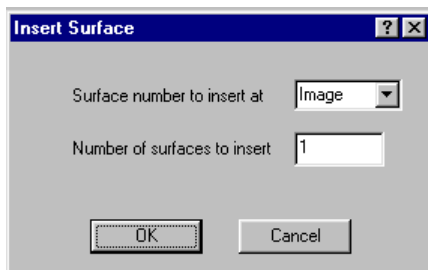
Information about the Geltech catalog is available on the LightPath Technologies Web site (<http://www.lightpath.com>). This catalog contains detailed descriptions of a number of lens elements designed for coupling applications at various wavelengths and conditions (e.g., laser to fiber as well as fiber to fiber). From this catalog, we chose the lens element 350430, a 5 mm EFL molded plano-convex asphere designed for 1550 nm. The main properties of this lens are a numerical aperture of 0.15, working distance of 4.36 mm, outside diameter of 2.0 mm (CIR EDG in CODE V), optical clear aperture diameter of 1.52 mm (CIR in CODE V). The glass is C0550, a special optical glass for molding applications. The surface data (radius of curvature, conic constant, thickness) are provided with the lens data and are listed in the setup instructions below.

Creating a Blank Lens

1. Choose the **File > New** menu to start the New Lens Wizard, click **Next** on the Welcome screen, click the **Blank Lens** button on the “Where do you want to start from?” screen, and click **Next**.
2. On the **Pupil** screen of the New Lens Wizard, keep the pupil type as **Entrance Pupil Diameter** for now, make the value **1.52** (Geltech’s specified clear aperture diameter) and click **Next**.



3. On the **Wavelengths** screen, change the single wavelength to **1550**, choose a color for plotting, and click **Next**. Then, click **Next** on the **Reference Wavelength** screen.
4. On the **Fields** screen, be sure the field type is **Object Height**, with X=0 and Y=0. Click **Next**, then click **Done** on the Congratulations screen.
5. In the LDM spreadsheet window, right-click the **Image** surface (click in the **Surface #** column) and choose **Insert** from the shortcut menu. In the **Insert Surface** dialog box, click **OK** to accept the default (inserting one surface).



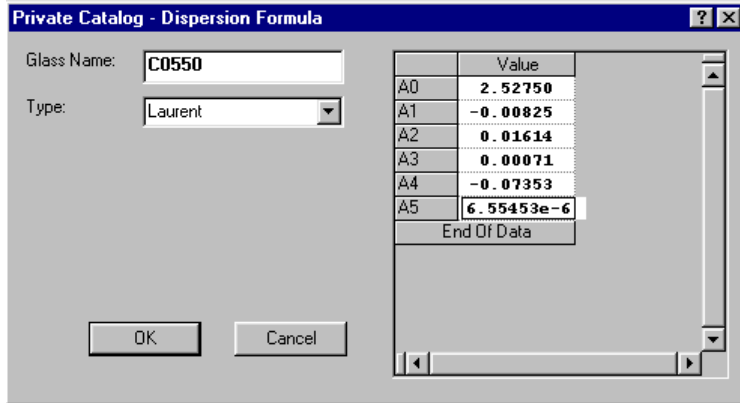
Defining the Glass and the Surfaces

The glass used for this aspheric lens element is called C0550, which is a glass with a relatively low melting point that works well in molding applications. The index of refraction as a function of wavelength is commonly defined by an equation called the Laurent Formula, and Geltech has supplied the coefficients for this material, shown in the table below, which can be used in CODE V to define a *private catalog* glass that is part of the lens data.

C0550					
A0 = 2.5275	A1 = -8.24759e-3	A2 = 1.61384e-2	A3 = 7.10762e-4	A4 = -7.35332e-5	A5 = 6.55454e-6

To define the glass and surfaces:

1. Choose the **Lens > Add Private Catalog Glass > Dispersion Formula** menu, and in the **Private Catalog** dialog box, type the name **C0550** (upper case C), accept the default type **Laurent**, and type the values for the six Laurent coefficients from the previous table. Check the values carefully (watch signs!), then click **OK**.

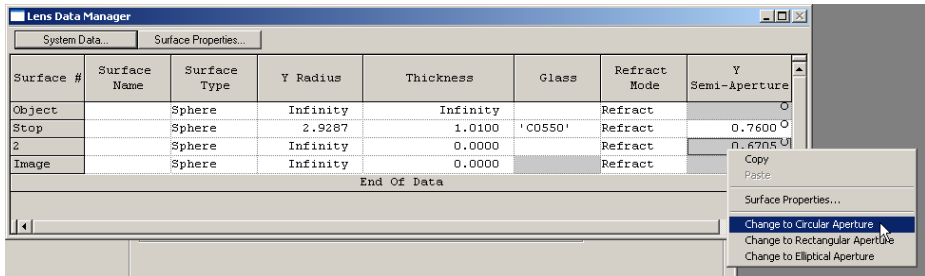


2. In the LDM spreadsheet, on surface 1 (stop surface), enter **2.928699** for radius, **1.01** for thickness, and **"C0550"** for glass (you must type the glass name in quotes, either single or double). Right-click on **Y Semi-Aperture** and choose **Change to Circular Aperture**, then enter **0.76** for the value (this is 1.52/2). (If you prefer aperture diameters to semi-diameters you can select the aperture diameter preference with the **Edit > Semi-Aperture Mode** menu.)

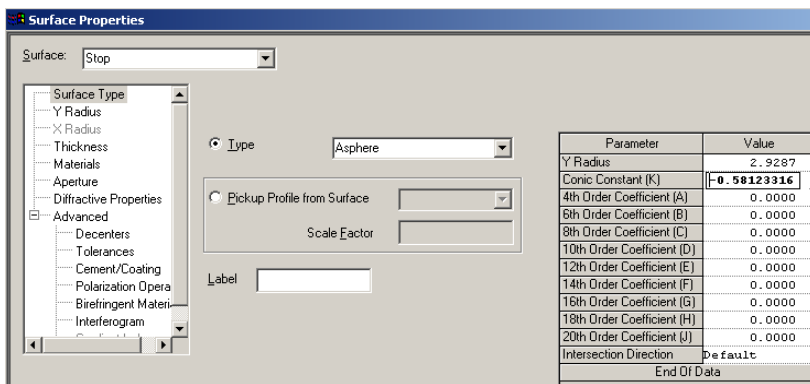


Note: Geltech also lists an outside diameter value of 2.0 mm, which corresponds to CODE V's edge (EDG) aperture. You could define an edge aperture in addition to the optical clear aperture on each surface, but this would mainly affect the lens drawing. Edge apertures do not affect ray tracing results in sequential lens models.

- On surface 2, or the back surface of the lens, right-click on **Y Semi-Aperture** and choose **Change to Circular Aperture**, then enter **0.76** for the value.



- Right-click on the surface type (Sphere) for surface 1 and choose **Surface Properties**. On the **Surface Type** page in the Surface Properties window, change the type to **Asphere** and click any other field to commit this change. Change the **Conic Constant (K)** value to **-0.58123316** and click any other field. You can then close the Surface Properties window (click the close box X in the upper right corner).

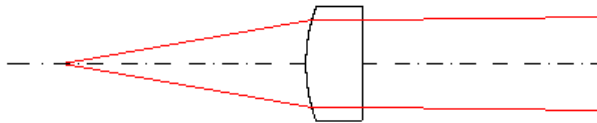


Back in the LDM spreadsheet, you need to determine the paraxial image distance and set the object distance to match this. The quickest way to do this is to define a paraxial image solve, delete the solve once the value is determined, then copy that value to the object thickness field.

- Right-click on thickness of surface 2 and choose **Solve**. In the **Thickness Solve Editor**, change the type to **Paraxial Image Distance Solve** and click **OK**. Right-click on the value (approximately 4.36) and choose **Copy**, then right-click the same cell again and choose **Delete Solve**. Finally, right-click on the thickness of the object surface and choose **Paste**.

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	4.3632		Refract	
Stop		Asphere	2.9287	1.0100	'CO550'	Refract	0.7600
2		Sphere	Infinity	4.3632		Refract	0.7600
Image		Sphere	Infinity	0.0000		Refract	0.8257
End Of Data							

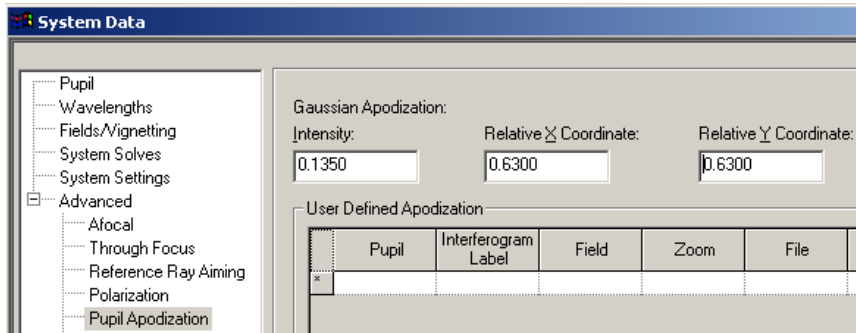
The LDM data should be as shown above, and if you choose the **Display > View Lens** menu, change the starting surface to **Object**, and click **OK**, you should get a picture like the following.



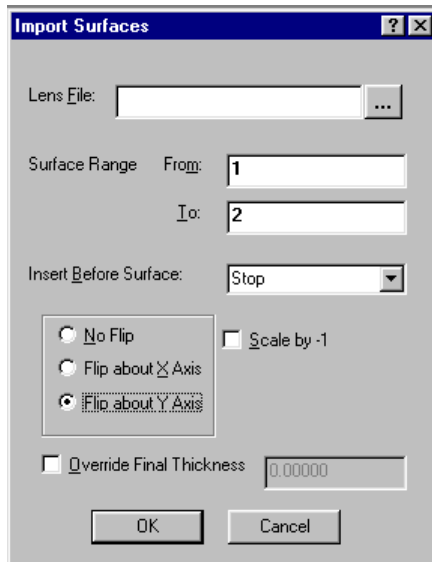
Setting Up Fiber Input and the Second Lens Element

Now that the lens has a finite object distance, you can define the numerical aperture on the object side (NAO) and input fiber intensity, just like the earlier examples in this guide. The lens element is facing the wrong way at the moment, but you will soon insert a flipped copy of it to complete the two-element coupler.

- Choose the **Lens > System Data** menu, and on the **Pupil** page, change the **Pupil Specification** to **Object Numerical Aperture** and the Value to **0.15**.
- On the **System Settings** page, change the **Title** to **Coupler from Geltech 350430 Asphere**.
- On the **Pupil Apodization** page, enter **0.135** for Intensity, and enter **0.63** for X and Y (this is 0.09488/0.15 as explained in the demux chapter, for the same mode radius and wavelength and a slightly larger NAO).



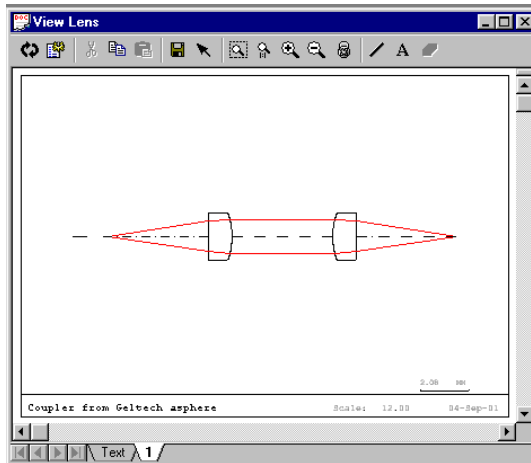
- In the LDM spreadsheet, select the Stop surface row and choose the **Edit > Import Surfaces** menu. In the **Import Surfaces** dialog box, enter the surface range from **1** to **2**, be sure that the **Insert Before Surface** is set to **Stop**, select the **Flip About Y Axis** button, then click **OK**.



The imported surface in this case is from the current lens file (the lens you are working with). This will insert a flipped copy of first element (s1..2) in front of the stop. The LDM spreadsheet will look like the following:

Lens Data Manager							
System Data...		Surface Properties...					
Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	4.3632		Refract	0
1		Sphere	Infinity	1.0100	'CO550'	Refract	0.7600
2		Asphere	-2.9287	4.3632		Refract	0.7600
Stop		Asphere	2.9287	1.0100	'CO550'	Refract	0.7600
4		Sphere	Infinity	4.3632		Refract	0.7600
Image		Sphere	Infinity	0.0000		Refract	0.0000
End Of Data							

- Click the Execute (re-calculate) button in the **View Lens** window to see the completed lens.



- Choose the **File > Lens Save As** menu and save this under a suitable name, such as **asph_coupler.len**

Ray Trace Method: CEF Default Results

Now that you have set up the lens system, you can start with the ray trace method for calculating coupling efficiency. In the ray trace method, CEF ray traces the system to determine the diffraction PSF which it can then combine with the fiber mode data to calculate the coupling efficiency. This method was demonstrated in the earlier chapters in this guide that discuss the ball lens and demux system, so we will just review the steps here without screen pictures.

1. In the **System Data** window (**Lens** menu), on the **Fiber Location** page, use the default values. Be sure that the **Location** is **Fixed** at (0,0,0) for all fields, zooms, and wavelengths (this is the default).
2. Choose the **Analysis > Diffraction > Fiber Coupling Efficiency** menu. The **Fiber Coupling Efficiency** dialog box is displayed.
3. On the **Fiber Specs** tab, change the Gaussian mode radius to **0.0052**.
4. On the **Beam Definition** tab, be sure that **Ray trace lens system** is selected (default).
5. On the **Computation** tab, select the **Decibel Scale** checkbox.
6. No inputs are needed on the **Sensitivity Analysis** tab.
7. Click **OK** to run CEF.

You can now change the thickness of surface 2 in the **Lens Data Manager** window and click the Execute/Recalculate button in the **Fiber Coupling Efficiency** window to update the CEF results. You will find that the insertion loss from CEF's default calculation is very close to **-0.049 dB** no matter what value you set for the separation between the elements.

But is this the right answer? For small separations between the elements, it is probably very close, but as the beam propagates over longer distances, it actually spreads out, while the rays in this calculation stay almost perfectly parallel (collimated). You can see this with the Gaussian Beam Trace option.

Gaussian Beam Trace Method

Another method for calculating coupling efficiency is the Gaussian beam trace method. It is based on real ray tracing, but only the chief ray and a few nearby differential rays are traced in order to determine matrix elements for calculating Gaussian beam parameters at each surface. This “quasi-paraxial” procedure ignores all apertures and also ignores aberrations other than astigmatism. It does take into account beam sizes and wavefront radii of curvature, both of which can be different in x and y. The Gaussian Beam Trace option (BEA) traces and displays the beam data, while the Coupling Efficiency option (CEF) performs the same calculation, but only uses the image surface value.

Running Gaussian Beam Trace (BEA)

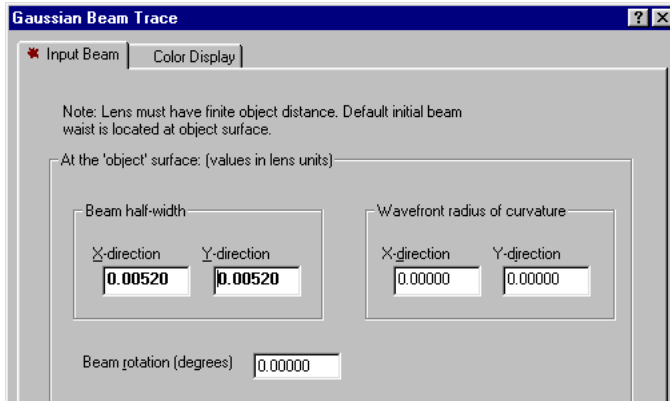
The Gaussian Beam Trace option can give you useful diagnostic information about beams in photonics systems. It can also help you visualize the Gaussian beams with shaded depictions of the beams superimposed on a lens picture.

1. In the LDM spreadsheet, make sure the lens has its original thickness value for surface 2 (4.3632 mm).
2. Choose the **Analysis > Diagnostics > Gaussian Beam Trace** menu.
3. Enter **0.0052** for both the X and Y beam half-width.



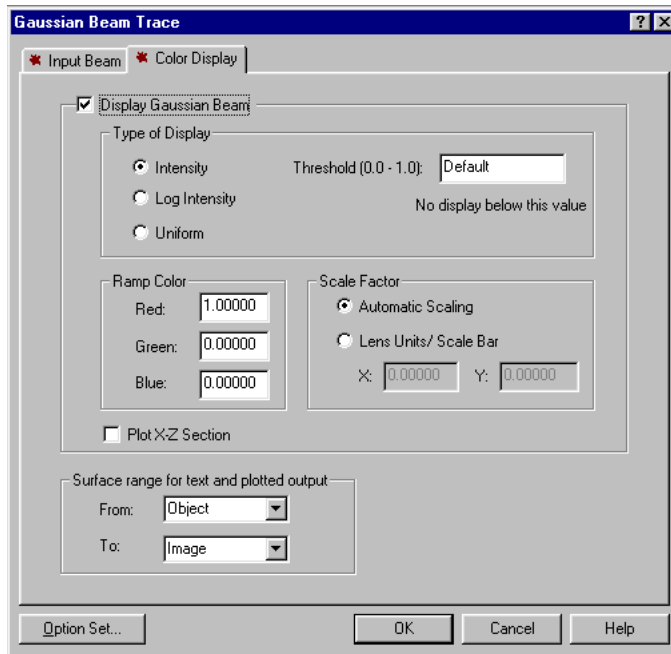
Note: Entering this value for both the X and Y beam half-width is not required, since CODE V by default assumes symmetry.

This defines the beam at the object (input fiber end point), and since this position is a beam waist, the wavefront is flat (radii of curvature set to zero as a shorthand way to define a flat wavefront, which is the default).



4. On the **Color Display** tab, click the **Display Gaussian Beam** checkbox, and do not make any changes to the other settings.

Note that for very long systems, separate scale factors can be set for X and Y directions.



5. Click **OK**.

The output (see the following figures) shows that the beam radius on the image surface is also 0.0052 mm, and that this is also a beam waist (beam waist distance is nearly zero). The wavefront radius at the image is -4.4352 mm.

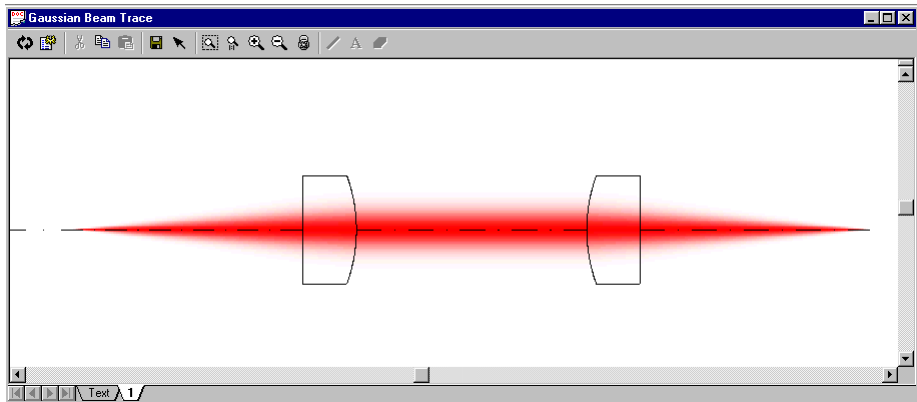
Gaussian Beam Trace

GAUSSIAN BEAM PROPAGATION

Coupler from Geltech 350430 asphere

WAVELENGTH = 1550.0 NM DIMENSIONS = MILLIMETERS FIELD POSITION = (0.00, 0.00)

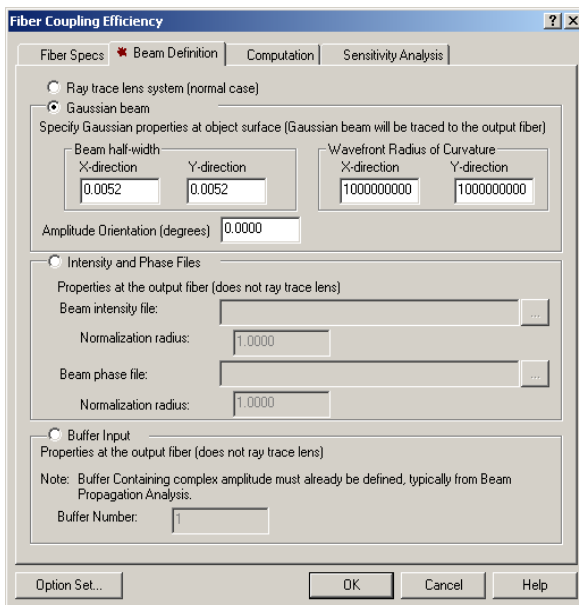
SUR	PROPAGATION DISTANCE TO NEXT SURFACE	BEAM RADIUS ON SURFACE		BEAM ORIENTATION (DEGREES)	WAVEFRONT RADIUS OF CURVATURE BEFORE REFRACTION		PHASE ORIENTATION (DEGREES)	WAIST RADIUS BEFORE REFRACTION		DISTANCE FROM WAIST TO SURFACE	
		X	Y		X	Y		X	Y	X	Y
OBJ	4.3632	0.0052	0.0052	0.0	INF	INF	0.0	0.0052	0.0052	0.0000	0.0000
1	1.0100	0.4140	0.4140	0.0	-4.3639	-4.3639	0.0	0.0052	0.0052	4.3632	4.3632
2	4.3632	0.4744	0.4744	0.0	-7.9298	-7.9298	0.0	0.0052	0.0052	7.9288	7.9288
3	1.0100	0.4744	0.4744	0.0	32672.6431326726.431	32672.6431	0.0	0.4744	0.4744	-0.6369	-0.6369
4	4.3632	0.4140	0.4140	0.0	6.9189	6.9189	0.0	0.0052	0.0052	-6.9178	-6.9178
5	0.0000	0.0052	0.0052	0.0	-4.4352	-4.4352	0.0	0.0052	0.0052	0.0007	0.0007
IMG		0.0052	0.0052	0.0	-4.4352	-4.4352	0.0	0.0052	0.0052	0.0007	0.0007



Running CEF with Gaussian Beam Inputs

1. Choose the **Analysis > Diffraction > Fiber Coupling Efficiency** menu.
2. In the **Fiber Coupling Efficiency** dialog box on the **Fiber Specs** tab, set the Gaussian mode radius again to **0.0052**
3. On the **Beam Definition** tab, click the **Gaussian Beam** button.

4. Enter **0.0052** for both X and Y beam half-widths on the object surface, just as you did in the Gaussian Beam Trace option.



5. On the **Computation** tab, select the **Decibel Scale** button.
6. Click **OK**.

The insertion loss for this case is -0.0002 dB (essentially zero). This represents an idealized case of no clipping and no aberration. The element separation is small, so there is not much beam spreading. With these factors and with the beam radius and mode radius both equal to 0.0052 mm, you could expect nearly perfect coupling efficiency. But what happens with larger separations?

7. In the LDM spreadsheet, change thickness of surface 2 to **100**.

- Click the Execute button in the **Fiber Coupling Efficiency** window.

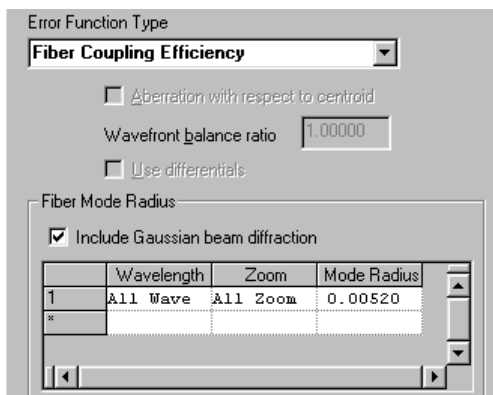
The new insertion loss value is -0.041 dB. Repeat steps 7 and 8 for 200 mm and 300 mm separations and you will find the following results. These results are due only to beam spreading -- aperture clipping and aberration will also affect the results, but this is a good approximation for a lens that has little clipping and aberration. To see the effects of beam clipping, aberration **and** beam spreading, you need BPR.

Separation, in mm	Gaussian Beam Insertion Loss
4.3632	-0.0002 dB
100	-0.0417 dB
200	-0.1831 dB
300	-0.4159 dB

Gaussian Effects in Optimization

You can also include Gaussian beam-spreading effects when you optimize the coupling efficiency in Automatic Design. For example, if you know that the aspheric coupler will actually be used at 300 mm separation, you would like to find a focal distance (lens to output fiber) to provide better coupling than the -0.4 dB shown above.

- Make sure the air space is 300 mm (surface 2 thickness), then, in the LDM spreadsheet, right-click on the thickness of the Image and choose **Vary** from the shortcut menu (this is the defocus variable).
- Choose the **Optimization > Automatic Design** menu and change the **Error Function Type** to **Fiber Coupling Efficiency**. Confirm that the **Fiber Mode Radius** value is 0.0052 mm (the default), and also check the **Include Gaussian beam diffraction** box as shown below.



3. Click **OK** to run the optimization.

The focal shift should be about 0.025 mm. If you now re-run the Fiber Coupling Efficiency calculation, you will see a coupling efficiency of about -0.12 dB. If you try this without checking the **Include Gaussian beam diffraction** box in optimization (reset the defocus to zero first), you will find only a slight improvement. This capability is useful whenever there are long propagation distances where beam spreading is an important effect.



Note: It may be more accurate to maintain symmetry between the input and output distances. To simulate this, freeze the image surface defocus (in the LDM spreadsheet, right-click and choose **Freeze**) and set it back to zero. Right-click on thickness 4 (the 4.3632 value) and choose **Pickup**, changing the pickup Surface to **Object**. Then, right-click on the object surface thickness and choose **Vary**. Re-run Automatic Design as described above. The new thickness value will be about 4.383, a shift of about 0.02 mm of both input and output fibers, and the Gaussian coupling efficiency will be -0.0002 dB, essentially perfect.

Coupling Efficiency from Beam Propagation Method

We presented the method for saving BPR data in a buffer for use in CEF calculations in Chapter 2. Rather than repeat the explanation here, we will briefly summarize the steps without screen pictures. Please see Chapter 2 for more details on the procedure.

Calculating the Beam Propagation Results

1. In the LDM spreadsheet window, make sure the thickness of surface 2 is reset to the original value, **4.3632** mm.
2. In the **Command Window**, enter the command **BUF DEL B1** to delete any previous contents of this buffer.



Note: A useful macro for this step, **BUFDEL.seq**, is available in the **Macro** dialog box, under **Sample Macros - Utilities**. By applying the macro to your toolbar, you will not have to remember the commands.

You will need to do this each time you run BPR, since BPR appends its data to the specified buffer rather than replacing it.

3. Choose the **Analysis > Diffraction > FFT Beam Propagation** menu.
4. On the **Computation** tab, change **Start Surface** to **Object** (End Surface should be **Image**).
5. On the **Input Beam** tab, select **Gaussian Beam** and change the beam half-width to **0.0052** for both X and Y.
6. On the **Output Controls** tab, change **Worksheet Buffer Output Quantity** to **Complex Amplitude**, and set buffer number to **1** (or other if buffer 1 is in use).
7. Click **OK**.

Importing BPR Results into CEF

1. Choose the **Analysis > Diffraction > Fiber Coupling Efficiency** menu. The **Fiber Coupling Efficiency** dialog box is displayed.
2. On the **Fiber Specs** tab, change Gaussian mode radius to **0.0052**.
3. On the **Beam Definition** tab, click **Buffer Input** and be sure the buffer number is **1** (or the value you used in BPR).
4. On the **Computation** tab, select the **Decibel Scale** checkbox.



Tip: When you import buffer data from BPR to CEF, you should not change FFT grid size or other grid parameters in CEF—these values are determined from the BPR data in the imported buffer.

5. Click **OK**.
6. If you repeat the above procedure for various separation values, you will find results as shown in the table below.

Separation, in mm	BPR Insertion Loss
4.3632	-.06270 dB
100	-.09222 dB
200	-.1649 dB*
300	-.3157 dB

* The automatic propagation method changes at 200 mm in this case, from far field to near field, causing a slight change in numbers. To get the result shown, the propagation method was changed to far field on surface 2..3 (DBP FFP S2..3). See “BPR - Diffraction-Based Beam Propagation” on page 19-37 in the *CODE V Reference Manual* for information on how propagators are chosen.

Assessing the Effect of Aperture Clipping

In the table below, we have repeated the BPR Insertion Loss column from the above table, and added two additional columns. The third column is calculated by the BPR-to-CEF procedure with oversized apertures (aperture radius of 1.5 mm on each surface, larger than the real lens in order to prevent any clipping by the apertures). The fourth column is repeated from the Gaussian Beam discussion above—this is the result of importing Gaussian Beam parameters into CEF, with no aperture or aberration information.

Separation, in mm	BPR Insertion Loss (True Apertures)	BPR Insertion Loss (Oversize Apertures)	Gaussian Beam Insertion Loss
4.3632	-.0627 dB	-.00149 dB	-0.0002 dB
100	-.092 dB	-.047 dB	-0.041 dB
200	-.165 dB *	-.184 dB	-0.183 dB
300	-.316 dB	-.418 dB	-0.416 dB

* See the table footnote on page 98 for details about this propagation result.

What does this table tell us? With the exception of the short 4.6 mm separation, the correlation between the oversize aperture BPR case and the Gaussian beam case is extremely good. BPR results for each value in this case show final **Fraction of Starting Energy** of **1.0**, which indicates that there is no aperture clipping. Since the lens is well corrected for spherical aberration (the only aberration in this on-axis monochromatic system), beam spreading should dominate. The short-separation case is really not inconsistent with this, since -0.001494 dB insertion loss represents 99.97% coupling efficiency, pretty close to 100%.

What about the first BPR column? This should be the most accurate calculation since it includes aperture clipping. Note that aperture clipping hurts you for the shorter separations, but actually improves the insertion loss in the 200 and 300 mm cases compared to the no-clipping calculation. This shows that the effects of beam spreading, aberrations, and aperture clipping interact in complex ways.

Energy Considerations

When CEF reports a coupling efficiency of 0.98, it is reporting that 98% of the light incident on the **output** fiber is coupled into it. This says nothing about the efficiency with respect to the light input to the optical system.

One factor to consider when using BPR is the **Fraction of Starting Energy** value reported at each surface. This number reflects energy lost due to aperture clipping in the optical system, but it does not include all losses.

The Transmission Analysis option (TRA, **Analysis > System > Transmission Analysis** menu) includes surface losses (with or without coatings) as well as bulk transmission losses. For example, you can use the **Surface Properties** window to assign the glass characteristics of Schott SK2 to the “C0550” glass in this example, in order to define absorption properties (SK2 is close in index at 1550 nm but may not perform at all like C0550—this is just an illustrative example). Then, if you

choose the **Analysis > System > Transmission Analysis** menu and click **OK**, you will find an average transmittance of 0.9661, which would directly multiply the (non-dB) coupling efficiency to estimate efficiency with respect to the input fiber.

Polarization

BPR does not include polarization effects, while the default (PSF) calculation of CEF does include them if you turn on polarization ray tracing (POL YES or **Lens > Activate Polarization Ray Tracing** menu). The Transmission Analysis option includes polarization effects in all cases, since this is needed to evaluate coating effects on transmission. If the main reason you would like polarization is for transmission calculation, the best combination is to use BPR and CEF for coupling efficiency, with TRA to calculate the transmission of the system up to the output fiber.

If polarization is more fundamental (such as isolators that use birefringent crystals and Faraday rotators), then you cannot use BPR. In these instances, you must use CEF with POL YES, which will be reasonably accurate as long as there are no long free-space separations or multiple small clipping apertures.

Conclusions

Coupling efficiency, or insertion loss, is a vital calculation for telecom systems. CODE V provides the tools to do a good job, but you must understand the interactions and limitations of the various components, especially the Beam Propagation and Fiber Coupling Efficiency (CEF) options. The following summarizes the coupling efficiency methods available in CODE V, along with their characteristics. These methods are defined in the **Fiber Coupling Efficiency** dialog box (**Analysis > Diffraction** menu), on the **Beam Definition** tab.

Ray Trace Lens System (with polarization ray trace inactive)

Point source approximation. CEF is calculated by overlap integral of PSF with output fiber mode profile. Does not include diffraction effects from clipping at multiple apertures, polarization effects, optical transmission, and truncation of beam.

Ray Trace Lens System (with polarization ray trace active)

Point source approximation. CEF is calculated by overlap integral of PSF with output fiber mode profile. Does not include diffraction effects from clipping at multiple apertures. Does include polarization effects, optical transmission (excluding bulk absorption) and truncation of the beam.

Gaussian Beam Trace

Diagnostic tool to allow users to calculate coupling efficiency if a beam with specified characteristics (on object surface) were traced to the output fiber. CEF does this Gaussian beam trace internally. The Gaussian Beam Trace option (BEA) is often used to view specified Gaussian beam characteristics. It does not include clipping or aberrations other than astigmatism.

Buffer Input (complex amplitude from Beam Propagation)

A rigorous Gaussian beam propagation that includes the finite source size (no point source approximation), diffraction effects of multiple apertures, and lens aberrations. Insertion loss is calculated by the overlap integral of the complex amplitude of the beam (generated in Beam Propagation) with the mode profile of the output fiber. Beam Propagation is the most accurate method of calculating insertion loss in CODE V. Transmission effects including truncation (see BPR output), bulk absorption, and surface reflections are **not** included in the insertion loss calculation and must be calculated and added separately. Additionally, polarization effects are not currently handled by Beam Propagation.

Chapter 5

Other Examples

This chapter shows other examples of photonics systems with brief explanations. Three of the examples are based on lens files supplied with CODE V. The fourth example is a multilayer coating for WDM applications, provided in command form.

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GRIN Lens Coupler

This example shows how to use catalog GRIN (gradient index) materials from NSG (<http://www.nsgamerica.com>) to set up a simple collimator followed by an identical element that re-focuses the light on a fiber. This is a common coupler configuration, and is similar in most respects to the aspheric coupler shown in the previous chapter.



To access the CODE V model for this system:

1. Choose the **File > Open** menu, and browse the **lens** subdirectory of the CODE V installation directory.

This will be something like C:\CODEV9xx\lens in a default installation.

2. Select the file **grincoupler.len** and click the **Open** button.

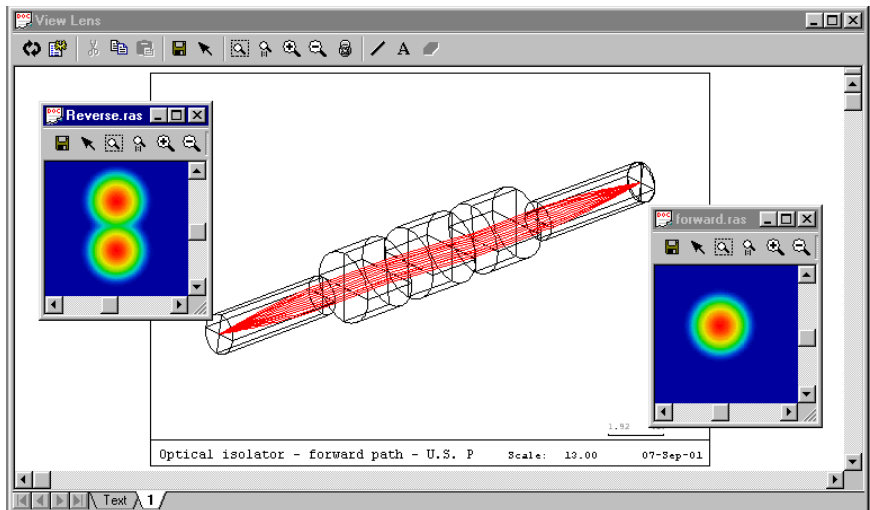
Things to Note

1. The lengths of the GRIN elements are kept equal by a pickup on the thickness of surface 3.
2. The lengths have been optimized for coupling efficiency, and are slightly different from the 4.80 mm quarter-pitch length listed for the SLW18 at 1300 nm element on NSG's Web site (<http://www.nsgamerica.com/technology/microlens.cfm>). In practice, you would probably optimize the input fiber position rather than the lens length.
3. The SLW18 name designates a diameter of 1.8 mm, although the optical clear aperture is smaller than this (0.5 mm aperture radius is defined in the lens model). If you want to also model the mechanical size, you can define additional EDGE apertures on the surfaces (e.g., CIR s1 EDG 0.9).
4. There are some important restrictions in using BPR (beam propagation) with GRIN systems. Specifically, ray tracing must be used in spaces containing a GRIN material. Diffraction beam propagation (DBP) can be used for the non-GRIN air spaces, but care must be taken to prevent conversion between wavefront and ray representations near a focus. See Appendix A for a discussion of this and other issues for GRIN modeling. Non-BPR coupling

efficiency (CEF with ray tracing) can be used on GRIN systems without restrictions, but you must be careful of large air spaces as discussed in the last chapter, since Gaussian beam spreading is not modeled by the default CEF calculation.

Optical Isolator

The optical isolator shown below includes GRIN lenses, tilted surfaces, birefringent crystals, and a Faraday rotator. Its performance as an isolator depends on polarization and is determined by the size and position of the focused Gaussian beam coupled into the output fiber. Note that because it depends on polarization, this device cannot be analyzed with the BPR (beam propagation) option.



This model uses birefringent crystals and a 45° Faraday rotator to control the polarization state of forward and back-reflected beams. The crystal axes are set to -22.5° and $+22.5^\circ$ for the forward direction. This orientation works with the sandwiched Faraday rotator's orientation, so that forward beams are passed with good efficiency (lower right PSF inset). When the reverse beam is traced, the polarization state is rotated so that the beam is split by the second crystal and little energy is coupled to the center (upper left PSF). This principle is used in various devices, but our sample is modeled after U.S. Pat. 5,208,876 (E-tek Dynamics).

To access the CODE V model for this system:

1. Choose the **File > Open** menu, and browse the **lens** subdirectory of the CODE V installation directory.

This will be something like C:\CODEV9xx\lens in a default installation.

2. Select the file **optiso.len** and click the **Open** button.

Things to Note

1. This system uses the same SLW18 GRIN material as the first example in this chapter, but the elements have 8° alpha (ADE) tilts on the fiber-interface ends. This wedge angle helps to minimize back reflections.
2. The crystal and Faraday rotator materials are defined as Private Catalog glasses (choose the **Display > List Lens Data > Private Catalog** menu to see the index data).
3. Birefringent materials have directional index of refraction data, with two index values (n_o and n_e) and a crystal axis direction that determine the paths of polarized light rays. The delta-index and crystal axis direction are defined in the **Surface Properties** window, **Polarization** page for surfaces with birefringent materials.
4. The Faraday Rotator is one of three ideal “polarization operators” that can be attached to a surface (the others are linear polarizers and retarders). See the *CODE V Reference Manual* for more information on polarization issues.

Reversing the Lens

Although this model can be used to model both the forward and reverse beam paths, the lens is not actually traced backwards. Instead, you must modify the crystal axis directions of the birefringent crystals to simulate what the beam “sees” in traversing the system in each direction.

The supplied lens is set up for the forward simulation. Here is the procedure to analyze and reverse it.

1. Confirm that the menu item **Lens > Activate Polarization Ray Tracing** has a check mark next to it.
2. Choose the **Analysis > Diffraction > Point Spread Function** menu, and on the **Normalization** tab, select **Decibels** as the PSF output mode. Then, on the **Color Display** tab, select the **Color Display** checkbox. Click **OK**.

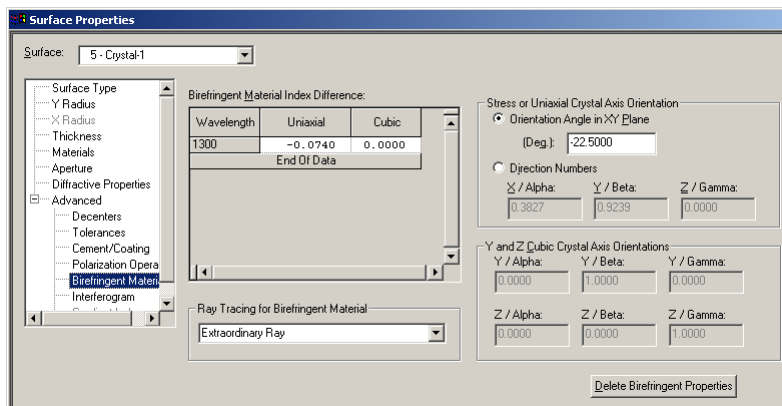
You should get a single circular PSF distribution (you can suppress the list and PSF Plot displays on the **Output Controls** tab if you wish, or just ignore them).

This circular beam is right on the Z axis and will give fairly good coupling efficiency.

3. Choose the **Analysis > Diffraction > Fiber Coupling Efficiency** menu and set the Gaussian mode radius to **0.005** mm, choose **Decibel Scale** on the **Computation** tab, and click **OK**.

You should get about -0.62 dB.

4. In the LDM window, right-click on surface 5 “Crystal-1,” choose **Surface Properties** from the shortcut menu, and select the **Birefringent Materials** page.



5. Change the Crystal Axis Orientation Angle to **+22.5** degrees (i.e., change its sign)
6. Use the surface selector to go to Surface 10 “Crystal-2” and change the Crystal Axis Orientation Angle to **-22.5** degrees (i.e., change its sign as well).

Note that by changing the signs of the crystal axis for the two birefringent crystals, you are simulating the situation that the reverse beam sees (plus, then minus) which is opposite the forward case (minus, then plus).

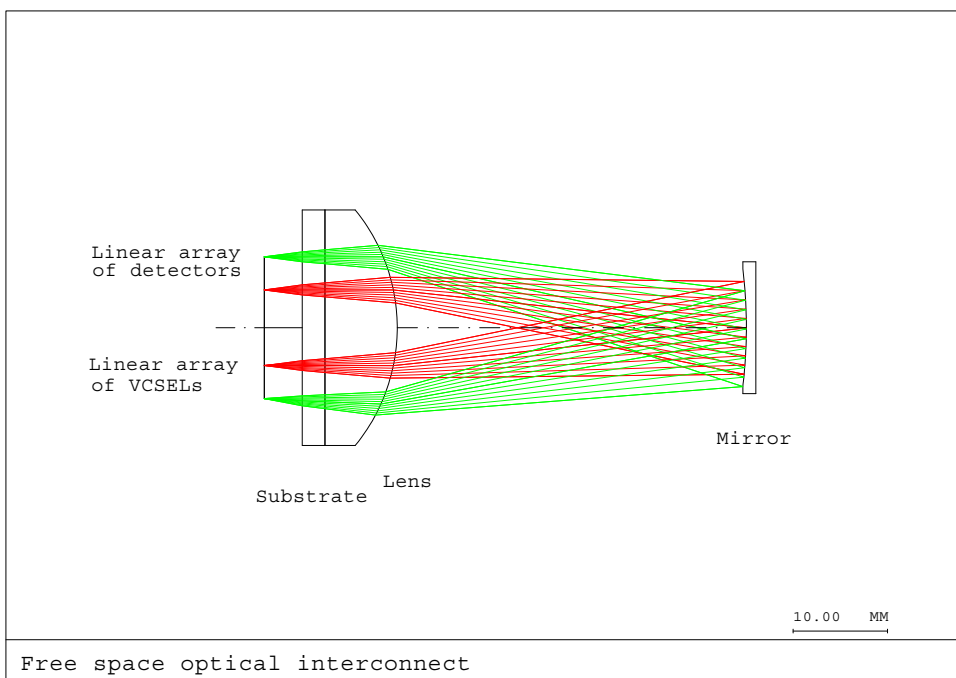
7. Click the Execute/Recalculate buttons in the **Point Spread Function** and **Fiber Coupling Efficiency** output windows to re-run the calculations.

You should see the split PSF as shown above, and the coupling efficiency should be around -18.5 dB. Note that with polarization, the CEF output includes additional information on polarization contrast and loss, so the coupling efficiency value will **not** be the last dB item in the text output (check the labels on the output to make sure you are using the right values). You may want to change the lens title to include REVERSE and save the lens in a separate file name such as optisoREV.len, to avoid confusion.

Note that the reverse direction insertion loss of -18.5 dB assumes that 100% of the energy is reflected from the output fiber. In reality, a typical Fresnel reflection from this fiber would be only about 4%, so total insertion loss in the reverse direction is -33.5 dB.

Free Space Optical Interconnect

This example is modeled after a design by Zheng, Marchand et al in Appl. Opt., 38, 5632 (1999) for optical computing applications. The source is a linear array of 12 VCSELs operating at 850 nm on one side of the optical axis. The receiver is a linear array of 12 detectors on the other side of the axis. The detectors are 80 microns square.



To access the CODE V model for this system:

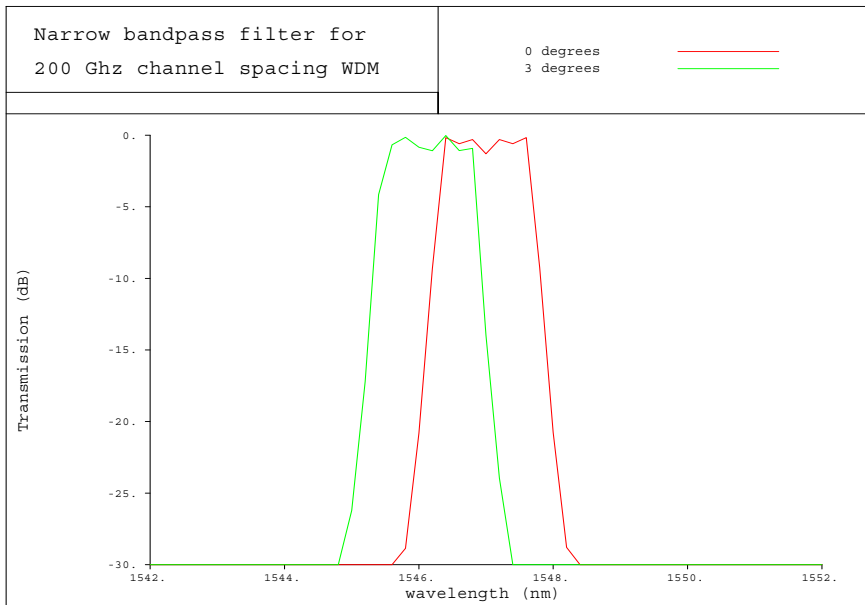
1. Choose the **File > Open** menu and browse the **lens** subdirectory of the CODE V installation directory.
2. Select the file **optinterconnect.len** and click the **Open** button.

Things to Note

1. The lens model is set up as a sequential double-pass system with pickups to link together identical surfaces.
2. The telecentric flag (TEL YES, found on the **Pupil** page of the **System Data** window; **Lens > System Data** menu) is used to keep the entering chief rays from all fields parallel to the Z axis.
3. Although VCSEL's are specified, there is no special model for these in CODE V—they are represented simply as object points with proper positioning (System Data). Similar to fibers, lasers have an output intensity distribution that is approximately Gaussian, and this is modeled with Pupil Apodization. Some lasers have significant inherent astigmatism, and this can be modeled with the Astigmatic Object feature, also found under System Data (not used in this example).

WDM Multilayer Coating

The figure below is the spectral transmission of a narrow bandpass filter for 200 GHz channel spacing WDM. It is a many-layer stack with high and low index materials of Ta_2O_5 and SiO_2 , respectively. Results are shown for normal incidence (this dB plot was created with the User Graphics option, UGR). The shift of the bandpass with respect to angle of incidence is about .2 nm/degree. This analysis was based on a design description in “High-Performance Filters for Dense Wavelength Division Multiplex Fiber Optic Communications,” by J. J. Pan of E-tek Dynamics, Inc. (subsequently acquired by JDS Uniphase Corporation; see <http://www.jdsu.com>).



Note: The Multilayer Coating option (MUL) is not available in the GUI; it must be run on the command line (Command Window) or as a macro. A macro to set up this filter (**wdmfilter.seq**) and another to attach it to a tunable filter lens model (**tunable_filter.seq**) are available on ORA’s Customer Support Web site, <http://www.oraservice.com>. Click the **CODE V Support** link on the main page and click on the **Macro Downloads** link.

The command sequence that follows runs the CODE V MUL option to create a narrow-band (wavelength selective) WDM filter of known prescription (i.e., we are simply entering known coating parameters, not designing the coating to a specific target, though MUL also has this capability). The MUL option can analyze the reflectance and transmittance properties of such coatings, independent of any lens

or optical system. If you save such a coating as a file, you can also attach the coating to a surface of a CODE V optical system model, in order to include the effects of the coating on transmission, polarization, and diffraction performance (including coupling efficiency).

In this model, we use macro variables to enter the index of refraction of the high-index (^h) and low-index materials (^l), making it easy to change later. Since coatings typically have repetitive structures, we also define several groups (GRO) of coating layers, giving each group a letter name. Defining a group of layers both enters the layers AND defines the letter name for later re-entry by name alone. The individual coating layers are defined with a COA command, which has the following format:

```
COA thickness control_code index [extinction_coefficient]
```

where *thickness* is expressed in fractions of the reference wavelength (in this case 1537.2 nm, the calculated center of the entered wavelength range), *control_code* is used for optimization (100 means frozen, 0 means variable, if we were to use MAU to optimize the coating), *index* is the index of refraction of the layer, and *[extinction_coefficient]* is the optional “imaginary part” of the complex index of refraction (if it is non-zero, the material will exhibit absorption as well as reflectance and transmittance).

The sequence ends with commands to print, analyze, plot, and save this multilayer coating design in a text file (WDMFILTER.MUL). The *CODE V Reference Manual* has much more information and more examples of multilayer coating designs.

Appendix A

Analyzing Systems with GRIN Materials

This appendix presents a short list of considerations when modeling and analyzing photonic systems that contain gradient index (GRIN) materials.

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Defining GRIN materials

CODE V contains several catalog GRIN materials available from Nippon Sheet Glass Company (NSG), LightPath Technologies, and Gradient Lens Corporation. The table below lists these catalog glasses.

NSG	LightPath Technologies	Gradient Lens Corporation (GLC)
SLA20	G14SFP	EG10
SLA12	G14SFN	EG20
SLA09	G23SFP	EG27
SLA06	G23SFN	EG31
SLN20	G32SFP	
SLS10	G32SFN	
SLS20	G41SFP	
SLW10	G41SFN	
SLW18	G51SFP	
SLW20	G51SFN	
SLH18	G4LAKP	
SLW30	G4LAKN	
SLW40		
SLC18		

The NSG glass names can be specified in the Glass column of the LDM spreadsheet. The LightPath and GLC materials require some additional information and are defined as “Private Catalog” materials. See “GLC (Gradient Lens Corporation) Catalog in CODE V” on page 5-66 in the *CODE V Reference Manual* for details.

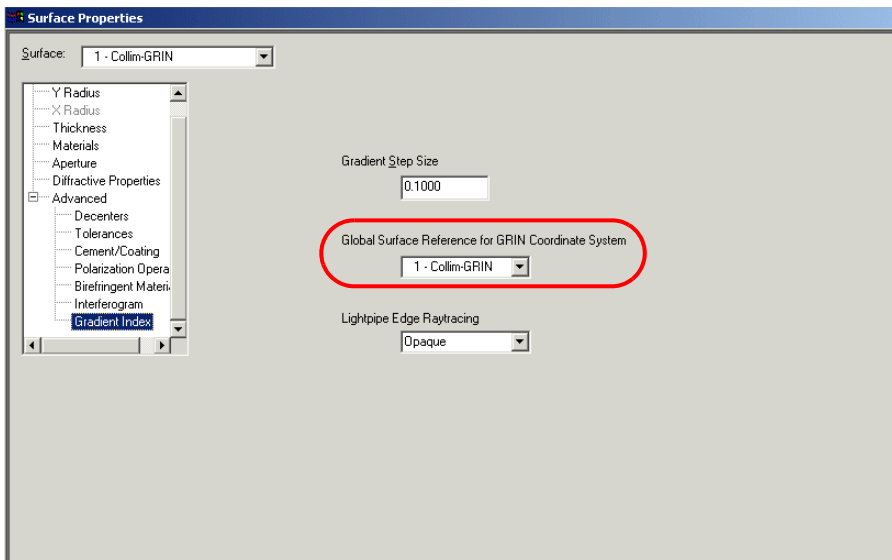
In addition, CODE V supports several GRIN dispersion equation forms that allow you to create a private-catalog material for any GRIN material for which you have refractive index profile data.

GRIN Material Coordinate System

Unlike homogeneous materials, the refractive index of GRIN materials varies as a function of location within the material. Thus, GRIN material properties are defined with respect to an X, Y, and Z coordinate system.

By default, the coordinate system of the GRIN assigned to a surface (Sk) is coincident with the local coordinate system *following* Sk. Usually, this means that the GRIN axes are the same as the surface's local axes. However, if a Decenter & Return decenter type is chosen for Sk, the GRIN axes will be aligned to the original coordinate system before the decenter. This feature allows easy modeling of GRIN elements with wedged faces, where the gradient index axes is *not* the same as the wedged face.

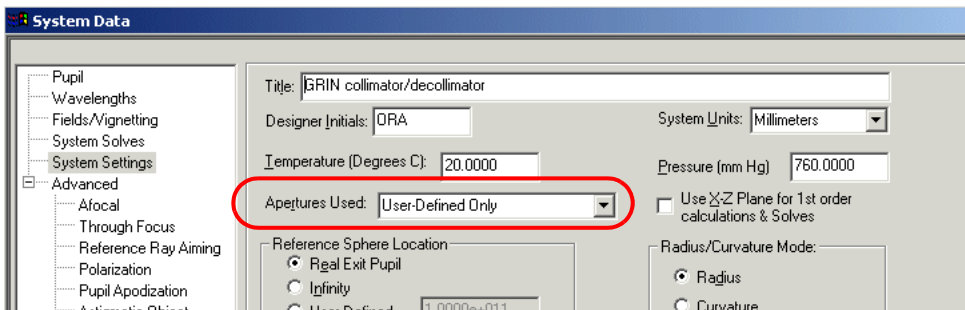
In addition, CODE V supports a global surface reference for the GRIN coordinate system. This control is found on the **Gradient Index** page in the **Surface Properties** window, shown below.



This feature allows you to associate the GRIN coordinate system with the coordinate system of an arbitrary surface before the GRIN surface. Defined this way, it is very easy to manipulate the GRIN coordinate axes without changing the model geometry. It can be very useful for tolerance studies associated with GRIN materials.

Apertures Near Beam Waists

This consideration is not exclusively related to the use of GRIN materials, but often, systems with GRIN materials have surfaces very close to beam caustics or beam waists. Remember that unless overridden, CODE V will define default apertures on every non-dummy surface in the model using five reference rays. For surfaces near beam caustics or beam waists, these apertures are generally undersized. It is very important for users to know what apertures CODE V is using (for any system). The **Apertures Used** control is available on the **System Settings** page of the **System Data** window, shown below, and can also be made a Status Bar item.



If necessary, set user-defined apertures in your model and change the Apertures Used control to **User-Defined Only**.

Considerations When Using Beam Propagation

Currently, diffraction beam propagation can be done only through a homogenous media. If your system has GRIN materials, you must use ray tracing through the GRIN. This may require converting between wave fronts and rays as the beam propagates through the system. The method is to beam propagate to the GRIN, convert to rays and ray trace through the GRIN, and then convert to a wave front and beam propagate after the GRIN. In order to get accurate results, it is important that the conversion between wave fronts and rays always be done in the far field (i.e., away from a beam waist).

If the GRIN surface is close to a beam waist, you must follow the steps below. Following this procedure will ensure that the conversion between rays and wave fronts is handled as accurately as possible:

1. Add a dummy surface in the far field relative to the beam waist (5 to 10 mm away is usually sufficient).
2. Set the thickness of this dummy surface so that the next surface is the front face of the GRIN (i.e., usually a negative thickness)
3. Set the propagation method controls on the **Computation** tab of the **FFT Beam Propagation** dialog box (**Analysis > Diffraction** menu) so that beam propagation is used up to the dummy surface. Ray tracing will be used back to the GRIN and then through the GRIN material.

The screenshot displays two software windows. The left window is the 'Lens Data Manager' with the 'Surface Properties...' tab active. It contains a table with the following data:

Surface #	Surface Name	Surface Type	Y Radius	Thickness
Object		Sphere	Infinity	5.0000
1	BPR Conversion 1	Sphere	Infinity	-5.0000
2	Collim-GRIN	Sphere	Infinity	4.7981 SLW
Stop	Back-GRIN-1	Sphere	Infinity	1.0000
4	Decol-GRIN	Sphere	Infinity	4.7981 SLW
5	Back-GRIN-2	Sphere	Infinity	5.0000
6	BPR Conversion 2	Sphere	Infinity	-5.0000
Image		Sphere	Infinity	0.0000

The right window is the 'FFT Beam Propagation' dialog box, with the 'Computation' tab selected. It features a table for 'Propagation Method (multiple range allowed)':

	Method	Start Surface	End Surface
1	Automatic	Object	1 - BPR Conversion 1
2	Automatic	Stop - Back-GRIN-1	4 - Decol-GRIN
3	Automatic	6 - BPR Conversion 2	Image

Below this table is the 'Computation Parameters' section, which includes fields for Start Surface, End Surface, FFT Grid Size, Grid Spacing, Region of Interest, and X Offset.

-
4. Insert additional dummy surfaces as required to avoid converting between rays and wave fronts near beam caustics or beam waists.
 5. Be sure that the beam propagation surface range includes propagating (not ray tracing) to the final (image) surface.

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