

OptiFiber

Technical Documentation

Optical Fiber Design Software

Version 2.1
for Windows® 2000/XP/Vista/XP 64/Vista 64™



OptiFiber

Technical Documentation

Optical Fiber Design Software

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Introduction to OptiFiber

Welcome

What is OptiFiber?

Telecommunications using fibers as the transmission media is now a major industry. Choosing appropriate fiber parameters is an important issue for a given optical system. Cross-sectional dimensions, material composition, and refractive index profile all influence the losses, dispersion and the nonlinearities of the fiber and must be chosen carefully to achieve a satisfactory tradeoff for a given application.

All these parameters of existing fiber samples could be experimentally measured and then the fiber manufacturing process adjusted towards an optimized production. However, this trial and error approach is extremely slow, expensive and unreliable. Moreover, some important fiber parameters, for example the total group-velocity dispersion and the effective nonlinear coefficient, are not directly measurable with compact tabletop devices. Because of that, the number of professionals who use an appropriate fiber design and modeling software is growing constantly across the photonics industry.

OptiFiber is the leading commercial product in that category. It is a powerful tool that blends numerical mode solvers for fiber modes with calculation models for group delay, group-velocity dispersion, effective mode area, losses, polarization mode dispersion, effective nonlinearity, etc. Among the most powerful features of OptiFiber are its abilities to predict how any given fiber could be optimized versus a design goal, for example small, but non-zero dispersion and maximal mode area. In addition, OptiFiber can supplement and extend the fiber characterization capabilities of real laboratory devices, such as EXFO's NR-9200 Optical Fiber Analyzer, by importing and analyzing the refractive index profiles of real fiber samples. OptiFiber is an indispensable tool for engineers, scientists and students who design fibers, fiber components and optical communications systems.

With OptiFiber the user can:

- Design a multilayer fiber with an arbitrary 2D refractive index profile by either:
 - Defining the profile internally, using a library of built-in functions or a using a user-specified formula
 - Importing an external profile (directly supports profiles scanned with NR-9200)
- Assign material dispersion based on Sellmeier model or user-defined functions
- Model material losses based on known experimental formulas
- Calculate the following characteristics of any supported mode, fundamental or higher order:
 - Mode field pattern, displayed in a number of ways
 - Effective refractive index and the propagation constant

- Group delay
- Three types of group-velocity dispersion (material, waveguide, total)
- Mode field diameters according to various definitions and eff. mode area
- Estimations of the cutoff wavelengths
- Macrobending, microbending and splicing losses
- Optimize the dependence of these characteristics on numerous technological parameters of the fiber:
 - geometry, profile shape, composition.
- Calculate and visually compare the parameters of an arbitrary group of modes vs. the mode number
- Calculate birefringence effects induced by intrinsic or extrinsic perturbations
- Estimate the PMD based on stochastic model
- Use two alternative ways of defining the profile of the fiber:
 - As a refractive index profile.
 - As a dopant concentration profile.
- Access the models:
 - Macrobending losses of higher order modes.
 - Estimations of the cutoff wavelength as given by the ITU-T recommended experimental procedure.
 - Effective mode area.
 - Effective nonlinear refractive indices of arbitrary mode as determined by the nonlinear indices of the bulk materials and on the waveguiding properties of the fiber: shape of mode pattern, degree of confinement, etc.
- Access a rich material library
- Try the examples.
- Use experimental profiles of real fiber samples scanned with NR-9200 from EXFO Inc.

What is new in OptiFiber version 2.0

Meshless mode solvers for LP and vector modes. As with the original mode solver of OptiFiber, the fibers can consist of an arbitrary number of concentric layers of lossless materials, and graded index fibers can be approximated using a sequence of constant index layers. The new mode solvers are different from the original one in that they do not use meshes to approximate the structure. Instead, they find an exact solution based on matching boundary conditions at layer boundaries. These mode solvers should be especially useful for multimode fiber calculations, where there are many modes in the spectrum. Another advantage of the meshless mode solver is the calculation of fields far from the fiber. Meshing introduces finite difference errors of a certain level, and fields weaker than the differencing error cannot be calculated. The

meshless mode solvers, on the other hand, have the correct asymptotic behavior far from the fiber, and can calculate fields of magnitude 10^{-15} or less. In OptiFiber version 2.0, the desired mode solver is selected by radio button in the Modes dialog box.

Propagation over distance feature. OptiFiber allows users to decompose an arbitrary field into the modes of a multimode fiber. It calculates the complex coefficients of the modes for the arbitrary field. Similarly, given the amplitude of a set of modes, OptiFiber can display the sum (composition of modes). OptiFiber 2.0 can also calculate this multimode field after propagating down the fiber by a specified distance. The user enters a distance. Each of the complex coefficients of the modes is multiplied by the appropriate phase factor, and the new field pattern is displayed in the preview box.

What is new in OptiFiber 2.1

In OptiFiber 2.1, four enhancements were introduced to the user interface. The first two enhancements, radius specified instead of layer widths, and layer index specified relative to cladding, are implemented in a Settings dialog box to customize data entry and display according to user preference. The parabolic function layer was enhanced with an option to reverse the sense of direction, and it is now possible to export the data found in the Cutoff dialog box.

Radius specified instead of layer widths. In OptiFiber, the fiber profile is specified as a list of Regions (layers) of various widths. There is a read only field to show the position (radius) of the selected layer. It is now possible to enter the radius of the layer instead of the layer width. In this option, the width field will become read only instead of the position field.

Layer index specified relative to cladding. In the Fiber Profile dialog box, the refractive index of the selected layer is displayed in the Refractive Index field. It is now possible to specify the refractive index relative to the cladding layer instead. With this option, when the last layer is selected, the cladding refractive index will be displayed in the Refractive Index field. However, when other layers are selected, the index of current layer relative to the cladding layer will be shown. Data entry is also relative.

Export Cutoff data. An option to export this data to a text file has been added.

Parabolic function layer can go both ways. The parabolic layer has its extreme value on the left side of the layer by default. Now the layer can have the extreme value on the right side as well.



Installation

Hardware requirements

OptiFiber requires the following system configuration:

- Personal computer with the Pentium processor
- 10 MB free hard disk space
- 32 MB of RAM recommended
- Graphic resolution of 1024 x 768, minimum 256 colors

Software requirements

OptiFiber requires one of the following operating systems:

- Microsoft Windows 2000
- Microsoft Windows XP

Installation procedure

To install OptiFiber on Windows 2000/XP:

1. Log on as the Administrator or on an account with Administrator privileges.
2. Insert the OptiFiber CD into your CD ROM drive.
3. Press the Start button and select Run.
4. In the Run dialog box, type 'F:\setup.exe,' where 'F' denotes your CD ROM drive.
5. Click the OK button and follow the screen instructions and prompts.
6. Reboot the computer.

Documentation

You can quickly become an efficient OptiFiber user by reading carefully and referring to the technical documentation OptiFiber provides.

OptiFiber is shipped with documentation that consists of the following sections:

- Introduction to OptiFiber
- Getting Started with OptiFiber
- Technical Background
- Tutorial Lessons
- Commands Reference
- Dialog Boxes Reference
- Output Views Reference
- Script Language

The Help system contains references and tips that do not exist elsewhere. You can easily search topics by using the Help system.

Online Help

OptiFiber online Help follows standard rules of Help design and usage. If you are familiar with the Help of your computer operation system, then you will quickly learn how to get the most from OptiFiber Help by following similar steps. The OptiFiber Help is organized in topics that follow the logic of a printed book. However, cross-references and jumps allow you to quickly find required information. Since OptiFiber dialog boxes usually contain complicated technical information, we described all of them in the Dialog Box Reference that forms a part of the Help system.

Support

Technical support

Optiwave provides technical support for all users of OptiFiber. The technical support includes:

Technical Support by Phone

Highly qualified Optiwave representatives are available for telephone assistance Monday to Friday, 8:30 a.m. to 5:00 p.m. Eastern Standard Time. Tel: (613) 224-4700.

Technical Support by Fax

To get technical assistance, you can also send a fax, and you will receive assistance to overcome whatever problems you may have. Fax: (613) 224-4706.

Technical Support by E-mail

You can also send e-mail to support@optiwave.com.

Using Optiwave's Web Page

For additional information, you can use the Optiwave web page. From the Help menu, click About OptiFiber and click www.optiwave.com.

Getting Started with OptiFiber

Learning Basic Features of OptiFiber

Starting and exiting OptiFiber

When you start the OptiFiber program, an empty workspace appears on the screen.

Use one of the following methods to open a project file:

- Select “New” from the “File” menu or double-click on the workspace for a new OptiFiber project
- Select “Open”, then browse to an existing OptiFiber file to open a previously saved project
- Select one of the recently opened files at the bottom of the File menu to open it

To exit OptiFiber:

- Select “Exit” from the “File” menu

The program will prompt you to save project files that were changed.

Looking at OptiFiber interface

The OptiFiber user interface is designed to provide you easy access to the frequently used commands.

After opening a new project file, you can see the OptiFiber workspace window containing the following elements:

- Main Menu bar with menus: File, View, Fiber, Simulation, Tools, Window, and Help
- Toolbars: Standard and Graph Tools
- Navigator pane with icons: Fiber Profile, Modes, Fundamental Mode, Higher Order Mode, Cutoff, Birefringence, and PMD
- View window with tabs: Profile, Modal Index, Group Delay, Dispersion, Mode Measures, Material Loss, Bending Loss, Splice Loss, Mode Field, Birefringence, PMD, Effective Nonlinear RI and Comments

Using menu commands

You can access the commands of OptiFiber using the interface menus. Each of the main menus has various command options.

The menu commands are described in the Commands Reference, where first sections titles correspond to the main menu options:

- File Menu Commands: New, Open, Close, Save, Save As, Export Profile, Import Profile, Print, Print Preview, Print Setup, Recent Files, Exit
- View Menu Commands: Status Bar, Navigator, Toolbars, Views

- Fiber Menu Commands: Profile
- Simulation Menu Commands: Modes, Fundamental Mode, Higher Order Modes, Cutoff, Birefringence, PMD
- Tools Menu Commands: Settings, Table, Calculated Results
- Window Menu Commands: New Window, Cascade, Tile, Arrange Icons

Using Standard toolbar commands

The Standard toolbar contains command buttons familiar to Windows users: New, Open, Save, Copy, Print, and About.



The Standard toolbar commands are described in the Commands Reference sections:

- New Command
- Open Command
- Save Command
- Print Command

Using Graph Tools toolbar commands

The Graph Tools toolbar contains commands frequently used in handling OptiFiber graphical views. They include such commands as Joints, Measure Distance, Tracking, Zoom X, Zoom XY, Zoom Off, Legend, Grid X, Grid Y, X Cut, and Y Cut.



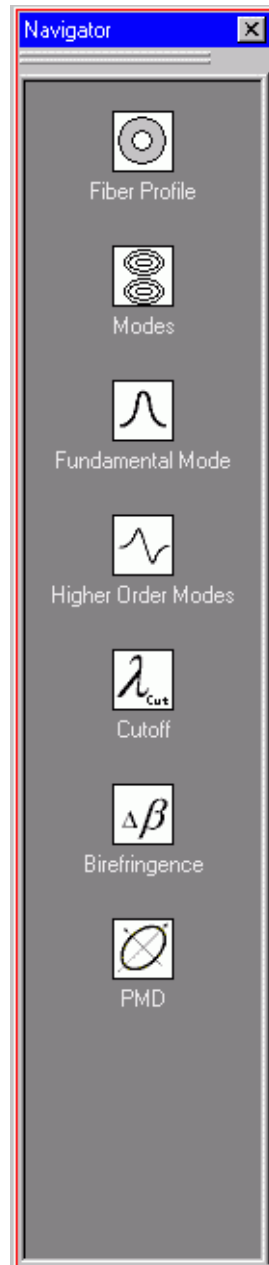
The Graph Tools toolbar commands are described in the Commands Reference sections:

- Joints Command
- Measure Distance Command
- Tracking Command
- Zoom X Command
- Zoom XY Command
- Zoom Off Command

- Legend Command
- Grid X Command
- Grid Y Command
- X Cut Command (Available only in the Mode Field view)
- Y Cut Command (Available only in the Mode Field view)

Using Navigator pane

The Navigator pane provides quick access to the most frequently used commands. It contains icons that activate start the main dialog boxes of OptiFiber. These dialog boxes are used to enter data and run calculations.



The Navigator options are described in the Commands Reference sections:

- Fiber Profile Command
- Modes Command
- Fundamental Mode Command
- Higher Order Modes Command
- Cutoff Command
- Birefringence Command
- PMD Command



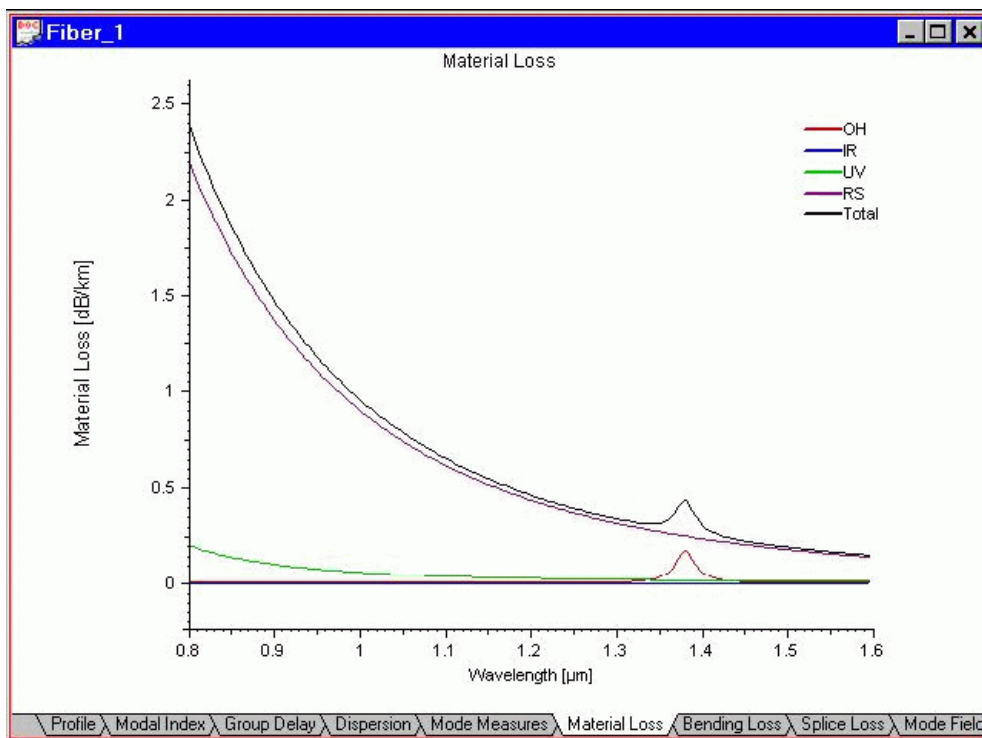
Using Views window

The Views window provides all graphical output from simulations. The graphs appear in the view tabs as they are calculated. In a new file, most views are empty, except the Material Loss tab, where a default loss characteristic is displayed.

The list of available view tabs is as follows:

- Profile view
- Modal Index view
- Group Delay view
- Dispersion view
- Mode Measures view
- Material Loss view
- Bending Loss view
- Splice Loss view
- Mode Field view
- Birefringence view
- PMD view

Click Material Loss to see the default material loss mechanisms and the total loss vs. wavelength.



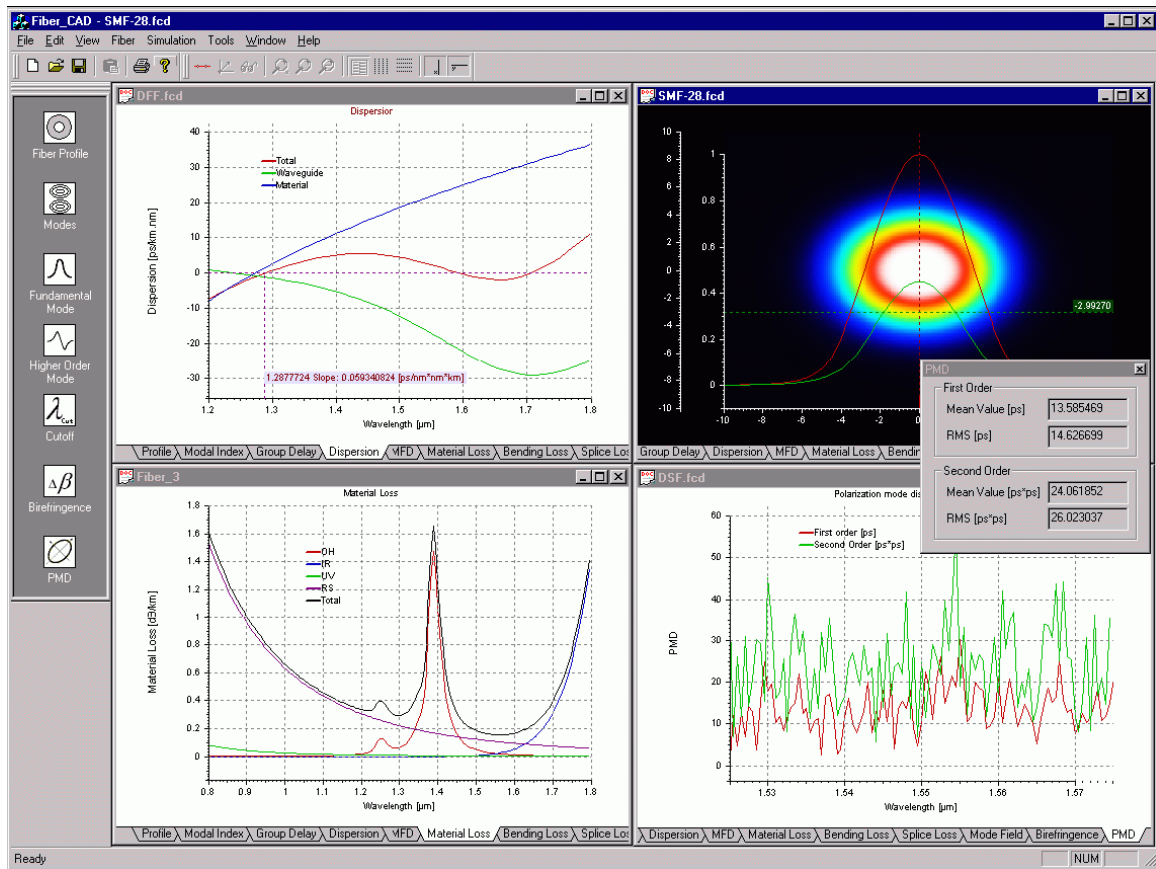
Later, you will learn how to change these fiber characteristics. The empty view tabs will be filled with graphs after execution of relevant simulations.



Views are described in the Output Views Reference beginning with the Profile View section.

Managing projects

You can open and work with many projects files using the same OptiFiber workspace. Different output view windows represent the project files. OptiFiber generates default titles to newly opened files, for example Fiber 1, Fiber 2, etc. It is convenient to tile several projects for the purpose of comparison.



The simulation commands always refer to the active view window.

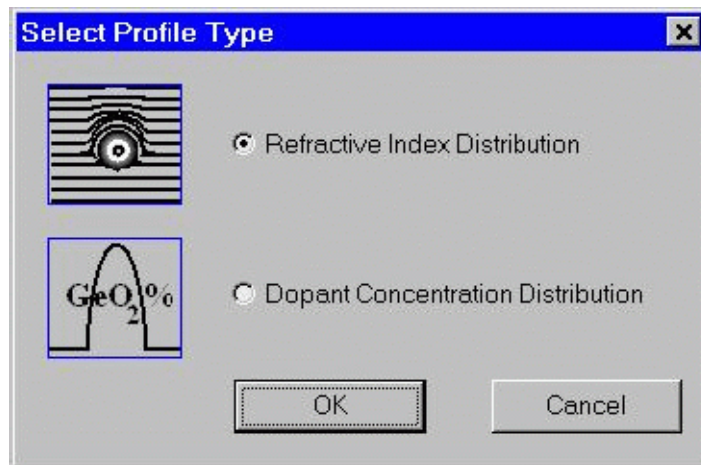


Designing and Calculating with OptiFiber

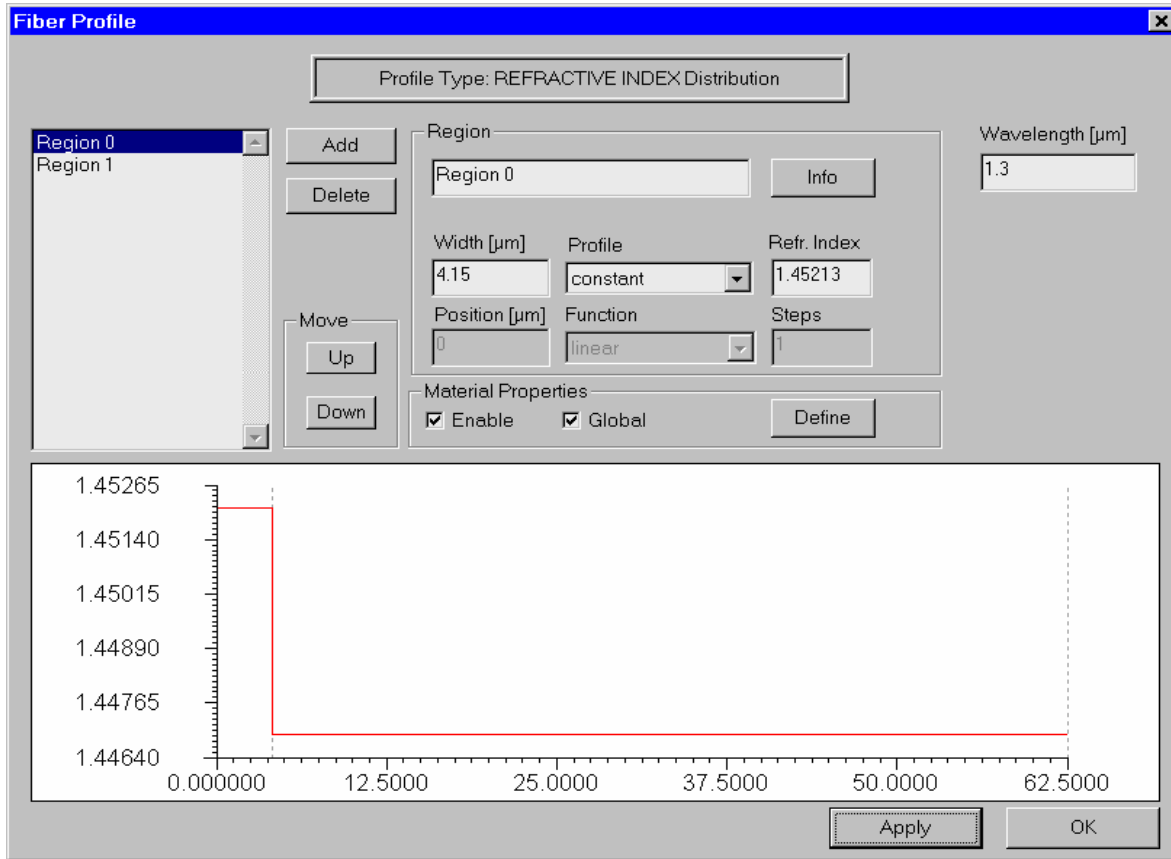
Designing a fiber profile

The process of designing a new fiber usually starts by defining its profile. Click the “Fiber Profile” icon in the Navigator pane or double-click the workspace or select the “Fiber/Profile” menu item.

Currently two types of profiles are supported: refractive index profile and dopant concentration profile. The “Select Profile Type” dialog box offers a choice between them.



After that the “Fiber Profile” dialog box appears. In case the user has selected refractive index profile type, it looks as shown:



To create a simple step-index fiber (similar to SMF-28) do the following steps:

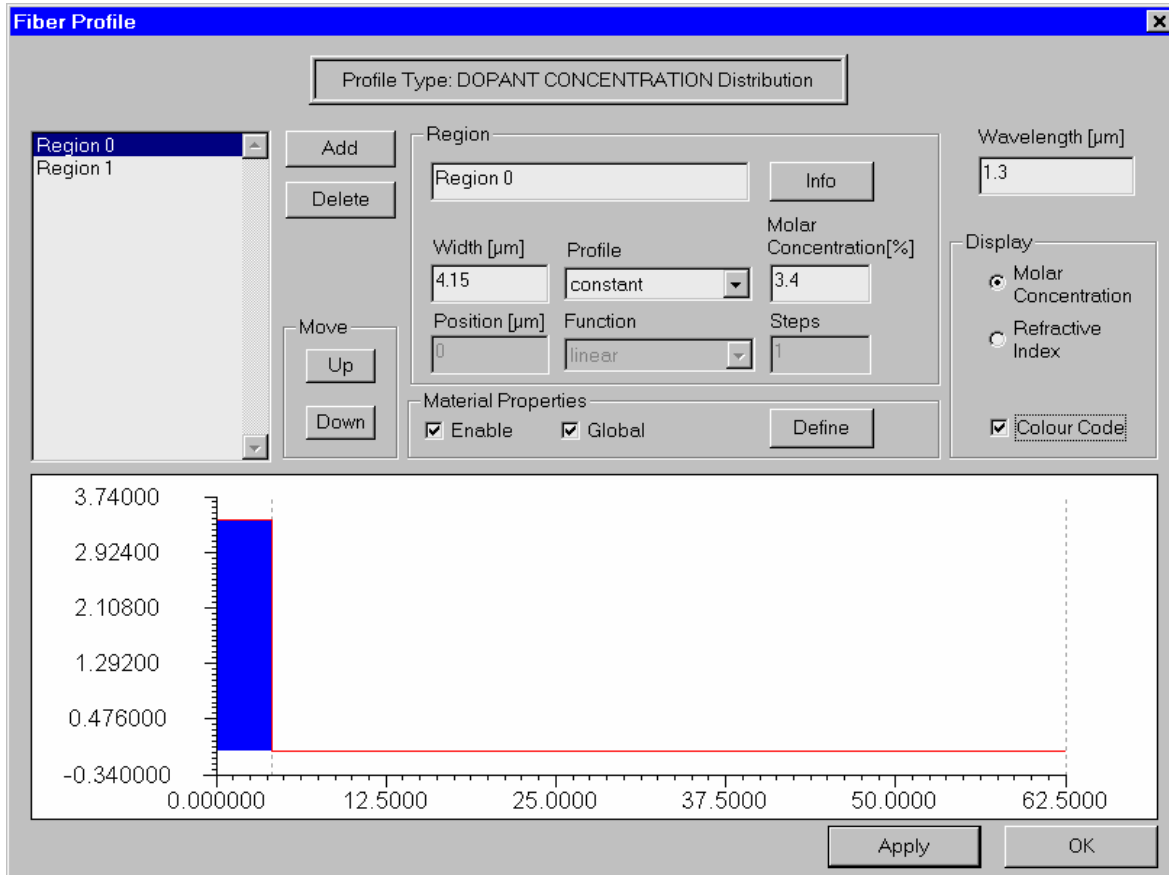
Step Action

- 1 In the “Fiber Profile” dialog box, click the “Add” button twice to create two radial index regions: “Region 0” and “Region 1”. These two regions will represent the fiber core and cladding, respectively.
- 2 Select “Region 0” on the list and enter its Width value 4.15 microns, then select the “Profile” option as “Constant”, and enter the “Refr. Index” value 1.45213.
- 3 Press “Apply”.
- 4 Select “Region 1” on the list and enter its “Width” value 58.35, then select the “Profile” option “Constant”, and enter the “Refr. Index” value 1.44692.
- 5 Press “Apply”.
- 6 Enter the “Wavelength” value 1.3.
- 7 Press “Apply”.
- 8 Press “OK” to close the “Fiber Profile” dialog box.

You just designed a simple fiber profile that is shown at in the graph pane at the bottom of the dialog box. The fiber profile is defined at the wavelength 1.3 microns.



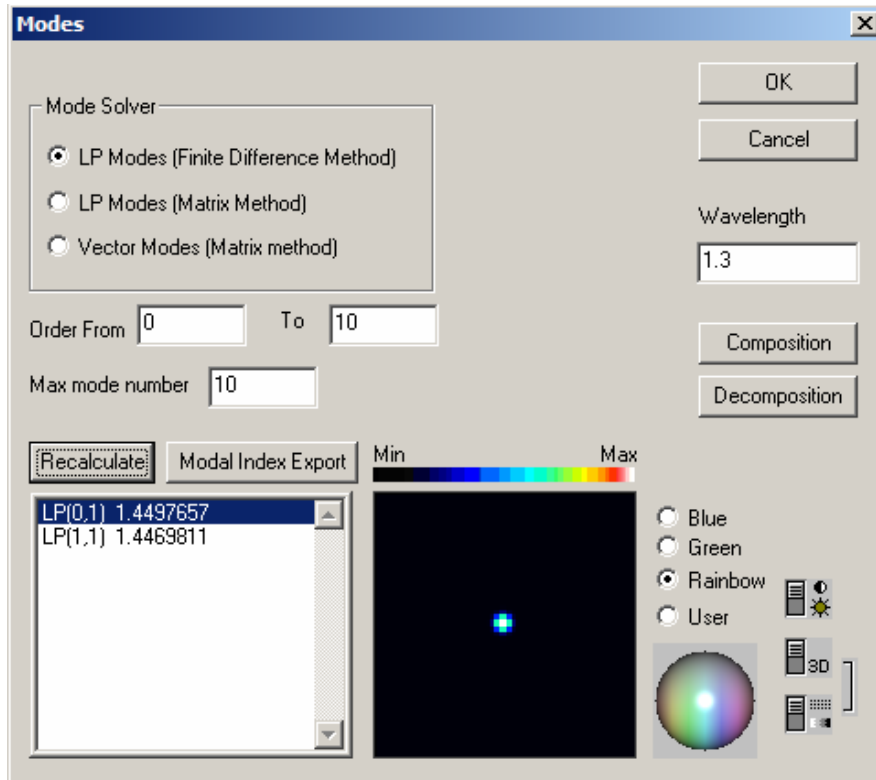
If in “Select Profile Type” dialog box the user has selected “dopant concentration type” then the ‘Fiber Profile’ dialog box looks as shown:



The difference from the previous case is that now the user enters the values of the molar concentration percentage of the dopant in the edit box where the refr. index values were entered. This dialog box contains also an additional group of controls - “Display” - allowing viewing of the profile as a refr. index or concentration type one, and to color-code the regions. The latter feature is useful for distinguishing neighboring regions: 1) having equal refr. indices but doped with different concentrations of different materials, or 2) doped with equal concentrations of different materials, thus having different refr. indices. The fiber shown in the picture above is equivalent to the one in the previous picture.

Calculating fiber modes

After having defined the fiber profile the user can proceed with the calculations. Click the “Modes” icon in the “Navigator” pane. The “Modes” dialog box appears.



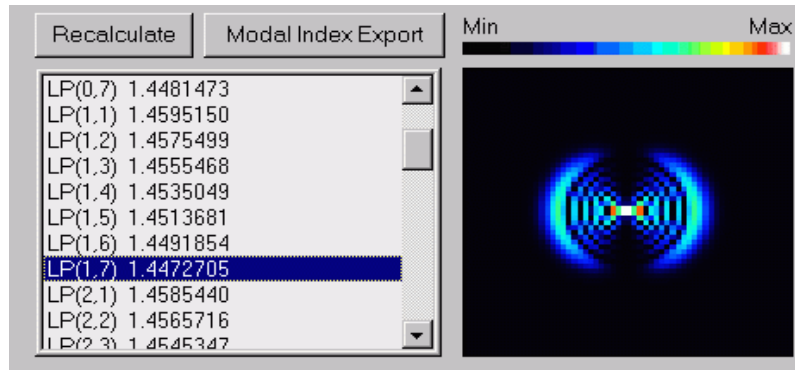
To recalculate this example fiber profile do the following steps:

Step Action

- 1 In the Mode Solver panel, check the LP Modes (finite difference method) option and leave the Order “From”, “To”, and “Max” entries with their default values.
- 2 Press the “Recalculate” button.

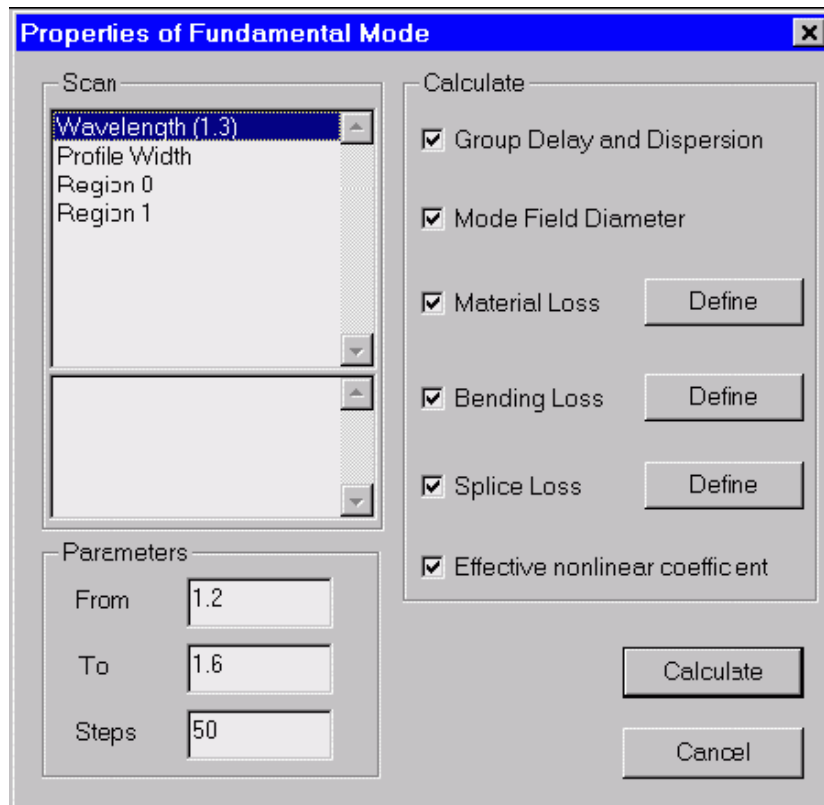
The program calculates guided LP modes of the fiber. In this example, the fiber is multimode, with the effective index of the fundamental mode, 1.4497657, listed along the mode name LP (0,1). A graph located to the right of the mode list provides you a small quick preview of the field pattern of the selected mode. It is handy in the case of fibers supporting multiple modes at the given wavelength, as shown below:





Calculating properties of fundamental mode

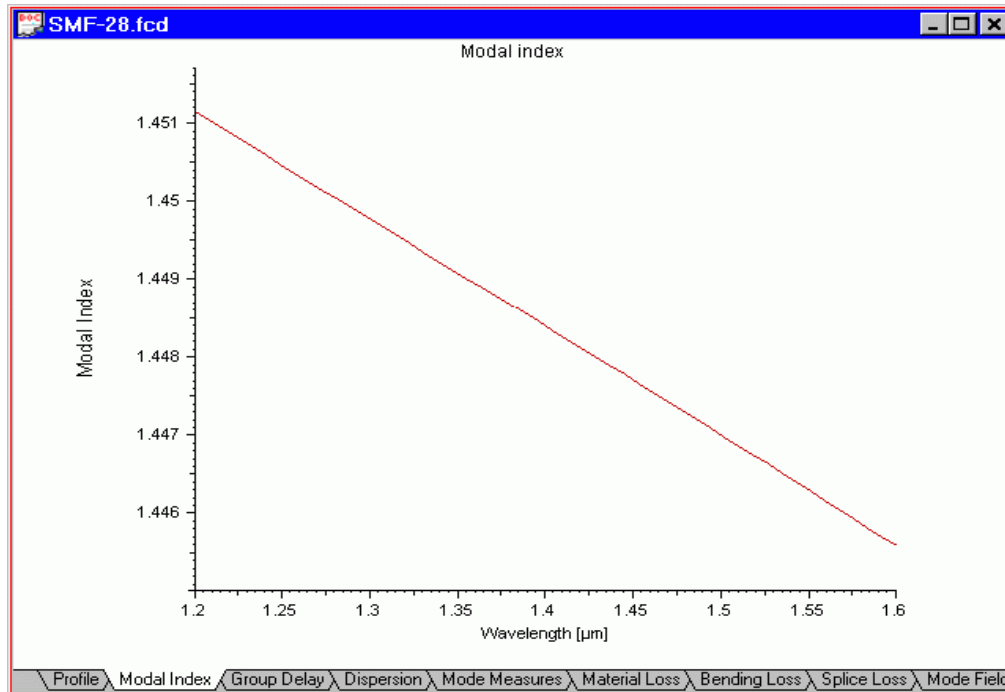
Click the “Scan Fundamental Mode” icon in the Navigator pane. The “Properties of Fundamental Mode” dialog box appears.



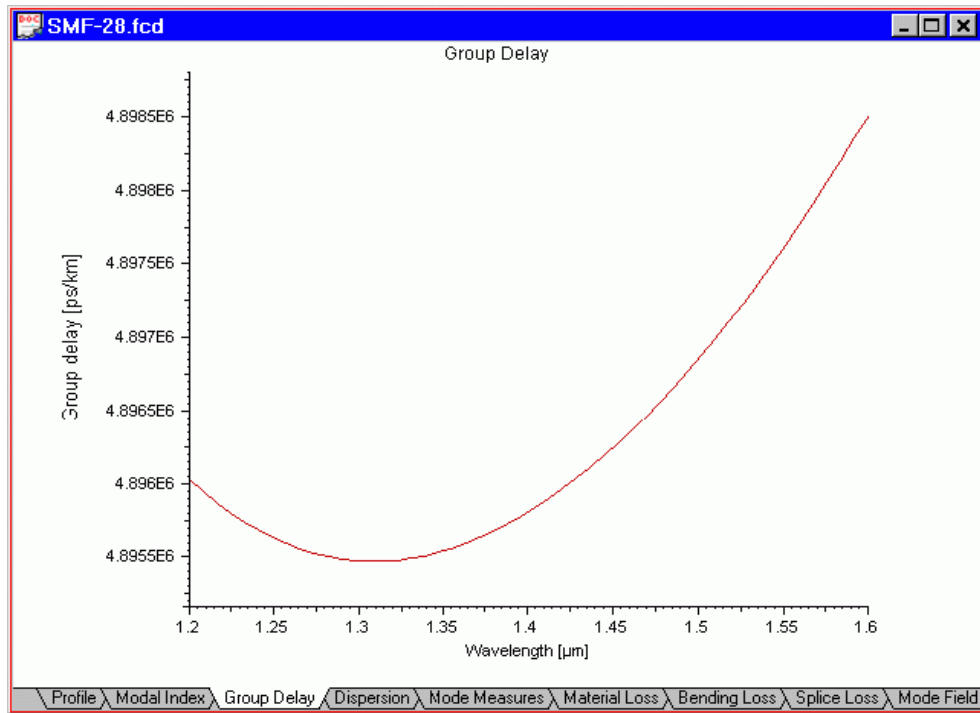
Do the following steps:

Step Action

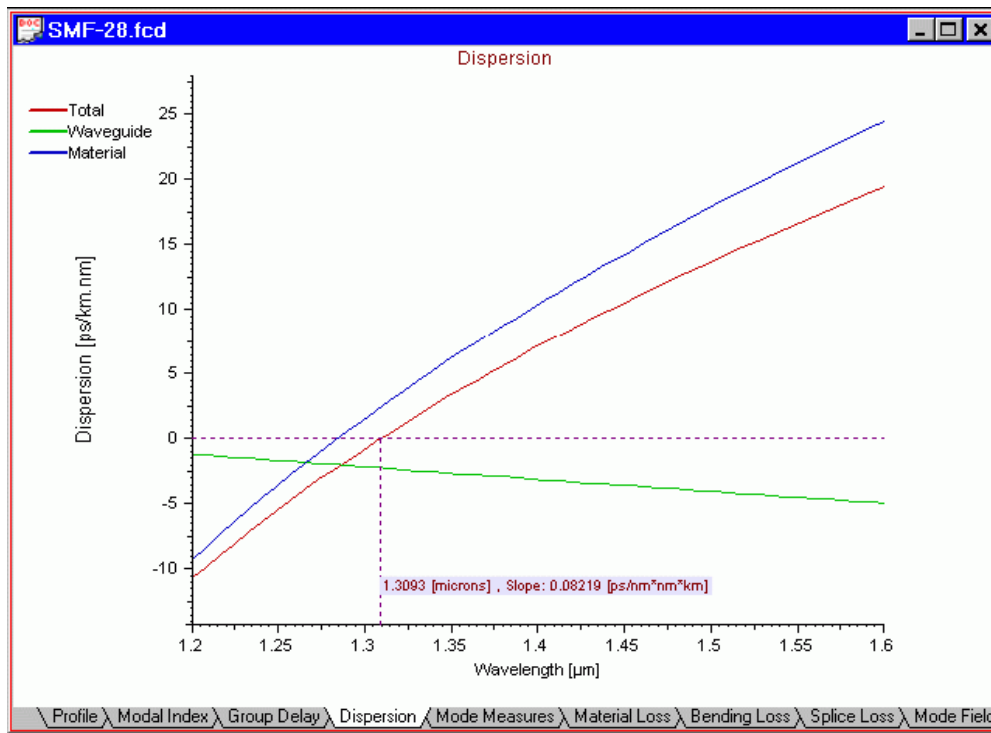
- 1 Press the “Calculate” button. The routines calculate all characteristics checked in the Calculate section. In the “Views” window, you can now see graphs of these characteristics.
- 2 Click the “Modal Index” tab to see the plot of the effective refractive index versus wavelength



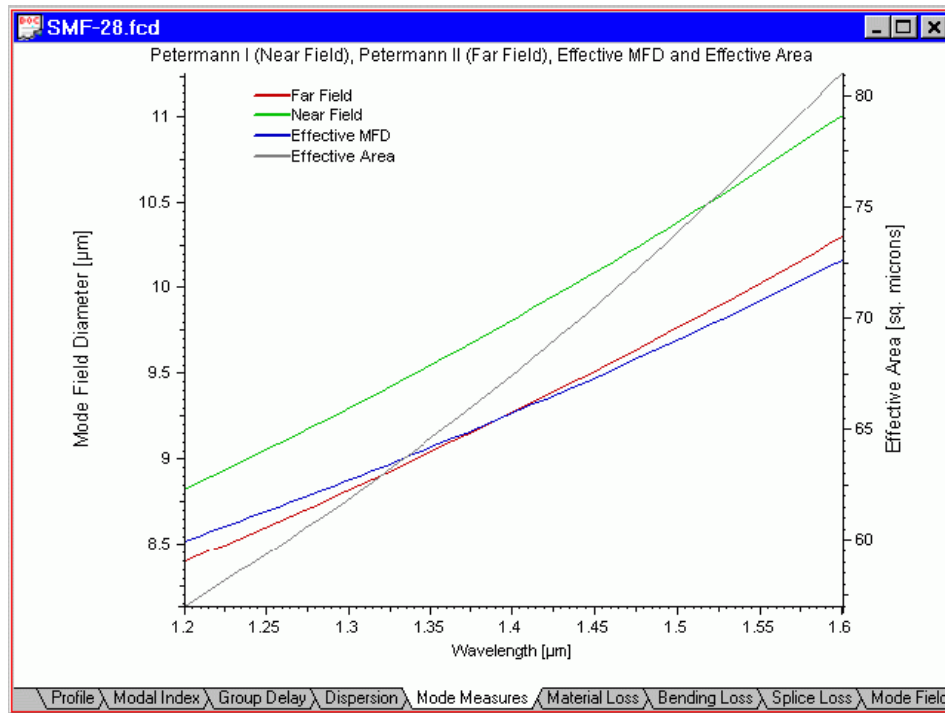
- 3 Click the “Group Delay” tab to see the plot of the group delay versus wavelength:



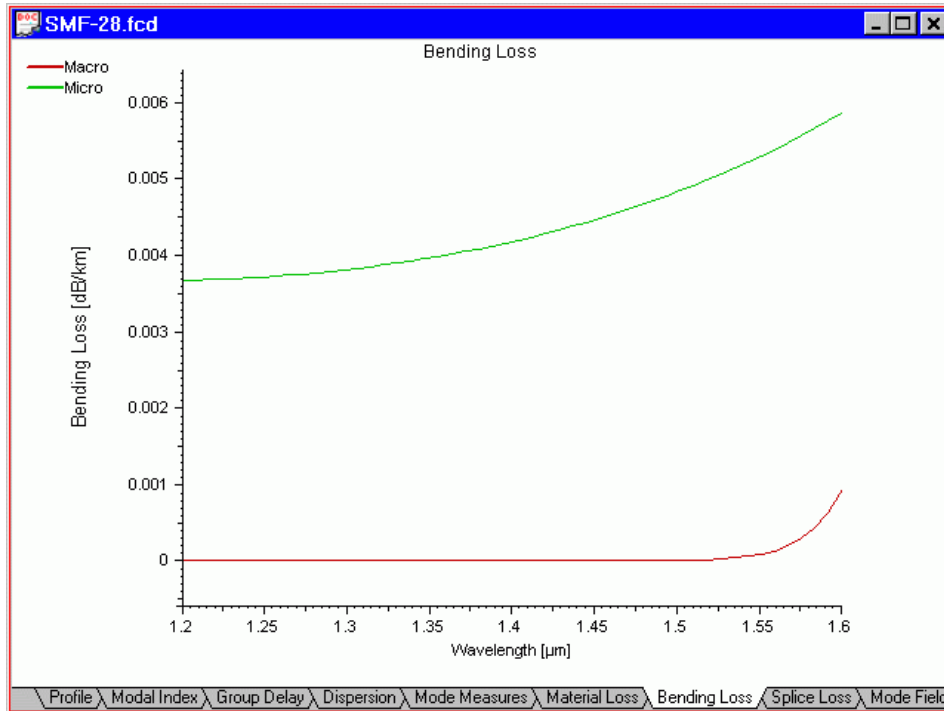
- 4 Click the "Dispersion" tab to see the plot of the group delay versus wavelength:



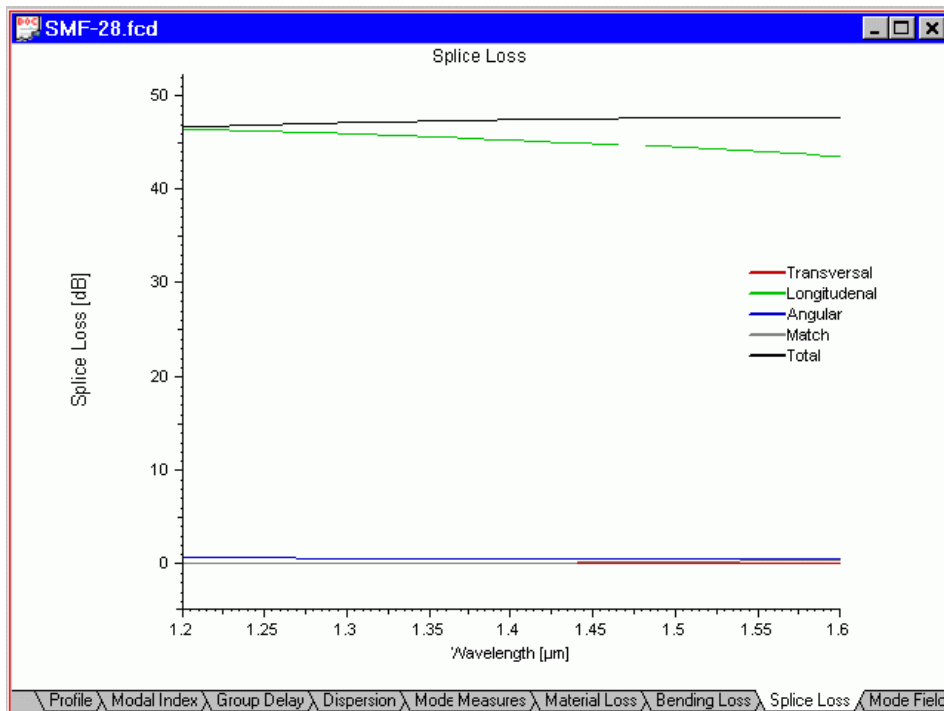
- 5 Click the "Mode Measures" tab to see the plot of the mode field diameters versus wavelength:



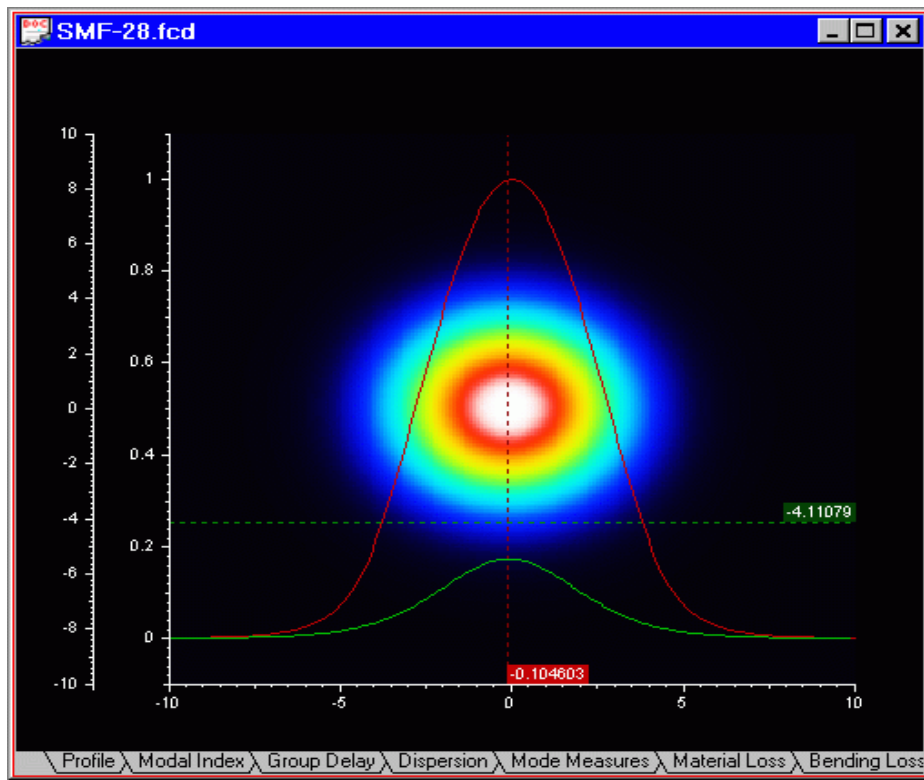
- 6 Click the “Bending Loss” tab to see the plot of the micro- and macrobending loss versus wavelength:



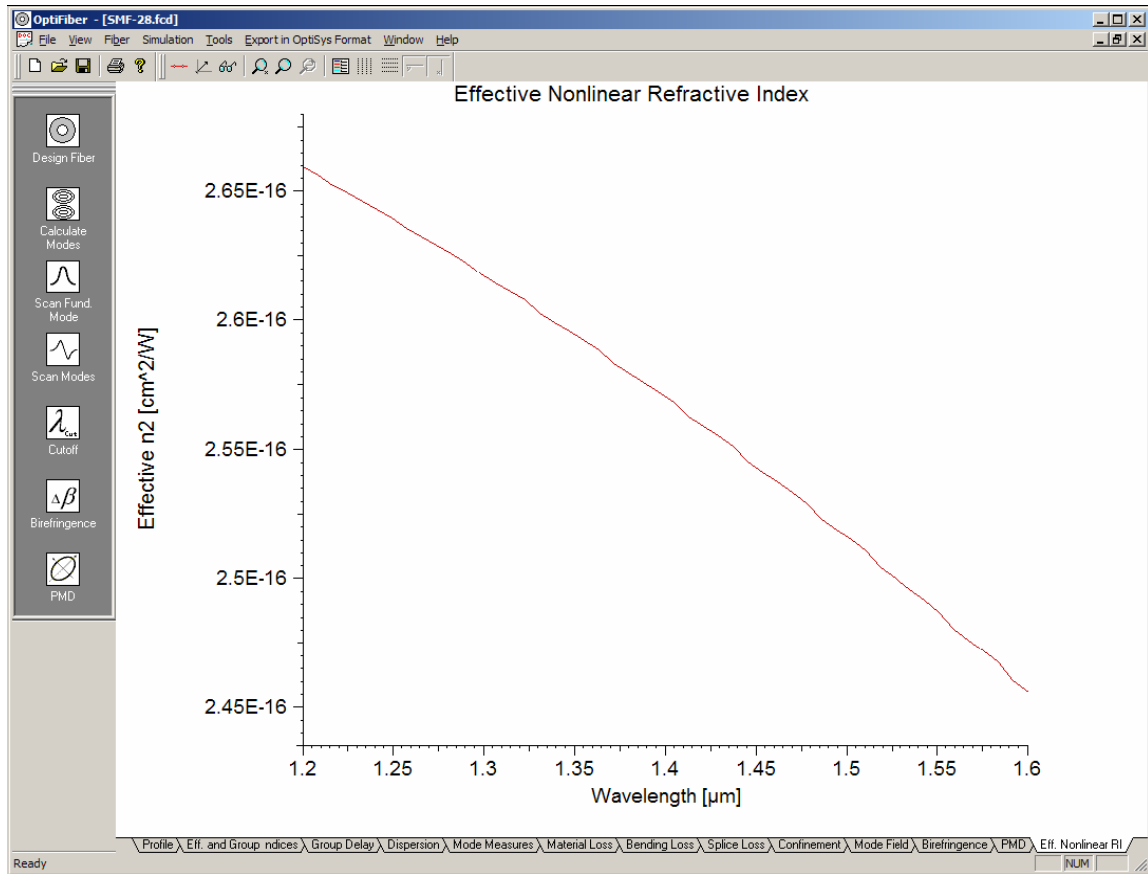
7 Click the “Splice Loss” tab to see the plot of splice loss versus wavelength:



- 8 Click the “Mode Field tab” to see the plot of the LP(0,1) mode field versus transverse dimensions of the fiber:



- 9 Click the “Eff. Nonlinear RI” to see the plot of this parameter. Its definition is given in the “Technical Background” section

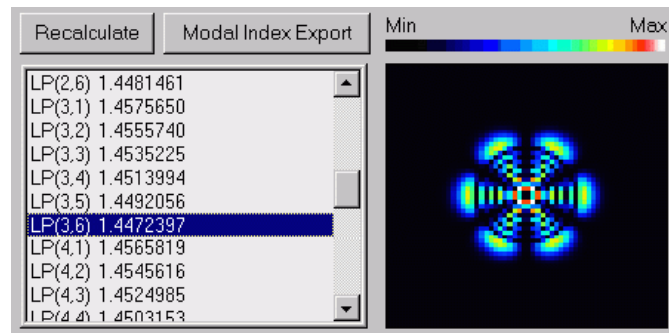


Calculating properties of higher order mode

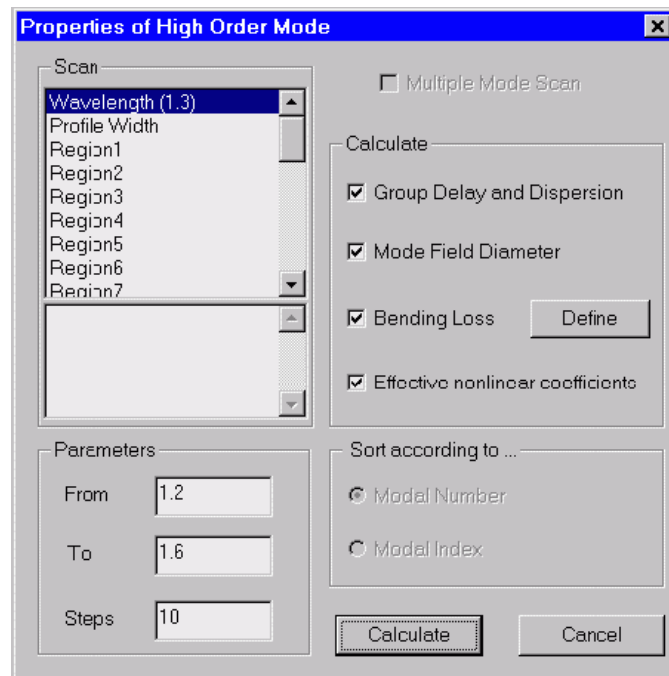
If the current fiber design supports multiple modes their characteristics can be calculated the following way:

Step Action

- 1 In the “Modes” dialog box recalculate and select the higher-order mode of interest. In that example of a typical 65/125 multi-mode graded-index fiber it is LP(3,6)



Click the “High Order Mode” icon in the Navigator pane. The “Properties of High Order Mode” dialog box appears.



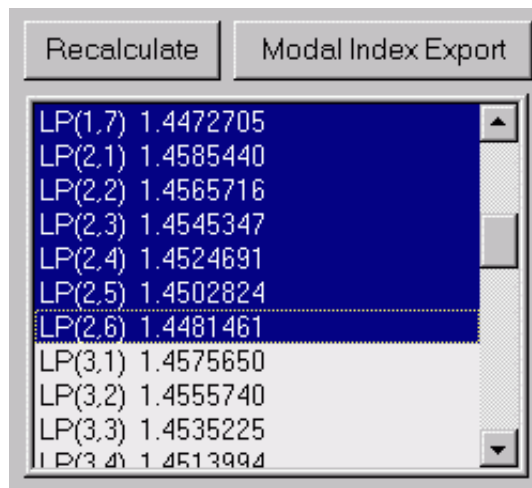
It offers the choices to calculate (scan) the characteristics of the selected mode vs. the wavelength, the proportionally reduced/expanded profile width, etc. After the calculation the results are displayed in the same view tabs described above.

Calculating properties of an arbitrarily selected group of modes

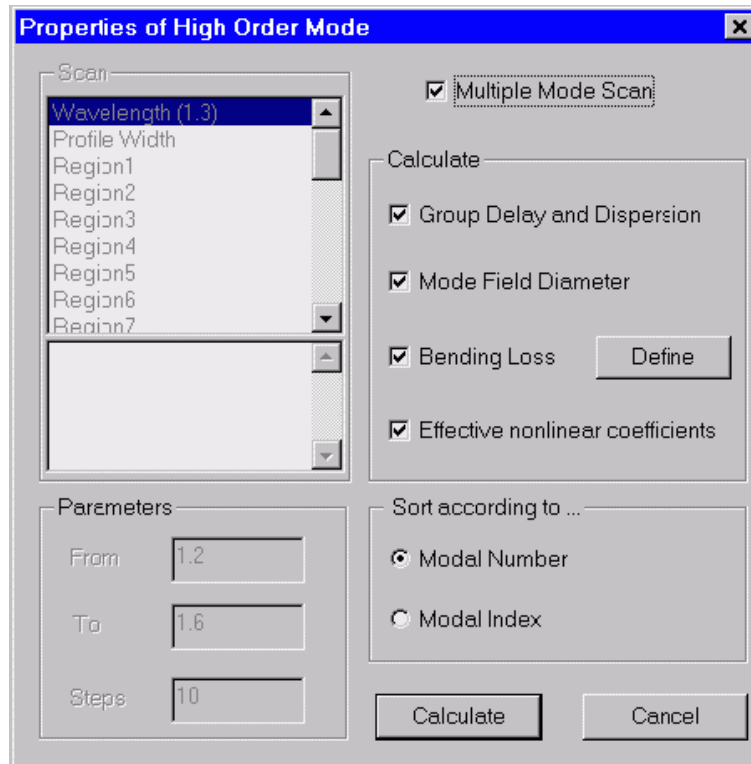
If the current fiber design supports multiple modes the characteristics of a group of modes can be calculated for comparison:

Step Action

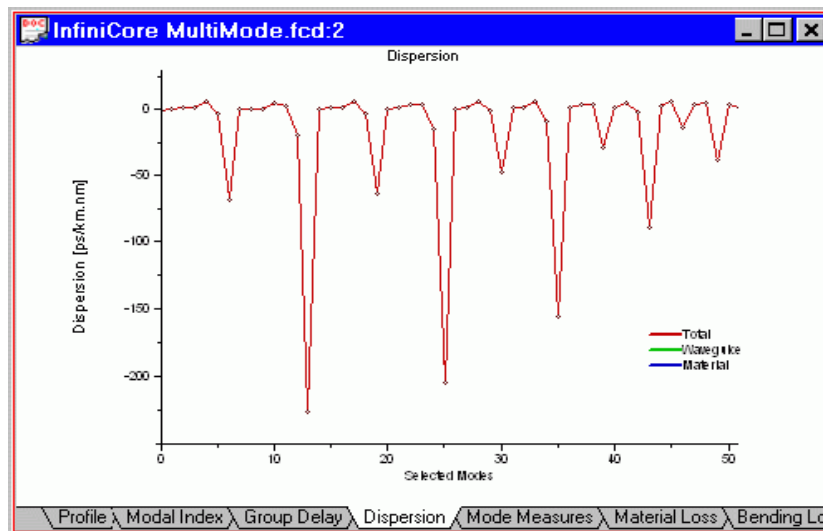
- 1 In the “Modes” dialog box recalculate and select the group of modes, in this case all the modes from LP(0,1) to LP(2,6)



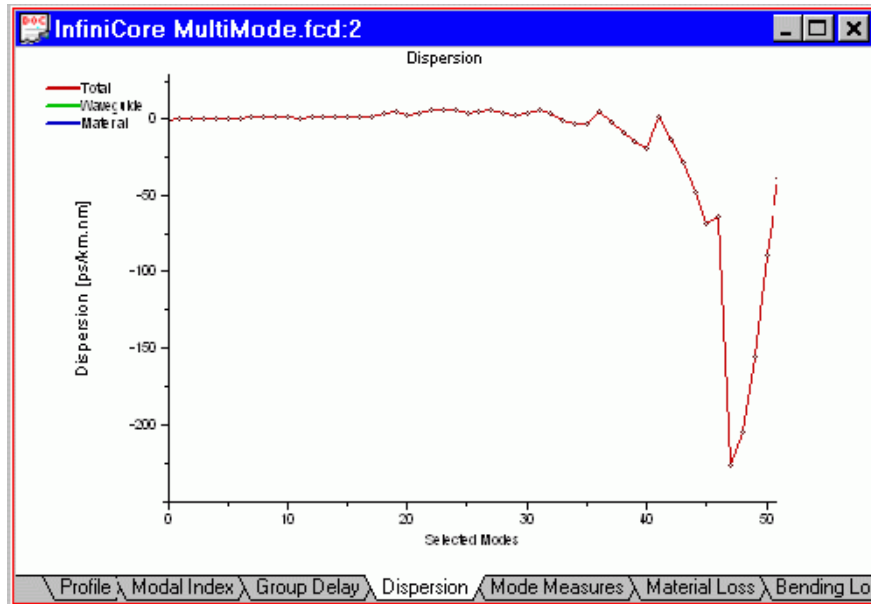
- 2 Then proceed to the “Properties of High Order Mode”. Its left-side controls are now disabled and the “Multiple Mode Scan” is checked as the parameter of this calculation is the mode itself, instead of some technological figure of the fiber.



The user can also choose to sort the results according to the initial sequential number of the mode in the selected group...



...or according to the effective refractive index in descending order.



Calculating cutoff wavelengths

Click the “Cutoff” icon in the “Navigator” pane. The “Cutoff” dialog box appears. Press “Recalculate” first to obtain the mode list. If the fiber is single-mode, reduce the wavelength value using the edit box with the same name (to 0.5 microns in the picture below).

Two types of cutoff calculations are currently supported and respectively two values are displayed for each selected mode:

Step Action

- 1 “Theoretical” cutoff values: the wavelength above which the given mode cannot propagate even in short regular samples of this fiber.
- 2 “Estimated ITU-T” cutoff values: these values are obtained by emulating the actual experimental cutoff measurements, as described in the ITU-T / TIA / EIA recommendations (see [ITU-T] in the Technical references).

After pressing the “Calc. Cutoff” button all cutoff wavelength values are displayed, except for the fundamental mode, where the cutoff does not apply. The values shown here correspond to a fiber similar to the popular SMF-28.

CutOff [X]

Mode Solver

LP Modes (Finite Difference Method)
 LP Modes (Matrix method)
 Vector Modes (Matrix Method)

OK

Cancel

Order From To

Max mode number

Recalculate Wavelength [μm] **Calc. Cutoff**

Modes	Theoretical values	Estimated ITU-T values
LP(0,1) -> (1.4674193)	LP(0,1) -> N/A	LP(0,1) -> N/A
LP(0,2) -> (1.4651550)	LP(0,2) -> 0.83749580	LP(1,1) -> 1.2312500
LP(1,1) -> (1.4665879)	LP(1,1) -> 1.3320522	
LP(1,2) -> (1.4635488)		
LP(2,1) -> (1.4655108)		
LP(3,1) -> (1.4642166)		
LP(4,1) -> (1.4627406)		



Calculating birefringence

Click the “Birefringence” icon in the “Navigator” pane. The “Birefringence” dialog box appears.

Birefringence

Central Wavelength
 Lambda [μm] 1.55

Photoelastic constants
 Young's Modulus E [kg.W/m²] 7750000000
 C [m²/kg.W] 3.44e-011
 Poisson Ratio 0.164

User Defined
 Delta Beta [rad/m] 6.28
 DGD [ps/km] 100

Induced by Perturbation Parameters

Intrinsic Elliptical core deformation Core ellipticity 0.01
 Thermal Stress Differential Thermal Expansion Coeff. [1/*C] 6.5e-008
 Temperature Difference [*C] -1000

Extrinsic Bending Bending Radius [m] 0.12
 Fiber Spooled with Tension [N] 0.2943
 Transverse Pressure [kg.W/m] 1.2

Output
 Spectral Range [μm] 0.4 Number of Steps 51

OK Cancel

Step Action

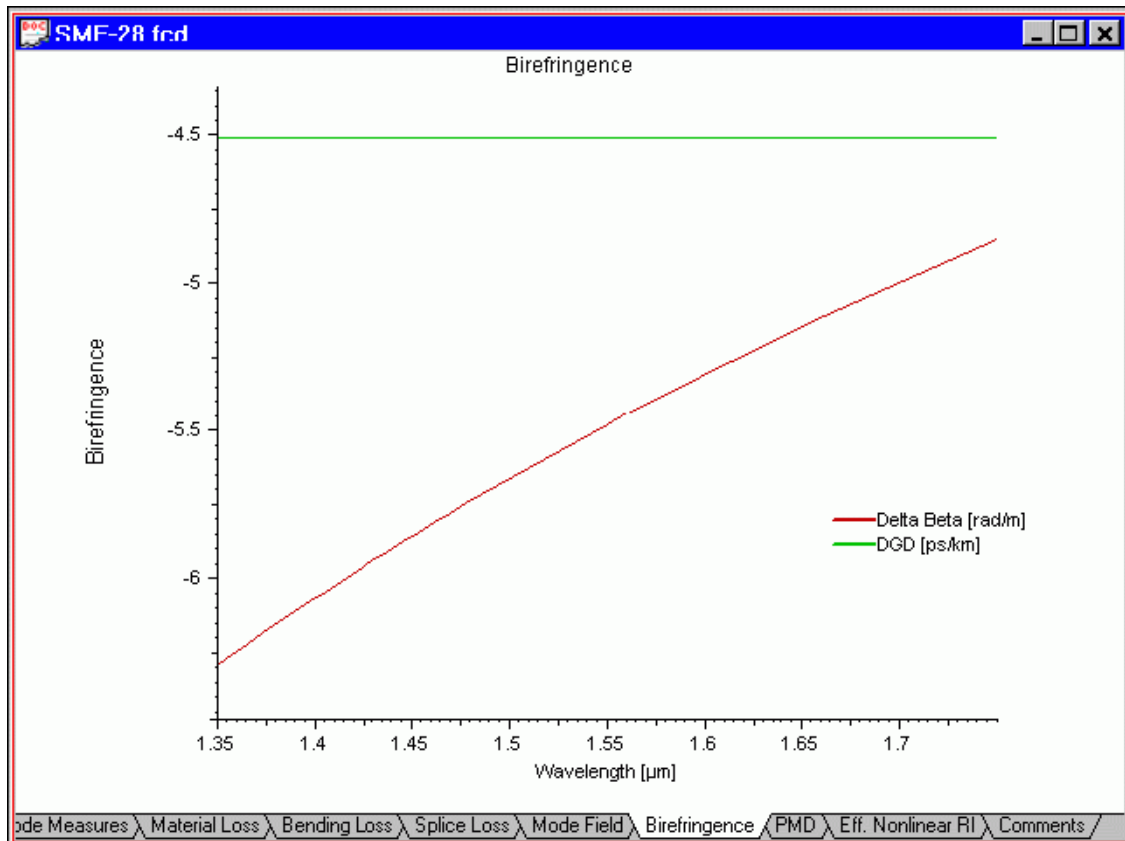
- 1 In the “Birefringence” dialog box, check the “Induced by Perturbation Parameters” option. The “Photoelastic Constants” entries become available.
- 2 In the “Photoelastic Constants” section, enter: Young Modulus 7750000000, C 3.44e-011, Poisson Ratio 0.164.
- 3 In the “Induced by Perturbation” Parameters section, check “Extrinsic”, “Bending”, and “Fiber Spooled With Tension”.
- 4 Enter the “Bending” value 0.12
- 5 Enter the “Fiber Spooled with Tension” value 0.5.
- 6 In the “Output” section, enter “Spectral Range” 0.4 and “Number of Steps” 51.



- 7 Press OK to close the “Birefringence” dialog box
- 8 Go to the “Birefringence” view tab. The birefringence and Differential Group Delay (DGD) vs. wavelength are plotted there.

Your “Birefringence” view tab should look like this:

The results can now be verified by selecting the “Birefringence” tab on the “Views” window:

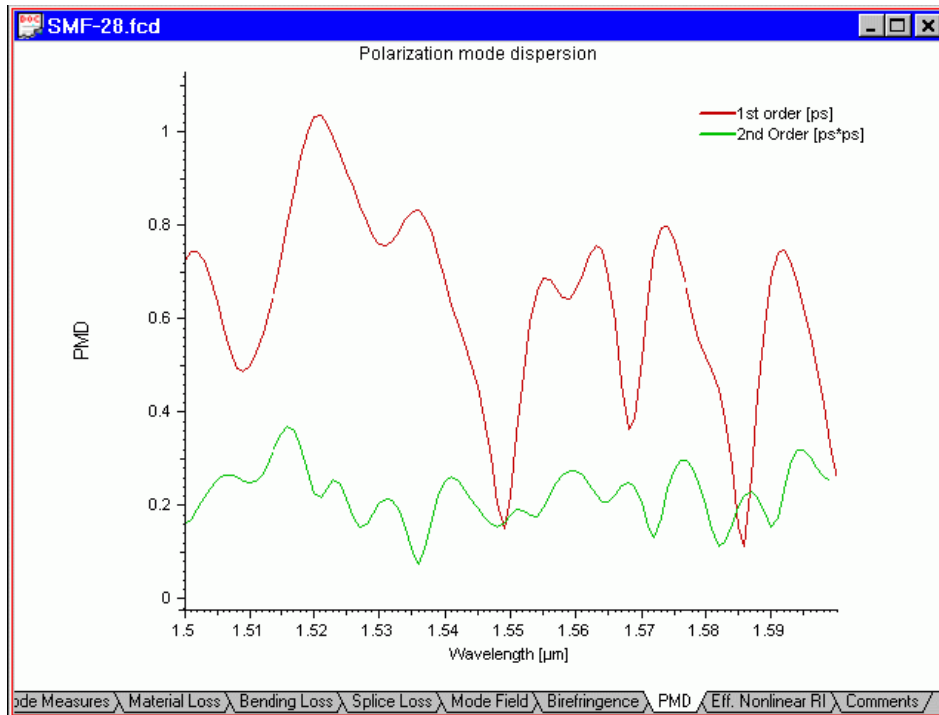


Calculating polarization mode dispersion

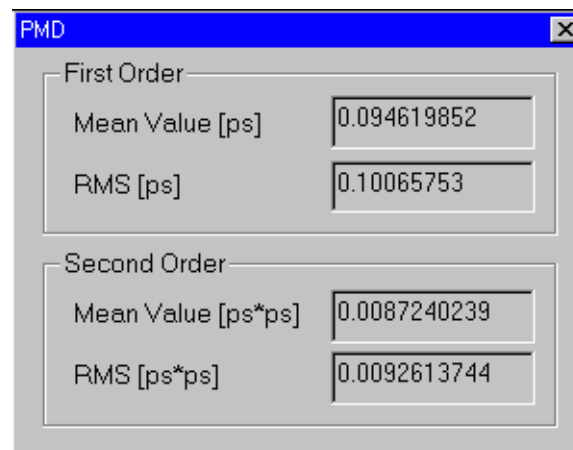
Click the “PMD” icon in the “Navigator” pane. The “Polarization Mode Dispersion” dialog box appears.

To execute the polarization mode dispersion calculations, leave the defaults and press “OK”.

The program calculates the polarization mode dispersion and updates the “PMD” tab in the “Views” window.



The “PMD” dialog box appears automatically showing numerical values related to the first two orders of the polarization mode dispersion. These are statistical values and can be different on your display.



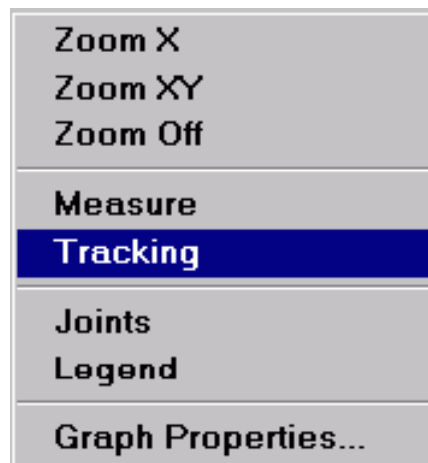
Using Graph Tools

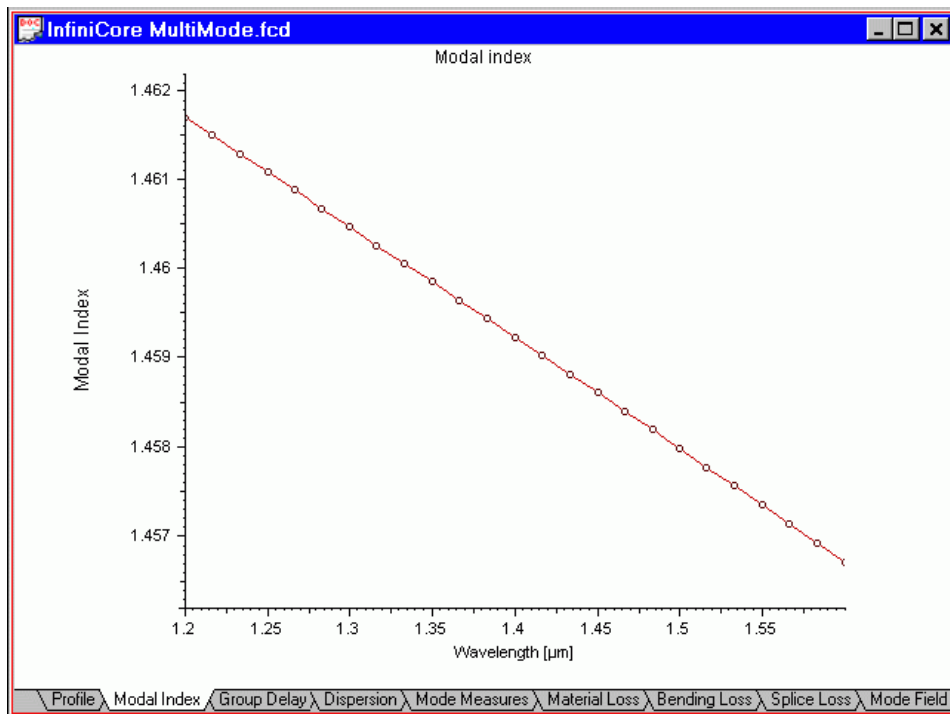
Using “Joints” tool

The “Joints” tool shows the actual calculated points of a curve.

Do the following steps:

- | Step | Action |
|------|--|
| 1 | Select a tab in the “Views” window, for example the “Modal Index” tab. |
| 2 | Press the “Joints” button on the “Graph Tools” toolbar or, select the “Joints” item from the floating context menu, accessible by right clicking in the Views windows. |





3 Select "Joints" again to turn it off.

Using “Zoom” tools

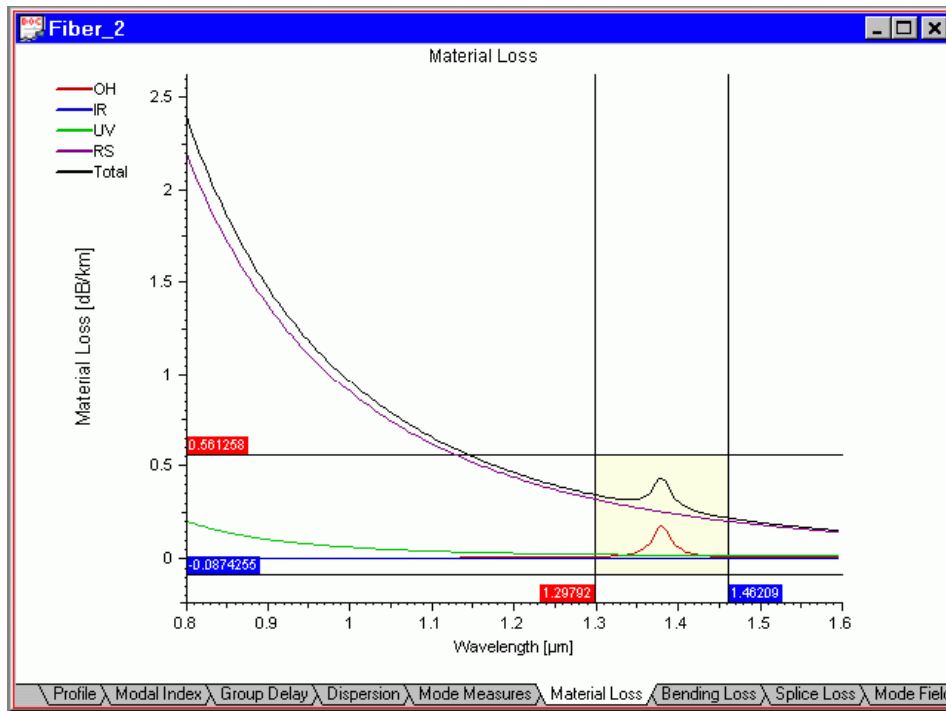
“Zoom X”, “Zoom XY” and “Zoom Off” are convenient tools for expanding a portion of the graph.

“Zoom X” expands the view only in horizontal direction, “Zoom XY” – in both.

Do the following steps:

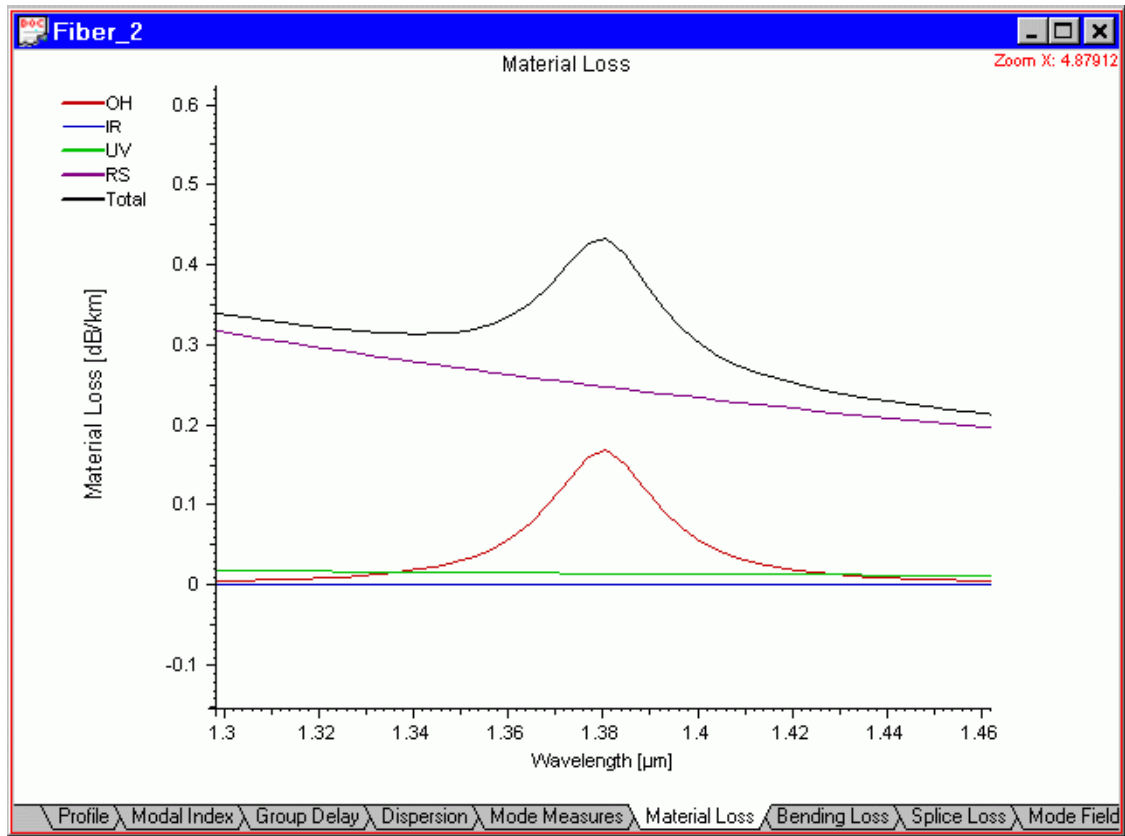
Step Action

- 1 Select, for example, the “Material Loss” tab in the Views window.
- 2 Select “Zoom XY” from the “Graph Tools” floating menu or the “Graph Tools” toolbar.
- 3 Now, with the left mouse button, click-and-drag a region to be expanded to a full graph. Before releasing the left mouse button, the View tab should look like this:



- 4 Release the left mouse button. The selected part is expanded to the full tab. The “View” tab should now look something like this:

USING GRAPH TOOLS



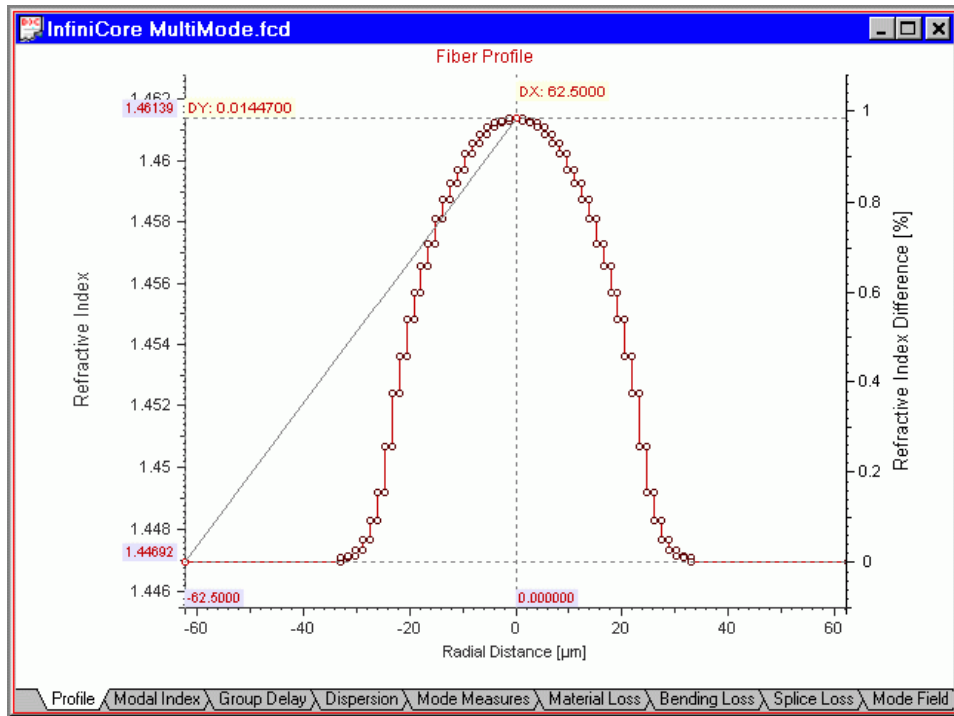
- 5 Select "Zoom Off " to restore the default view scale.

Using “Measure” tool

The “Measure” tool measures the difference between two points of the curve.

Do the following steps:

- | Step | Action |
|------|---|
| 1 | Select, for example, the “Profile” tab in the Views window. |
| 2 | Select “Measure” from the “Graph Tools” floating menu or the “Graph Tools” toolbar. |
| 3 | With the left mouse button, click-and-drag to measure the coordinates' difference. |
| 4 | Select “Measure” again to turn it off. |

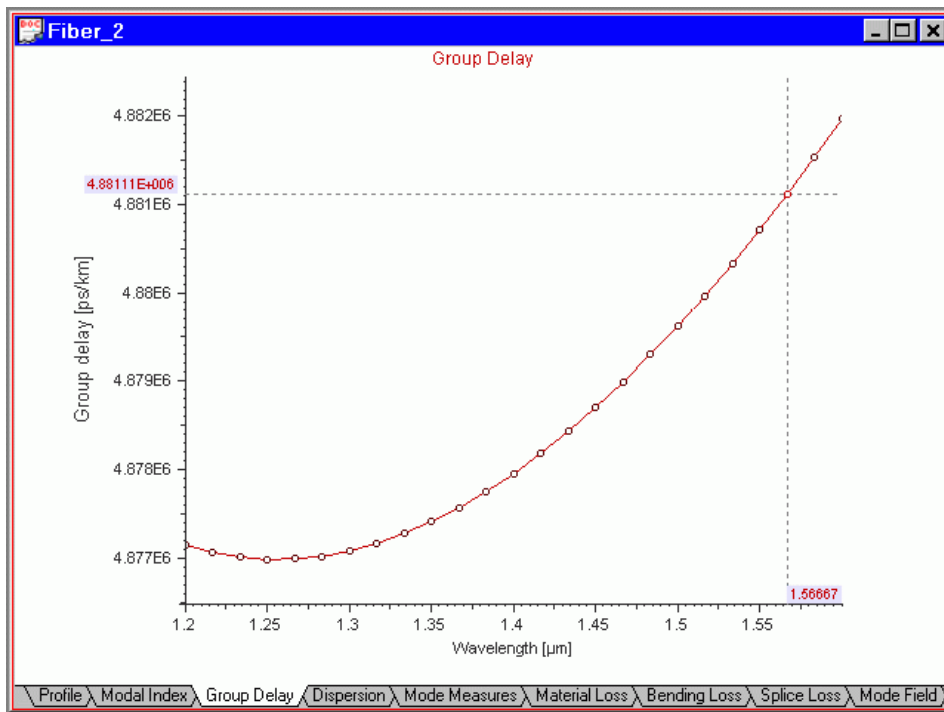


Using “Tracking” tool

The “Tracking” tool shows the XY coordinates of a point of a curve.

Do the following steps:

- | Step | Action |
|------|--|
| 1 | Select the “Group Delay” tab in the Views window. |
| 2 | Select “Tracking” from the “Graph Tools” floating menu or the “Graph Tools” toolbar. |
| 3 | With the left mouse button, click-and-drag to track the coordinates. |
| 4 | Select “Tracking” again to turn it off. |



Using “Legend” tool

The “Legend” tool shows the short descriptions of the curves in multi-curve graphs. Its use is identical to that of the other graph tools. The legend can be dragged, so the user can position it anywhere on the “Views” tab.



Technical Background

Refractive Index of Fibers

Host materials

Optical telecommunication-grade fibers are made usually from silica glasses. The high purity glass is called the host material or substrate. Its bulk refractive index usually defines the refractive index of the fiber cladding. Adding dopant materials to the host material forms the fiber core.

Dopant materials

To change the refractive index of optical fiber, pure silica is often doped with dopants. For example, adding germanium can result in an increase in the refractive index, while adding fluorine reduces it. The refractive index of doped material can be determined by the linear relationship between the doped material's mole percentage and permittivity.

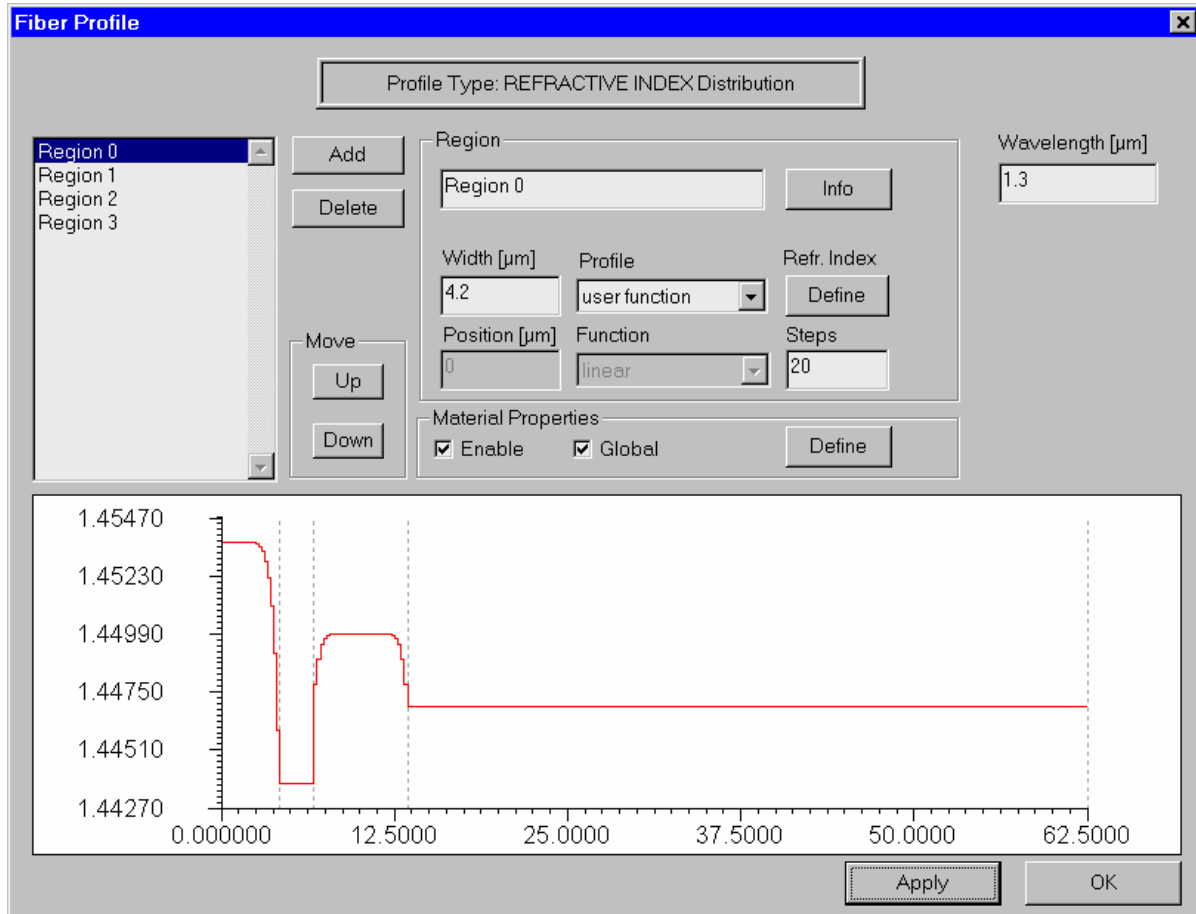
Assume that n_0 is the refractive index of the host material and n_1 is the refractive index of m_1 molepercentage doped material. Then, the refractive index n of m molepercentage doped material can be interpolated as:

$$n^2 = n_0^2 + \frac{m}{m_1}(n_1^2 - n_0^2) \quad (1)$$

Index profile of fibers

The radial distribution of the fiber refractive index is called the index profile. That profile determines guiding properties of the fiber. In general, the core region has a higher index than the cladding region. However, the index profile can have regions where the index is lower than the cladding value. Modern fiber designs are based on index profiles that assure proper operation within a range of wavelengths.

For example, a dispersion flattened fiber design involves a couple of concentric index regions.



In OptiFiber “regions” define a rotationally symmetric fiber profile. In the picture above, the fiber profile consists of four regions. Each region has its dimension (width) and profile. The default profile options are listed below, where x is the region’s local coordinate, w is the width of the region.

Constant profile:

$$n(x) = \text{const} \quad (2)$$

Linear profile:

$$n(x) = n(0) + x \cdot \frac{n(w) - n(0)}{w} \quad (3)$$



Parabolic profile:

$$n(x) = [n(w) - n(0)] \cdot \left(\frac{x}{w}\right)^2 + n(0) \quad (4)$$

Exponential profile:

$$n(x) = [n(0) - n(w)] \cdot \frac{e}{e-1} \cdot \exp\left(-\frac{x}{w}\right) + \frac{e \cdot n(w) - n(0)}{e-1} \quad (5)$$

where $n(0)$, $n(w)$ is the refractive index at $x = 0$ and $x = w$, respectively.

Gaussian profile:

$$n(x) = n_{max} \exp\left\{-\ln 2 \cdot \left[\frac{2 \cdot (x - x_0)}{h \cdot w}\right]^2\right\} \quad (6)$$

where n_{max} is the maximum value, x_0 is the peak position, and h is the normalized value of FWHM.

Alpha –peak profile:

$$n(x) = n_{max} \cdot \sqrt{1 - 2\Delta \cdot \left(\frac{x}{w}\right)^\alpha} \quad (7)$$

where n_{max} is the maximum value, Δ is normalized difference. It is defined as:

$$\Delta = \frac{n_{max}^2 - n_{min}^2}{2n_{max}^2} \quad (8)$$

Alpha –dip profile:

$$n(x) = n_{max} \cdot \sqrt{1 - 2\Delta \cdot \left(1 - \frac{x}{w}\right)^\alpha} \quad (9)$$

where n_{max} is the maximum value, Δ is normalized difference.

Two techniques for defining the refractive index profile

Currently OptiFiber implements two methods for defining the geometry and the material composition of the fiber:

- Direct definition of the refractive index profile: the abscissa values $n(x)$ in the formulae above are interpreted directly as refractive index values at a user specified wavelength. Wherever needed, the dopant concentration in each region is internally calculated by interpolating the given value between the refractive index values of two materials – “Dopant +” and “Dopant -” and using the formula given in “Dopant Materials”. The material dispersion and dispersion of the profile are calculated from the known Sellmeier coefficients of “Dopant +” and “Dopant -”. The parameters of the materials “Dopant +” and “Dopant -” are either taken from the internal extendable material library of OptiFiber or user specified. They can be different for each region or global for the whole profile. This method is convenient whenever the distribution of the refr. index is known from experimental measurements, estimations, etc.
- Definition of a dopant concentration profile: the abscissa values $n(x)$ in the formulae are interpreted as molar concentration of a certain dopant. The material dispersion and dispersion of the profile are calculated from the known Sellmeier coefficients of the dopant, which are taken from the internal extendable material library of OptiFiber or are user specified.

This method is convenient when the dopant concentration distribution of the fiber or at least of its preform are known with sufficient accuracy.



Fiber Propagation Modes

Scalar fiber modes

The designation of Linearly Polarized (LP) Fiber modes is based on the assumption of weak guidance. Weakly guiding fibers have a small difference between core and cladding refractive index.

Two numbers designate the LP (m, n) modes:

m – azimuthal number

n – orbital number where $m = 0, 1, 2, \dots$ and $n = 1, 2, \dots$

Both guided and cladding modes of arbitrary circular symmetric refractive index profile are calculated either by the accurate finite difference method or by the analytical matrix method.

Vector fiber modes

The designation of vector fiber modes TE, TM, EH, and HE follows the convention:

TE (0,n) – transverse electric family of modes

TM (0,n) – transverse magnetic family of modes

EH (m, n) – hybrid family of modes

HE (m, n) – hybrid family of modes

where m and $n=1, 2, \dots$

See Appendix A, Fiber Mode Solvers by Matrix Method, for details on the LP and Vector mode solvers that use the matrix method.

Group Delay and Dispersion Definitions

Material dispersion of the bulk glasses

If the refractive index of the fiber material varies with wavelength, thus causing the group velocity to vary, it is classified as material dispersion.

The group delay T_g is given by the product of the propagation distance z by the first frequency-derivative of the propagation constant:

$$T_g = z \frac{d\beta}{d\omega} = z \frac{d\lambda}{d\omega} \frac{d(nk_0)}{d\lambda} \quad (10)$$

where n is the refractive index, $\lambda = 2\pi c/\omega$, $k_0 = 2\pi/\lambda$

We have:

$$T_g = \frac{-2\pi cz}{\omega^2} \left(k_0 \frac{dn}{d\lambda} + n \frac{dk_0}{d\lambda} \right) = \frac{z}{c} \left(n - \lambda \frac{dn}{d\lambda} \right) \quad (11)$$

The dispersion coefficient D is defined as:

$$D = \frac{dT_g}{d\lambda} \quad (12)$$

In bulk materials, we have:

$$D = -\frac{z}{c} \lambda \frac{d^2n}{d\lambda^2} \quad (13)$$

Material dispersion of the fiber

In a fiber, the materials of core and cladding are different. If there are L layers in the fiber cross-section, each layer has different refractive index.



The total material dispersion of a fiber is calculated by:

$$D(\lambda) = -\frac{\lambda z}{c} \sum_{i=1}^L \Gamma_i \frac{d^2 n_i}{d\lambda^2} \quad (14)$$

where the confinement factor of each layer is Γ_i . The confinement factor is the portion of total power guided in the i -th layer.

Waveguide dispersion of the fiber

Waveguide dispersion is the result of the wavelength-dependence of the effective refractive index N_{eff} of the fiber mode. First, the mode solver calculates the relation between N_{eff} and wavelength λ , then the waveguide dispersion is calculated by:

$$D_{wg} = -\frac{z}{c} \lambda \frac{d^2 N_{eff}}{d\lambda^2} \quad (15)$$

Total dispersion of the fiber

The total dispersion is the total effect of material and waveguide dispersion. It is calculated in a similar way as for calculating waveguide dispersion. In this case, the fiber refractive index profile depends on the wavelength. The material dispersion effect should be calculated first. Then the mode solver calculates the mode effective index N_{eff} . The total dispersion of a fiber is:

$$D_{total} = -\frac{z}{c} \lambda \frac{d^2 N_{eff}}{d\lambda^2} \quad (16)$$

Mode Field Diameter and Mode Area Definitions

Mode field diameter and area importance

The Mode Field Diameter (MFD) is an important parameter related to the optical field distribution in the fiber. It has been shown that MFD provides useful information about the cabling performances, such as possible joint, macrobending, and microbending losses. The effective area of the fibers has a direct relation to the nonlinear distortions in long fiber links. Currently OptiFiber calculates the following spatial measures of the modes:

Near-field diameter definition

The near-field Mode Field Diameter (near-field MFD) is also known in the literature as the “Petermann I” diameter. It is defined as the diameter at which the near field power falls to $1/e^2$ of its maximum value. It can be calculated by [Artiglia, 1989[2]:

$$d_n = 2\sqrt{2} \left(\frac{\int_0^\infty E^2(r)r^3 dr}{\int_0^\infty E^2(r)r dr} \right)^{1/2} \quad (17)$$

where $E(r)$ is the optical mode field distribution.

Far-field diameter definition

The far-field Mode Field Diameter (far-field MFD) is also known in the literature as the “Petermann II” diameter. It is defined as the diameter at which the far field power falls to $1/e^2$ of its maximum value. It can be calculated by [Artiglia, 1989[2]:

$$d_f = 2\sqrt{2} \left(\frac{\int_0^\infty E^2(r)r dr}{\int_0^\infty [E'(r)]^2 r dr} \right)^{1/2} \quad (18)$$

where $E(r)$ is the optical mode field distribution, and prime denotes differentiation of a function with respect to its argument.



Effective mode area definition

The effective Mode Area (eff. MA) is calculated as [see, for example, G. Agrawal, 1995]

$$A_{eff} = \frac{\left[\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x, y)|^2 dx dy \right]^2}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x, y)|^4 dx dy} \quad (19)$$

where $E(x,y)$ is the optical mode field distribution.

Effective diameter definition

OptiFiber calculates also the effective Mode Field Diameter (eff. MFD), defined as:

$$d_{eff} = \frac{2\sqrt{2} \int E_i^2 r dr}{\left[\int E_i^4 r dr \right]^{\frac{1}{2}}} \quad (20)$$

$$d_{eff} = \frac{2}{\sqrt{\pi}} \sqrt{A_{eff}}$$

where $E(r)$ is the optical mode field distribution.

Cutoff Wavelengths

The cutoff wavelength for any mode is defined as the maximum wavelength at which that mode will propagate. The cutoff wavelength λ_c of LP_{11} is an important specification for a single-mode fiber. The operation wavelength must be greater than the cutoff wavelength of LP_{11} to operate the fiber in a single mode regime. λ_c can be determined analytically for some specified fiber profiles. For a general fiber profile, a highly accurate numerical mode solver should be involved to calculate cutoff wavelength. OptiFiber currently implements two different approaches for finding the cutoff and respectively two different values can be calculated for each mode:

A “Theoretical” cutoff value

This is the wavelength, above which the given mode cannot propagate, even in short and unperturbed samples of this fiber. This value is calculated using the general numerical mode-solvers of OptiFiber. It is defined as the wavelength, above which the Eigenvalue problem formulated for the current fiber design and for the given mode does not have real solutions.

An “Estimated ITU-T” cutoff value

These values are obtained by emulating the actual experimental cutoff measurements, as described in the ITU-T / TIA / EIA recommendations (see [ITU-T[23]] in the Technical references). It employs a macrobending loss formula [J. Sakai and T. Kimura, 1978 [26]] applicable to any mode in arbitrary-index profile optical fibers. The ITU-T/EIA-455-80A recommendation is formulated only for the cutoff of LP_{11} .



Fiber Loss Models

Fiber propagation loss definition

The total fiber loss can be divided into material losses and fiber induced losses. Material losses include Rayleigh scattering, ultraviolet (UV), infrared (IR) absorption, and hydroxyl (OH) absorption losses. Material losses are the limiting losses in fibers.

Fiber loss is defined as the ratio of the optical output power P_{out} from a fiber of length L to the optical input power P_{in} . The symbol α is commonly used to express loss in decibels per kilometer:

$$\alpha = \frac{10}{L} \log \left(\frac{P_{in}}{P_{out}} \right) \quad (21)$$

Rayleigh scattering model

Because of the granular appearance of atoms or molecules of the glass fiber, light transmitted through the fiber suffers scattering loss. This is known as Rayleigh scattering loss.

Rayleigh scattering losses in a fiber are typically determined through experimental measurement. The loss is expressed in decibels per kilometer through [Buck, 1995[4]]:

$$\alpha_s = \frac{A}{\lambda^4} \quad (22)$$

For a single-component glass such as SiO_2

$$A = \frac{8\pi^3}{3} n_0^8 p^2 \beta k T \quad (23)$$

where n_0 is the refractive index, p is the photoelastic coefficient, β is the thermal compressibility, k is the Boltzmann coefficient, and T is the absolute temperature of the sample.

Ultraviolet absorption model

Ultraviolet or UV absorption results from electronic absorption bands in the ultraviolet region. The electronic absorption bands are associated with the band gaps of amorphous glass materials. Absorption occurs when a photon interacts with an electron in the valence band and excites it to a higher energy level. The UV absorption



at any wavelength can be expressed as a function of the mole fraction x of GeO_2 [Buck, 1995[4]]:

$$\alpha_{uv}(\lambda) = 10^{-2} \frac{154.2x}{46.6x + 60} \exp\left(\frac{4.63}{\lambda}\right) \quad (24)$$

UV loss is small compared to scattering loss in the near infrared region.

OH-radical absorption model

The OH radical of H₂O molecule vibrates at a fundamental frequency corresponding to IR light wavelength of $\lambda = 2.8\mu m$. Since the OH radical is slightly anharmonic, “overtones” can occur. These cause OH absorption lines to occur at $\lambda = 1.39$, 0.95 , and $0.725\mu m$, the second, third, and fourth harmonics of fundamental frequencies, respectively. Broad peaks can appear [see, for example, Marcuse, 1981[7]]. OH absorption can be characterized by fitting the absorption lines by Lorentzian or Gaussian method.

Lorentzian fit method:

$$\alpha_{OH}(\lambda) = \sum_{i=1}^7 \frac{A_i}{1 + \left(\frac{\lambda - \lambda_i}{\sigma_i}\right)^2} \quad (25)$$

Gaussian fit method:

$$\alpha_{OH}(\lambda) = \sum_{i=1}^7 A_i \exp\left[-\left(\frac{\lambda - \lambda_i}{\sigma_i}\right)^2\right] \quad (26)$$

In the above two equations, A_i is amplitude, λ_i is absorption peak position, and σ_i is the width of the i -th absorption line. Using up to seven absorption lines fits the OH absorption spectrum here.

In contemporary state-of-the-art fibers the hydroxyl-group absorption is greatly reduced, and only the peak at $\lambda = 1.38 - 1.39\mu m$ still retains some practical importance.



Infrared absorption model

Infrared or IR absorption is associated with the characteristic vibration frequency of the particular chemical bond between the atoms of which the fiber is composed. An interaction between the vibrating bond and the electromagnetic field of the optical signal results in a transfer of energy from the field to bond, thereby causing absorption.

The IR absorption expression for $GeO_2 - SiO_2$ glass is [Buck, 1995[4]]:

$$\alpha_{IR} = 7.81 \times 10^{11} \exp\left(\frac{-48.48}{\lambda}\right) \quad (27)$$

Macrobending loss model

The macrobending loss γ is a radiative loss when the fiber bend radius is large compared to the fiber diameter. It is defined as usual by $P(z)=P(0) \exp(-\gamma z)$ where $P(0)$ is the input power and $P(z)$ is the output power at distance z respectively.

Currently OptiFiber implements two different macrobending loss models:

- 1 The first model uses the closed-form integral formula, published by J. Sakai and T. Kimura [J. Sakai and T. Kimura, 1978[26]]. It is appropriate for calculating the macrobending loss of any LP mode, both fundamental and higher-order, in arbitrary-index profile optical fibers. Using this formula the macrobending power loss coefficient is expressed as a function of the bending radius R_b in the form:

$$\gamma = \frac{\sqrt{\pi}(P_{clad}/P)}{2sr_c[K_{v-1}(W)K_{v+1}(W) - K_v^2(W)]} \frac{\exp\left(\frac{-4\Delta W^3}{3r_c V^2} R_b\right)}{W\left(\frac{WR_b}{r_c} + \frac{V^2}{2\Delta W}\right)^{\frac{1}{2}}} \quad (28)$$

The parameters appearing above are given by:

$$V = k_0 r_c \sqrt{N_{max}^2 - N_{clad}^2} \quad (29)$$

(the normalized dimensionless frequency)



$$W = r_c \sqrt{\beta^2 - (k_0 N_{clad})^2} \quad (30)$$

$$\Delta = \frac{(N_{max}^2 - N_{clad}^2)}{2N_{max}^2} \quad (31)$$

where r_c denotes the fibre core radius, N_{max} is the maximum value of the refractive index and N_{clad} is the cladding index, β is the propagation constant of the mode, k_0 is the prop. constant in vacuum, V is the azimuthal mode number, $s = 2$ if $v = 0$ or $s = 1$ for $v \neq 0$ and K_v is the modified Bessel function of the second kind of order v .

- 2 Using the second macrobending loss model the coefficient γ can be expressed as [Snyder and Love, 1983[20]]:

$$\gamma = \left(\frac{\pi V^8}{16 r_c R_b W^3} \right)^{1/2} \exp\left(-\frac{4 R_b \Delta W^3}{3 r_c V^2} \right) \frac{\left[\int_0^\infty (1-f) F_0 R dR \right]^2}{\int_0^\infty F_0^2 R dR} \quad (32)$$

where F_0 is the radial field of the fundamental mode:

$$f = \frac{N_{max}^2 - N(R)^2}{N_{max}^2 - N_{clad}^2} \quad (33)$$

and $N(R)$ is the refractive index profile of the fiber. The other parameters are given above.

The two models give similar results for step-index fibers.

The loss coefficient γ can be converted to loss in decibels per kilometer units as follows:

$$\alpha_{macro} = \frac{10}{L} \cdot \log\left(\frac{P_{in}}{P_{out}}\right) = \frac{10}{L} \cdot \log[\exp(\gamma L)] = \frac{10}{\ln(10)} \cdot \gamma \quad (34)$$

Microbending loss model

Microbending loss is a radiative loss in fiber resulting from mode coupling caused by random microbends,

which are repetitive small-scale fluctuations in the radius of the curvature of the fiber axis.

An approximate expression for the attenuation coefficient is given by [Petermann, 1976[12]]:

$$\alpha_{micro} = A(kn_1d_n)^2(kn_1d_n^2)^{2p} \quad (35)$$

where A is a constant, d_n is the near field diameter, n_1 is the core refractive index of fiber, k is the free space wavenumber, and p is the exponent in the power law.

Splice loss model

A splice is the dielectric interface between two optical fibers. Any index-of-refraction mismatch at any point in this interface will produce reflection and refraction of the light incident at that point. For splicing calculations, we assume that the mode field of single-mode fibers is nearly Gaussian. The coupling losses for the splicing connectors can be calculated by evaluating the coupling between two misaligned Gaussian beams.

Based on the above model, the coupling loss between two single mode fibers is given by [Miller and Kaminow, 1988[10]]:

$$\alpha_{splice} = -10 \cdot \log \left[\left(\frac{16n_1^2 n_2^2}{(n_1 + n_2)^4} \right) \frac{\sigma}{q} \exp\left(\frac{-\rho u}{q}\right) \right] \quad (36)$$



where

$$\rho = \frac{(kw_1)^2}{2} \quad (37)$$

$$q = G^2 + \frac{(\sigma + 1)^2}{4} \quad (38)$$

$$u = (\sigma + 1)F^2 + 2\sigma FG \sin\theta + \sigma \left(G^2 + \frac{\sigma + 1}{4} \right) \sin^2\theta \quad (39)$$

$$F = \frac{x}{kw_1^2} \quad (40)$$

$$G = \frac{z}{kw_1^2} \quad (41)$$

$$\sigma = \left(\frac{w_2}{w_1} \right)^2 \quad (42)$$

$$k = \frac{2\pi n_2}{\lambda} \quad (43)$$

The symbols above are:

n_1 - core refractive index of the fiber

n_2 - refractive index of the medium between the two fibers

λ - wavelength

w_1 - near field mode field radius of transmitting fiber

w_2 - near field mode field radius of receiving fiber

x - lateral offset

z - longitudinal offset

θ - angular misalignment



Fiber Birefringence Models

Fiber birefringence definition

The birefringence is defined by the difference between the propagation constants of the polarization Eigenmodes, that is:

$$\Delta\beta = \beta_x - \beta_y \quad (44)$$

The Differential Group Delay (DGD) per unit length is defined by:

$$\partial\tau = \frac{\partial\Delta\beta}{\partial\omega} = -\frac{\lambda^2}{2\pi c} \frac{\partial\Delta\beta}{\partial\lambda} \quad (45)$$

Intrinsic perturbations birefringence

Intrinsic perturbations are accidentally introduced in the manufacturing process and are permanent feature of the fiber. These include a noncircular core and nonsymmetrical stress fields in the glass around the core region. A noncircular core gives rise to geometric birefringence, whereas a nonsymmetrical stress field creates stress birefringence. These results were obtained by the perturbation theory and applied only for step index fibers.

Elliptical core birefringence definition

The geometrical anisotropy of a non-circular core introduces a linear birefringence in the fiber. This birefringence depends strongly on the frequency, or on the normalized frequency V , at which the fiber is being operated.

The non-circulatory or ellipticity of the core is defined by the parameter ε :

$$\varepsilon = 1 - \frac{a}{b} \quad (46)$$

where a and b are respectively the minor and major axis of the elliptical core.

The birefringence induced by an elliptical core is linear. The fast axis and slow axis of the birefringence corresponds respectively to the major and minor axis of the ellipse.

In the case of a step index fiber, the birefringence



$$\Delta\beta_{ell} = \beta_x - \beta_y \quad (47)$$

is given by [Sakai and Kimura, 1981[17]]:

$$\Delta\beta_{ell} = \varepsilon n_1 k_0 \Delta^2 G(V) \quad (48)$$

where

$$\Delta = \frac{n_1 - n_2}{n_1} \quad (49)$$

is the relative index difference between the core refractive index n_1 and the cladding refractive index n_2 .

The wave propagation constant is

$$k_0 = \frac{2\pi}{\lambda} \quad (50)$$

The function $G(V)$ in the birefringence formula is given by

$$G(V) = \frac{W^2}{V^4} \left[U^2 + (U^2 - W^2) \left[\frac{J_0(U)}{J_1(U)} \right]^2 + UW^2 \left[\frac{J_0(U)}{J_1(U)} \right]^3 \right] \quad (51)$$

with the following definitions of waveguide parameters

$$U = a \sqrt{n_1^2 k_0^2 - \beta^2} \quad (52)$$

$$W = a \sqrt{\beta^2 - n_2^2 k_0^2} \quad (53)$$

$$V = \sqrt{U^2 + W^2} = ak_0 \sqrt{n_1^2 - n_2^2} \quad (54)$$

where a is the core radius.

The Differential Group Delay (DGD) per unit length is

$$\partial\tau_{ell} = \frac{\varepsilon n_1 \Delta^2}{c} \frac{d}{dV} [VG(V)] \quad (55)$$

where c is the speed of light in vacuum.

Internal stress birefringence definition

Stress birefringence caused by a nonsymmetrical stress field in the core region of a fiber typically arises in combination with noncircular fiber geometry. The necessarily different chemical composition of the core relative to the cladding in single-mode fiber usually results in a slightly different thermal expansion coefficient for the two regions. This gives rise to radially directed stresses when the fiber is cooled after being drawn.

In an ideal, circularly symmetrical fiber, these stress fields are symmetrical and thus do not cause anisotropy. However, if there is a noncircular shape to either the core or the cladding in the preform, the drawn fiber will have internal stress fields that are not circularly symmetrical.

In a step index fiber with an elliptical core, the birefringence is given by [Sakai and Kimura, 1982[18]]:

$$\Delta\beta_{InternalStress} = -\varepsilon \frac{\Delta\alpha\Delta T}{2(1-\nu)} E C k_0 \left[S(V) - 3\left(\frac{2a}{d}\right)^4 + \left(\frac{2a}{d}\right)^6 H(V) \right] \quad (56)$$

where

$$\Delta\alpha = \alpha_{co} - \alpha_{cl} \quad (57)$$

is the difference between the thermal expansion coefficients of the core α_{co} and cladding α_{cl}

and

$$\Delta T = T_r - T_s \quad (58)$$

is the difference between the room temperature T_r and the softening temperature T_s of the more heavily doped material.

The remaining symbols in the above internal-stress induced birefringence are:

ε - core ellipticity

ν - Poisson's ratio

E - the Young modulus

C - photoelastic constant

k_0 - wave propagation constant in vacuum

a - the average core radius

d - the cladding outer diameter of the fiber

and

$$S(V) = \frac{W^2}{V^2} \quad (59)$$

$$H(V) = 2 + \frac{4(U^4 - W^4)}{U^2 V^2 W^2} + \frac{4J_0(U)}{UJ_1(U)} \quad (60)$$

The symbols U,V, and W are defined in section: Elliptical core birefringence definition.

The Differential Group Delay (DGD) per length unit is given by:

$$\partial\tau_{InternalStress} = -\frac{\varepsilon}{c} \frac{\Delta\alpha\Delta T}{2(1-\nu)} EC \left[\frac{d}{dV} [VS(V)] + \left(\frac{2a}{d}\right)^6 \frac{d}{dV} [VH(V)] \right] \quad (61)$$



Extrinsic perturbations birefringence

Birefringence can also be created in a fiber when it is subjected to external forces in handling or cabling. Such extrinsic sources of birefringence include lateral stress, fiber bending and fiber twisting. All three of these mechanisms are usually present to some extent in spooled and field-installed telecommunications fiber.

Lateral stress birefringence definition

When two equal and opposite forces p act across an axis of a fiber with a diameter d , the birefringence induced is linear. The fast axis of birefringence is aligned with the axis defined by the two opposite forces.

The birefringence is given by [Sakai and Kimura, 1981[17]]:

$$\Delta\beta_{LateralStress} = -8 \frac{Cp k_0}{\pi d} \left[1 - \left(\frac{a}{d} \right)^2 H(V) \right] \quad (62)$$

where

C - photoelastic constant

p - lateral force

k_0 - wave propagation constant in vacuum

d - the outer diameter of the fiber

a - the average core radius

and $H(V)$ was defined previously in the section: Internal stress birefringence definition.

The Differential Group Delay (DGD) per unit length $\partial\tau_{LateralStress}$ is:

$$\partial\tau_{LateralStress} = -8 \frac{Cp}{\pi c d} \left[1 - \left(\frac{a}{d} \right)^2 \left(H(V) + V \frac{dH(V)}{dV} \right) \right] \quad (63)$$

Bending birefringence definition

Bending on a fiber with a bending radius $R \gg a$ (fiber core) gives rise to a linear birefringence. The fast axis of birefringence is perpendicular to the bending plane. The slow axis is aligned with the bending radius.

The birefringence is given by [Sakai and Kimura, 1981[17]]:



$$\Delta\beta_{Bending} = -\frac{1}{8}\left(\frac{d}{R}\right)^2 ECk_0\left[1 - \frac{1}{3}\left(\frac{a}{d}\right)^2 H(V)\right] \quad (64)$$

with R being the bending radius, and other symbols are:

d - the outer diameter of the fiber

E - the Young modulus

C - photoelastic constant

k_0 - wave propagation constant in vacuum

a - the average core radius

and $H(V)$ was defined previously in the section: Internal stress birefringence definition.

The Differential Group Delay (DGD) per unit length is:

$$\partial\tau_{Bending} = \frac{-EC}{8c}\left(\frac{d}{R}\right)^2\left[1 - \frac{1}{3}\left(\frac{a}{d}\right)^2\left[H(V) + V\frac{dH(V)}{dV}\right]\right] \quad (65)$$

Bending under tension birefringence definition

If we consider a pure axial stress applied to the fiber, simple symmetry considerations show that there is no induced birefringence. But winding a fiber with axial tension f onto a drum introduces an additional linear birefringence that adds to the bending birefringence. This tension-coiled birefringence results from the lateral force exerted by the drum on the fiber in reaction to the tensile force f .

The definition is given by [Sakai and Kimura, 1981[17]]:

$$\Delta\beta_{Tension-coiled} = -2\frac{2-3\nu}{1-\nu}C\frac{f}{\pi dRc}k_0 \quad (66)$$



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where

C - photoelastic constant

f - axial tension

k_0 - wave propagation constant in vacuum

R - bending radius

The Differential Group Delay (DGD) per unit length is given by:

$$\partial\tau_{Tension-coiled} = -2\frac{2-3\nu}{1-\nu}C\frac{f}{\pi dRc} \quad (67)$$



Polarization Mode Dispersion Models

Polarization mode dispersion

In ideal single-mode fibers, propagation constants of the two polarization Eigenmodes are degenerate. In real telecommunications fibers, perturbations act on the fiber in a way that it induces a birefringence, which splits this degeneracy. Consequently, when a pulse is launched in a fiber, it gives rise to a differential group delay between the two polarization Eigenmodes. The stochastic behavior of these perturbations is an issue because it yields to the phenomenon of random mode coupling which makes impossible the basic definition of the differential group delay.

Principal states of polarization

The Principal States of Polarization (PSP) model [Poole and Wagner, 1986[14]] is based on the observation that at any given optical frequency, there exists a set of two mutually orthogonal input states of polarization for which the corresponding output states of polarization are independent of frequency to first order. The Differential Group Delay (DGD) resulting from Polarization Mode Dispersion (PMD) is then defined between the two output principal PSPs.

The birefringence in telecommunication single-mode fibers varies randomly along the fiber length, an artifact of variation in the drawing and cabling process. Furthermore, owing to the temperature dependence of many of the perturbations that act on the fiber, the transmission properties typically vary with ambient temperature. In practice, fluctuations in temperature strongly affect PMD time evolution. To evaluate properties of long fiber spans, one adopts a statistical approach. In this case of long span fibers, the polarization Eigenstates can only be defined locally and the birefringence vector has to be considered as stochastic.

Dispersion vector definition

In the time domain, the Polarization Mode Dispersion (PMD) induces a time shift between the two Principal States of Polarization (PSP).

In the frequency domain, the output state of polarization undergoes a rotation on the Poincaré sphere about an axis connecting the two PSPs.

The rate and direction of rotation is given by the dispersion vector $\Omega(\omega, z)$ given by:

$$\Omega(\omega, z) = \Delta\tau \cdot P_b \quad (68)$$

where P_b - represents the negative output principal state.

The strength of the dispersion vector $\Omega(\omega, z)$ is equal to the differential delay time $\Delta\tau$ between the two output principal states, where its combined Stokes vector corresponds to the Stokes vector of the negative output principal state. The direction of the Dispersion Vector Ω defines an axis whose two intercepts with the surface of

the Poincaré sphere correspond to the two principal states of polarization at the fiber output.

Poincaré sphere

The Poincaré sphere is a graphical tool that allows convenient description of polarized signals and polarization transformations during propagation. A point within a unit sphere can uniquely represent any state of polarization, where circular states of polarization are located at the poles. The coordinates of a point within or on the Poincaré sphere are the normalized Stokes parameters.

Ensemble simulation

Based on the Principal States of Polarization (PSP) model, one can model the whole fiber as a sum of N trunks where each trunk represents a uniform and constant birefringent device. A recursive formula describing the evolution of the dispersion vector for N and $N-1$ concatenated trunks is the basis for the calculus of the first and second order of the Differential Group Delay (DGD) induced by the Polarization Mode Dispersion (PMD).

In the ensemble simulation model, the PMD calculation is repeated in a number of runs. First, a set of concatenated fiber trunks is generated randomly. Then the polarization mode dispersion is calculated. In the second run, a second set of trunks is generated, followed by the PMD calculations. The process is repeated as many times as it is required. Statistics of the PMD are calculated using the same number of runs as the ensemble representation.

Spectral simulation

In the frequency domain, the Polarization Mode Dispersion (PMD) causes the state of polarization at the output of a fiber to vary with frequency for a fixed input polarization, which occurs in a cyclic fashion. When displayed on the Poincaré sphere, the polarization at the output moves on a circle on the surface of the sphere as the optical frequency is varied.

In the spectral simulation, a set of concatenated fiber trunks is generated randomly. The calculations of polarization mode dispersion are performed over a range of wavelengths.

First order dispersion definition

The Differential Group Delay (DGD) that is calculated based on a stochastic fiber model (first order PMD) quantifies the first order Polarization Mode Dispersion.

This latter represents the discrete model for Polarization Mode Dispersion (PMD) and is given by the following recursive formula [Bruyère, 1994[3]]



$$\begin{aligned}
 \Omega_N(\omega) &= \frac{\partial(W_N \Delta z \mathbf{S}_N)}{\partial \omega} + (\mathbf{S}_N \cdot \Omega_{N-1}(\omega)) \mathbf{S}_N \\
 &+ \cos(W_N \Delta z) [\Omega_{N-1}(\omega) - (\mathbf{S}_N \cdot \Omega_{N-1}(\omega)) \mathbf{S}_N] \\
 &+ \sin(W_N \Delta z) \mathbf{S}_N \times \Omega_{N-1}(\omega)
 \end{aligned} \tag{69}$$

where

$$\mathbf{S}_N = \frac{1}{W_N} \begin{pmatrix} \Delta\beta + \delta\beta_1^N \\ \delta\beta_2^N \\ \delta\beta_3^N \end{pmatrix} \tag{70}$$

$$\mathbf{W}_N = \begin{pmatrix} \Delta\beta + \delta\beta_1^N \\ \delta\beta_2^N \\ \delta\beta_3^N \end{pmatrix} = W_N \mathbf{S}_N \tag{71}$$

In the above, the symbol \mathbf{W} with index N represents the birefringence of the fiber. It consists of a background linear birefringence $\Delta\beta$ on top of which is added a perturbation birefringence $\delta\beta$. On the Poincaré sphere, the $\Delta\beta$ vector is $(\Delta\beta, 0, 0)$ and the $\delta\beta$ vector is $(\delta\beta_1, \delta\beta_2, \delta\beta_3)$, respectively. The above recursive formula represents the discrete version of the Poole's dynamical equation [Poole et al., 1991[16]].

Mean value of the first order PMD

For a long fiber span, the average Differential Group Delay (DGD) has a square root dependence on fiber length z as follows:

$$\langle \Delta\tau \rangle = \sqrt{\frac{8}{3\pi}} \Delta\beta' \sqrt{l_c} \sqrt{z} \tag{72}$$

Root Mean Square (RMS) of the first order PMD

The root mean square differential delay time has also a square root of length dependence:

$$\sqrt{\langle \Delta\tau^2 \rangle} = \Delta\beta' \sqrt{l_c} \sqrt{z} \quad (73)$$

The probability Density Function (PDF) of the differential delay time is Maxwellian:

$$PDF(\Delta\tau, z) = \sqrt{\frac{2}{\pi}} \frac{\Delta\tau^2}{\sigma_w^3(z)} e^{-\frac{\Delta\tau^2}{2\sigma_w^2(z)}} \quad (74)$$

Second order dispersion definition

The second order Polarization Mode Dispersion (second order PMD) is defined by the following expression [Foschini and Poole, 1991[6]]:

$$\Delta\tau_\omega(\omega, z) = |\Omega_\omega(\omega, z)| \quad (75)$$

where $\Omega_\omega(\omega, z)$ the first frequency derivative of the dispersion vector Ω :

$$\Omega_\omega(\omega, z) = \frac{\partial \Omega(\omega, z)}{\partial \omega} \quad (76)$$

The dispersion vector is defined in the section: Dispersion vector definition.



Effective Nonlinear Refractive Index

Usually one of the design goals when constructing a fiber is to minimize its nonlinearities. The effective nonlinear coefficients of optical fibers depend on the nonlinear indices of the bulk materials building the fiber and on its waveguiding properties: shape of modes, degree of confinement, etc. As a result it can vary within broad limits. OptiFiber calculates the eff. nonlinear coefficient as [Marcuse, 1991[8]]:

$$n_2^{eff} = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} n_2(x, y) |F(x, y)|^4 dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |F(x, y)|^2 dx dy} \quad (77)$$

where $n_2(x, y)$ is the user-defined spatially dependent nonlinear refractive index of the various fiber layers and $F(x, y)$ is the normalized mode field pattern.

Interference (speckle) patterns (linear superposition/composition of modal fields)

With OptiFiber the user can calculate the superposition/interference pattern of an arbitrary group of modes. Each of the modes has an arbitrary user defined guided power and initial phase (a complex weighting coefficient assigned). This feature targets applications such as coupling efficiency calculations, switching phenomena in a few mode fiber sensors, etc.

Coupling efficiencies (linear decomposition of an input beam)

OptiFiber calculates the per-mode coupling efficiencies (the linear decomposition) of a user defined input beam into an arbitrarily selected group of supported modes.

The decomposition coefficient is calculated using the following well-known expression:

$$\eta_{m,n} = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F_i(x,y) \cdot F_{m,n}(x,y) dx dy}{\left(\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |F_i(x,y)|^2 dx dy \right)^{1/2} \left(\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |F_{m,n}(x,y)|^2 dx dy \right)^{1/2}} \quad (78)$$

where $F_i(x,y)$ is the input field, $F_{m,n}(x,y)$ is the modal field.

Scanning

One of the most powerful features of OptiFiber software is the design optimization by means of parameter scanning. “Scanning” is the name of the parametrical calculations of some fiber characteristic versus certain technological properties or quantities of the fiber design: for example the core/cladding refractive index difference, the spatial width or some region, etc. It predicts automatically how any given fiber could be optimized versus a design goal, for example small, but non-zero dispersion and maximal mode area.

Compatibility with the NR-9200 Optical Fiber Analyzer from EXFO Inc.

Version 1.5 and later versions of OptiFiber are designed and developed to be fully compatible with NR-9200 in the sense that it directly imports the ASCII files with the experimental refractive index profile data, recorded by the low level drivers of the device. It is as a software tool that supplements and extends the fiber characterization capabilities of the NR-9200.

When the user chooses a NR-9200 Data File with a valid format the experimental data is processed and the following parameters are extracted and imported in OptiFiber:

- Fiber Data: Fiber name, Fiber type, Cladding index
- Measurement Info: Operator, Date, Measurement wavelength, Comments
- Scanning details: Scan type, Data type, Number of points, Scan step, Data format
- The actual data

The input files may contain just one scan (X) or two scans (X and Y).

After that, the experimental data is processed and a single, axially symmetric profile is formed from the available raw data.

The details of this process are controlled by the “Refractive index profile preconditioning dialog” described in the “Dialog Boxes Reference”. It offers two features:

- The ability to define the step (inversely proportional to the resolution) of the numerical approximation of the refractive index. This is the minimal refractive

index difference between two adjacent experimental points that are to be considered belonging to different reference index regions in OptiFiber. It is entered as a percentage of the maximal core-cladding difference. Lower values mean finer approximation/more layers/longer computations and vice-versa. The value of the step should be the best trade-off between accuracy and numerical efficiency.

- It offers the user the (optional) choice to reduce the ripples, imperfections and spurious mechanical or optical noises of the data by means of low-pass Fourier filtering and/or averaging. The bandwidth of the filter is given in percentage of the highest frequency of the profile curve as a function of the point number. The averaging substitutes every data point with the symmetrical mean value of the respective number of adjacent points. When this is not possible (for example the first point lacks left-standing neighboring points) the number of averaged points is reduced accordingly. The recommended values of the filtering and averaging parameters are 10 –15% and 2-3 respectively, however the overall quality of smoothing depends also on the value of refractive index step (as described above), so the user might prefer to fine-tune these three values for optimal results in his particular case.

When the experimental data is imported, the user can proceed with defining other parameters of the fiber, altering the profile data manually (for example by merging some marginal layers of the cladding) and with running the various models currently supported by OptiFiber.

The process of importing NR-9200 data is described in detail in “Tutorial Lessons/Lesson 2”. See also the description of the “Menu/Import Profile” command and of the “Refractive index profile preconditioning” dialog box.

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Tutorial Lessons

Lesson 1: Designing Single Mode Fiber

In this example, we will show you how to simulate a simple single-mode optical fiber that is optimized for use in the 1310 nm wavelength region. The main features of OptiFiber will be addressed in this example. You can find this example as the SMF-28.fcd file in the Samples directory.

Defining fiber profile

To define a fiber profile, follow these steps:

Step	Action
------	--------

- | | |
|---|---|
| 1 | From the “File” menu click “New” to open a new project. |
| 2 | 2. Click the “Fiber Profile” icon in the “Navigator” pane. |
| 3 | 3. In the “Select Profile Type” dialog box click “Refractive Index Profile” |
| 4 | 4. In the “Fiber Profile” dialog box add two regions: “Region 0” and “Region 1” |

For “Region 0”, enter the following data:

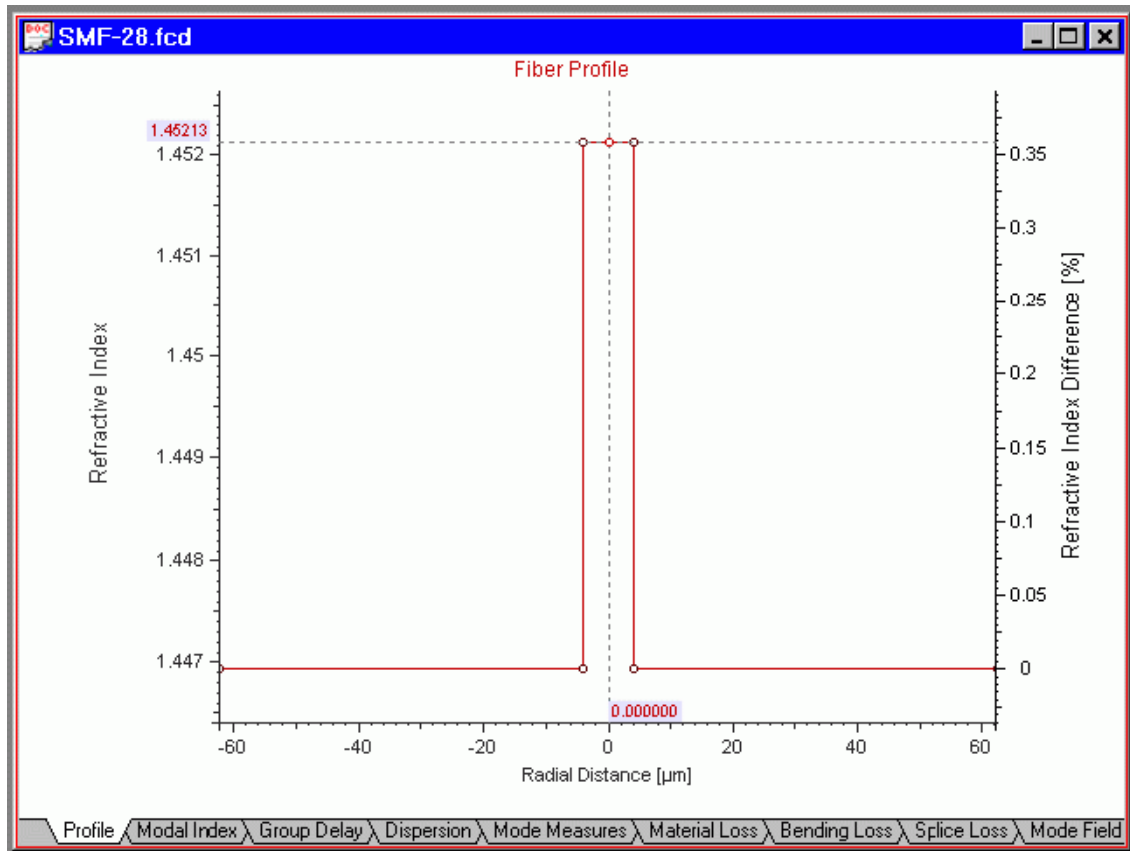
Width: 4.15
Profile: constant
Index: 1.45213
Click “Apply”

For “Region 1”, enter the following data:

Width: 58.35
Profile: constant
Index: 1.44692
Click “Apply”

Enter the wavelength value 1.3 microns.

Your fiber profile should look like the one below:



Note that both the absolute values of the reference indexes and the normalized difference Δ are shown.

Defining dispersion models

To define a dispersion model, follow these steps:

Step Action

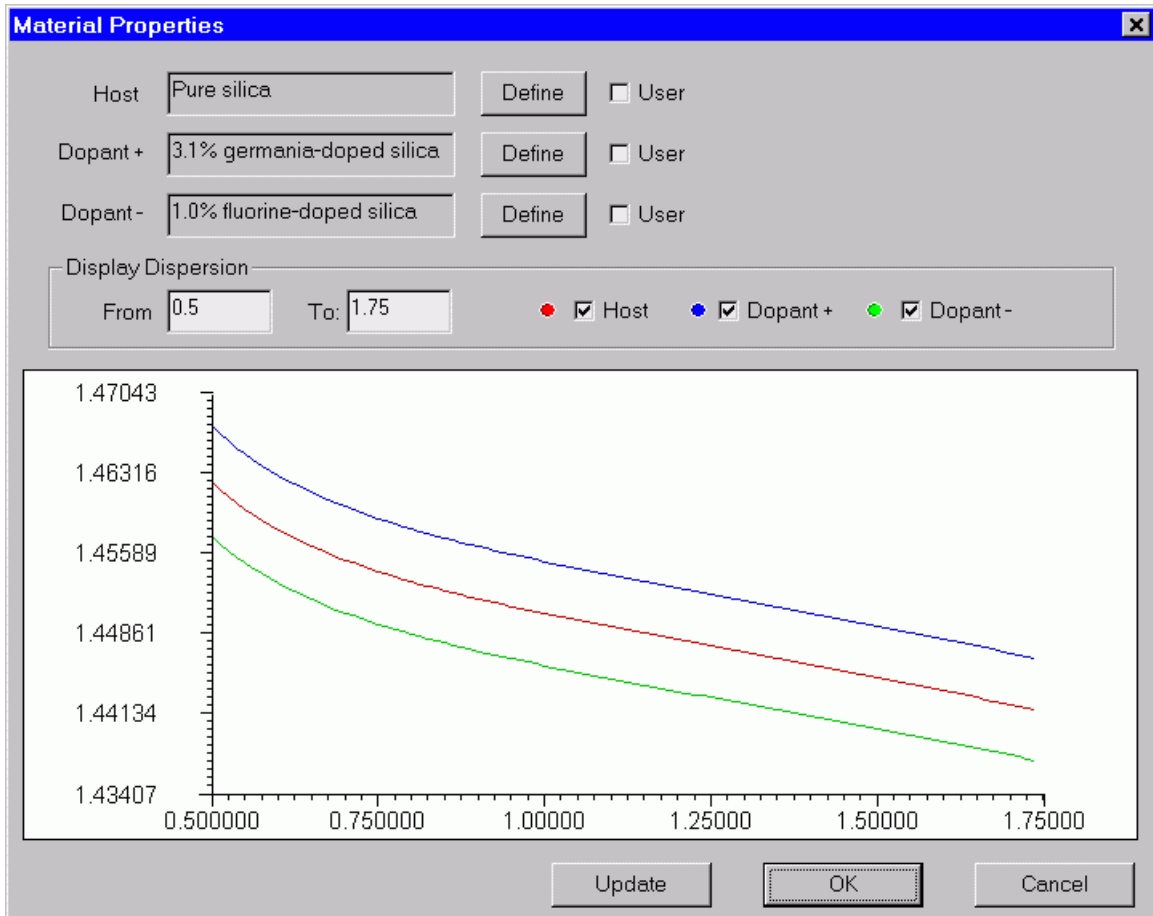
- 1 In the “Fiber Profile” dialog box, select “Define” in the “Material Properties” group of controls.
- 2 In the “Material Properties” dialog box, select “Define” in the “Host” section.
- 3 In the “Parameters of Material” dialog box, select “Pure Silica” from the library and press Get, followed by pressing OK to close the “Parameters of Material” dialog box. You can see in the “Material Properties” dialog box that the host material is now “Pure Silica”.
- 4 Similarly as in the previous step, define 3.1% germanium-doped silica for the “Dopant+” material
- 5 Similarly as in the previous step, define 1% fluorine-doped silica for the “Dopant-“ material. Thus you defined two reference materials that will be



used to calculate the material dispersion and the profile dispersion of the fiber.

- 6 Press OK in the “Material Properties” dialog box to close it.
- 7 Press OK in the “Fiber Profile” dialog box to close it.

Your “Material Properties” dialog box looks like this:

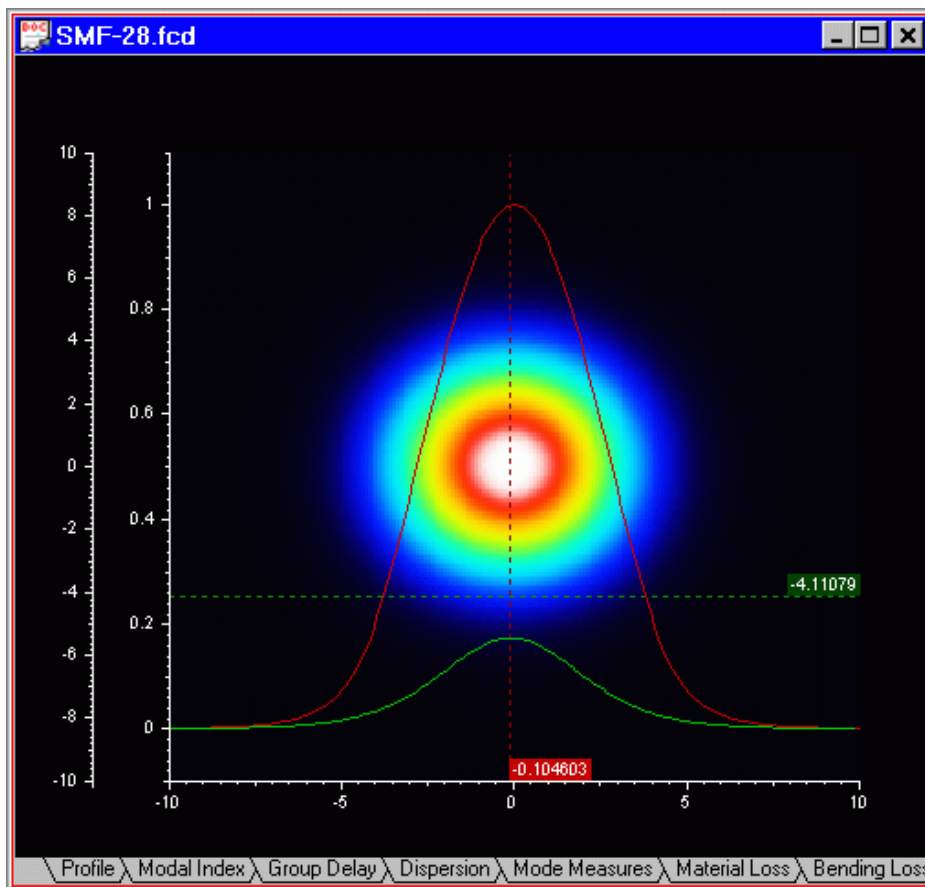


Calculating fiber modes

To calculate a fiber profile, follow these steps:

- | Step | Action |
|------|--|
| 1 | Click the "Modes" icon in the "Navigator" pane |
| 2 | Select the "LP Modes (Matrix Method)" option |
| 3 | Press "Recalculate Modes". The program provides the modal index at the given wavelength and shows a preview of the modal field. |
| 4 | In the "Views" window, select the "Mode Field" tab to view the modal field. |
| 5 | From the "Graph Tools" toolbar select "X Cut", then click-and-drag the cursor over the graph to inspect the mode field normalized "X-section". The default color for "X Cut" lines is green. |
| 6 | From the Graph Tools toolbar select "Y Cut", then click-and-drag the cursor over the graph to inspect the mode field normalized Y-section. The default color for "Y Cut" graph lines is red. |

When you click-and-drag the left mouse button inside your "Mode Field" view tab with "X Cut" and "Y Cut" active, then the view looks like this:



Calculating cutoff wavelength

To calculate the cutoff wavelength, follow these steps:

- | Step | Action |
|-------------|---|
| 1 | Click the “Cutoff” icon in the “Navigator” pane. |
| 2 | Select the “LP Modes (Matrix Method)” option. |
| 3 | Press “Recalculate”. The program shows guided modes on the list. If only LP01 is supported – decrease the wavelength. |
| 4 | Select the “LP11” mode on the list. |
| 5 | Press the Calc. “Cutoff” button. The program shows: <ul style="list-style-type: none"> — a “theoretical” cutoff wavelength value of 1.33204 microns. — a “ITU-T” compliant cutoff value of 1.231 microns. |

Calculating properties of fundamental mode

To calculate the properties of the fundamental mode, follow these steps:

- | Step | Action |
|-------------|--|
| 1 | Click the “Scan Fundamental Mode” icon in the “Navigator” pane. |
| 2 | In the “Properties of Fundamental Mode” dialog box, select all available “Calculate” options |
| 3 | Leave the defaults for material, bending, and splice loss parameters |
| 4 | In the “Scan” section list, select “Wavelength”, which is also the default option. 68 |
| 5 | In the “Parameter” section, enter “From” = 1.2, “To” = 1.6, “Steps” = 100. |
| 6 | Click “Calculate”. |



Viewing results

You can inspect the output graphs in the Views window by selecting appropriate tabs:

- “Modal Index” tab: Plot of the modal index vs. the current scanning parameter, i.e. wavelength
- “Group Delay” tab: Plots the group delay vs. the scanning parameter.
- “Dispersion” tab: Plots material, waveguide and total dispersion vs. the scanning parameter. The zero dispersion wavelength and the slope are shown on the graph.
- “Mode Measures” tab: Plots the near-, far-field, effective mode field diameter and the effective mode area vs. the scanning parameter.
- “Material Loss” tab: Plots the material loss vs. wavelength.
- “Bending Loss” tab: Plots the micro and macro bending losses vs. the scanning parameter.
- “Splice Loss” tab: Plots the splice loss vs. the scanning parameter.
- “Eff. Nonlinear RI” tab: Plots the effective nonlinear refractive index of the fiber vs. the scanning parameter.

Simulating polarization mode dispersion

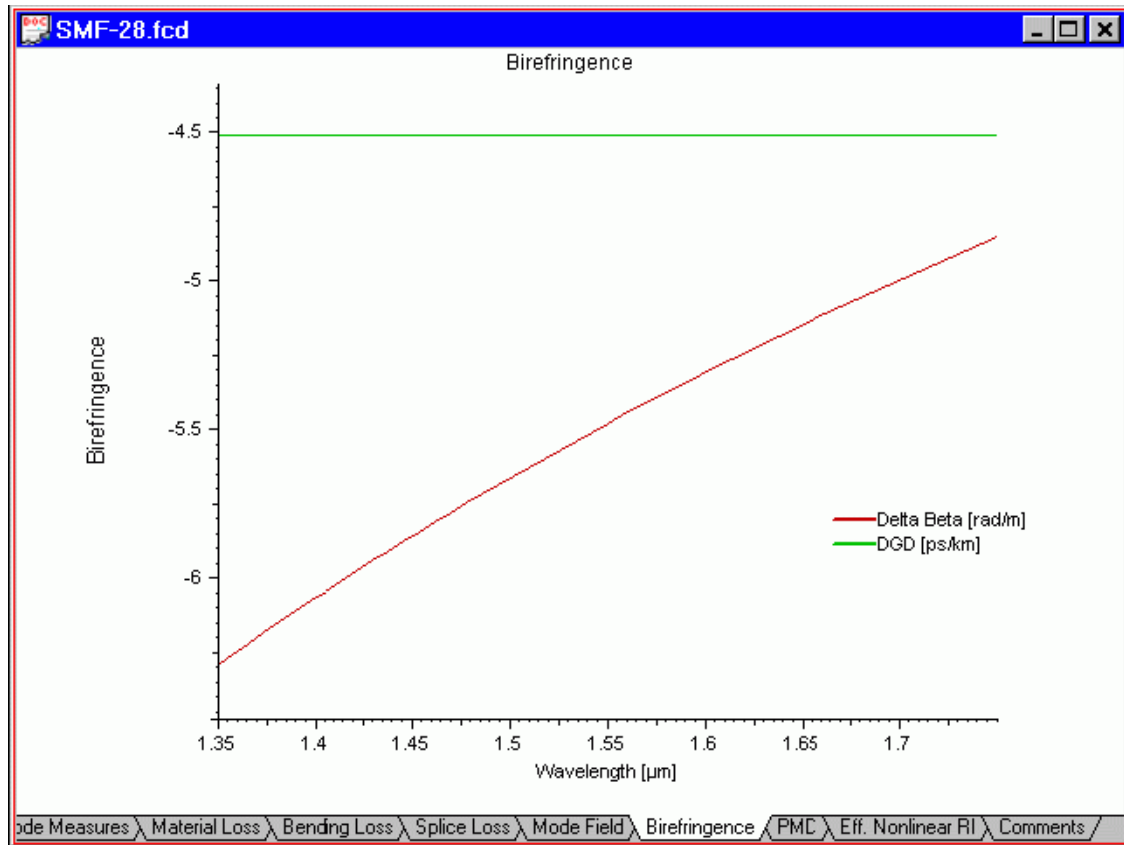
Birefringence

To simulate the birefringence, follow these steps:

- | Step | Action |
|-------------|--|
| 1 | Click the “Birefringence” icon in the “Navigator” pane |
| 2 | In the “Birefringence” dialog box, check the “Induced by Perturbation Parameters” option. The “Photoelastic Constants” entries become available. |
| 3 | In the “Photoelastic Constants” section, enter: Young Modulus 775000000, C 3.44e-011, Poisson Ratio 0.164. |
| 4 | In the “Induced by Perturbation” Parameters section, check “Extrinsic”, “Bending”, and “Fiber Spooled With Tension”. |
| 5 | Enter the “Bending” value 0.12 |
| 6 | Enter the “Fiber Spooled with Tension” value 0.5. |
| 7 | In the “Output” section, enter “Spectral Range” 0.4 and “Number of Steps” 51. |
| 8 | Press OK to close the “Birefringence” dialog box |
| 9 | Go to the “Birefringence” view tab. The birefringence and Differential Group Delay (DGD) vs. wavelength are plotted there. |

Your “Birefringence” view tab should look like this:





Polarization mode dispersion

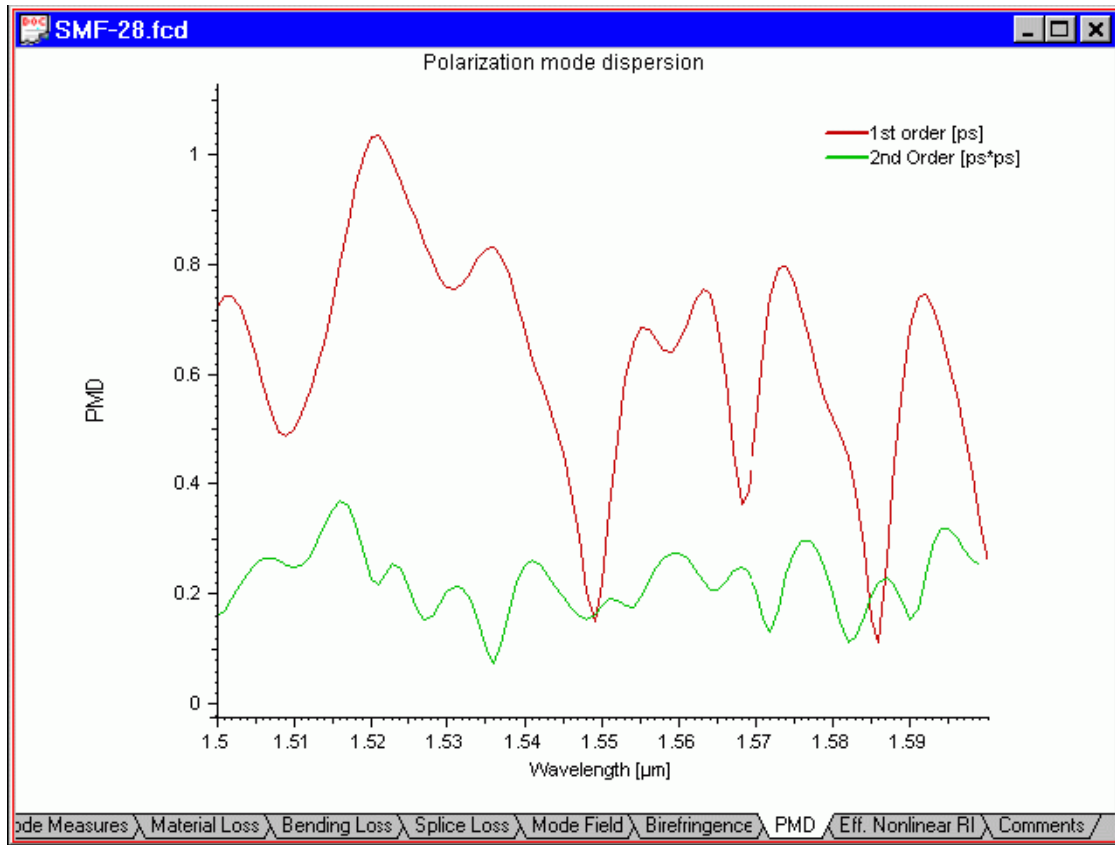
To simulate the polarization mode dispersion, follow these steps:

Step Action

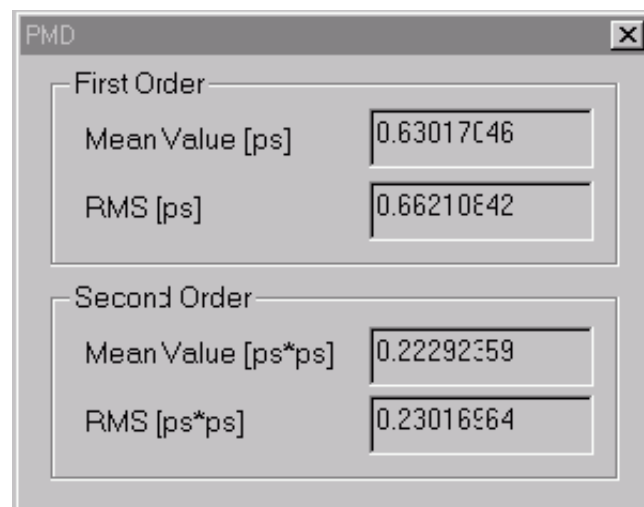
- 1 Click the "PMD" icon in the "Navigator" pane
- 2 Define the parameters for PMD simulation: Fiber Length 1000, Coupling Length 20. The Birefringence Characteristics are provided for your information and are disabled in this dialog box.
- 3 Choose "Spectral simulation": Spectral Range 0.1, Number of Steps 201.
- 4 Press "OK" to close the polarization Mode dispersion dialog box and start the simulation.
- 5 Go to the "PMD" graphics tab. The first order and second order PMD vs. wavelength are plotted for spectral simulation. (For Ensemble simulation, the first order PMD vs. Number of Runs would be plotted).

Your "PMD" view tab should look something like this:





Also, you will have the mean value and the root mean square, (RMS value) of the first and second order PMD displayed in a separate window.



Performance Characterization

Here is the table that compares OptiFiber results with a typical fiber (Corning SMF-28.):

<i>Characterized Parameter</i>	<i>Calculated Value</i>	<i>Typical value</i>
Zero dispersion wavelength, λ_0	1.309 μm	$1.302\mu\text{m} < \lambda_0 < 1.322\mu\text{m}$
Zero dispersion slope, S0	0.0856 ps/(nm ² *km)	<0.089ps/(nm ² *km)
Eff. MFD at 1310nm	8.9 μm	$9.20 \pm 0.4\mu\text{m}$
EFF. MFD at 1550nm	9.9 μm	$10.4 \pm 0.5\mu\text{m}$
Effective group index	1.4676	1.4675
Cut-off wavelength of LP11	1.23 μm	<1.260 μm

The data of SMF-28 were taken from the public-domain specifications at Corning's web-site www.corning.com/opticalfiber/

Corning is a registered trademark and SMF-28 is a trademark of Corning incorporated, Corning, NY, USA.



NOTES:



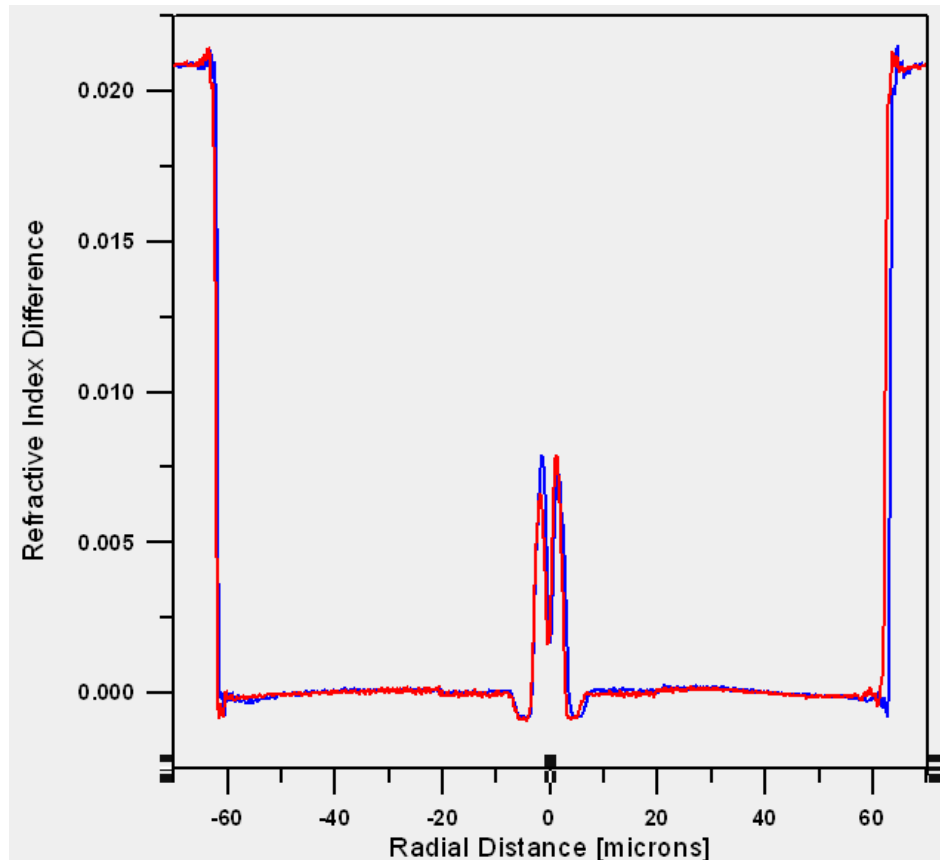
Lesson 2: Characterizing A Real Fiber Sample

OptiFiber 1.5 directly supports experimental reference. index profiles scanned with the NR-9200 optical fiber analyzer from EXFO Inc. The fiber parameters calculated in that way provide indispensable feedback information to the product designer and reduce the optimization cycle and the time-to-market.

The experimental profile “FromNR9200.asc” and the OptiFiber project “FromNR9200.fcd” used in this lesson can be found in the Samples directory.

Experimental procedures

- | Step | Action |
|------|--|
| 1 | First measure the refractive index profile of the fiber sample under test as described in the user manuals of NR-9200. The raw scanned profile data usually look as in the picture below. The X- and Y-axis scans are shown in different colors. |



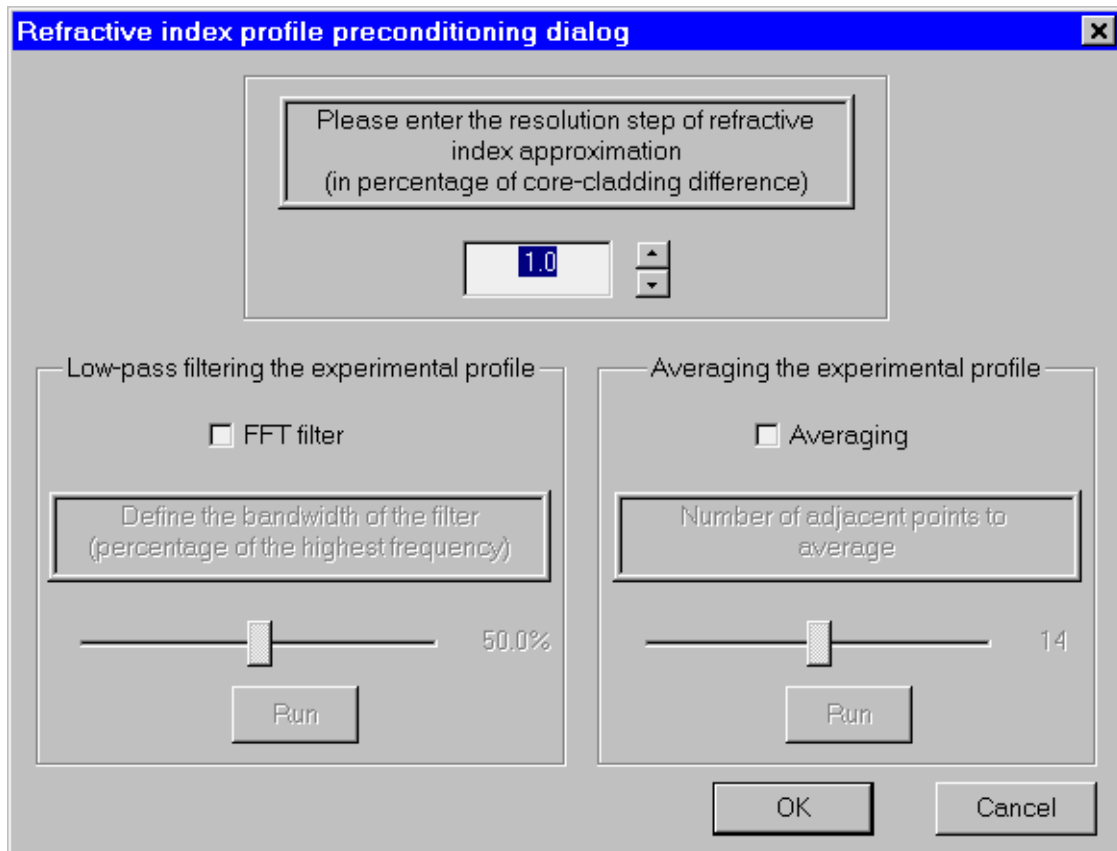
- Save the refractive index data using the native NR-9200 format in a file named, for example, “FromNR9200.asc” . . “.asc” is the default file extension, however the profile files may have any extension, provided their internal structure is in the NR-9200 format.
- Transfer this file to the computer, where OptiFiber is installed.



Importing the experimental profile

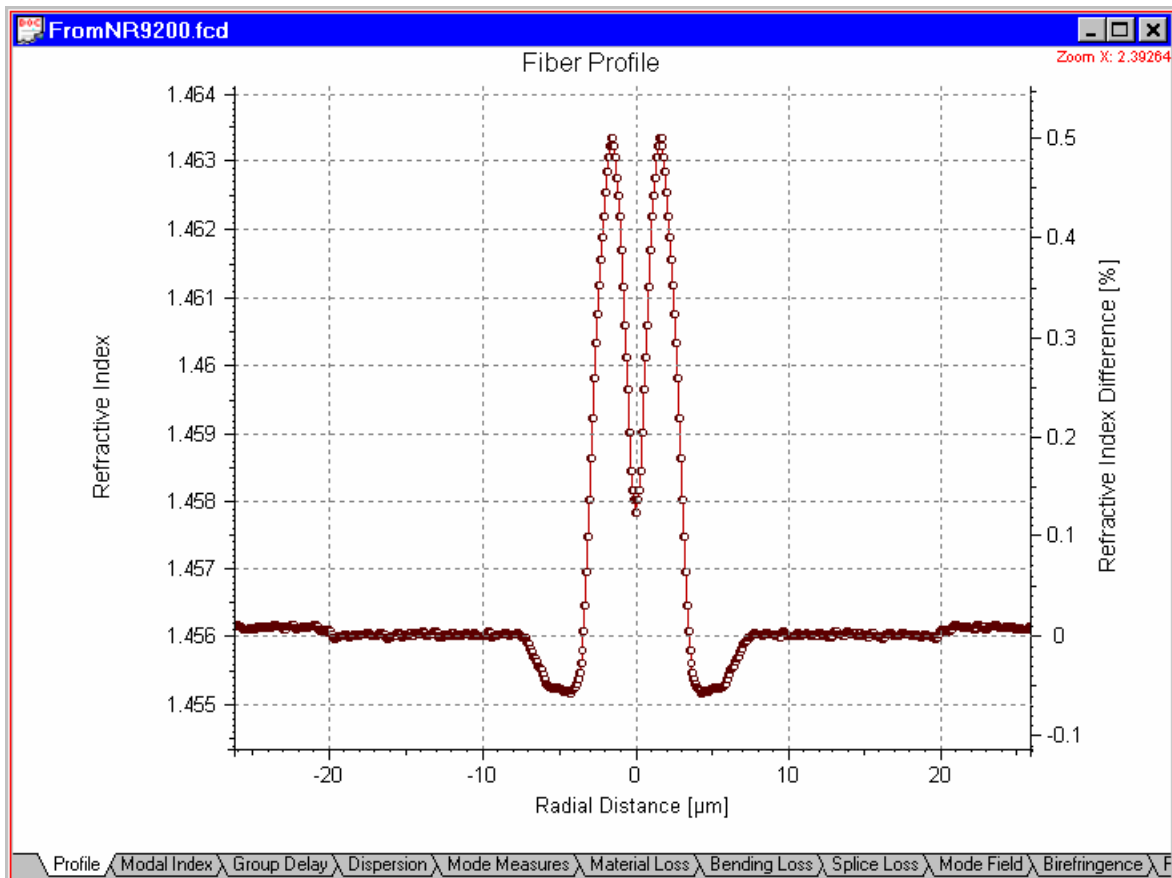
OptiFiber is loaded with drivers that directly interpret the experimental data measured and recorded by NR-9200. In order to use the profile data of the sample under test do the following:

- | Step | Action |
|------|--|
| 1 | Start a new blank project by selecting "File/New" |
| 2 | Import "FromNR9200.asc" by selecting "File/Import Profile..." . Within the "File Open" dialog select "Files of Type" - "EXFO NR-9200 Data File (*.asc)", which is the default file type. |
| 3 | After the file has been read the "Refractive index profile preconditioning dialog" appears: |



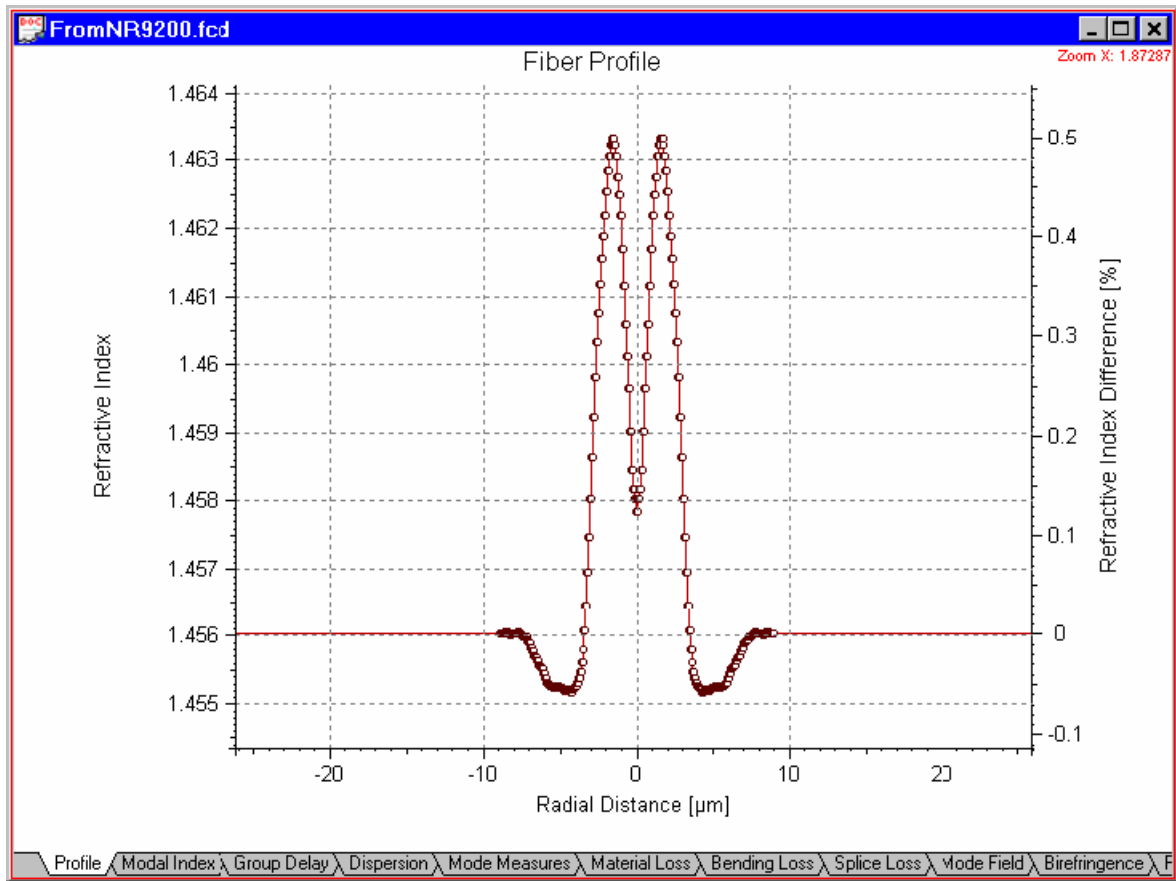
It offers the choice of reducing the number of fiber layers (which is typically > 1000) in a search for a reasonable compromise between accuracy and computer load. It allows also to filter and smooth the profile.

- 4 Select the default resolution step of 0.0, which means that every experimental point will be interpreted as a distinct layer, and press "OK".
- 5 At that point OptiFiber processes the experimental profile: makes it symmetrical, finds the axis position, etc. (see Technical Background/Compatibility with the NR-9200 Optical Fiber Analyzer ...). The adapted profile looks in the "Profile" view tab of OptiFiber as shown below...



If the user is interested in the general trend of fiber parameter change vs. some technological parameter (layer thickness, reference. difference) instead of its exact absolute value, he may prefer to delete manually some of the cladding layers. The next profile is obtained from the one shown above after such operation.



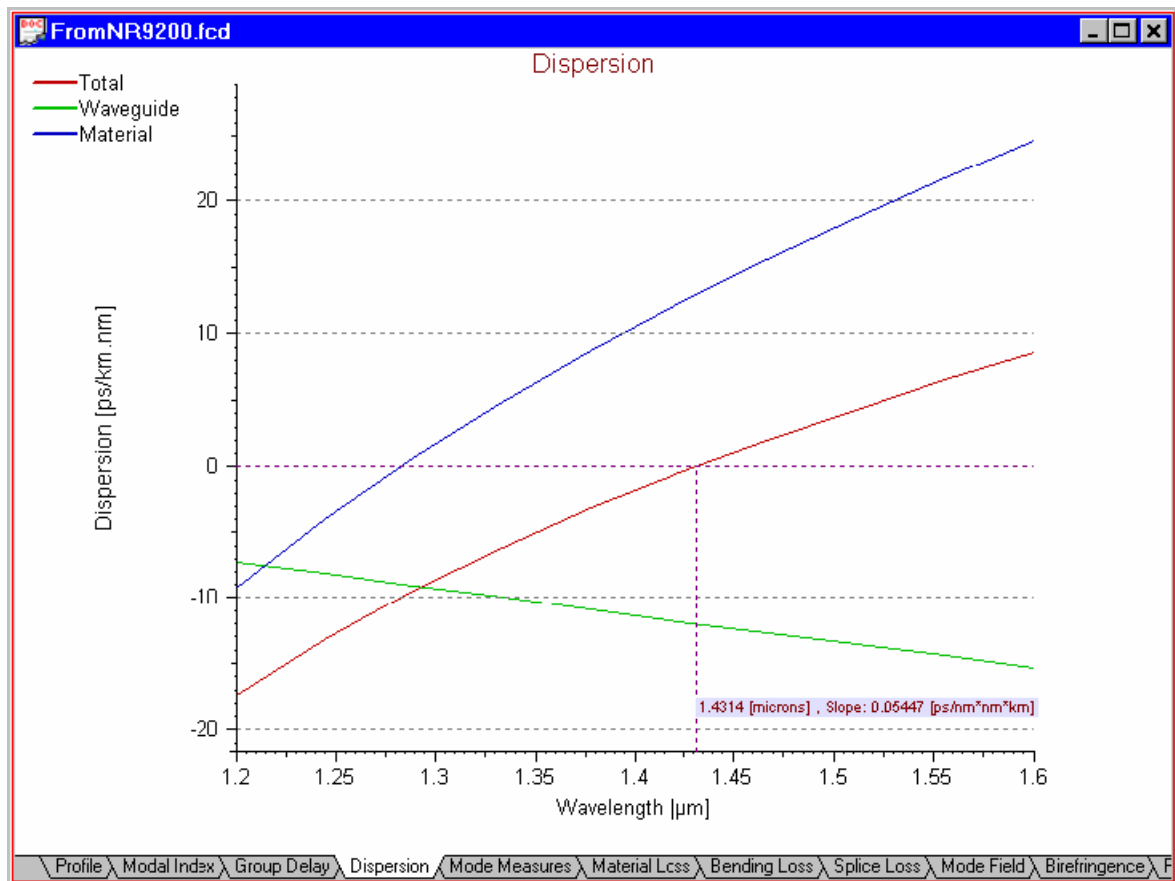


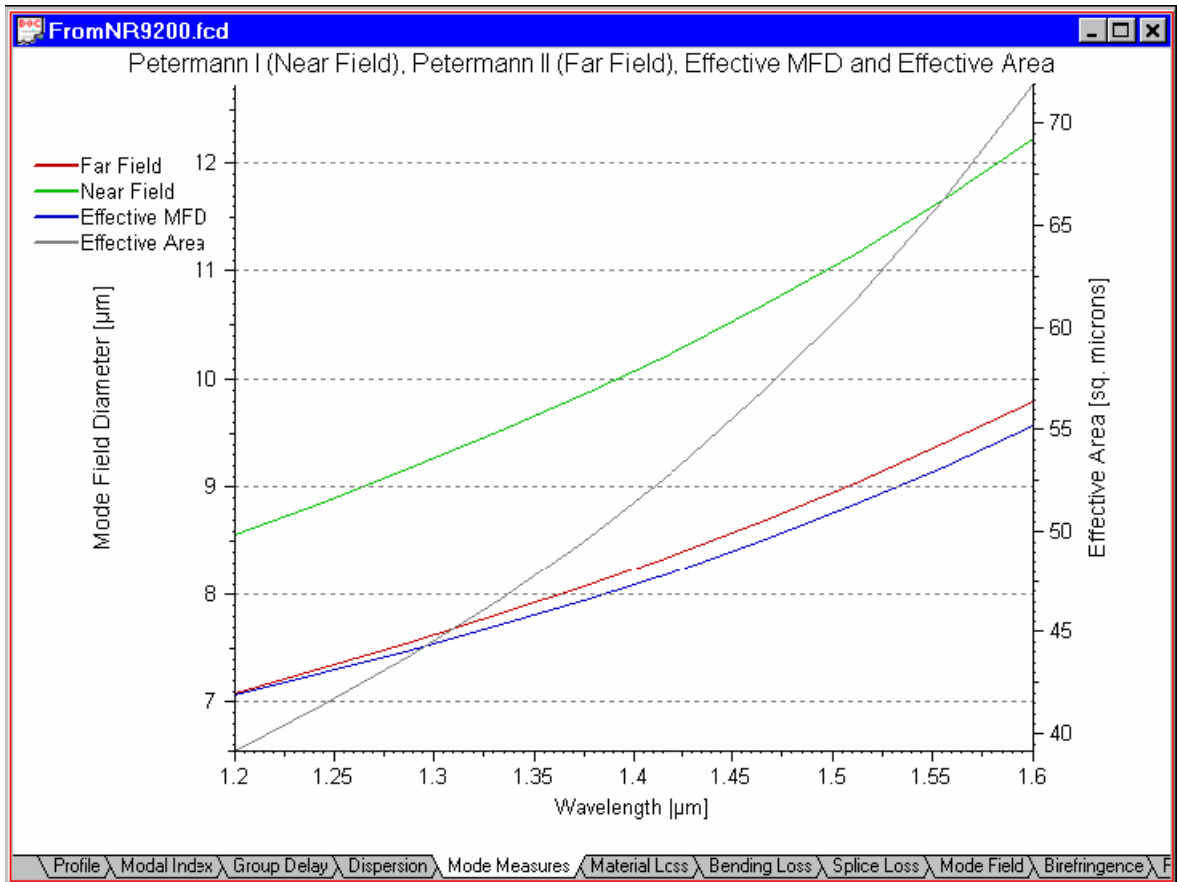
In that way the number of layers is reduced by ~75%, which greatly alleviates the resource needs of the optimization calculations. When the trends in the behavior of the design vs. its parameters are known, the user can return to the initial full profile.



Calculating the parameters of the fiber sample

- Proceed with the usual routines. For example, the calculated dispersions and MFD of that particular experimental profile are shown in the following pictures:





NOTES:



Lesson 3: Designing Dispersion Shifted Fiber

In this example, we will show you how to simulate optical fiber that has a triangular with annular ring profile. In addition, we will show you how to optimize given fiber profile to have zero dispersion at 1550 nm by the powerful parameter scan routines of OptiFiber.

You can find this example as the DSF.fcd file in the Samples directory.

Defining fiber profile

To define a fiber profile, follow these steps:

- | Step | Action |
|------|--|
| 1 | From the "File" menu click "New" to open a new project. |
| 2 | Click the Fiber Profile icon in the "Navigator" pane. |
| 3 | In the Fiber Profile dialog box, add four regions: "Region 0" through "Region 3" |

For "Region 0", enter the following data:

Width: 3.1
Profile: function
Function: linear
Refr. Index: Define: Start = 1.4615, End = 1.44692
Steps: 100
Click Apply

For "Region 1", enter the following data:

Width: 0.6
Profile: constant
Index: 1.44692
Click Apply

For "Region 2", enter the following data:

Width: 1.5
Profile: constant
Index: 1.45
Click Apply



For “Region 3”, enter the following data:

Width: 57.

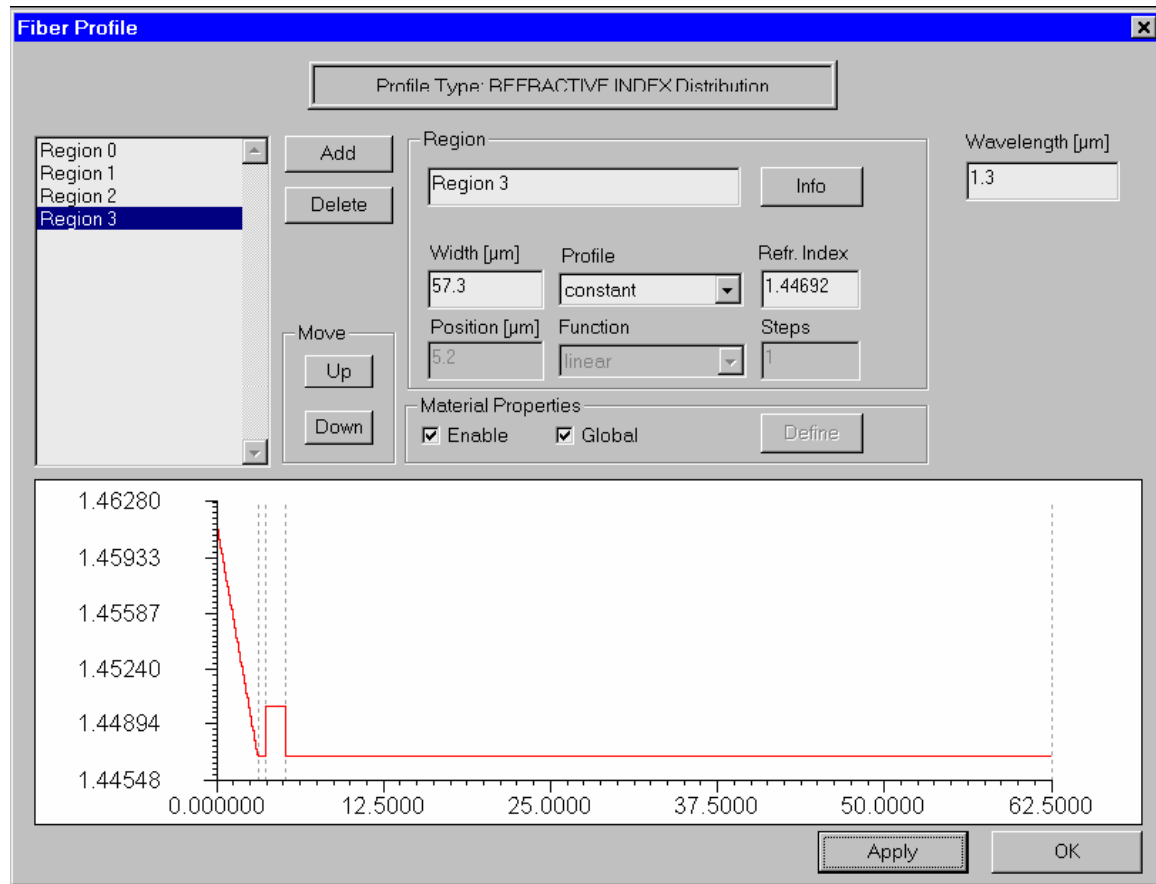
Profile: constant

Index: 1.44692

Click Apply

Enter the wavelength value 1.3 microns.

Your fiber should look like the one below:



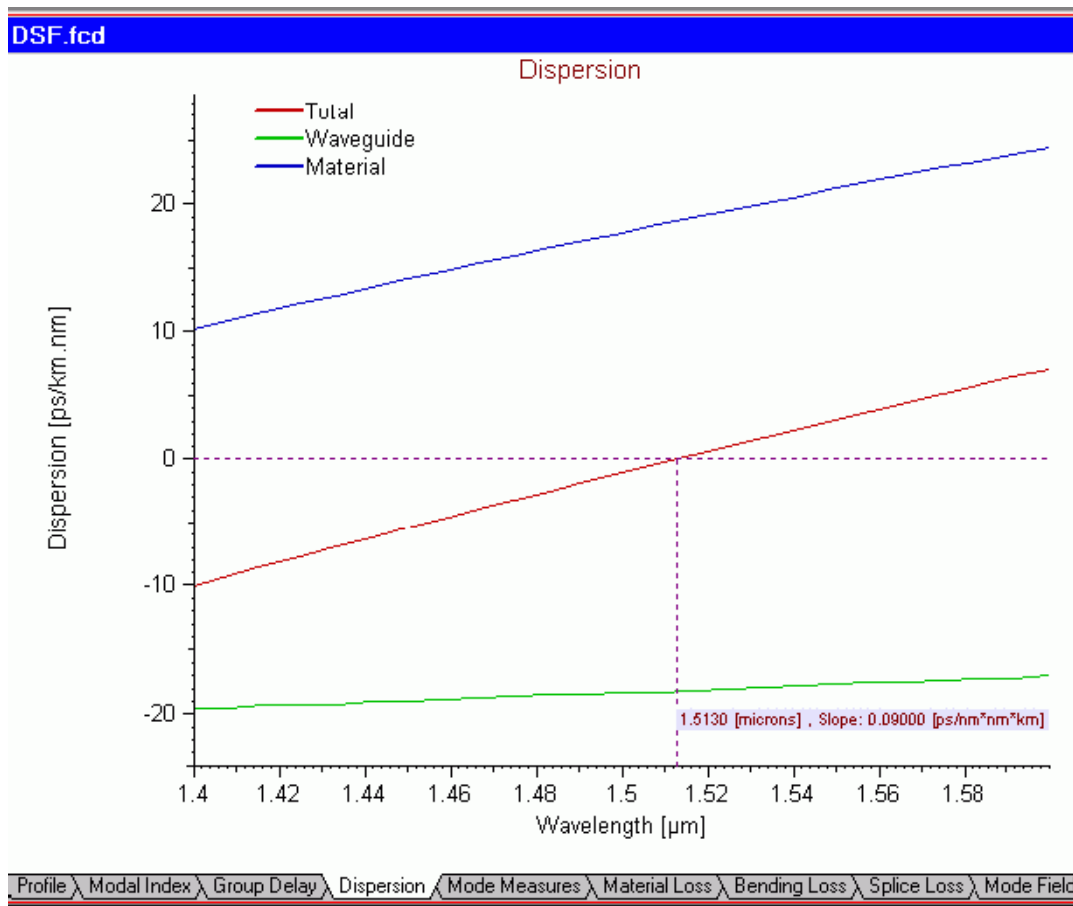
4 Click “OK” to close the “Fiber profile” dialog box.

Finding the zero dispersion wavelength

To find the zero dispersion wavelength, follow these steps:

- | Step | Action |
|------|--|
| 1 | Click the "Modes" icon in the "Navigator" pane |
| 2 | Select the "LP Modes (Matrix Method)" option |
| 3 | Press "Recalculate ". The program provides the modal index at the given wavelength and shows a preview of the modal field. |
| 4 | Click "OK" to leave the "Modes" dialog box. |
| 5 | Click the "Scan Fundamental Mode" icon in the "Navigator" pane. |
| 6 | In the "Properties of Fundamental Mode" dialog box, click "Calculate" to scan "Wavelength" from 1.4 to 1.6 in 50 steps. |
| 7 | Go to "Dispersion" view tab. The zero dispersion wavelength is located in the vicinity of 1513 nm. |

Your "Dispersion" view tab should look like this:



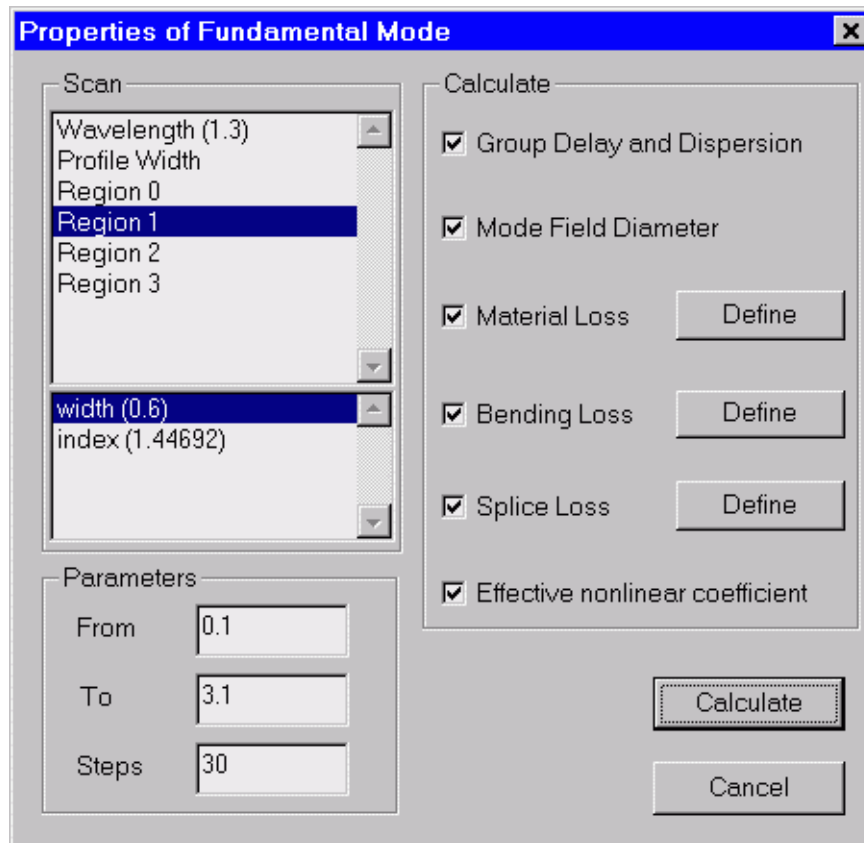
Optimizing profile for a required zero dispersion wavelength

Now, we can use the powerful capability of OptiFiber to scan over our design parameters. Let's define, as a design goal, to achieve zero dispersion at a certain wavelength, say 1550 nm. As we will see, we can accomplish that by changing, for example, the distance between the triangular core and the annular ring, i.e. the width of "Region 1".

When we find the optimal width we can use it to calculate the global dispersion characteristics vs. wavelength.

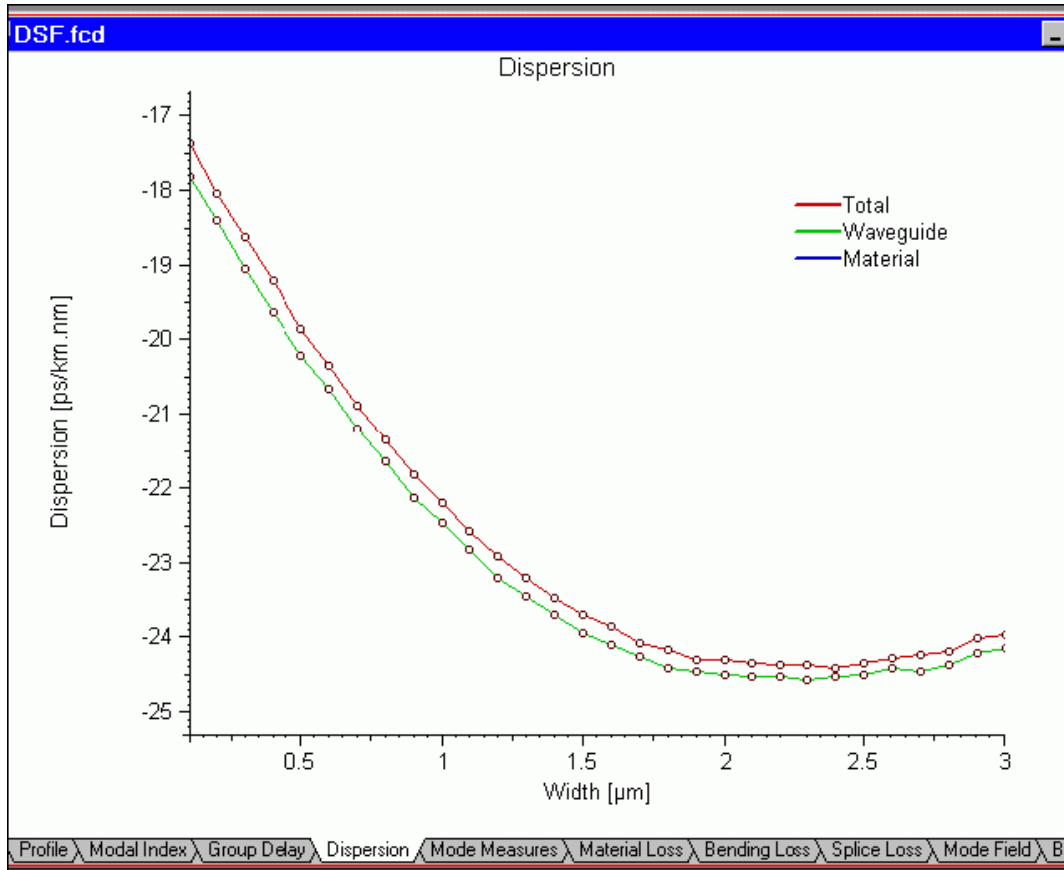
Step Action

- 1 Now, go back to the "Properties of Fundamental Mode" dialog box by selecting "Scan Fundamental Mode" in the "Navigator" pane.
- 2 In the "Properties of Fundamental Mode" dialog box, select "Region 1" from the "Scan" upper list, then select "Width" from the "Scan" lower list.
- 3 In the "Parameters" section, enter the following values: From 0.1, To 3.1, Steps 30.



- 4 Click "Calculate".
- 5 Go to "Dispersion" view tab. The dispersion vs. the width of the intermediate layer is shown there:



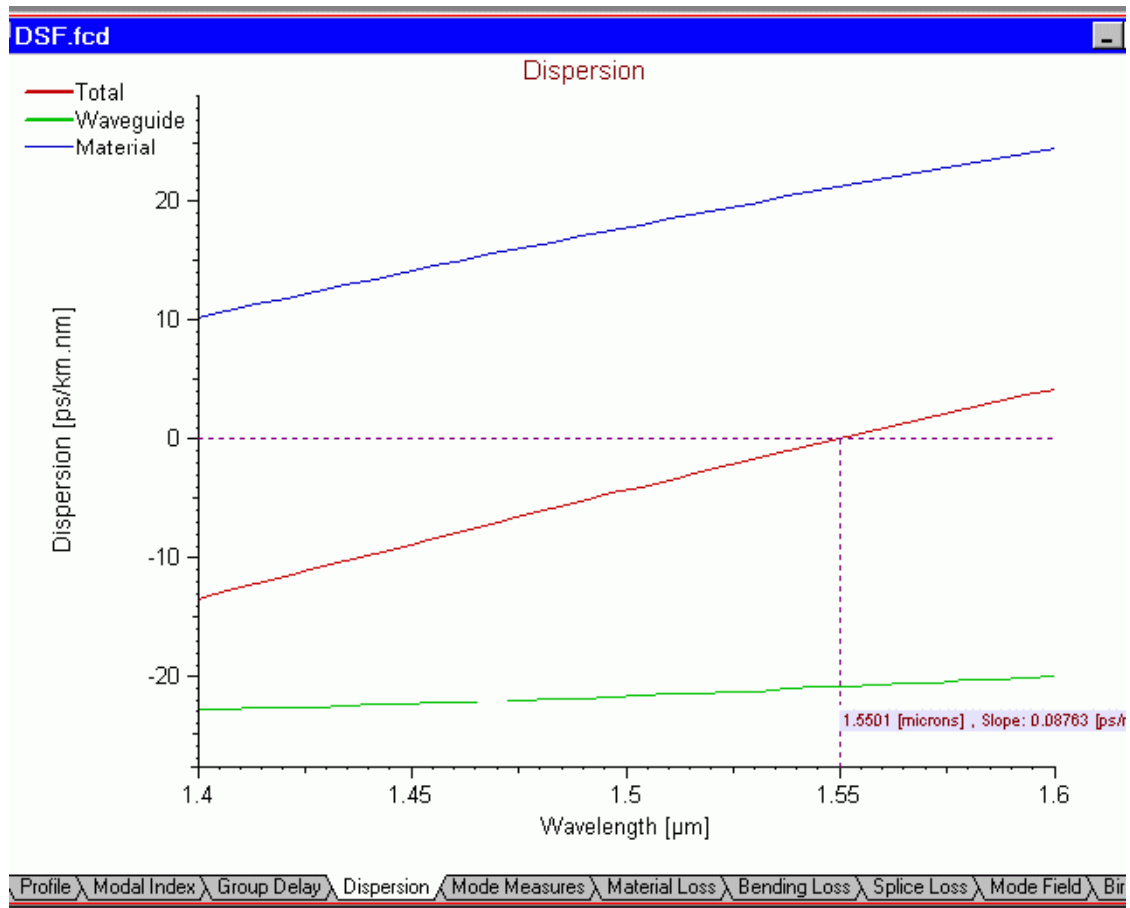


6. From the previous dispersion vs. wavelength picture we know that we need ~ 3 [ps/nm/km] reduction of the total dispersion at 1550 nm. With the left mouse button, click-and-drag over the “Total dispersion” curve to find the point, whose dispersion is 3 [ps/nm/km] less than the dispersion, corresponding to the current width of 0.6 μm . One can see that the 3 [ps/nm/km] reduction falls between the widths of 1.3 and 1.4 μm .
7. Go back to the “Fiber Profile”, select “Region 1”, and change its width to 1.32 μm .
8. Go to the “Properties of Fundamental Mode” dialog box and scan over the wavelength from 1.4 to 1.6 μm in 50 steps.
9. Go to “Dispersion” view tab. The zero dispersion wavelength is 1550 nm.

You just optimized the fiber design to obtain the zero-dispersion wavelength close to 1.55 microns.



Your "Dispersion" view tab should look like this:



Lesson 4: Designing Dispersion Flattened Fiber

In this example, we will simulate a dispersion flattened fiber. We will also demonstrate the use of the internal scripting language of OptiFiber for defining profiles.

You can find this example as the DFF.fcd file in the Samples directory.

Defining fiber profile

To define a fiber profile, follow these steps:

- | Step | Action |
|-------------|---|
| 1 | From the “File” menu click “New” to open a new project. |
| 2 | Click the “Fiber Profile” icon in the “Navigator” pane. |
| 3 | <p>Add four regions in the new profile. For “Region 0” enter the following data:
 Width: 4.2
 Profile: user function
 Click “Define” to enter the script parser editor. In its window enter the following expression:
 background = 1.4437
 delta = 0.01
 alpha = 10
 background + delta*(1-(x /WIDTH)^alpha)</p> <p>(Thus you defined one half of an “alpha profile” function using the interpreted script language of OptiFiber.)
 Click “OK”
 Steps: 20
 Click “Apply”</p> |
| 4 | <p>For “Region 1”, enter the following data:
 Width: 2.5
 Profile: constant
 Index: 1.4437
 Steps: 1
 Click “Apply”</p> |
| 5 | <p>For “Region 2”, enter the following data:
 Width: 6.75
 Profile: user function
 Click “Define” to enter the script parser editor. In its window enter the following expression:</p> |



background = 1.44692

delta = 0.003

alpha = 10

background + delta*(1-((2*x - WIDTH)/WIDTH)^alpha)

Click "OK"

Steps: 30

Click "Apply"

6 For "Region 3", enter the following data:

Width: 49.05

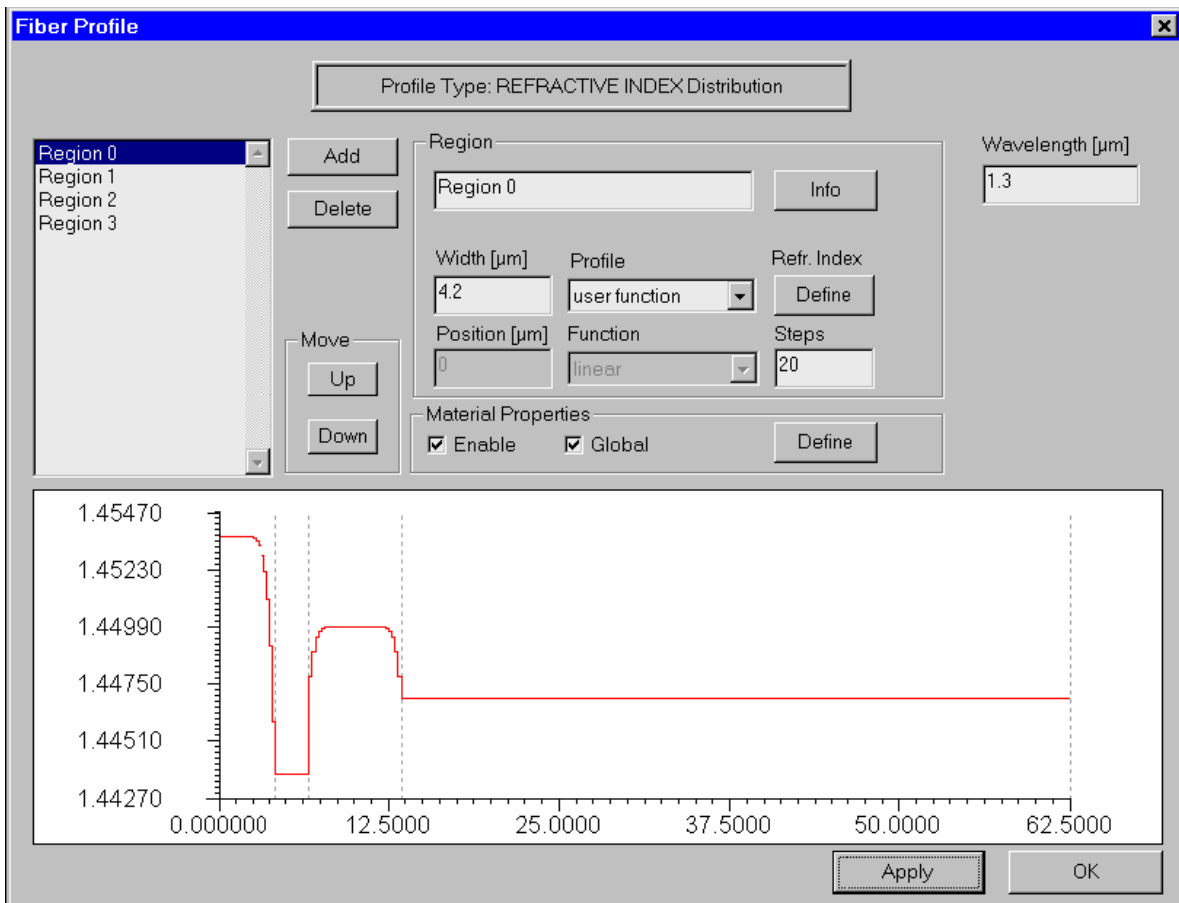
Profile: constant

Index: 1.44692

Steps: 1

Click "Apply"

You fiber profile dialog should look like the one below:



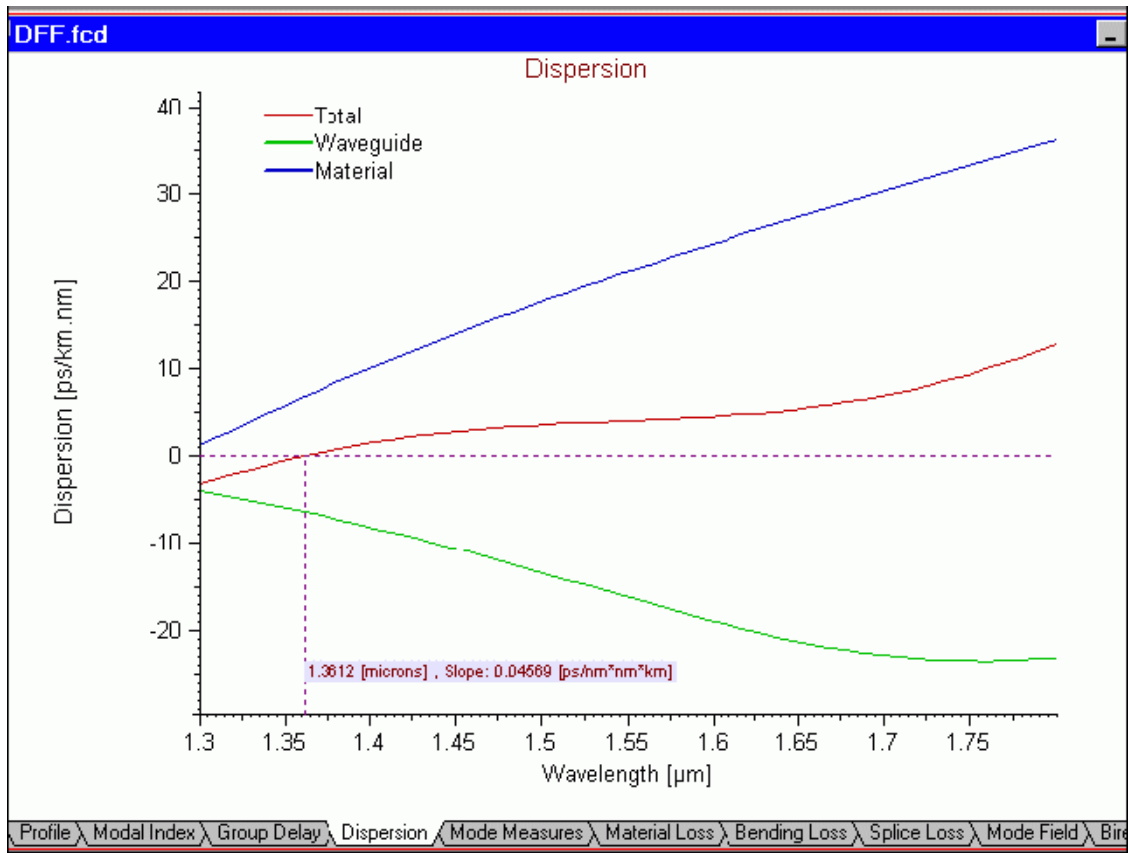
Calculating the characteristics of the dispersion flattened fiber

To calculate the characteristics of the dispersion-flattened fiber, follow these steps:

- | Step | Action |
|-------------|---|
| 1 | Click the "Modes" icon on the "Navigator" pane |
| 2 | Select the "LP Modes" option |
| 3 | Press "Recalculate Modes". The program provides the modal index at the given wavelength and shows a preview of the modal field. |
| 4 | Click "OK" to leave the "Modes" dialog box. |
| 5 | Click the "Scan Fundamental Mode" icon in the "Navigator" pane. |
| 6 | In the "Properties of Fundamental Mode" dialog box, click "Calculate" to scan the wavelength from 1.3 to 1.8 in 50 steps. |
| 7 | Go to "Dispersion" view tab. The total dispersion is small and uniform within the 1.3 - 1.8 μm wavelength range. |



Your Dispersion view tab should look like this:



You may experiment with scanning some fiber profile parameters, as in “Lesson 3: Designing Dispersion Shifted Fiber” in order to obtain even better dispersion flatness or certain value of the average dispersion within a wavelength interval of interest.





Commands Reference

File Menu Commands

New command

The “New” command opens a new OptiFiber file with empty “Views” window, except the “Material Loss” view. Fiber parameters have default values. OptiFiber creates a default name for the newly opened file.

This command can be accessed from:

- File menu
- Standard toolbar

Open command

The “Open” command opens an existing OptiFiber file. The “Views” window tabs are empty, except the “Profile” view and the “Material Loss” view. Fiber parameters have the last saved values.

This command can be accessed from:

- File menu
- Standard toolbar

Close command

The “Close” command closes the active OptiFiber file. The program prompts for saving fiber parameters.

This command can be accessed from:

- File Menu
- Standard toolbar

Save command

The “Save” command saves the active OptiFiber file. The file is saved under the current name.

This command can be accessed from:

- File Menu
- Standard toolbar

Save As

The “Save As” command saves the active OptiFiber file. The program prompts for a file name.



This command can be accessed from:

- File menu

Export Profile command

The “Export Profile” command saves the existing refractive index profile in an ASCII file. The file is saved in the OptiFiber’s own text format.

This command can be accessed from:

- File menu

Import Profile command

The “Import Profile” command loads a file with a refractive index profile data in OptiFiber. The file should be in one of the supported formats. Currently two formats are supported:

- EXFO’s proprietary NR-9200 file format
- OptiFiber’s own text format

However, any ASCII data representing a refractive index profile can easily be transformed by the user into the OptiFiber’s format (for example using MS Excel) and imported for modeling.

This command can be accessed from:

- File menu

For description of the OptiFiber’s format, see the respective section in the “Technical background”

Print command

The “Print” command prints the active output view.

This command can be accessed from:

- File menu
- Standard toolbox

Print Preview command

The “Print Preview” command shows the active output view on the screen as it would appear after print with current print settings.

This command can be accessed from:

- File menu

Print Setup command

The “Print Setup” command allows to change the default printer, paper, and orientation.

This command can be accessed from:



- File menu

Recent Files command

The “Recent Files” command refers to the list files at the bottom of the “File” menu. By selecting one of the files, the user opens that file.

Exit command

The “Exit” command of the “File” menu stops the OptiFiber program. The program prompts for saving unsaved files.

View Menu Commands

Status Bar

The “Status Bar” command toggles the display of the status bar at the bottom of the OptiFiber workspace window.

This command can be accessed from:

- View menu

Navigator command

The “Navigator” command toggles the display of the “Navigator” pane in the OptiFiber workspace window.

This command can be accessed from:

- View menu

Toolbars command

The “Toolbars” command toggles the display of the toolbars in the OptiFiber workspace window.

This command can be hid or displayed:

- Standard toolbar
- Graph Tools toolbar

This command can be accessed from:

- View menu

Views command

The “Views” command switches the display of the output “Views” window.

This command can be accessed from:

- View menu



The following views can be accessed by this command:

- Profile view
- Modal Index view
- Group Delay view
- Dispersion view
- Mode Measures view
- Material Loss view
- Bending Loss view
- Splice Loss view
- Mode Field view
- Birefringence view
- PMD view
- Effective Nonlinear Refr. Index
- Comments

Fiber Menu Commands

Profile command

The “Fiber” command opens the “Fiber Profile” dialog box, where you can design the refractive index profile of the fiber and have access to the dispersion properties of the fiber materials.

This command can be accessed from:

- Fiber menu
- Fiber Profile icon on the Navigator pane:



Simulation Menu Commands

Modes command

The “Modes” command opens the “Modes” dialog box, where you can perform initial calculations and select fiber modes to be calculated further.

This command can be accessed from:

- Simulation menu



- Modes icon on the Navigator pane:



Fundamental Mode command

The “Fundamental Mode” command opens the “Properties of Fundamental Mode” dialog box, where you can select calculation options for the fundamental fiber mode.

This command can be accessed from:

- Simulation menu
- Fundamental Mode icon on the Navigator pane:



Higher Order Modes command

The “Higher Order Modes” command opens the “Properties of Higher Order Mode” dialog box, where you can select calculation options for a higher order fiber mode.

This command can be accessed from:

- Simulation menu
- Higher Order Mode icon on the Navigator pane:



Cutoff command

The “Cutoff” command opens the “Cutoff” dialog box, where you can calculate the cutoff wavelength for a selected higher mode.

This command can be accessed from:

- Simulation menu



- Cutoff icon on the Navigator pane:



Birefringence command

The “Birefringence” command opens the “Birefringence” dialog box, where you can enter the fiber birefringence data.

This command can be accessed from:

- Simulation menu
- Birefringence icon on the Navigator pane:



PMD command

The “PMD” command opens the “Polarization Mode Dispersion” dialog box. When the “Birefringence” command was not previously executed, then the program opens the “Birefringence” dialog box first and, after performing the birefringence calculations, opens the “Polarization Mode Dispersion” dialog box.

This command can be accessed from:

- Simulation menu
- PMD icon on the Navigator pane:



Tools Menu Commands

Settings command

The “Settings” command opens the “Global Settings” dialog box, where you can set up graphics properties for the output views.

This command can be accessed from:

- Tools menu

Table command

The “Table” command opens the “Table” dialog box, where you can preview, copy (for pasting in another application, such as Excel) or export to a text file the numerical values that correspond to the current output view.

This command can be accessed from:

- Tools menu

Calculated results command

The “Calculated results” opens the “Calculated results” dialog box, where you can preview, copy (for pasting in another application, such as Excel) or export to a text file the numerical values that correspond to the last calculation.

Window Menu Commands

New Window command

The “New Window” command creates a copy window of the active output view window. The program adds a default name to the newly created window.

This command can be accessed from:

- Window menu

Cascade command

The “Cascade” command creates a cascade view of the output view windows within the OptiFiber workspace.

This command can be accessed from:

- Window menu

Tile command

The “Tile” command creates a tile view of the output view windows within the OptiFiber workspace.

This command can be accessed from:

- Window menu

Arrange Icons command

The “Arrange Icons” command orderly arranges iconized view windows within the OptiFiber workspace.

This command can be accessed from:

- Window menu



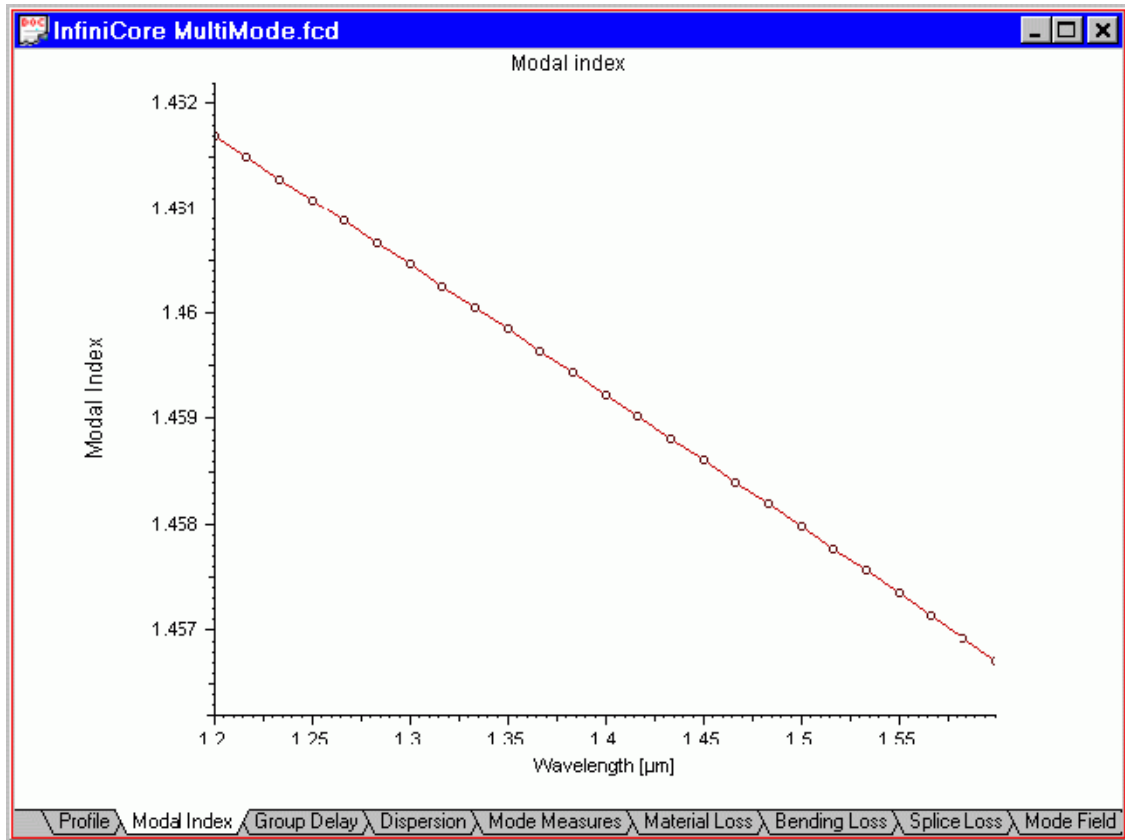
List of Windows command

The “List of Windows” area at the bottom of “Window” menu contains a list of the currently loaded windows. By selecting one of them, the user activates it.

Graph Tools Commands

“Joints” command

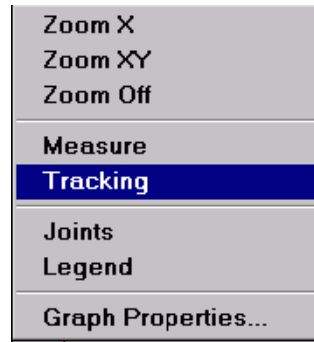
The “Joints” command activates the display of data points in the active output view. The data points are marked as small circles.



This command can be accessed from:

- Graph Tools toolbar
- Floating menu (right mouse button on a graph)





“Zoom XY” command

The “Zoom XY” command serves to expand horizontally and vertically a part of the active output view.

This command can be accessed from:

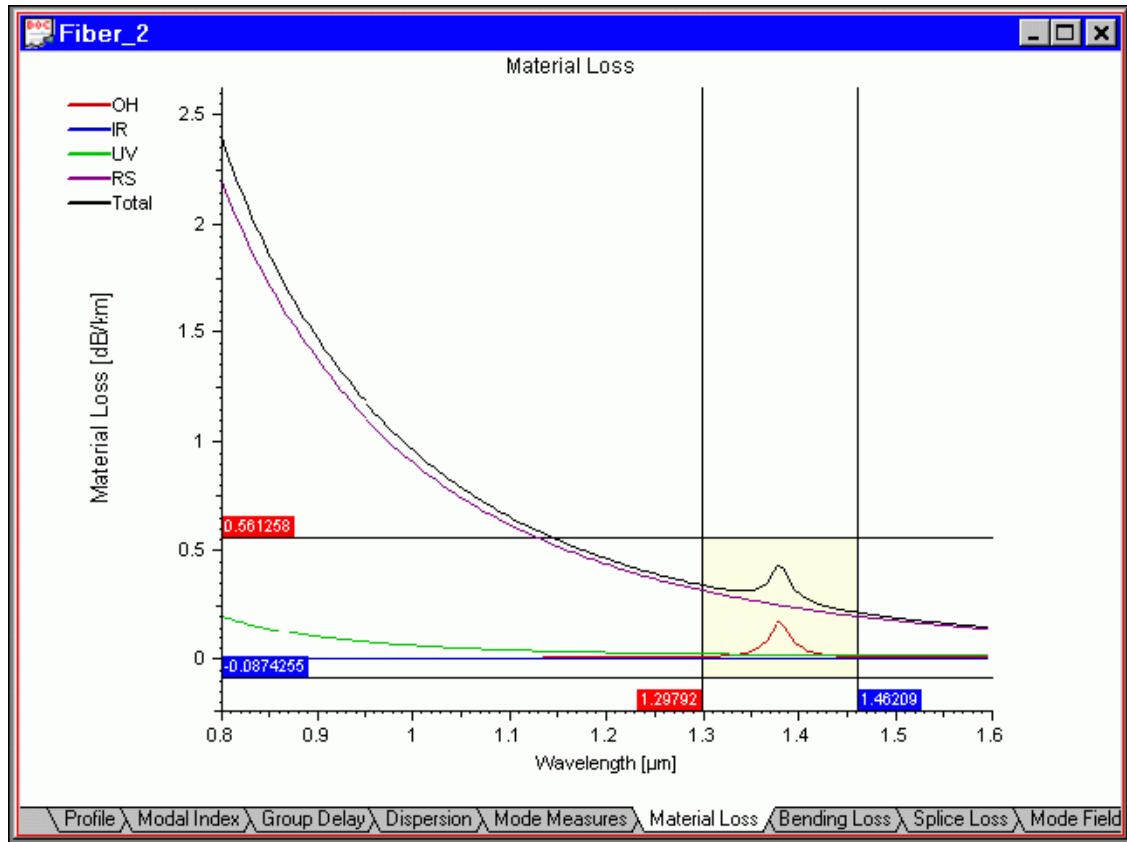
- Graph Tools toolbar
- Floating menu (right mouse button on a graph)

To use this command:

Step	Action
-------------	---------------

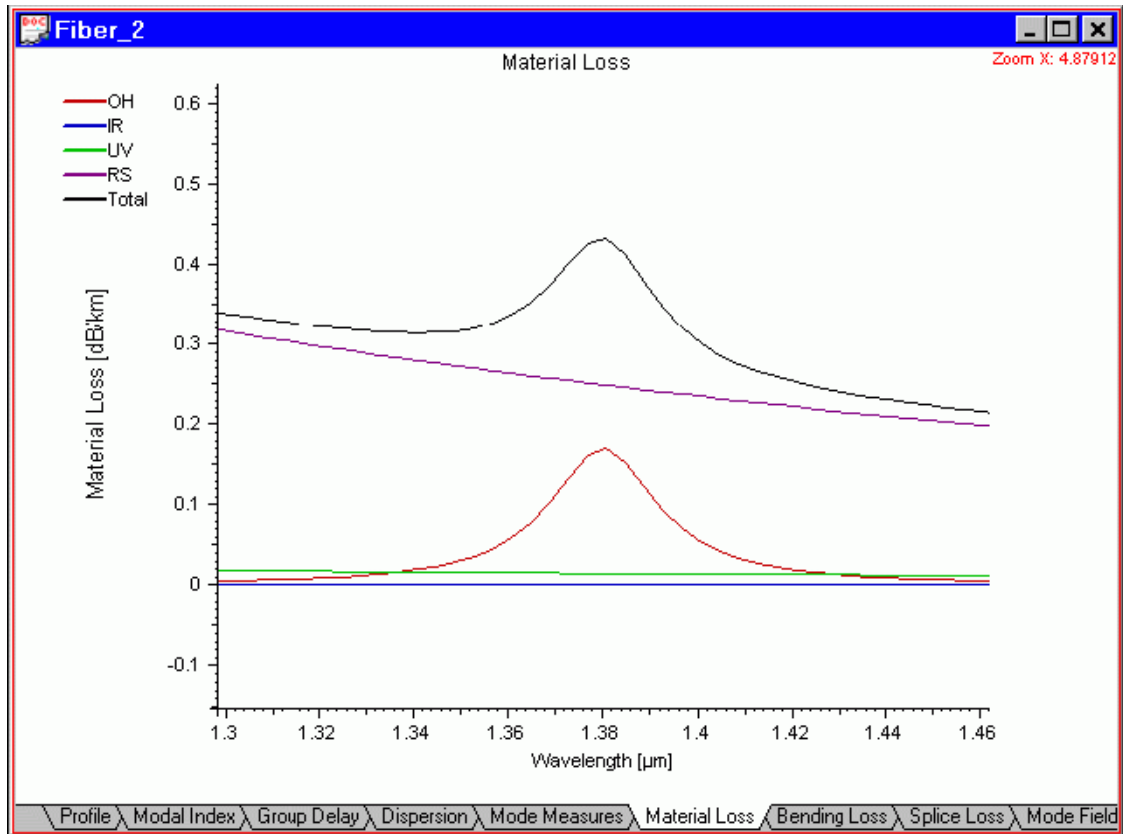
- | | |
|----------|--|
| 1 | Select “Zoom XY” from the Graph Tools toolbar or from the floating graph menu. |
| 2 | Now, with the left mouse button, click-and-drag a horizontal and vertical region to be expanded to a full graph. For example, before you release the left mouse button, your “Material Loss” view should look something like this: |





After you release the left mouse button, the selected horizontal and vertical region is expanded to the full view.





To revert to the original graph, select “Zoom Off” from the floating menu or “Graph Tools” toolbar.

“Zoom X” command

The “Zoom X” command works identically with “Zoom XY” command except that it expands the view only in horizontal direction.

“Zoom Off” command

The “Zoom Off” command turns off the current expansion in graph view and returns the graph settings to the default scale.

This command can be accessed from:

- Graph Tools toolbar
- Floating menu (right mouse button on a graph)

“Measure” distance command

The “Measure” distance command activates the display of two crossing-line sets in the active output view. The horizontal and vertical crossing lines show two data points



on a curve along with a display of their XY coordinates and distances. The displayed coordinates refer to the curve data points.

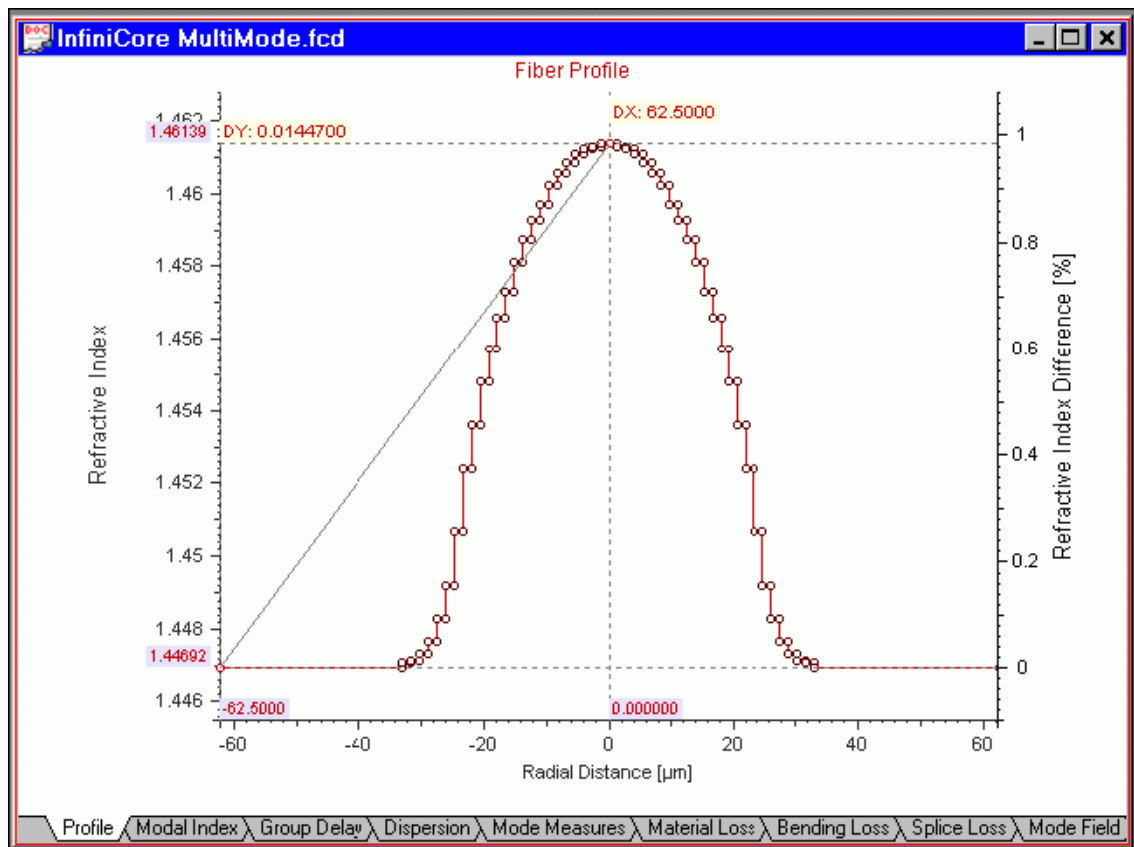
This command can be accessed from:

- Graph Tools toolbar
- Floating menu (right mouse button on a graph)

To use this command:

Step Action

- 1 Select "Measure" from the "Graph Tools" toolbar or from the floating graph menu.
- 2 Click the curve with the left mouse button. The nearest data point is displayed as a small circle with a set of XY lines passing through it. The point coordinates are displayed along the XY lines.
- 3 Move the cursor along the curve. During that move, the point closest to the cursor will be displayed as small circle with a second set of XY lines passing through it. The second set of lines displays the second point coordinates as well as the XY distances from the first point.



The “Measure” distance tool works well with the “Joints” command active.

“Tracking” command

The “Tracking” command activates the display of a crossing-line set in the active output view. The horizontal and vertical crossing lines show data points on a curve along with a display of their XY coordinates.

This command can be accessed from:

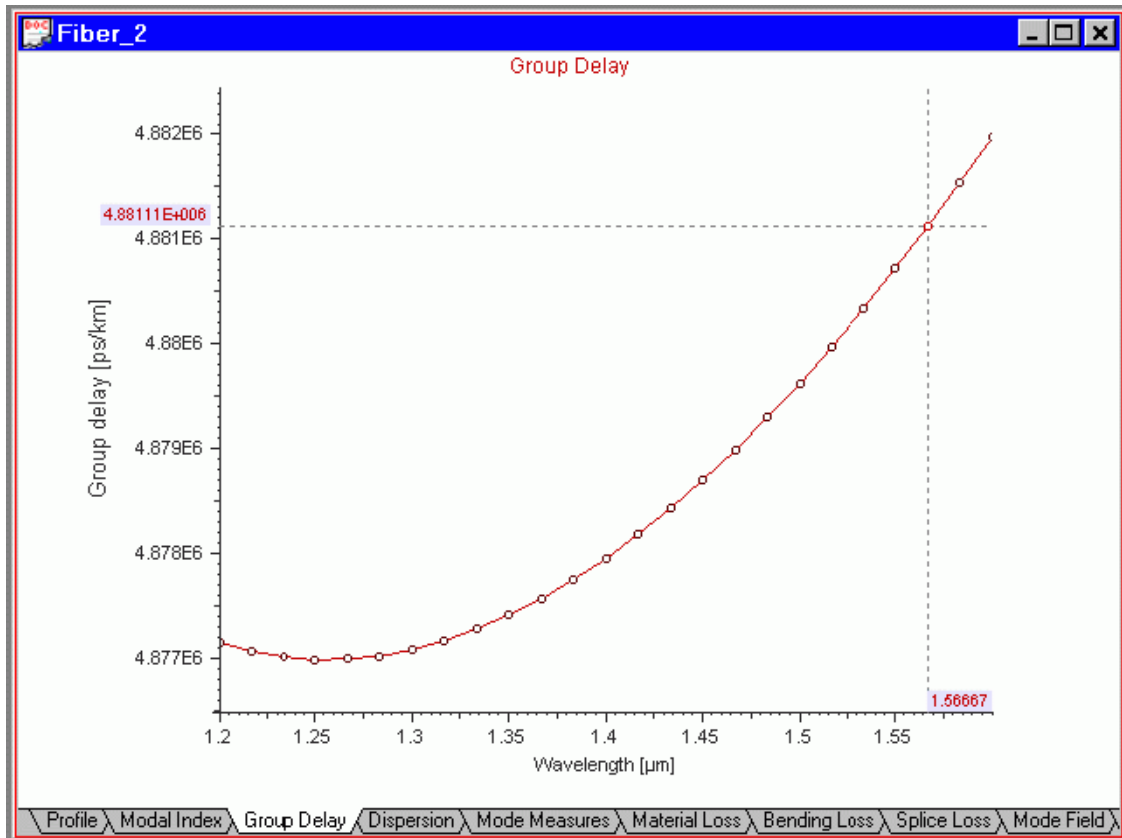
- Graph Tools toolbar
- Floating menu (right mouse button on a graph)

To use this command:

Step	Action
-------------	---------------

- | | |
|----------|---|
| 1 | Select “Tracking” from the “Graph Tools” toolbar or from the floating graph menu. |
| 2 | Click the curve with the left mouse button. The nearest data point is displayed as a small circle with a set of XY lines passing through it. The coordinates of the point are displayed along the XY lines. |





Note: The simplest way to use this command is to click-and-drag on the graph using only the left mouse button. In that case you do not need to use the Graph Tools toolbar nor the floating menu.

The “Tracking” tool works well with the “Joints” command active.

“Legend” command

The “Legend” command toggles the display of the curves legends in the output “Views” window.

This command can be accessed from:

- Graph Tools toolbar
- Floating menu (right mouse button on a graph)

For example the Material Loss view legend looks like this:





You can drag the legend around the graph to position it in a convenient spot.

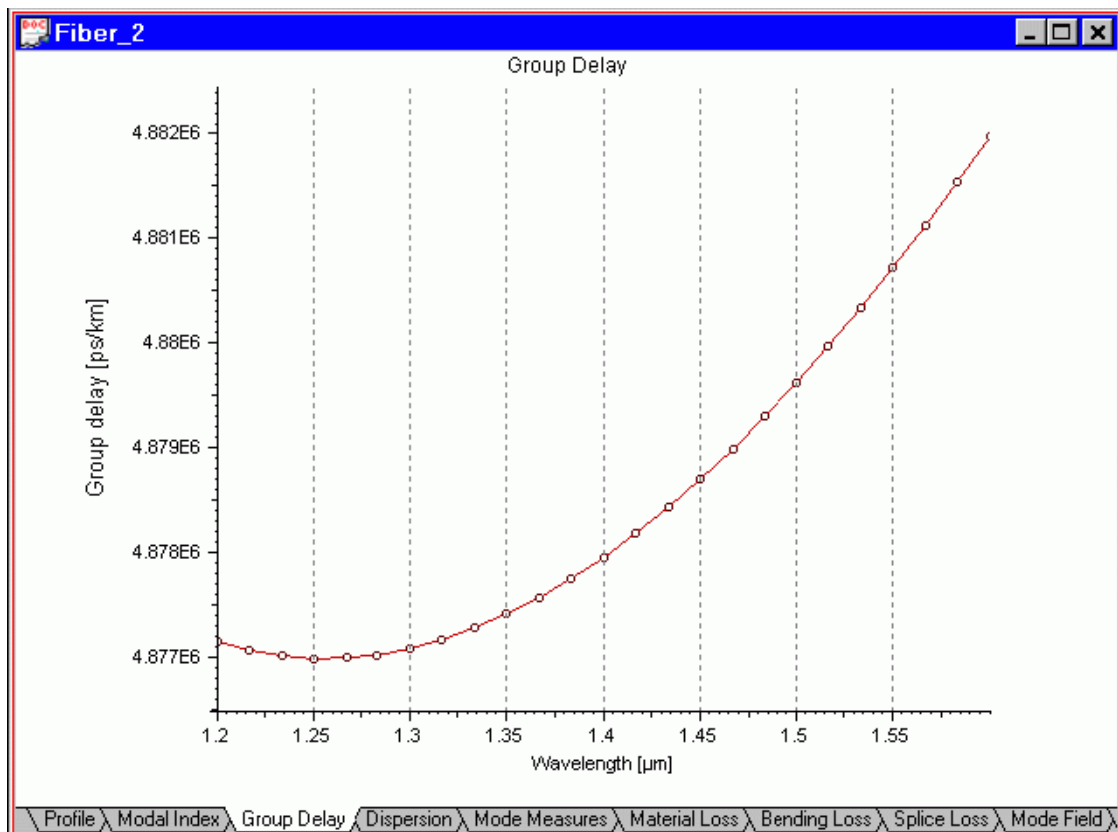
“Grid X” command

The “Grid X” command toggles the display of the vertical grid in the active output Views window.

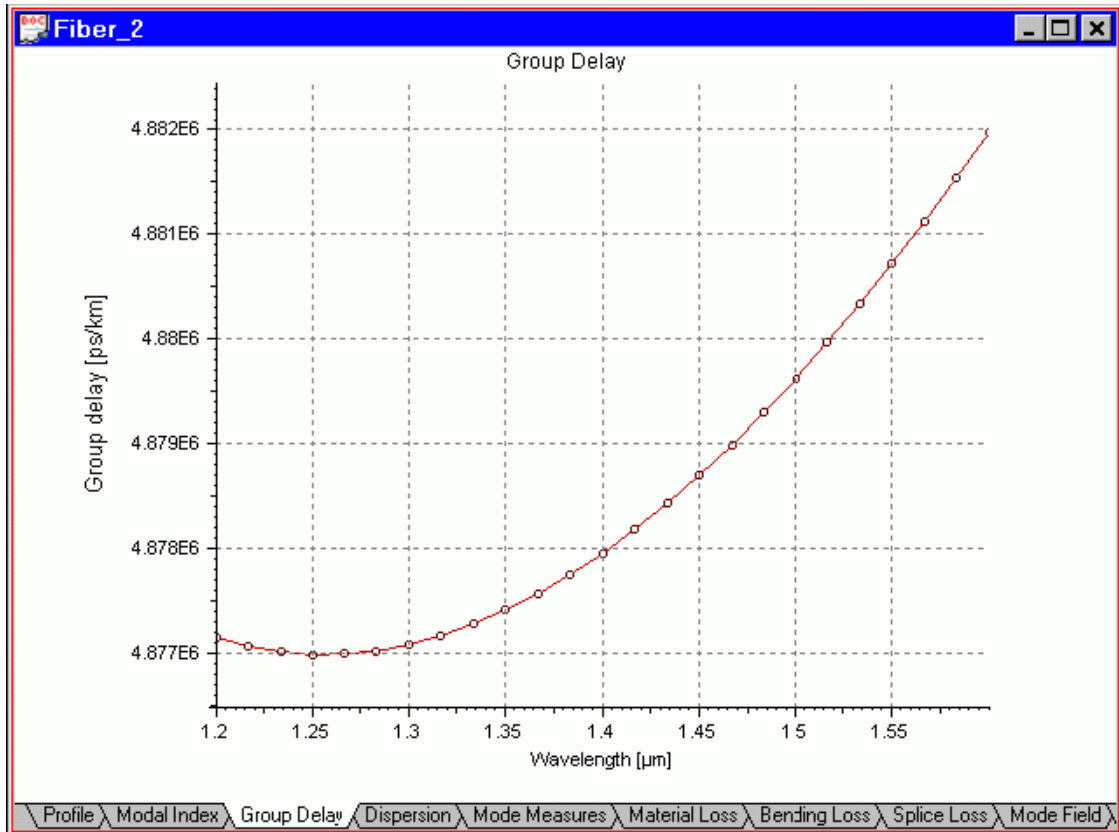
This command can be accessed from:

- Graph Tools toolbar

When you select the “Grid X” command, your display will have a set of vertical lines. The grid lines correspond to the coordinate-labeled points on the X-axis.



You can combine the “Grid X” and “Grid Y” command to obtain a rectangular XY grid on the display.



“Grid Y” command

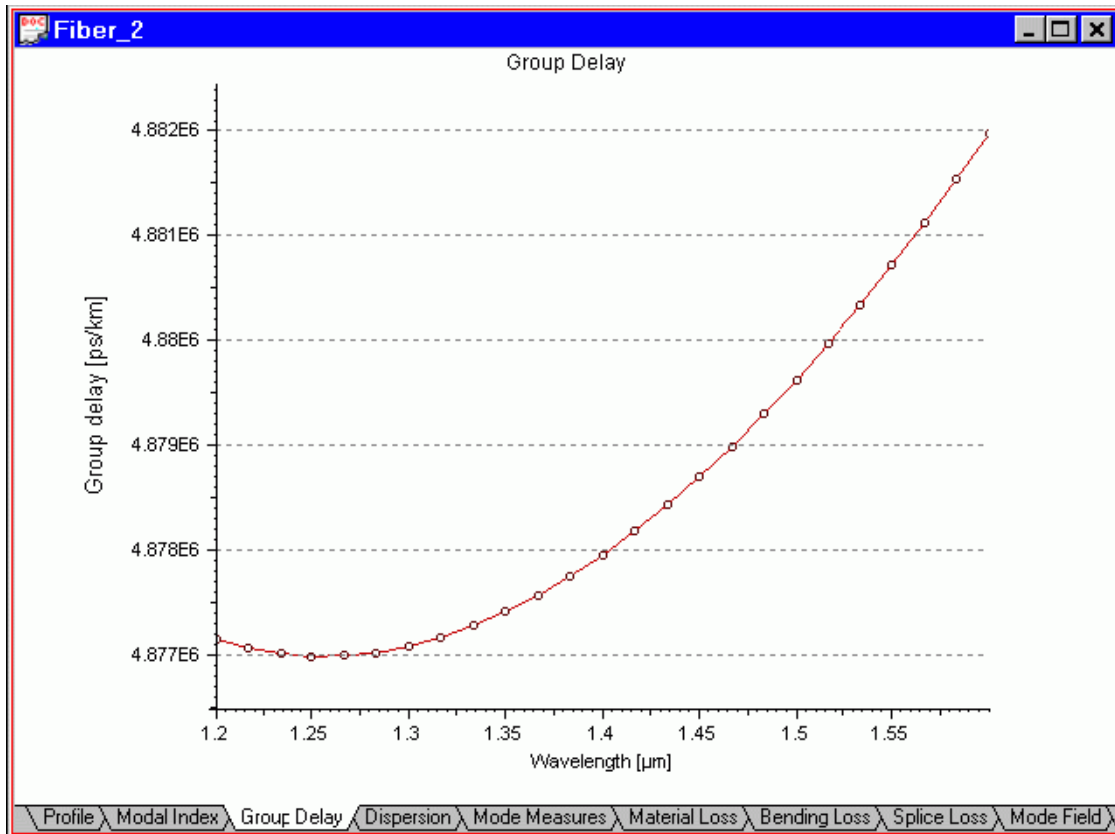
The “Grid Y” command toggles the display of the vertical grid in the active output Views window.

This command can be accessed from:

- Graph Tools toolbar

When you select the “Grid Y” command, your display will have a set of horizontal lines. The grid lines correspond to the coordinate-labeled points on the Y-axis.





You can combine the “Grid X” and “Grid Y” command to obtain a rectangular XY grid on the display.

“X Cut” command

The “X Cut” can be used in the “Mode Field” output view. It allows you to track an X cross-section of the

XY mode field. By default it is turned on.

This command can be accessed from:

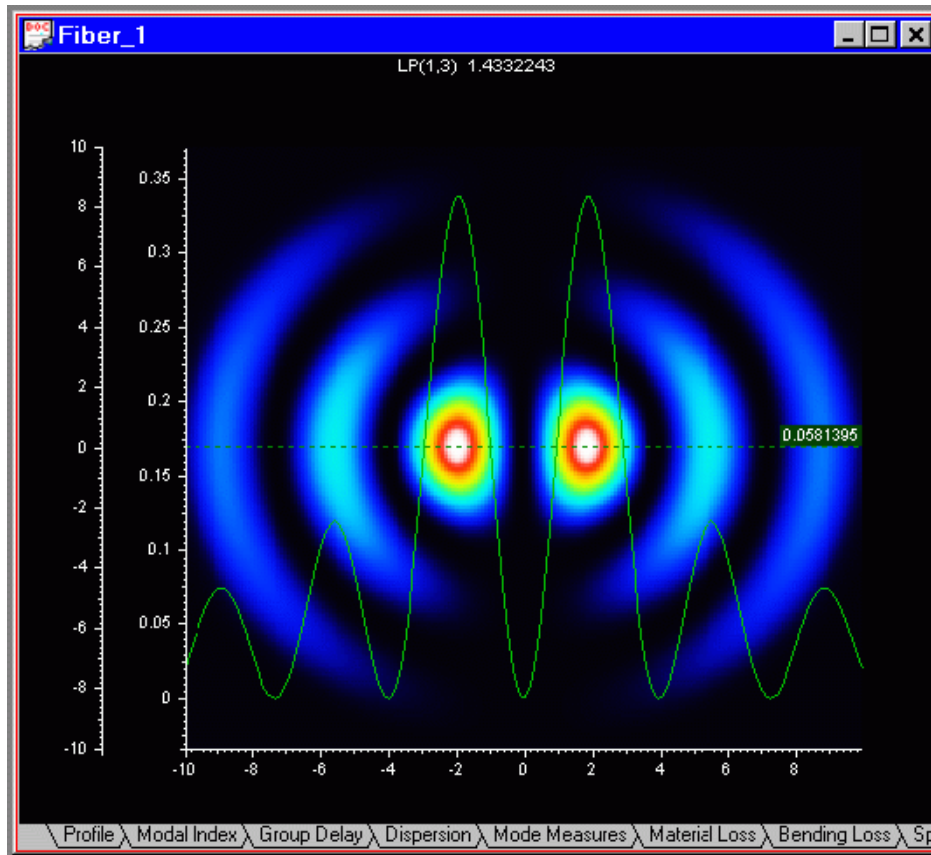
- Graph Tools toolbar

To use this command

Step Action

- 1 Select “X Cut” from the Graph Tools toolbar.
- 2 In the “Mode Field” view, click-and-drag the X-section position along the Y-axis. Along with the X-section green horizontal line, the program displays the X-section field curve.





On the graph, there are two vertical scales: one corresponding to the Y-dimension of the fiber, and the other one corresponding to the mode field section.

“Y Cut” command

The “Y Cut” can be used in the Mode Field output view. It allows you to track a Y cross-section of the XY mode field. By default it is turned on.

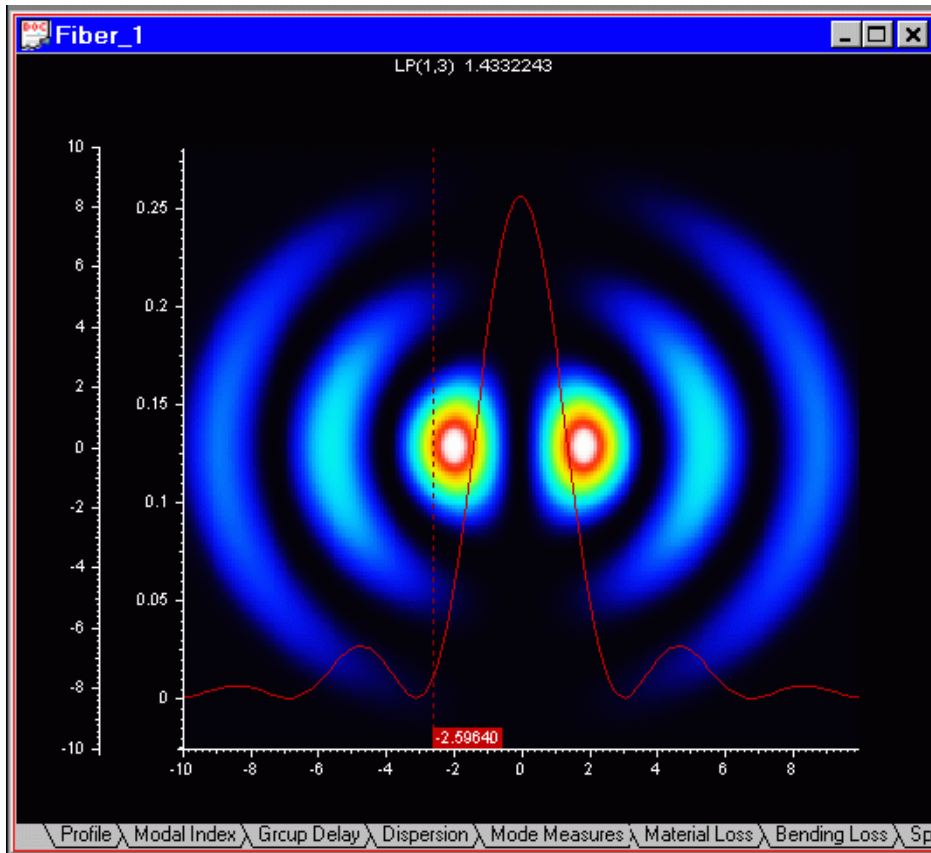
This command can be accessed from:

- Graph Tools toolbar

To use this command:

Step	Action
1	Select “Y Cut” from the “Graph Tools” toolbar.
2	In the “Mode Field” view, click-and-drag the Y-section position along the X-axis. Along with the Y-section red vertical line, the program displays the Y-section field curve.





On the graph, there are two vertical scales: one corresponding to the Y-dimension of the fiber, and the other one corresponding to the mode field section.



Dialog Boxes Reference

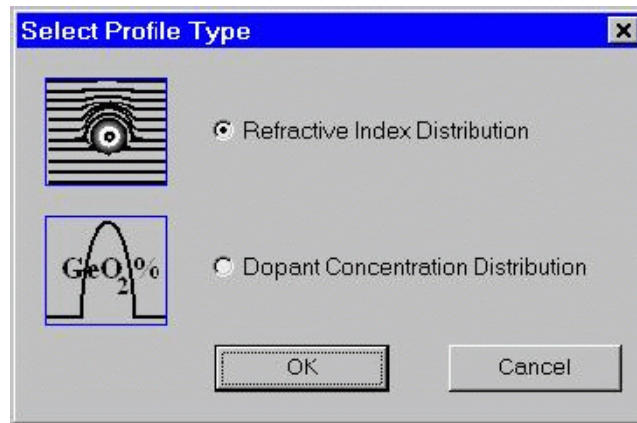
Fiber Profile Related Dialogs

Select Profile Type dialog box

Currently OptiFiber supports two types of profiles

- Refractive index profile
- Dopant concentration profile

The “Select Profile Type” dialog box offers a choice between them. After that it pops-up the “Fiber Profile” dialog box.



Fiber Profile dialog box

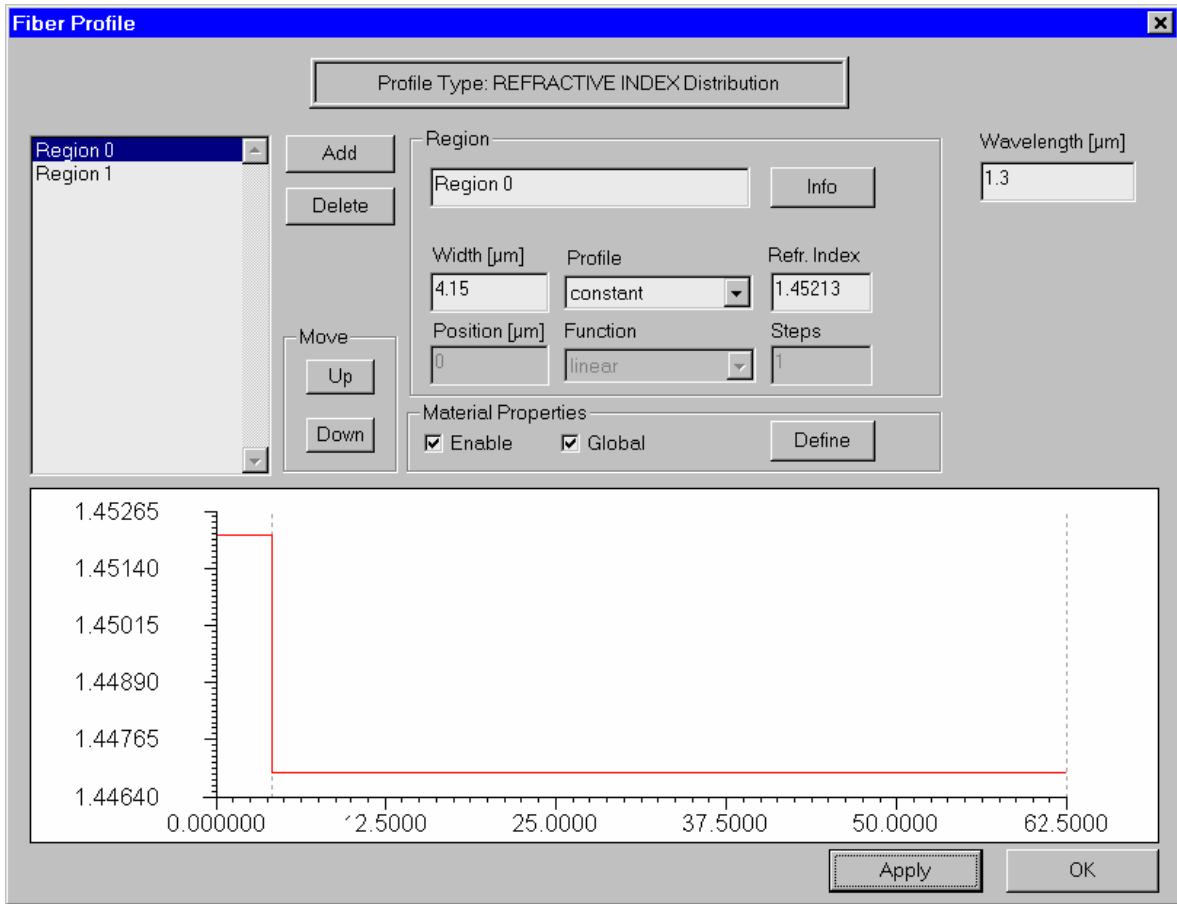
The “Fiber Profile” dialog box helps you design the refractive index profile of the fiber.

To access this dialog box do one of the following:

- Select “Profile” on the “Fiber” menu, or
- Click the “Fiber Profile” icon in the “Navigator” pane

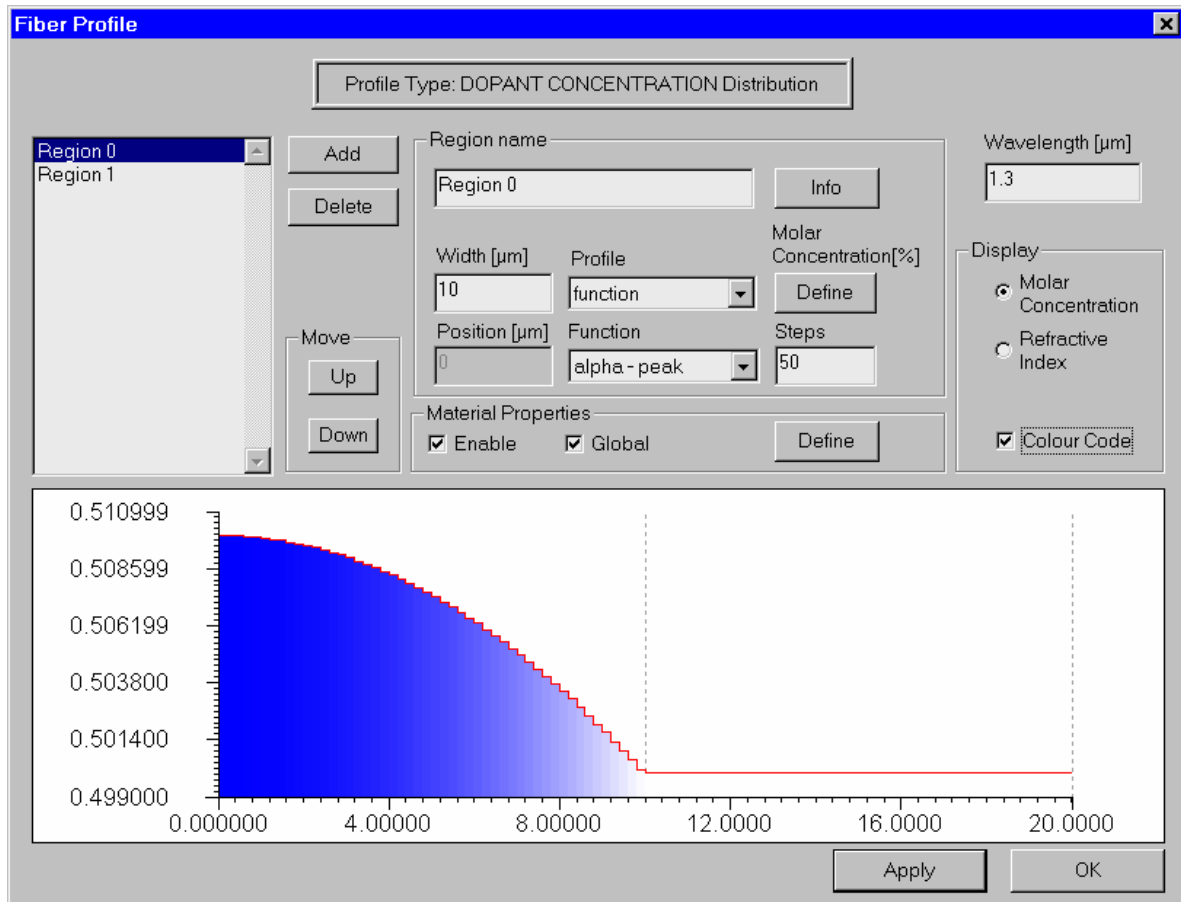
When the profile type is “Refractive index” the dialog box looks as shown:





When the profile type is "Dopant concentration" the dialog box look as shown:





The elements and controls of the “Fiber Profile” dialog box are described below.

List of Regions

Shows the radial refr. index or concentration regions by their names.

Add

Adds a region to the list.

Delete

Deletes the selected region from the list.

Up

Moves the selected region one position up the list.

Down

Moves the selected region one position down the list.



Region Name

Edits and changes the name of the selected region.

Info

Opens the “Region Info” display box, where you can see the region refractive index with its start and end values. This option is particularly useful when dealing with user defined regions, where the start and end index values may not be obvious.

Width

Enter the width of the selected region in microns.

Profile

Select one of the following options for the index profile within the current region:

- Constant - Constant value of the refractive index.
- Function - Functional dependence of the index, where the function is selected from the list in the “Function” option (see “Function” below for the list of available functions).
- User Function - Functional dependence of the index, where the function is defined or programmed using the powerful Script Language environment.

Refr. Index / Molar Concentration [%]

Depending on the select profile type this edit control is interpreted in two different ways:

Refr. Index

Depending on the “Profile” option, you have different options for the “Refr. Index” entry:

- Numerical data entry box - Present when the “Constant” profile option was selected. Enter the refractive index value for the selected region.
- “Define” button - Present when the “Function” or “User Function” option was selected. Press the “Define” button to specify the function. For the “Function” profile option, a dialog box related to one of the predefined functions appears. For the “User Function” profile option, pressing the “Define” button launches the “User Defined Function” script programming environment.

Molar Concentration [%]

Similar to the previous case, however all numerical values are interpreted as molar concentration percentages, instead of refractive indices.

Position

Shows the region radial position in microns. The region position is measured from the fiber center to the beginning of the region.



Function

This option is enabled when the “Function” profile option is selected. The program provides the following predefined index functions:

- Linear
- Parabolic
- Gaussian
- Exponential
- Alpha-peak
- Alpha-dip

The notation convention for these functions is described in the “Technical Background”, section “Refractive Index of Fibers”. Usually, the functions' argument is the radial local distance that is zero at the beginning of the region and is equal to the “Width” value at the end of the region.

Steps

Enter the number of steps for discretization of the index profile function. The OptiFiber mode solver requires the step-like discretization of smooth index profiles. Increasing the number of steps provides better mode solving accuracy, however, at the expense of calculation time.

Enable

Enable the material dispersion model for the current region. To access the model definition press the “Define” button in the “Material Properties” section of the dialog box (also see “Material Properties” dialog box).

Global

Assign the global material dispersion model to the current region. The global model assumes that a fiber is formed by doping the host material with one dopant that rises the refractive index and another dopant that lowers the index (see “Material Properties” dialog box).

Define

Opens the “Material Properties” dialog box, where you can assign material dispersion model based on the Sellmeier coefficients library or on your custom model, as well as nonlinear refractive index of the material.

Wavelength

The wavelength entered here is considered the measurement wavelength, that is, the wavelength at which the current profile is exact. At other wavelength values used in the program, for example when scanning over a spectral range, the profile shape is adjusted accordingly based on the material dispersion model.

Apply

Apply the changes made in the dialog box.



Display

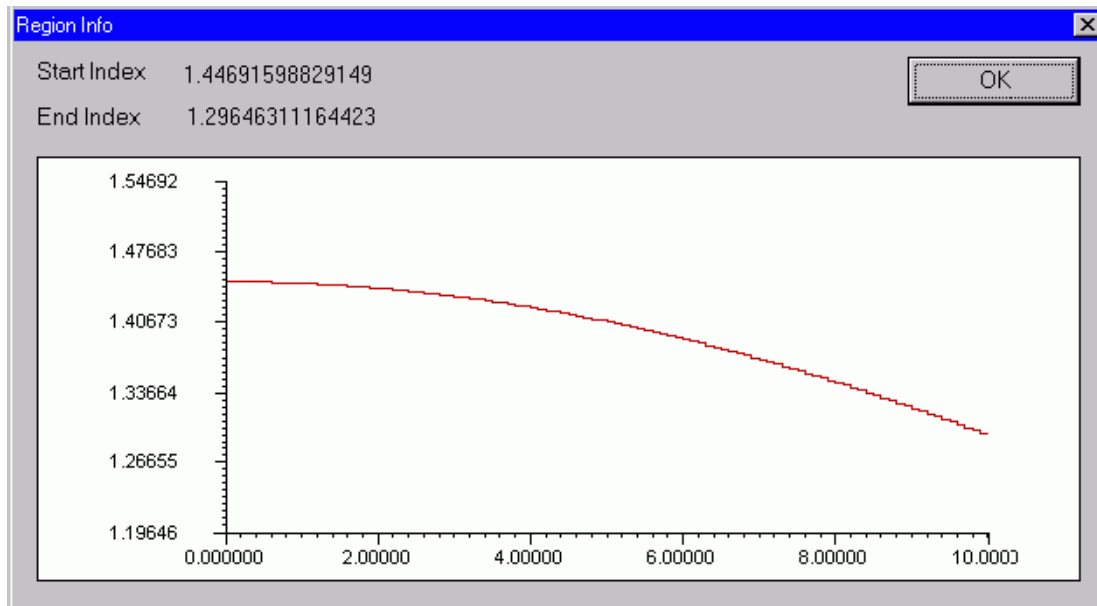
This group of controls allows to show the profile in one of the two alternative ways: 1) as a refractive index profile, or 2) as dopant concentration profile. A check-box that switches the color-coding of the profile on/off is also available.

Info dialog box

The “Info” dialog box displays the selected index profile region. You can see the region refractive index with its start and end values. This option is particularly useful when dealing with user defined regions, where, due to the functional dependence, the start and end index values may not be obvious.

To access this dialog box, do the following steps:

- | Step | Action |
|------|--------------------------------------|
| 1 | Open the “Fiber Profile” dialog box. |
| 2 | Click the “Info” button. |



Material Properties dialog box

The “Material Properties” dialog box looks and functions differently in dependence if the type of profile is “Refractive Index” or “Dopant Concentration”.

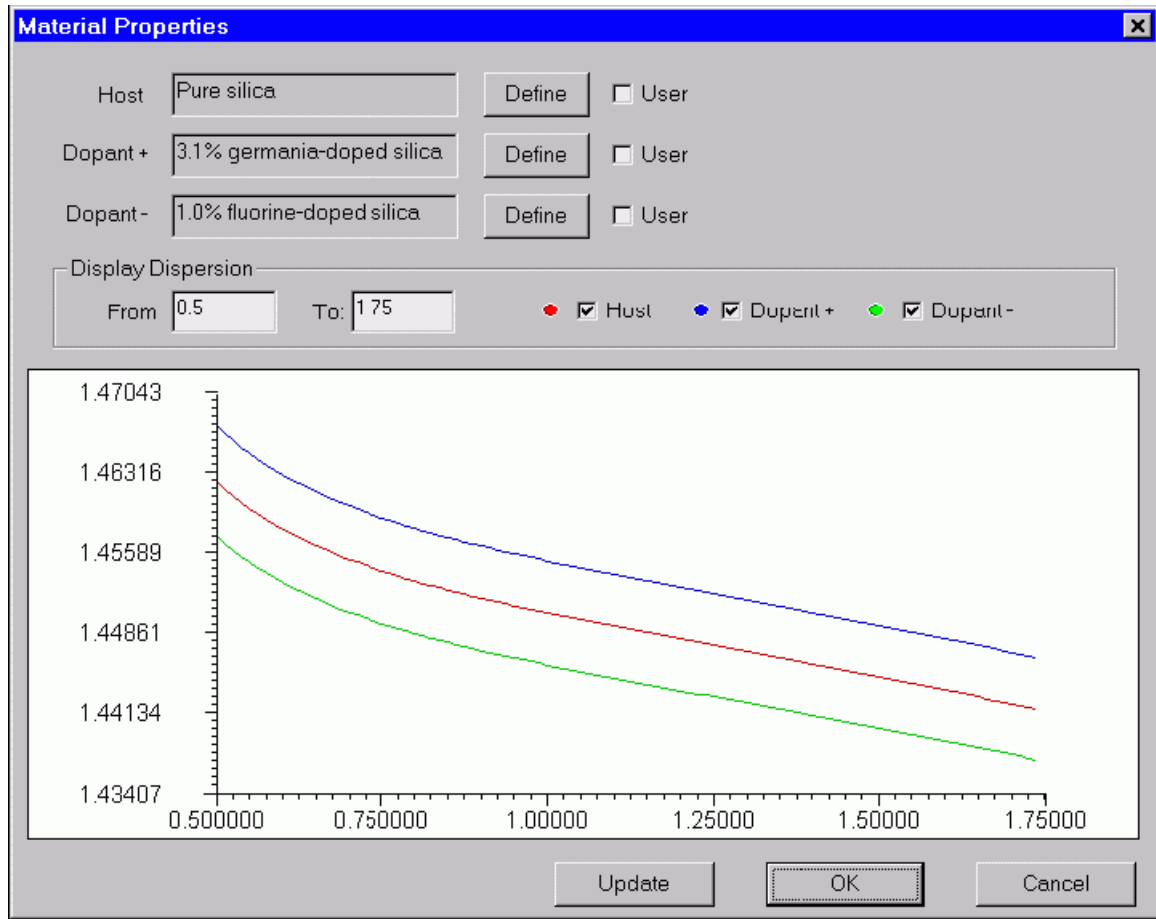
Material Properties dialog box (Profile type is “Refractive Index”)

The “Material Properties” allows the user to specify the Sellmeier and nonlinear coefficients of the fiber material. It also displays the material refr. index as a function of wavelength. For the dispersion model it is assumed that the fiber profile consists of regions with only the host material and doped regions. One of the dopants rises the refractive index, while the other dopant lowers it.

To access this dialog box, do the following steps:

- | Step | Action |
|------|---|
| 1 | Open the “Fiber Profile” dialog box. |
| 2 | Select “Enable” in the “Material Properties” section. |
| 3 | Press the “Define” button in the “Material Properties” section. |





The elements and controls of the “Material Properties” dialog box options are described below.

Host

Shows the name of the fiber host material. Press “Define” to specify the material and its dispersion model. When the “User” option is cleared, the “Define” button activates the “Parameters of Material” dialog box. When the “User” option is checked, the “Define” button launches the “User Defined Function” script programming environment (see the Script Language section of the documentation).

Dopant +

Shows the name of the fiber material that has higher index due to an index-rising dopant. The “Define” button and the “User” option work the same way as for the “Host” option.



Dopant -

Shows the name of the fiber material that has lower index due to an index-decreasing dopant. The “Define” button and the “User” option work the same way as for the Host option.

Update

Update the dispersion display after recent changes.

Display From

Enter the minimum wavelength for the dispersion display.

Display To

Enter the maximum wavelength for the dispersion display.

Host, Dopant + and Dopant – check boxes

Serve to switch on /off the display of the respective curves

Material Properties dialog box (Profile type is “Dopant Concentration”)

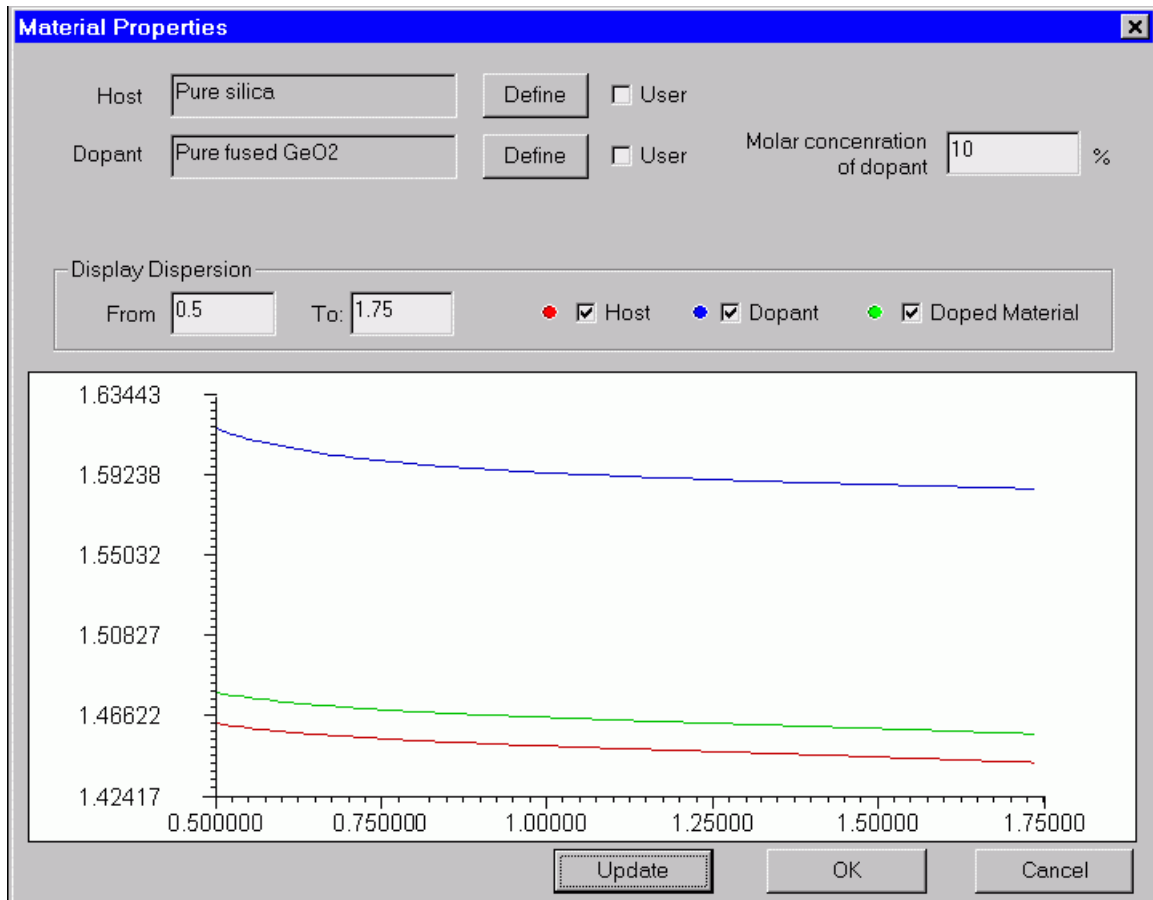
The “Material Properties” allows the user to specify the chemical composition, Sellmeier and nonlinear coefficients of the fiber material. It also displays the material refractive indices of the pure host material, the dopant and the doped material as a function of wavelength.

To access this dialog box, do the following steps:

Step Action

- 1** Open the “Fiber Profile” dialog box.
- 2** Select “Enable” in the “Material Properties” section.
- 3** Press the “Define” button in the “Material Properties” section.





The elements and controls of the “Material Properties” dialog box options are described below.

Host

Shows the name of the fiber host material. Press “Define” to specify the material and its dispersion model. When the “User” option is cleared, the “Define” button activates the “Parameters of Material” dialog box. When the “User” option is checked, the “Define” button launches the “User Defined Function” script programming environment (see the Script Language section of the documentation).

Dopant

Shows the name of the material doping the host. The “Define” button and the “User” option work the same way as for the “Host” option.



Molar Concentration of Dopant

Enter the molar concentration of the doping material in [%].

Update

Update the dispersion display after recent changes.

Display From

Enter the minimum wavelength for the dispersion display.

Display To

Enter the maximum wavelength for the dispersion display.

Host, Dopant and Doped Material

Serve to switch on /off the display of the respective curves

Parameters of Material dialog box

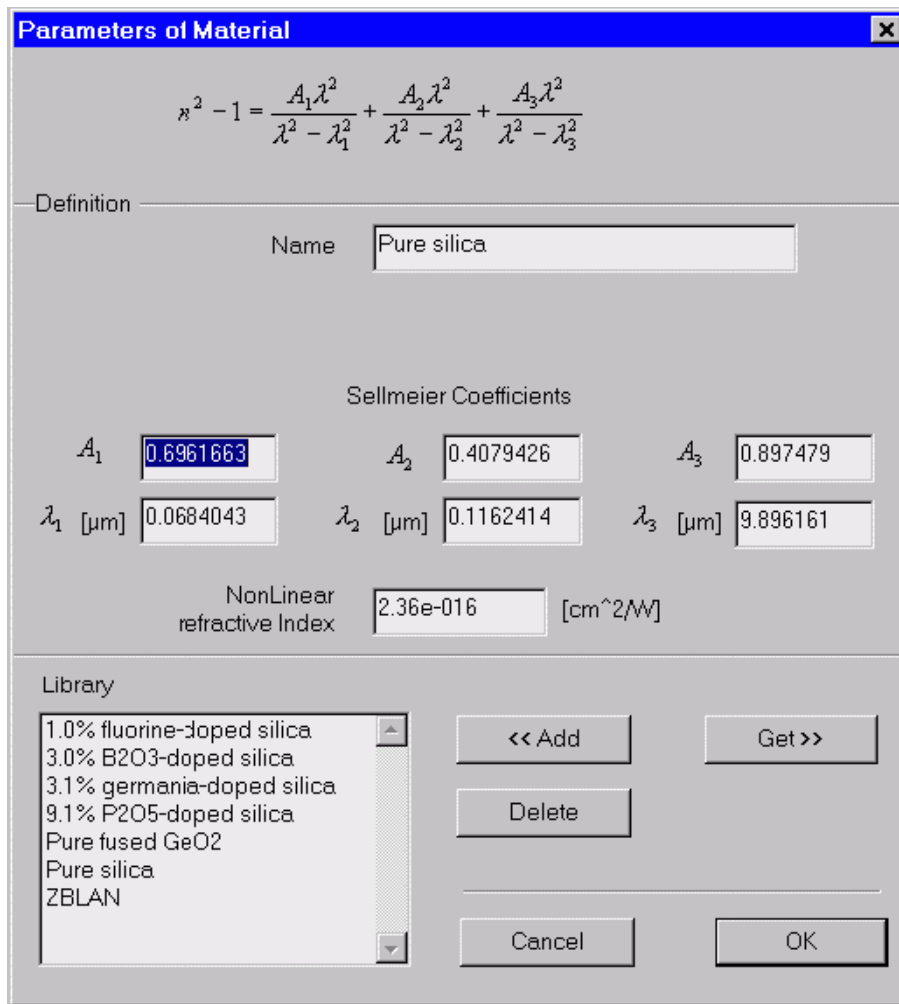
The “Parameters of Material” dialog box allows you to specify:

- The material dispersion model based on the Sellmeier theory. OptiFiber uses six Sellmeier coefficients, three wavelengths and three amplitudes, to define the dispersion curve.
- The nonlinear coefficient of the material
- The molar concentration of dopant in case the profile type is ”dopant concentration”.

To access this dialog box, do the following steps:

- | Step | Action |
|-------------|---|
| 1 | Open the “Fiber Profile” dialog box. |
| 2 | Select “Enable” in the “Material Properties” section. |
| 3 | Press the “Define” button in the “Material Properties” section. The “Material Properties” dialog box opens. |
| 4 | In it press the “Define” button for formulate the material model of the host or the dopants. |





Sellmeier Formula

The Sellmeier formula is displayed for reference. The formula reads:

$$n^2(\lambda) - 1 = \frac{A_1 \cdot \lambda^2}{\lambda^2 - \lambda_1^2} + \frac{A_2 \cdot \lambda^2}{\lambda^2 - \lambda_2^2} + \frac{A_3 \cdot \lambda^2}{\lambda^2 - \lambda_3^2}$$

where n is the wavelength-dependent refractive index, A1, A2 and A3 are the Sellmeier amplitudes, and $\lambda_1, \lambda_2, \lambda_3$ are the Sellmeier resonance wavelengths.

The elements and controls of “Parameters of Material” dialog box are described below.



Name

Enter the name of the material. If you select the material from the Library list (see Get below) then the name appears automatically.

A1, A2, A3

Enter the amplitude Sellmeier coefficients.

$$\lambda_1, \lambda_2, \lambda_3$$

Enter the wavelength Sellmeier coefficients.

NonLinear Refractive Index

The nonlinear refractive index of the bulk material, as defined for example in [G. Agrawal, 1995].

Add

If you entered new material along with its Sellmeier coefficients, you can add it to a data base library by pressing the Add button. Using this feature the user can build rich user-defined material libraries.

Delete

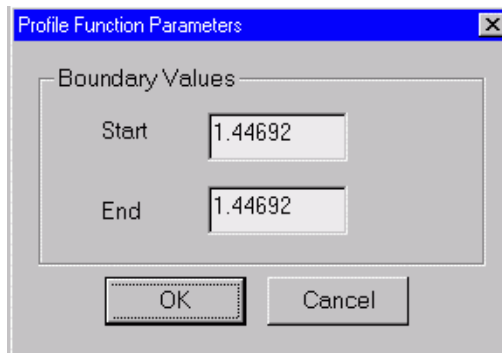
Delete the selected material from the library.

Get

Get the material from the Library list. The library materials are stored in a data base. OptiFiber provides some of the known materials along with the Sellmeier coefficients.

Profile Function Parameters dialog box

The “Profile Function Parameters” dialog box allows you to define the relevant parameters of the profile function in the current region.



It covers the following types of function profiles (see also the “Refractive Index of Fibers” section in the “Technical Background”):



- Linear index profile:
- Exponential index profile:

To access this dialog box, do the following steps:

Step	Action
1	Open the “Fiber Profile” dialog box.
2	Select the region profile as “Function”.
3	In the “Function” list, select Linear, Parabolic, or Exponential.
4	Press the “Define” button.

The elements and controls of “Profile Function Parameters” dialog box are described below.

Start

Enter the start value of the refractive index or the concentration at the beginning of the region.

End

Enter the end value of the refractive index or the concentration at the end of the region.

Gaussian Function Parameters dialog box

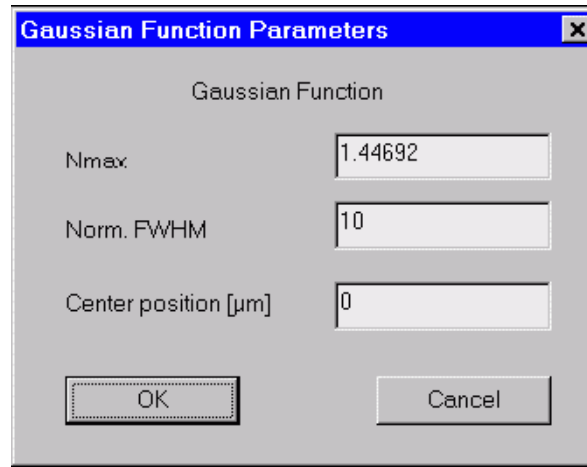
The “Gaussian Function Parameters” dialog box allows you to specify the relevant parameters when the

profile function in the current region is Gaussian (see also the “Refractive Index of Fibers” section in the “Technical Background”).

To access this dialog box, do the following steps:

Step	Action
1	Open the “Fiber Profile” dialog box.
2	Select the region profile as “Function”.
3	On the “Function” list, select “Gaussian”.
4	Press the “Define” button.





The elements and controls of “Gaussian Function Parameters” dialog box options are described below.

Nmax

Enter the maximum value of the refractive index described by the Gaussian function.

Norm. FWHM

Enter the normalized Full Width at Half Maximum (FWHM) of the Gaussian function.

Center Position

Enter the peak position of the Gaussian function. The position is measured from the beginning of the current region.

Parabolic Layer Parameters

The Parabolic Layer Parameters dialog box specifies relevant parameters for function layers of parabolic type. See the Technical Background for the formula defining the parabolic layer. To access this box, perform the following steps

1. Open the Fiber Profile dialog box
2. Select the Region profile as Function
3. On the function list, select Parabolic
4. Press the Define button





The elements of the Parabolic Layer Parameters dialog box are listed below

Orientation – indicates whether the curve will start at the left and go the right side of the layer (the default), or if the direction is to go the other way. In the default position, the extremum of the parabola is on the left, the other orientation will put the extremum on the right side.

Start - enter the refractive index of the layer at the start (left side in Left to Right orientation)

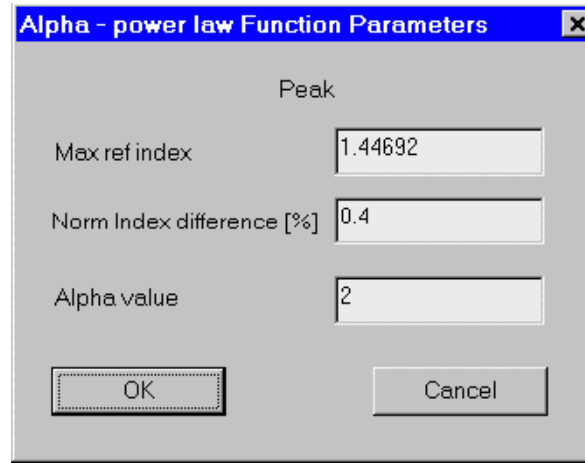
End - enter the refractive index of the layer at the end (right side in Left to Right orientation)

Alpha Power Law Function Parameters dialog box

The “Alpha Power Law Function Parameters” dialog box allows you to specify the relevant parameters when the profile function in the current region is of the following types (see also the “Refractive Index of Fibers” section in the “Technical Background”):

- Alpha –peak index profile:
- Alpha –dip index profile:





To access this dialog box, do the following steps:

- | Step | Action |
|-------------|---|
| 1 | Open the “Fiber Profile” dialog box. |
| 2 | Select the region profile as “Function”. |
| 3 | On the “Function” list, select “Alpha-Power Peak” or “Alpha-Power Dip”. |
| 4 | Press the “Define” button. |

The elements and controls of “Alpha Power Law Function Parameters” dialog box options are described below.

Max Ref Index

Enter the maximum value of the refractive index described by the Alpha-Power function.

Norm Index Difference %

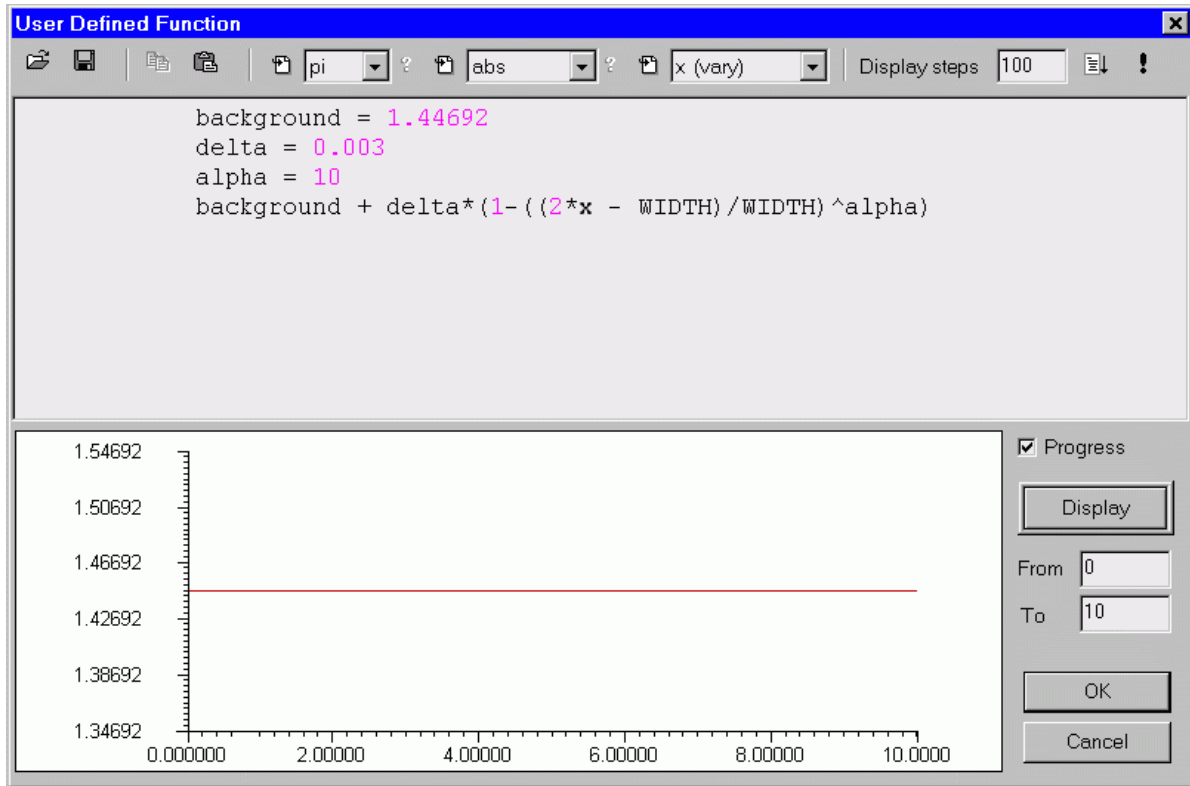
Enter the normalized index difference of the Alpha Power function.

Alpha Value

Enter the alpha power coefficient value.

User Defined Function dialog box

The “User Defined Function” dialog box allows you to define unusual, specific functional dependencies of the profile or the material dispersion model. The user defined function can be almost anything that conforms to the rules of the Script Language programming.



Working with user defined functions

Since User Defined Functions are important for your work, you may want to have a look at the following example:

Let's say that you want to use a user-defined function to define a fiber profile region. To do this, open the "Fiber Profile" dialog box and select the index region where you want the user function to apply. Next, select the "User Function" profile option for that region and press "Define" under the "Refr. Index" or "Molar Concentration" heading (depending on profile type) to open the "User Defined Function" dialog box. It is split into two: the editing area and the display area.

The Editing Area

You define the function in the editing area. For your convenience, the editing area is a simplified programming editor. To define a function, you type the function formula or simply select a function from a combo box (see below: Using Combo Boxes). In the formula, you can use numbers, constants, variables, and other functions. Standard mathematical operators are supported. The program keeps a list of mathematical constants, design (global) variables, and mathematical functions.

In general, the User Defined function has one independent variable, called x.

The Display Area

The graph of the function is shown in the display area.



Working in the Editing Area

Let's assume that you need the profile of the zero-order Bessel function, $J_0(x/s)$, where $s=4$. All you have to do is type the following two lines in the User Function Definition editing area:

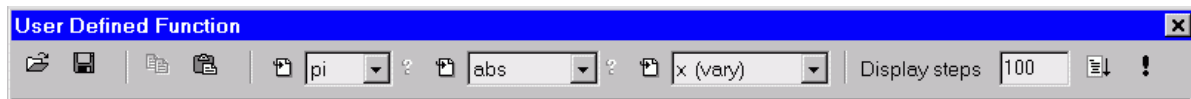
```
s=4
bessj0(x/s)
```

Exploring the User Defined Function program editor

As mentioned above, the editing area is a simplified programming editor. You can write your own functions and also test and debug the program. The format of the language is very close to BASIC. For more information, see the Script Language documentation.

Using Combo boxes

There are three combo boxes. Each of them contains an icon and a list of options:



The icon on the left side of any combo box is for inserting a selected item into the text (at the cursor position). The list of options in the first combo box contains all constants, in the second one all functions, and in the last one the actual global variables. The question marks on the right side of the first and the second combo box will give you a short help about a constant or a function. (Usually a value for a constant and syntax for a function.)

Using the Display Steps box

You use the "Display Steps" box for testing. In this box, you type the number of points you will calculate when you press the Display button in the display area. The number you type in this box is not the number of points this function will calculate in a real calculation. To do the calculation, just press the "OK" button in the display area.

Running the Program and Debugging



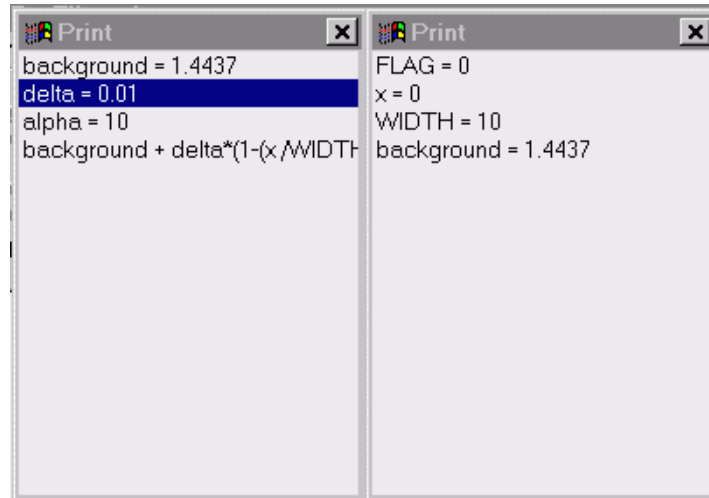
The User Defined Function program editor allows you to Debug and Run (Display) the program.

Run

The "!" button, has exactly the same function as the Display button. It is put on the Toolbar for convenience.

Debug

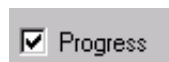
You can not only run your program but also debug it. If the function is not simple, i.e. it may have an IF - THEN structure for example, and gives you bad results, you can easily debug your program by pressing the Debug button and following the prompts. In that case, you will see two new windows. The first one contains the Source Code and shows you where you are in debugging; the second one contains a list of all global (system defined) and local (defined by you) variables.



Exploring the Display Area

In the display area, you see the actual graph. You can also define the variable range of x in the “From” and “To” boxes.

The Progress check box



If you enable the “Progress” check box, you will be able to see the Progress Bar while the program is running. To perform this, you have to enable the Progress check box and press the Display button. You may want to disable the Progress check box if you are using some output windows or FOR - NEXT loops that will give you many Progress/Message bars.

The Load and Save buttons

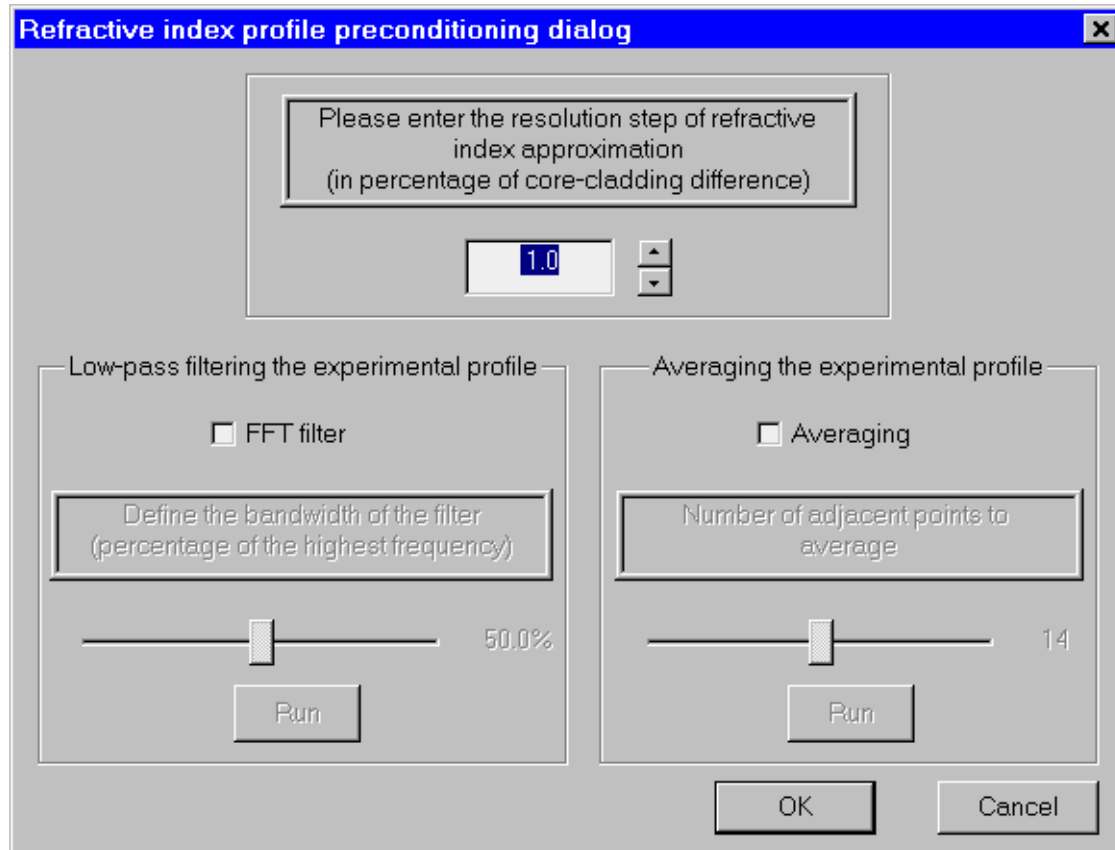


You can load or save any functions to disk as a separate text so that you can build your own library of new functions.



Refractive index profile preconditioning dialog

This dialog box controls the process of importing experimental refractive index data scanned with the NR- 9200 Optical Fiber Analyzer from EXFO Inc.



The elements and controls of “Profile Function Parameters” dialog box are described below.

Resolution step

This is the minimal refractive index difference between two adjacent experimental points that are to be considered belonging to different refr. index regions in OptiFiber. It is entered in percentage of the core/cladding difference of the current profile. By choosing larger step the user can reduce the number of fiber layers at the expense of lower refractive index resolution. As the number of experimental points could be quite large (thousands) the choice of the step is a matter of a reasonable compromise between accuracy and computer load. A step value of 0 (the default value) means that every experimental point will be considered a separate layer/region in OptiFiber.



Low-pass FFT filtering / Averaging

These two features serve to smooth the experimental profiles and remove ripples, small spurious peaks due to vibrations, etc. The Filtering/Averaging operations are optional, not obligatory and can be skipped. Therefore the respective areas of the dialog are initially grayed. However, in such cases the number of interpreted fiber layers and thus the computational effort are increased considerably. If the user opts to smooth the profile, he has to activate the respective controls by checking the check-boxes "FFT Filter On" and/or "Averaging On".



Fiber Modes Related Dialogs

Modes dialog box

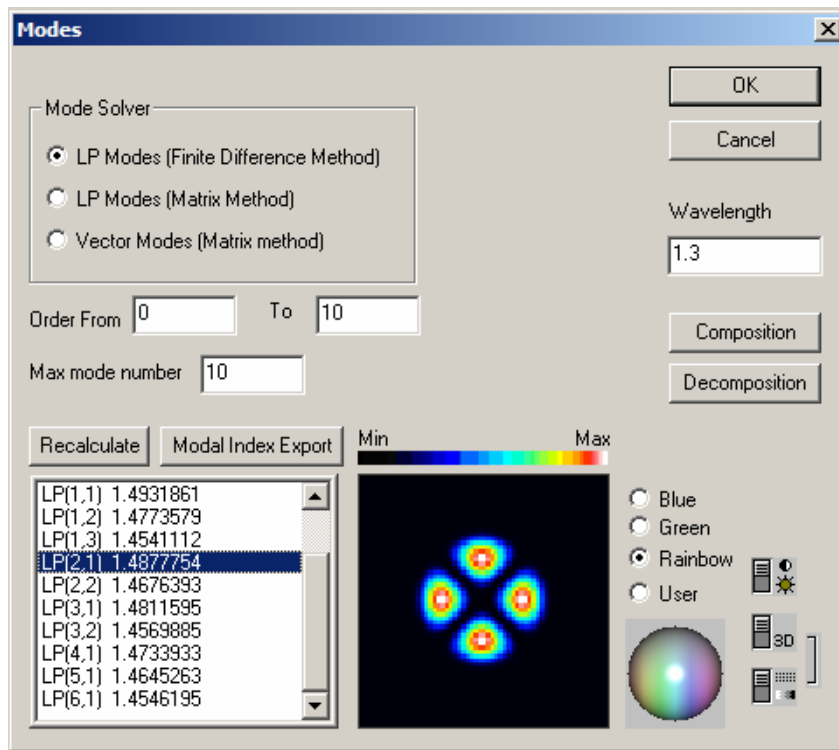
The “Modes” dialog box allows you to:

- Select the types of modes you are interested in
- Select the range of mode numbers you are interested in
- Find the spectrum of supported modes at the specified wavelength with their mode numbers and effective refractive indices
- Select a mode or group of modes for subsequent calculations.
- Preview the mode pattern of a selected mode in a number of ways.
- “Compose” a beam by the interference of an arbitrary group of supported modes.
- “Decompose” in input beam into an arbitrary group of supported modes (calculate input coupling efficiencies.)

To access this dialog box, do one of the following steps:

Step Action

- 1 Select “Modes” on the “Simulation” menu, or
- 2 Click the “Modes” icon in the “Navigator” pane



The elements and controls of “Modes” dialog box options are described below.



LP Modes (Finite Difference Method)

Check this option to calculate fiber propagation modes in the Linear Polarization (LP) approximation (scalar modes). LP(m,n) modes are conventionally labeled using two numbers: the azimuthal number m (the Order), and the radial number (mode number) n. You can select the range of Order and the maximum n number for the solver.

LP Modes (Matrix Method)

This option finds LP modes as above, but by an exact method that uses radial transfer matrices. See Appendix A - Fiber Mode Solvers by Matrix Method for details. This method sometimes runs more slowly, especially if the profile has many layers. However, the far field has the correct asymptotes, and this method is more accurate, especially in the calculation of dispersion and other derivatives with wavelength.

Vectorial Modes

Check this option to calculate fiber propagation modes without the scalar approximation. Conventionally, the vector modes have subsets of the hybrid HE and EH modes, the Transverse Electric (TE) modes, and the Transverse Magnetic (TM) modes. Hybrid (m,n) modes are conventionally labeled using the numbers: the azimuthal number m (Order), and the radial number n. The vector modes are found by a 4x4 transfer matrix method, see Appendix A - Fiber Mode Solvers by Matrix Method for details.

Wavelength

This is the wavelength the calculated spectrum of modes relates to. It is independent of the wavelength specified in the "Fiber Profile" dialog box.

Recalculate

Press the "Recalculate" button to start the mode solver.

List of modes

The results found by mode solver are displayed in the list of modes. The modes are labeled according to the calculation option, with the modal index beside the label.

Modal Index Export

Export the contents of "List of modes" to a text file.

Mode field preview

Mode field can be previewed on the small display, where you can select the display color mode and contrast.

Composition

Starts the "Composition" dialog box allowing to calculate arbitrary interference combinations of the currently selected group of modes.



Decomposition

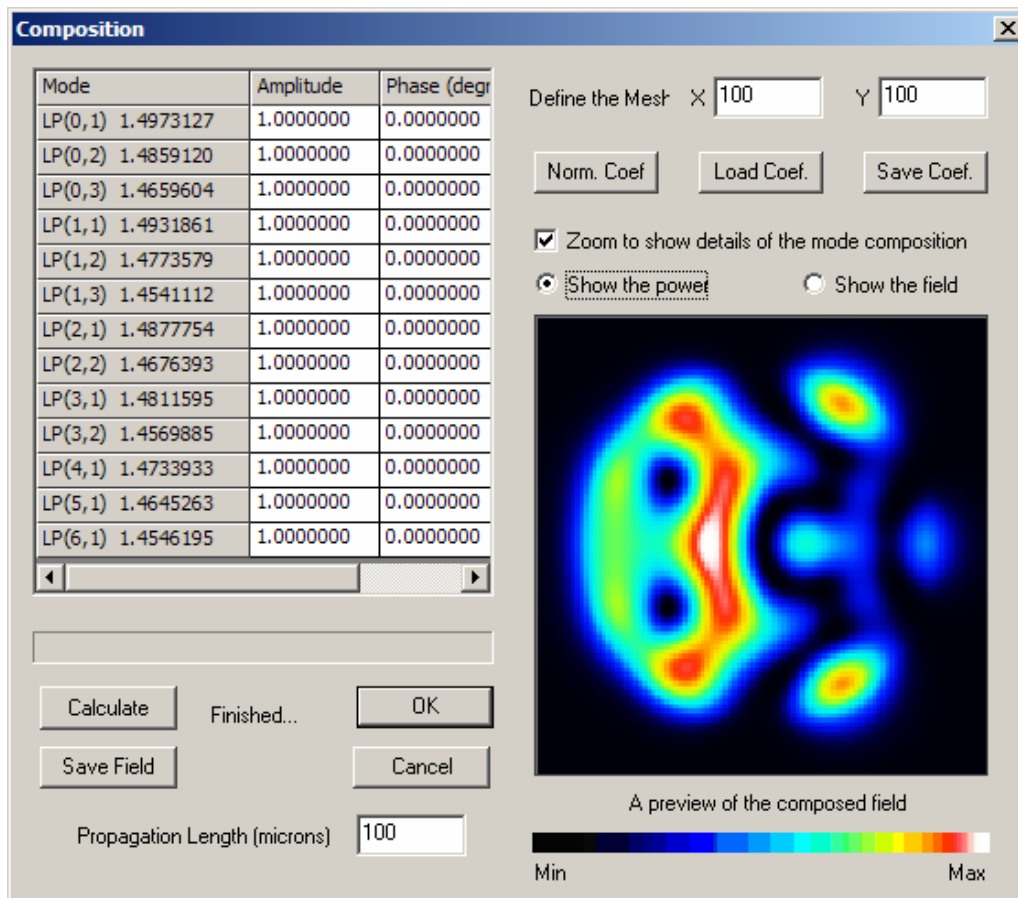
Starts the “Decomposition” dialog box allowing to calculate the coupling efficiencies of an arbitrary input beam into each mode of the currently selected group of modes.

Composition dialog box

This dialog box controls the calculation of the superposition/interference pattern of an arbitrary group of modes each of them having arbitrary power and input phase.

To use this feature, do the following steps:

- | Step | Action |
|------|---|
| 1 | In the “Modes” dialog box, select a group of modes by using Ctrl-, Shift- and the left mouse button. |
| 2 | Press the “Composition” button. In the “Composition” dialog box, enter the weighting coefficient for each mode. |
| 3 | Press “OK” |



The elements and controls of “Composition” dialog box options are described below.

Weighting coefficients table

Enter the complex coefficients assigned to each participating mode in the three-column table (grid) in the upper left part of the dialog box

Preview display area

The graphical window in the lower right part of the dialog box shows a color-coded topological view of the current pattern.

Calculate

Find the current interference pattern as defined by the set of modes and the coefficients.

Define the Mesh

Increase/Decrease the resolution of the preview screen.

Norm Coef.

Normalizes the weighting coefficients. After normalization, the sum of the squared magnitudes of all of the weighting coefficients is equal to 1.

Load Coef.

Load the weighting coefficients to a text file.

Save Coef.

Save the weighting coefficients to a text file.

Zoom

Check this option to zoom the details of the speckle pattern. Useful for fibers with narrow core and wide cladding.

Power/Field

Display the intensity or the amplitude of the composed field.

Save field

Saves the calculated field to a text file. The saved file has the complex BCF3DCX 3D file Format, described in the "Technical Background".

Propagation Length

When this field is 0.0, the preview is the sum of the modes with amplitudes and phases as indicated in the list. Enter a distance in microns in this field, and press Calculate, to see the field as it would appear after a propagation of this distance.



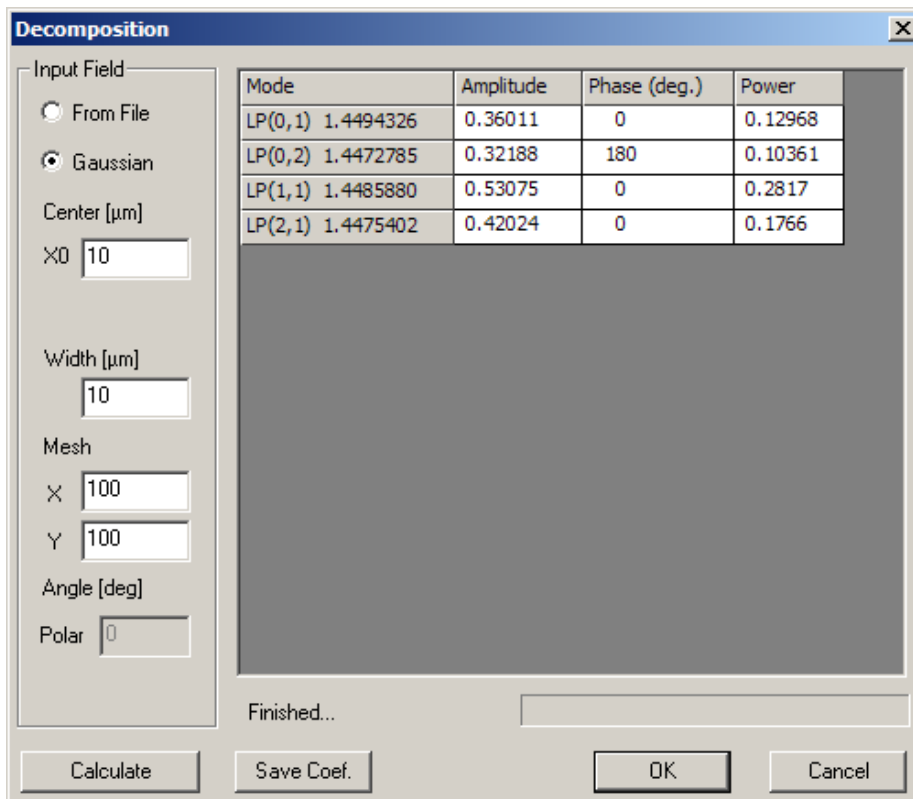
Linear decomposition of a given field distribution

This dialog box controls the calculation of the per-mode coupling efficiencies (the linear decomposition) of an user defined input beam into an arbitrarily selected group of supported modes.

To use this feature, do the following steps:

Step Action

- 1 In the “Modes” dialog box, select a group of modes by using Ctrl-, Shift- and the left mouse button.
- 2 Press the “Decomposition” button. In the “Decomposition” dialog box, define the parameters of the input beam.
- 3 Press “OK”



The elements and controls of “Decomposition” dialog box options are described below.



Calculate

Find the decomposition coefficients for the current set of modes and the current input beam.

Weighting coefficients table

Contains the calculated field (with their real and imaginary parts) and power decomposition coefficients. The values in the “Power” are the squared sum of the real and imaginary parts and have the meaning of the usual coupling coefficients.

From File

Read the input beam from a user defined file having the BCF3DCX complex 3D file Format (please see the description in “Technical Background”).

Gaussian

The input beam is modeled as Gaussian field defined by the several parameters, FWHM Width and polar angle.

Gaussian for Decomposition

$$G(x, y) = 2^{-r^2}$$

Where

$$r^2 = \frac{(x - x_0)^2 + y^2}{(w_0/2)^2}$$

Center

The center position x_0 of the input Gaussian beam.

Width

The width w_0 of the input Gaussian beam.

Mesh

The number of point of the internal calculations. Higher value means better accuracy of the coefficients at the expense of computing time.

Angle

Enter the polar angle between the input beam and the fiber axis.

Save Coef.

Export the coefficients to a text file.

Properties of Fundamental Mode dialog box

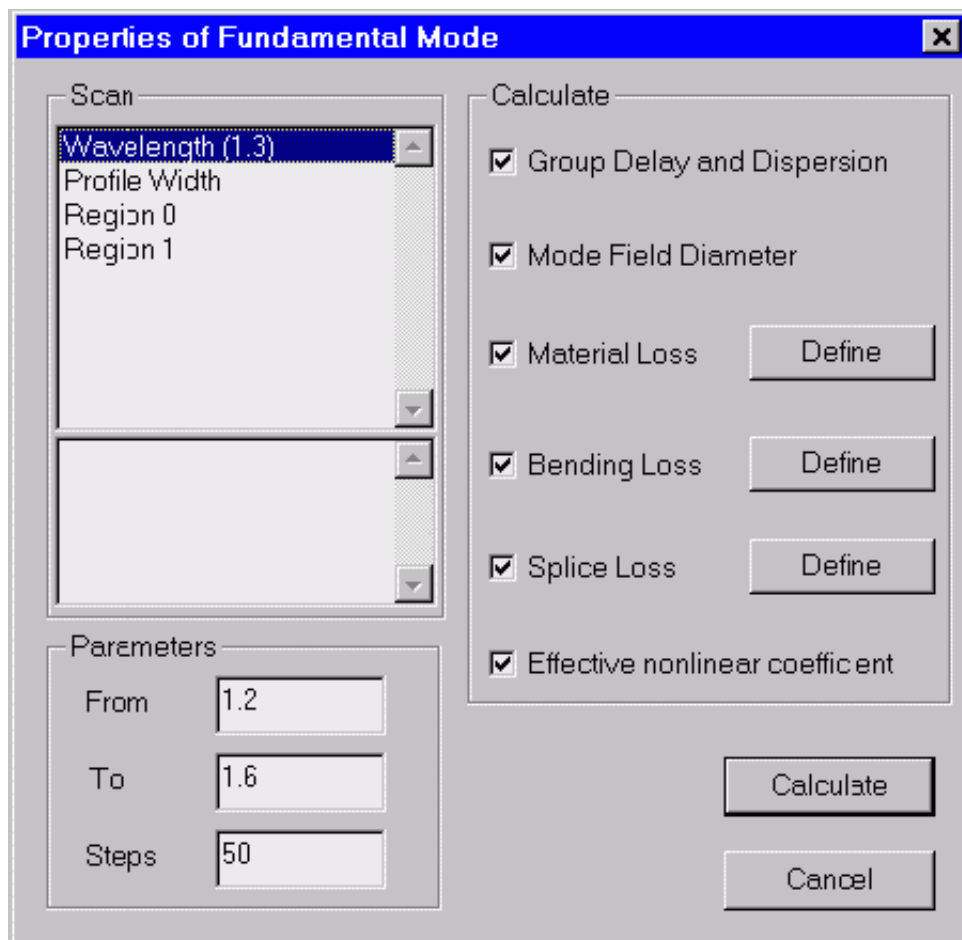
The “Properties of Fundamental Mode” dialog box controls the powerful parameter scanning routines of OptiFiber related to the fundamental mode. It also allows the user to select which characteristics of the fundamental mode to be calculated.

To access this dialog box, take one of the following steps:

Step Action

- 1 1. Select “Fundamental Mode” on the “Simulation” menu
- 2 2. Click the “Fundamental Mode” icon in the “Navigator” pane

In the case of a simple step-index fiber it look as shown:



In order to use this dialog the user should have defined a legitimate profile in the “Profile” dialog box.



The elements and controls of the “Properties of Fundamental Mode“ dialog box are described below.

Scan

The “Scan” section is split into two panes.

- The upper pane lists what is subjected to scanning:
 - The wavelength within a spectral region.
 - The profile as a whole within user-specified limits, for example between 0.8 and 1.2 of the original width. This means that all spatial dimensions of the original design are proportionally shrunk/expanded at regular steps from 0.8L to 1.2L, where L is the initial width.
 - The single spatial regions of the profile.
- The lower pane lists the various technological parameters of the current region that are available for scan calculations.

When “Wavelength” or “Profile Width” is selected in the upper pane, then there is no other parameter to scan. When a region is selected, then all region parameters available for scan calculations are displayed in the lower pane. Their number and physical meaning depends on the type of the region. The available parameters may include function parameters for function-defined regions. For example:

- If a simple “constant” region is selected, then for scanning are available:
 - its spatial width and
 - maximal refr. index
- If a “Gaussian function” region is selected, then for scanning are available:
 - its spatial width
 - maximal refr. index
 - FWHM and
 - central position

Parameters

The “Parameters” section refers to the range of parameter being scanned and the number of steps. “From” - Initial value of the scan parameter “To” - Final value of the scan parameter “Steps” - Number of calculation steps in the scan calculations

Calculate

The “Calculate” section allows you to select the fundamental mode characteristics to be calculated versus the scan parameter.

The options are:

- Group Delay and Dispersion
- Mode Field Diameter
- Bending Loss



- Splice Loss
- Effective nonlinear coefficient

The Material Loss option always refers to scanning over the wavelength parameter. You start the calculations by pressing the “Calculate” button.

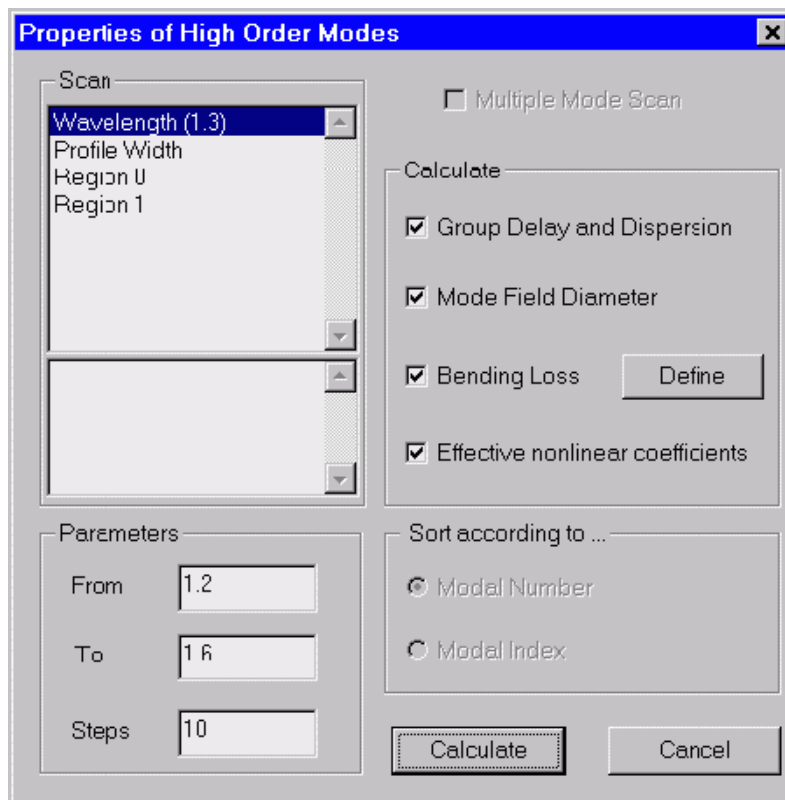


Properties of Higher Order Modes dialog box

The “Properties of Higher Order Modes” dialog box controls the powerful parameter scanning routines of OptiFiber related to a higher order mode or a group of modes. It also allows the user to select which modal characteristics to be calculated.

To access this dialog box, take the following steps:

- | Step | Action |
|-------------|---|
| 1 | Select “Higher Order Modes” on the “Simulation” menu, or |
| 2 | Click the “Higher Order Modes” icon in the “Navigator” pane |



In order to use this dialog the user should have:

- Defined a legitimate profile
- Solved for the spectrum of modes in the “Modes” dialog box and found that the fiber is multi-mode at that wavelength.
- Selected in the “Modes” dialog box
 - a higher order mode, or
 - a group of modes



If some of these conditions are not fulfilled, the user is automatically sent to the respective place of

OptiFiber to alter the design, to solve for modes, etc.

The logic of the scanning routines depends alternatively on the number of modes that have been selected in the “Modes” dialog box. In the case of one selected higher mode the “Properties of Higher Order Modes” works in the same way as the “Properties of Fundamental Mode” dialog – it allows the defined characteristics of that mode to be calculated versus some scanned parameter.

In the case of multiple selected modes the “Properties of Higher Order Modes” calculates the defined characteristics of each mode. An option is offered to sort and display the results:

- according the sequential number of the modes in the selected group.
- according the effective refr. index of the modes in descending order.

The elements and controls of “Properties of Higher Order Modes” are almost the same as those of the “Properties of Fundamental Mode” dialog box and will not be described separately.

Note: The calculations are performed for the mode or modes previously selected in the “Modes” dialog box.

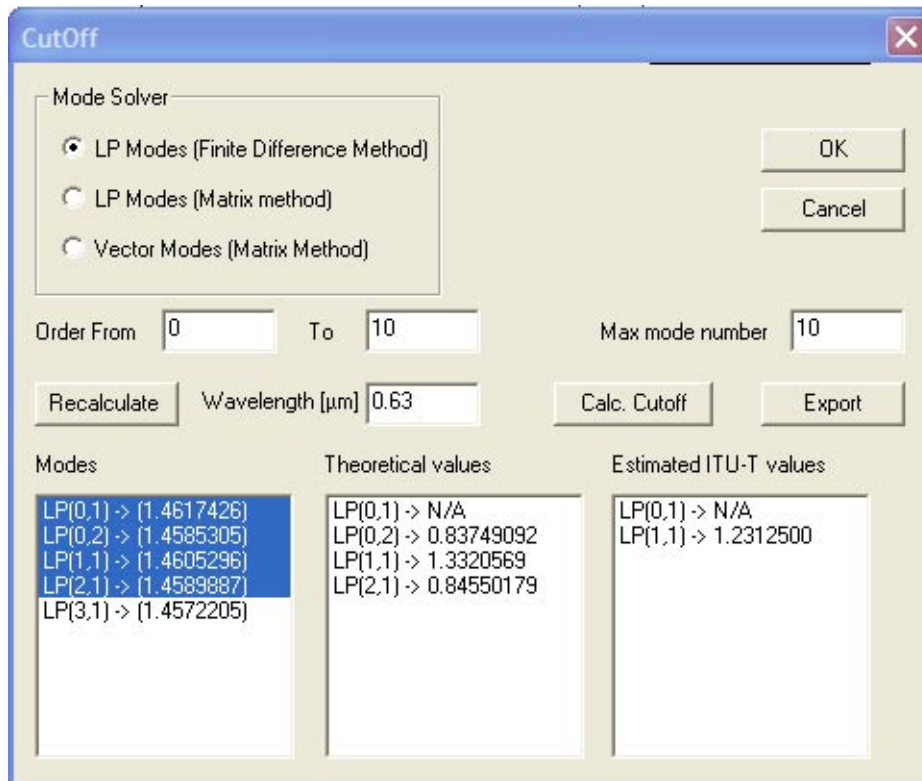
Cutoff dialog box

The “Cutoff” dialog box finds the spectrum of supported modes at a specified wavelength, to select a set of the supported modes, and to find their cutoff wavelengths. For explanation of the methods used to estimate the cutoffs, please refer to the section “Cutoff Wavelengths” in the “Technical Background”.

To access this dialog box, take the following steps:

Step	Action
1	Select “Cutoff” on the Simulation menu, or
2	Click the “Cutoff” icon in the “Navigator” pane
3	Enter wavelength and click Recalculate.





The elements and controls of the “Cutoff” dialog box are described below.

LP Modes (Finite Difference Method)

Check this option to calculate fiber propagation modes in the Linear Polarization (LP) approximation (scalar modes). LP(m,n) modes are conventionally labeled using two numbers: the azimuthal number m (the Order), and the radial number (mode number) n. You can select the range of Order and the maximum n number for the solver.

LP Modes (Matrix Method)

This option finds LP modes as above, but by an exact method that uses radial transfer matrices. See Appendix A - Fiber Mode Solvers by Matrix Method for details. This method sometimes runs more slowly, especially if the profile has many layers. However, the far field has the correct asymptotes, and this method is more accurate, especially in the calculation of dispersion and other derivatives with wavelength.

Vectorial Modes

Check this option to calculate fiber propagation modes without the scalar approximation. Conventionally, the vector modes have subsets of the hybrid HE and EH modes, the Transverse Electric (TE) modes, and the Transverse Magnetic (TM) modes. Hybrid (m,n) modes are conventionally labeled using the numbers: the azimuthal number m (Order), and the radial number n. The vector modes are found

by a 4x4 transfer matrix method, see Appendix A - Fiber Mode Solvers by Matrix Method for details.

Wavelength

The wavelength at which the initial spectrum of modes is calculated. If the fiber is single-mode at the specified wavelength – decrease it, in order to be able to select a mode for the calculations.

Recalculate

Press the “Recalculate” button to start the mode solver.

List of modes

The results found by mode solver at the specified wavelength are here. The modes are labeled according to the calculation option. The mode effective index of each modes is given in parenthesis.

Lists of cutoff values

Displays the estimated cutoff wavelength values for the selected modes.

Two lists are available:

- “Theoretical values” and
- “Estimated ITU-T values”

in accordance with the two cutoff definitions. A cutoff wavelength is not defined for the fundamental mode

and therefore is marked 'N/A' (although occasionally, for quite inappropriate combination of parameters, the fundamental mode could be unsolvable for, a condition called “a numerical cutoff”).

Export

Click here to make an ascii text file that contains the modes listed in the columns Theoretical values and Estimated ITU-T values.



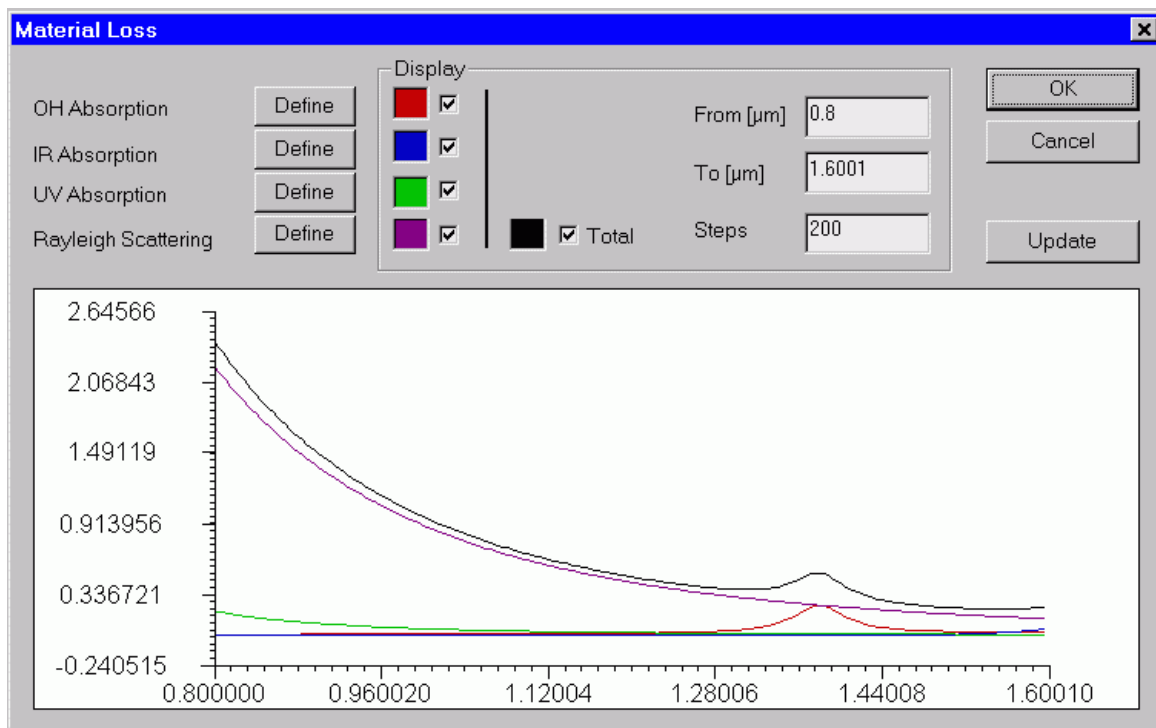
Fiber Loss Related Dialogs

Material Loss dialog box

The “Material Loss” dialog box allows you to define parameters for the material loss models and preview them on the attached display. The material loss includes the OH radicals, infrared, and ultraviolet absorption models, as well as the Rayleigh scattering model.

To access this dialog box, do the following steps:

- | Step | Action |
|------|---|
| 1 | Open the “Properties of Fundamental Mode” dialog box |
| 2 | Check the “Material Loss” option |
| 3 | Press the “Define” button for the “Material Loss” option, or |
| 4 | Access it by double-clicking in the “Material Loss” view tab. |



The elements and controls of the “Material Loss” dialog box are described below.

Define

You can define the hydroxyl (OH), infrared (IR), ultraviolet (UV) absorption parameters, and the Rayleigh scattering parameters by pressing the “Define” buttons corresponding to each of the loss listing. If the “User” box is cleared, then the program



displays a loss model dialog box that corresponds to the current option. If the “User” box is checked, the program launches the “User Defined Function” dialog box, where you can define custom models.

Display

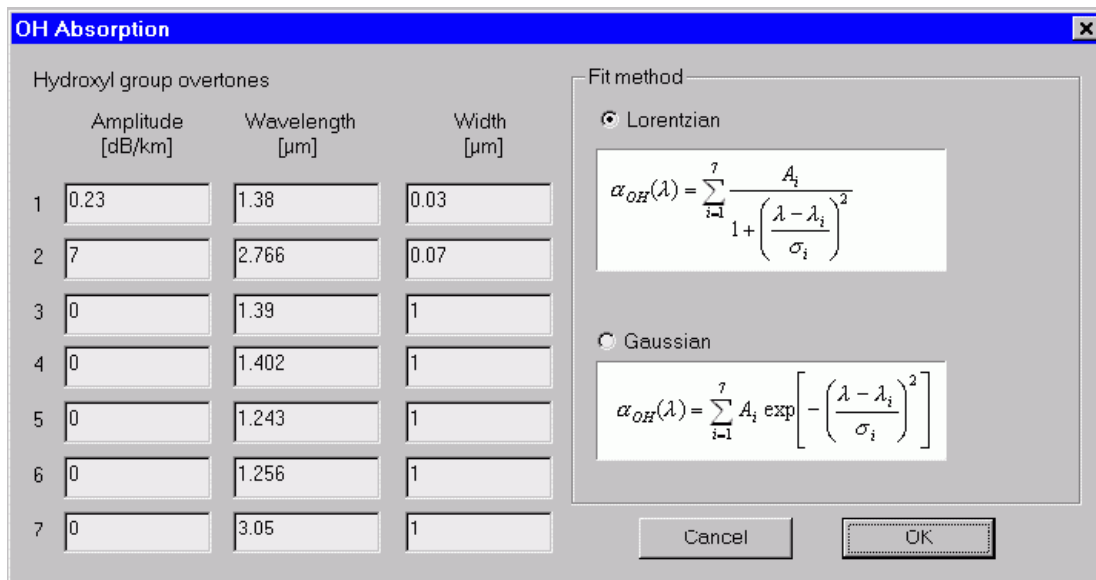
You can select the wavelength range for the material loss display and toggle between displaying different curves.

Update

By pressing the Update button, you can refresh the display after recent changes.

OH Absorption dialog box

The “OH Absorption” dialog box allows you to define the hydroxyl group absorption characteristics. The characteristics are defined by fitting to the OH overtone resonance curves. You can form the absorption curve either by adding Lorentzian or Gaussian shaped resonance.



To access this dialog box, do the following steps:

- | Step | Action |
|------|---|
| 1 | Open the “Properties of Fundamental Mode” dialog box |
| 2 | Check the “Material Loss” option |
| 3 | Press the “Define” button for the “Material Loss” option |
| 4 | Press the “Define” button for the “OH Absorption option” , or |
| 5 | Access it by double-clicking in the “Material Loss” view tab. |

The elements and controls of the “OH Absorption” dialog box are described below.

Hydroxyl Group Overtones

The Hydroxyl Group Overtones section refers to resonance in the absorption spectra caused by the presence of OH impurities in the fiber material. The OH absorption curve is composed of a series of independent resonance characteristics that are added together. You can create up to seven resonance by providing their amplitudes, central wavelengths, and widths.

Fit Method

The particular resonance may be modeled by Lorentzian or Gaussian curves. You select one or the other as the OH absorption fitting model. Formulas for both fitting methods are displayed in the dialog box

See also the “OH-Radical Absorption Model” section in the “Technical Background”.

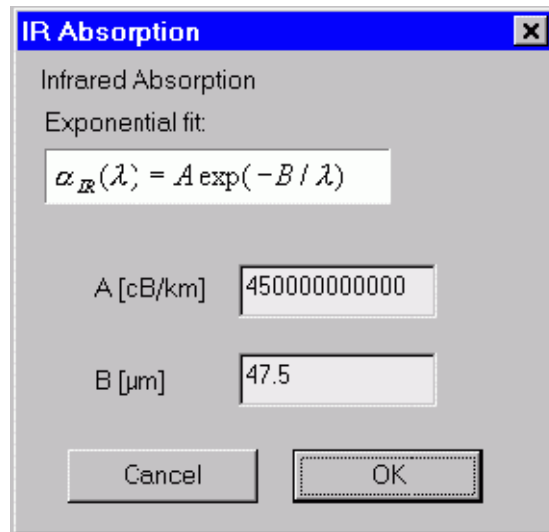
IR Absorption dialog box

The “IR Absorption” dialog box allows you to define the parameters of an experimental-fit model of infrared absorption. The experimental fit is based on the exponential curve with two parameters.

To access this dialog box, do the following steps:

- | Step | Action |
|-------------|---|
| 1 | Open the “Properties of Fundamental Mode” dialog box |
| 2 | Check the “Material Loss” option |
| 3 | Press the “Define button” for the “Material Loss” option |
| 4 | Press the “Define” button for the “IR Absorption” option, or |
| 5 | Access it by double-clicking in the “Material Loss” view tab. |





The elements and controls of the “IR Absorption” dialog box are described below.

A

Enter the amplitude of the exponential fit curve.

B

Enter the exponential 1/wavelength decay coefficient.

See also the “Infrared Absorption Model” section in the “Technical Background”.

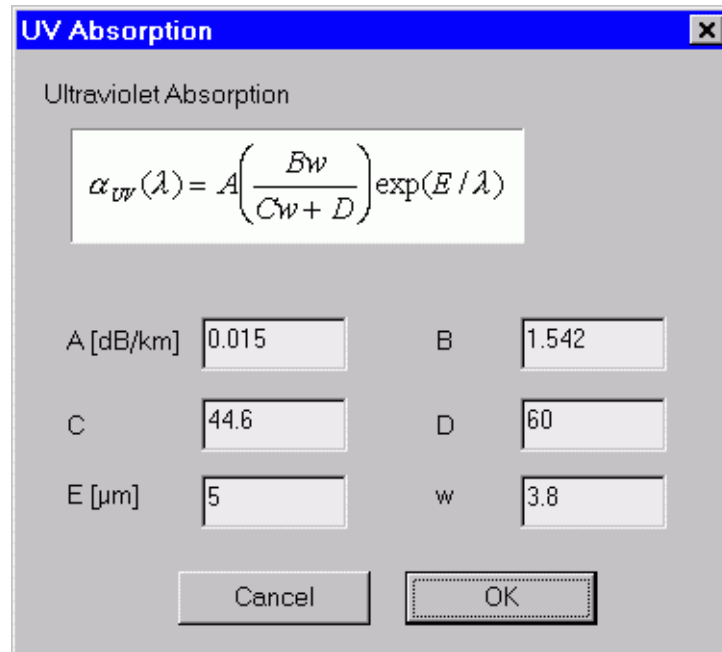
UV Absorption dialog box

The “UV Absorption” dialog box allows you to define the parameters of an experimental-fit model of ultraviolet absorption. The fit is based on the exponential curve with six parameters.

To access this dialog box, do the following steps:

- | Step | Action |
|-------------|---|
| 1 | Open the “Properties of Fundamental Mode” dialog box |
| 2 | Check the “Material Loss” option |
| 3 | Press the “Define” button for the “Material Loss” option |
| 4 | Press the “Define” button for the “UV Absorption” option, or |
| 5 | Access it by double-clicking in the “Material Loss” view tab. |





The elements and controls of the “UV Absorption” dialog box options are described below.

A

Enter the amplitude of the exponential fit curve.

B, C, D

Enter the B, C, and D coefficients of the fit curve.

E

Enter the 1/wavelength decay coefficient of the fit curve.

w

Enter the mole fraction of the impurity.

See also the “Ultraviolet Absorption Model” section in the “Technical Background”.

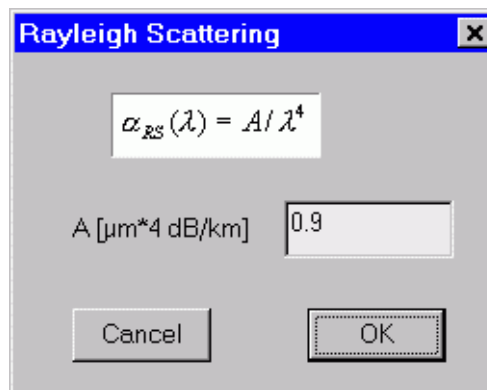
Rayleigh Scattering dialog box

The “Rayleigh Scattering” dialog box allows you to define the parameters of an experimental-fit model of Rayleigh scattering in fibers. The fit is based on the typical inverse wavelength dependence of the small dipole scattering.



To access this dialog box, do the following steps:

- | Step | Action |
|-------------|--|
| 1 | Open the “Properties of Fundamental Mode” dialog box |
| 2 | Check the “Material Loss” option |
| 3 | Press the “Define” button for the “Material Loss” option |
| 4 | Press the “Define” button for the “Rayleigh Scattering” option, or |
| 5 | Access it by double-clicking in the “Material Loss” view tab. |



The elements and controls of the “Rayleigh Scattering” dialog box options are described below.

A

You can adjust only one number, the scattering amplitude A, to fit the Rayleigh scattering curve.

See also the “Rayleigh Scattering Model” section in the “Technical Background”.

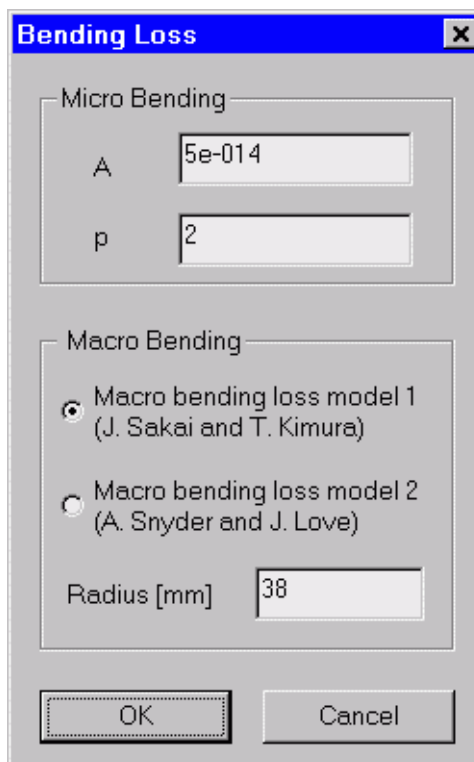


Bending Loss dialog box

The “Bending Loss” dialog box allows you to define parameters for the microbending and macrobending loss models.

To access this dialog box, do the following steps:

- | Step | Action |
|------|---|
| 1 | Open the “Properties of Fundamental Mode” dialog box |
| 2 | Check the “Material Loss” option |
| 3 | Press the “Define” button for the “Bending Loss” option |



The elements and controls of the “Bending Loss” dialog box options are described below.

Microbending

In the microbending loss model, A is an arbitrary fit constant and p is the power coefficient. Typical values for A are much smaller than 1, while typical p is about 2.



Macrobending

In the macrobending loss model you can only select the bend radius. An alternative choice between two models is allowed if the selected mode is the fundamental one.

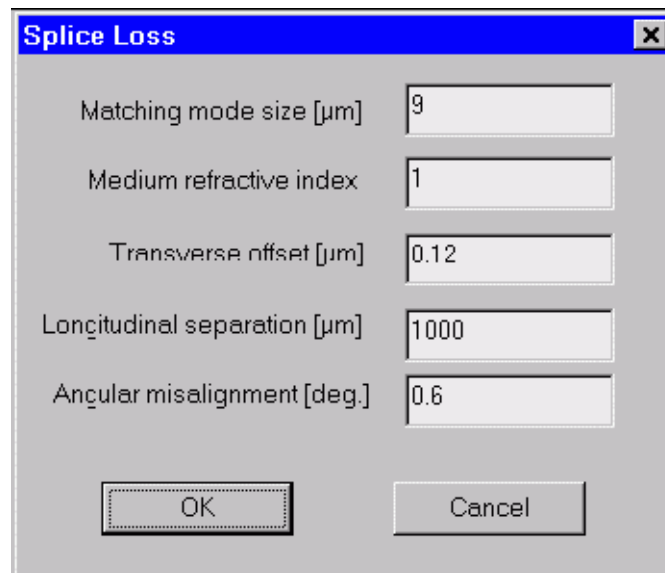
See also the “Macrobending Loss Model” and “Microbending Loss Model” sections in the “Technical Background”.

Splice Loss dialog box

The “Splice Loss” dialog box allows you to define parameters for the splice loss model. The model is based on a formula derived for the case of two glass rods with approximate Gaussian modes. The rods represent cores of two spliced fibers, while the finite cladding dimension is ignored - it is assumed that the core rods are in an infinite cladding medium.

To access this dialog box, do the following steps:

- | Step | Action |
|-------------|--|
| 1 | Open the “Properties of Fundamental Mode” dialog box |
| 2 | Check the “Material Loss” option |
| 3 | Press the “Define” button for the “Splice Loss” option |



The elements and controls of the “Splice Loss” dialog box options are described below.

Matching Mode Size

Enter the mode size of the other fiber that would be spliced with the fiber under design.



Medium Refractive Index

Enter the common cladding index of the fibers.

Transverse Offset

Enter the transverse offset between the two fibers' axes.

Longitudinal separation

Enter the longitudinal separation gap between the two fibers.

Angular Misalignment

Enter the angular tilt between the two fibers.

See also the "Splice Loss Model" section in the "Technical Background".



Fiber Birefringence Related Dialogs

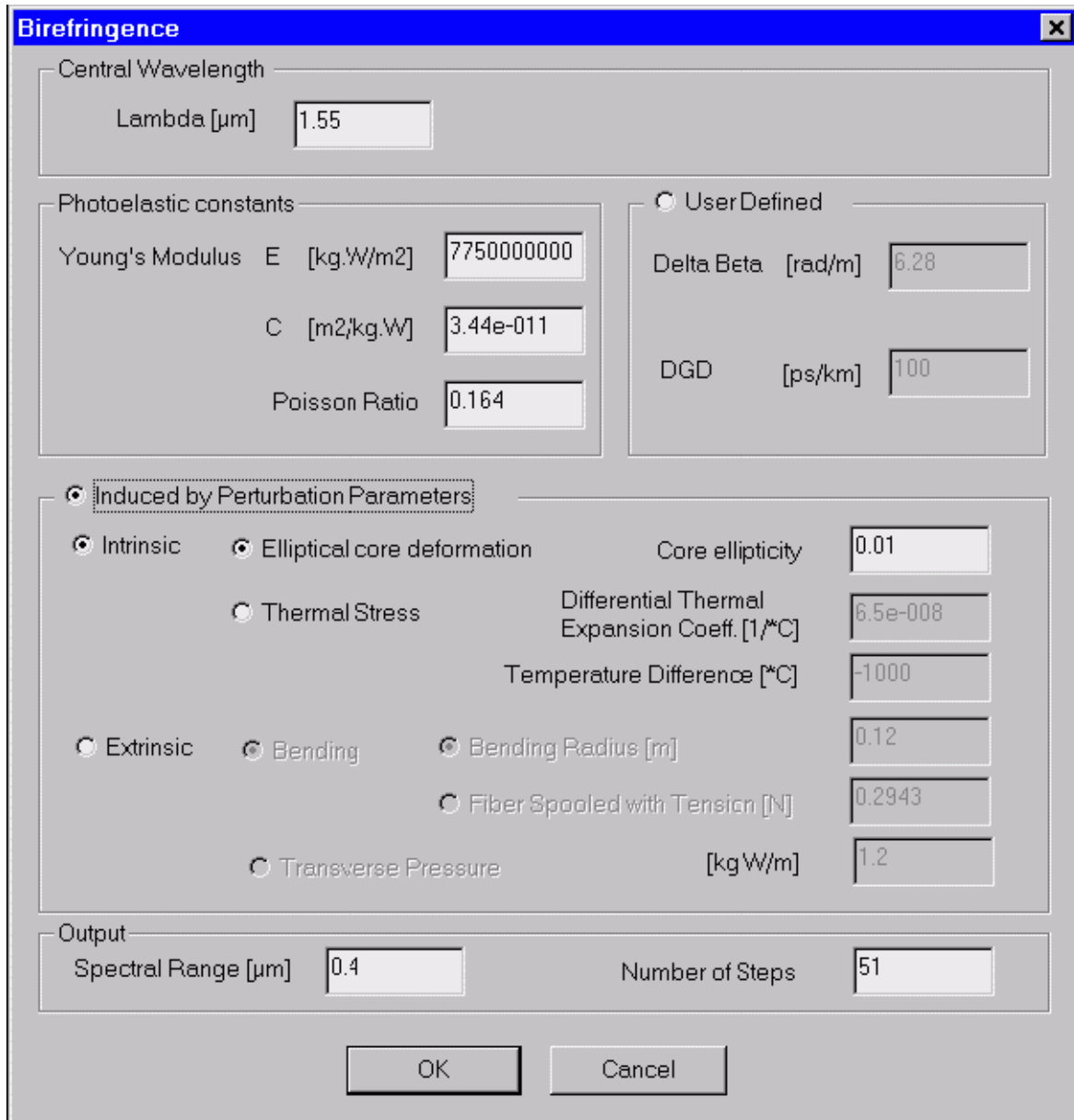
Birefringence dialog box

The “Birefringence” dialog box allows you to define parameters of the fiber birefringence model. As described in the “Technical Background”, various mechanisms contribute to fiber birefringence. You can simply define birefringence values or follow one of the OptiFiber models.

To access this dialog box, do one of the following steps:

- | Step | Action |
|-------------|---|
| 1 | Select “Birefringence” on the Simulation menu |
| 2 | Click the “Birefringence” icon in the “Navigator” pane , or |
| 3 | Access it by double-clicking in the “Birefringence” view tab. |





The elements and controls of the “Birefringence” dialog box options are described below.

Central Wavelength

Enter the central wavelength for the birefringence calculations.

User Defined

To characterize the birefringence phenomena without OptiFiber models, enter the following coefficients:



- Delta Beta - Difference between the propagation constants of the two orthogonally polarized modes
- DGD - Differential Group Delay (DGD) related to fiber birefringence

Photoelastic Constants

A group of constants characterizes photoelastic properties of the fiber: the Young modulus, C coefficient, and Poisson ratio. This section is enabled when you intend to use OptiFiber birefringence models.

Induced by Perturbation Parameters

This section refers to birefringence caused by intrinsic and extrinsic fiber perturbations.

Intrinsic options:

- Elliptical Core Deformation - Enter the Core Ellipticity parameter.
- Thermal Stress - Enter the Differential Thermal Expansion Coefficient and Temperature Difference values.
- Extrinsic options:
- Bending Radius - Enter the bending radius.
- Fiber Spooled with Tension - Enter the tension force value.
- Transverse Pressure - Enter the transverse pressure value.

Output

The birefringence calculations are performed over a spectral range around the Central Wavelength value. You enter the spectral range and the number of calculation steps.

See also the following sections in the Technical Background:

- Fiber Birefringence Definition
- Intrinsic Perturbations Birefringence
- Elliptical Core Birefringence Definition
- Internal Stress Birefringence Definition
- Extrinsic Perturbation Birefringence
- Lateral Stress Birefringence Definition
- Bending Birefringence Definition
- Bending Under Tension Birefringence Definition



Polarization Mode Dispersion Related Dialogs

Polarization Mode Dispersion dialog box

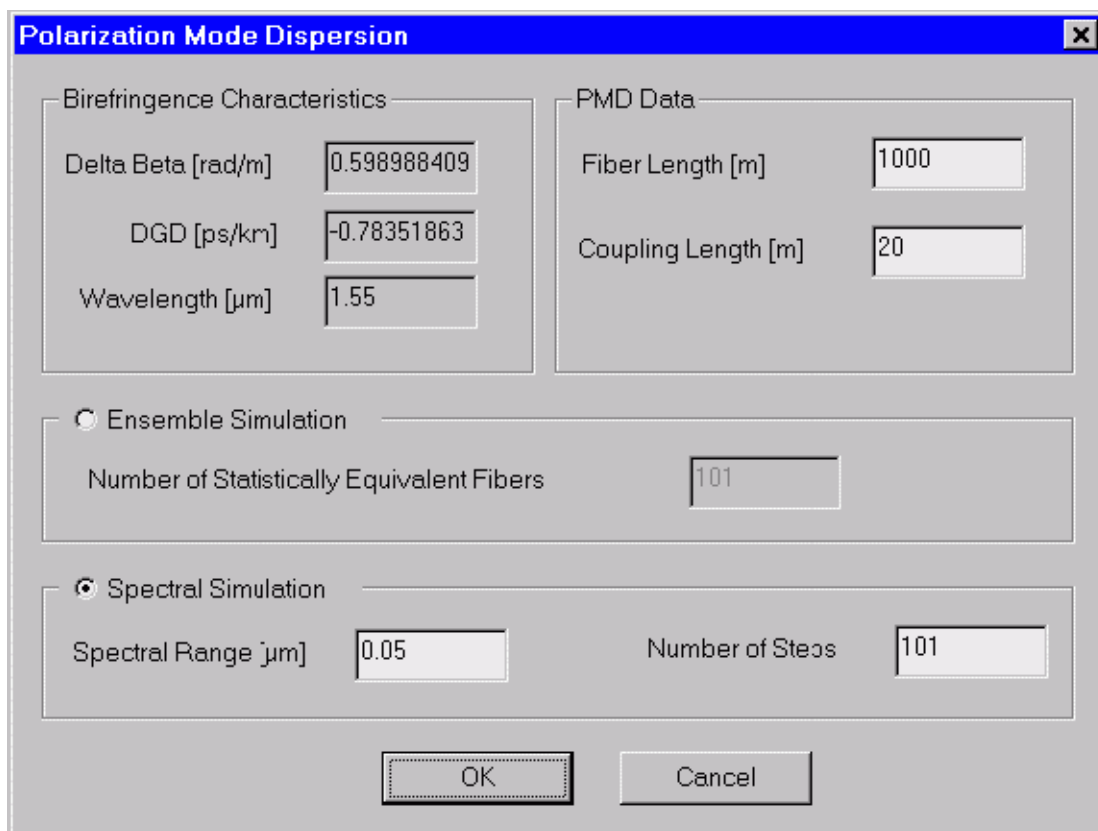
The “Polarization Mode Dispersion” dialog box allows you to define parameters of the PMD model as well as choose the PMD simulation method as the ensemble simulation or spectral simulation. Theoretically, both methods are equivalent.

To access this dialog box, do the following steps:

Step Action

- 1 Select “PMD” on the Simulation menu
- 2 Click the “PMD” icon in the Navigator pane

Note: N.B.! The “Polarization Mode Dispersion” dialog box is accessible only after the Birefringence calculation. If the “Birefringence” was not calculated before, its dialog box will appear after clicking the “Polarization Mode Dispersion” dialog box.



The elements and controls of the “Polarization Mode Dispersion” dialog box options are described below.



Birefringence Characteristics

This section provides only a display of the birefringence parameters as calculated using the Birefringence dialog box setup.

PMD Data

The PMD Data refers to the stochastic trunks model used to calculate the Polarization Mode Dispersion characteristics. Enter the fiber length and the coupling length parameter.

Ensemble Simulation

With this option selected, the program performs the PMD calculations based on a number of stochastic fibers that are generated during the simulation. You enter the number of stochastically generated fibers.

Spectral Simulation

With this option selected, the program performs the PMD calculations using only one stochastic fiber. However, the calculations are repeated for a number of steps within the spectral range. You enter the spectral range and the number of steps.

See also the following sections in the Technical Background:

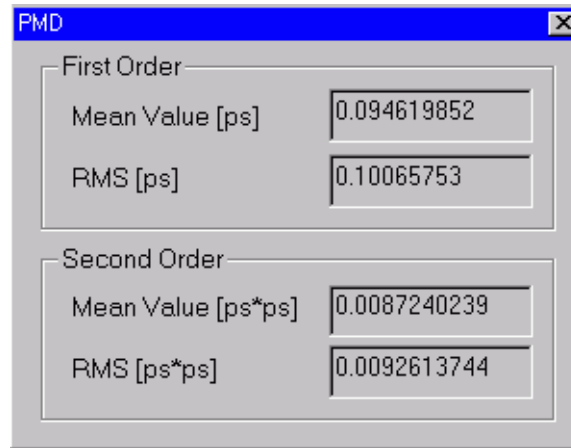
- Polarization Mode Dispersion
- Principal States of Polarization
- Dispersion Vector Definition
- Poincaré Sphere
- Ensemble Simulation
- Spectral Simulation
- First Order Dispersion Definition
- Second Order Dispersion Definition



PMD dialog box

The “PMD” dialog box is only a display of the numerical values related to the Polarization Mode Dispersion (PMD) calculation.

This dialog box appears automatically when the PMD calculations are finished and the PMD tab is selected in the output Views window.



The screenshot shows a dialog box titled "PMD" with a close button (X) in the top right corner. The dialog is divided into two sections: "First Order" and "Second Order". Each section contains two input fields for numerical values.

Order	Parameter	Value
First Order	Mean Value [ps]	0.094619852
	RMS [ps]	0.10065753
Second Order	Mean Value [ps*ps]	0.0087240239
	RMS [ps*ps]	0.0092613744

Graph Related Dialogs

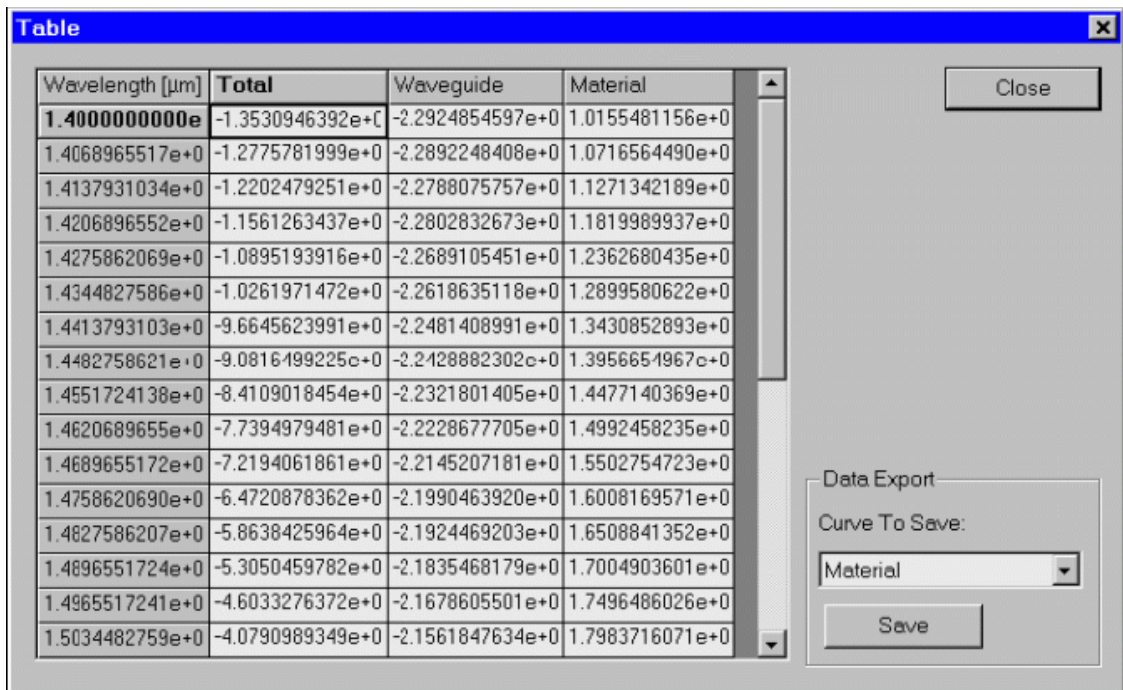
Table dialog box

The “Table” dialog box allows you to inspect and export numerical data related to plots in the “Views” window.

To access this dialog box, do the following steps:

Step Action

- 1 Select one of the tabs in the output “Views” window
- 2 Select “Table” on the “Tools” menu



The elements and controls of the “Table” dialog box options are described below.

Numerical Data

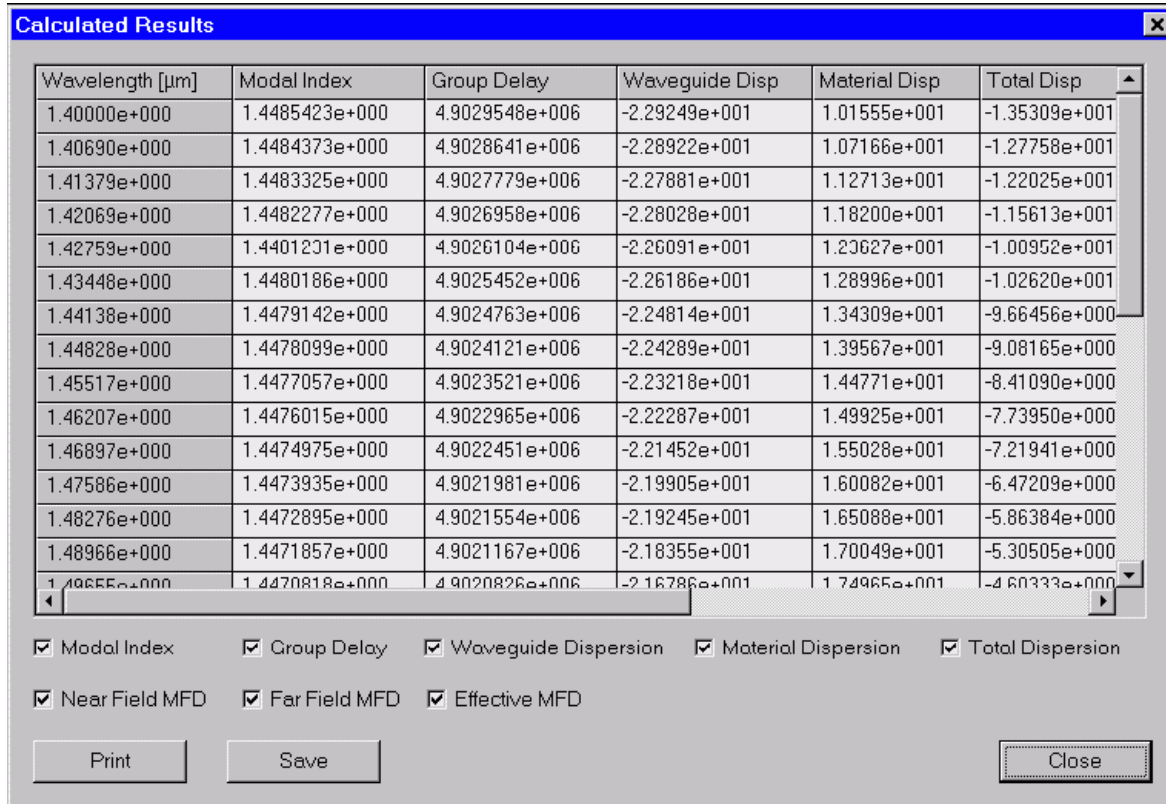
The first column lists the current scan parameter, for example the wavelength. The subsequent columns display numerical values of curves in the current plot.

Data Export

You can save any of the listed curves to a file.

Calculated results dialog box

The “Calculated results” opens the “Calculated results” dialog box, where you can preview, copy (for pasting in another application, such as Excel) or export to a text file the numerical values that correspond to the last calculation.



The elements and controls of the “Calculated results” dialog box options are described below.

Check boxes

The different calculated results will be added to this dialog box if it is checked.

The following check boxes are available:

- Modal Index
- Group Delay
- Waveguide Dispersion
- Material Dispersion
- Total Dispersion
- Near Field MFD
- Far Field MFD



Save result

Press the “Save” button to save the data shown in this dialog box.

Print result

Press the “Print” button to print the data shown in this dialog box.



Graphic Properties dialog box

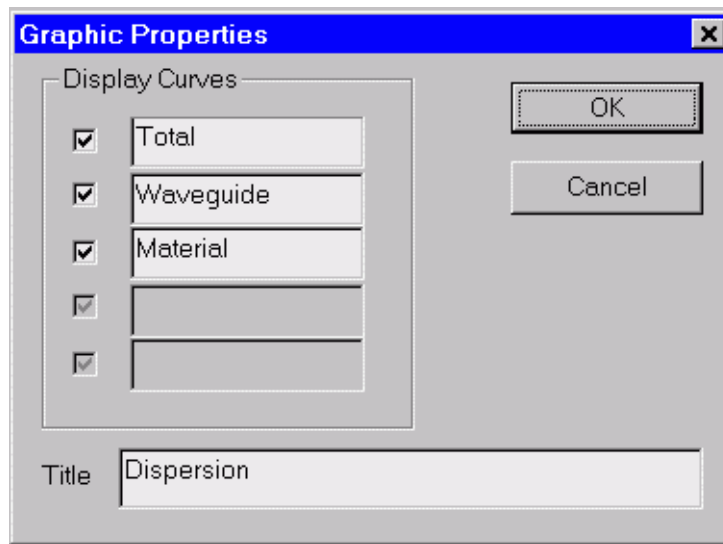
This dialog box allows you to tweak the details of the active display view. It is accessible through the context menu “Tools” activated by the right button of the mouse.

To access the graphic properties dialog box, do the following steps:

Step Action

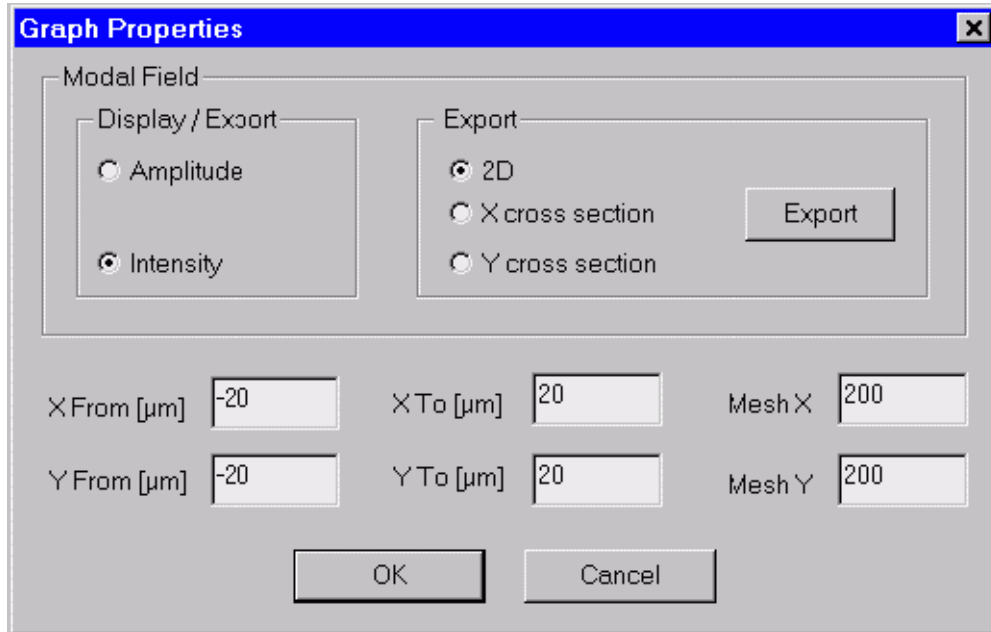
- 1 Go to one of the tabs in “Views” window
- 2 Click the right mouse button to activate the floating “Tools” menu
- 3 From the “Tools” menu, select “Graph Properties”

The dialog looks and functions differently depending on the type of graphic. For all the 2D view tabs it looks as shown:



The user can select/deselect each curve for displaying and can enter the graph title.

If the active view is the topological “Mode Field” view, then the “Graph Properties” dialog box looks as shown:



Its elements and controls are described below.

Display / Export

This option allows the user to select what how to view and/or export the modal field: as amplitude or as intensity.



Export

Determines what characteristic of the modal field to export:

- The topological pattern of the mode. The exported file has a real 3D file Format: BCF3DPC (please, see the “Supported File Formats” description at the end of the “Technical Background”).
- The current X-cut 2D graph. The exported file has is a simple text file starting with a header indicating the Y position of the X-cut and having two columns:
 - 1st column - X position,
 - 2nd column - amplitude or intensity
- The current Y-cut 2D graph. The file format is the same as in the X-cut case, with the meaning of X and Y- alternatively interchanged.

The currently selected option in “Display / Export” determines whether intensity or amplitude will be exported.

Press the “Export” button to perform the actual file saving.

Modal Field window Parameters

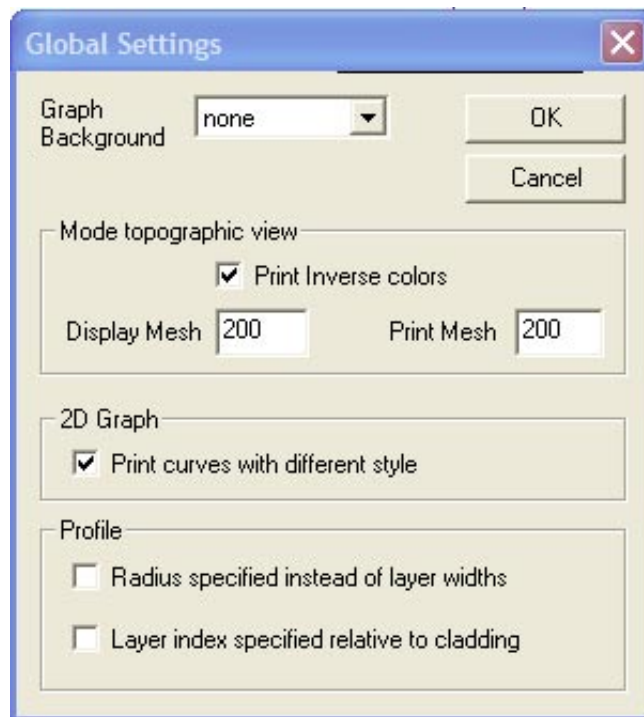
You can specify the modal field window limits by entering values for “X From”, “X To”, “Y From”, “Y To”. “Mesh X” and “Mesh Y” are the sampling points in X and Y directions and determine the resolution.



Settings

Global Settings dialog box

The Global Settings dialog box can be used to change OptiFiber's style of data entry and presentation according to user preference. The information in the Global Settings dialog box will be stored in the system registry. This means that the settings are remembered after OptiFiber is closed, and will remain in effect on the current computer until changed by this dialog box. The illustration shows the dialog box with its default settings. To access this dialog box, select Tools >> Settings ...



The elements and controls of the “Global Settings” dialog box options are described below.

Graph background

Refers to the graph background in the Views window. The available options are: none, wood, paper, and wall.

Mode topographic View

This section refers to graph setup for the mode field display and printing. The default background for the mode field display is black, so you may use the Print Inverse Colors option.

Display Mesh - Enter the number of points in the X and Y dimension of the mode field screen display.



Print - Enter the number of points in the X and Y dimension of the mode field printed picture.

2D Graph

Check Print Curves with Different Styles to distinguish curves on black and white output prints.

Profile

Radius specified instead of layer widths – In the Fiber Profile dialog box, the profile is specified as a list of Regions (layers) of various widths. There is a read only field to show the position (radius) of the selected layer. Check this box if you prefer to enter the radius of the layer instead of the layer width. With this box checked, the width field will become read only instead of the position field.

Layer index specified relative to cladding – In the Fiber Profile dialog box, the refractive index of the selected layer is displayed in the Refr. Index field. Check this box if you prefer to specify the refractive index relative to the cladding layer instead. With this box checked, the last layer must be constant, and when the last layer is selected, the cladding refractive index, N_c , will be displayed in the Refr. Index field. However, when other layers are selected, the index of current layer relative to the cladding layer will be shown. Since these differences are typically small, the difference is multiplied by 1000. When any inner layer is selected, the label of the field will change to $(N - N_c) * 1000$, as a reminder that the refractive index is being specified and displayed as a relative value. The display of refractive index in other parts of OptiFiber is not changed by this setting.



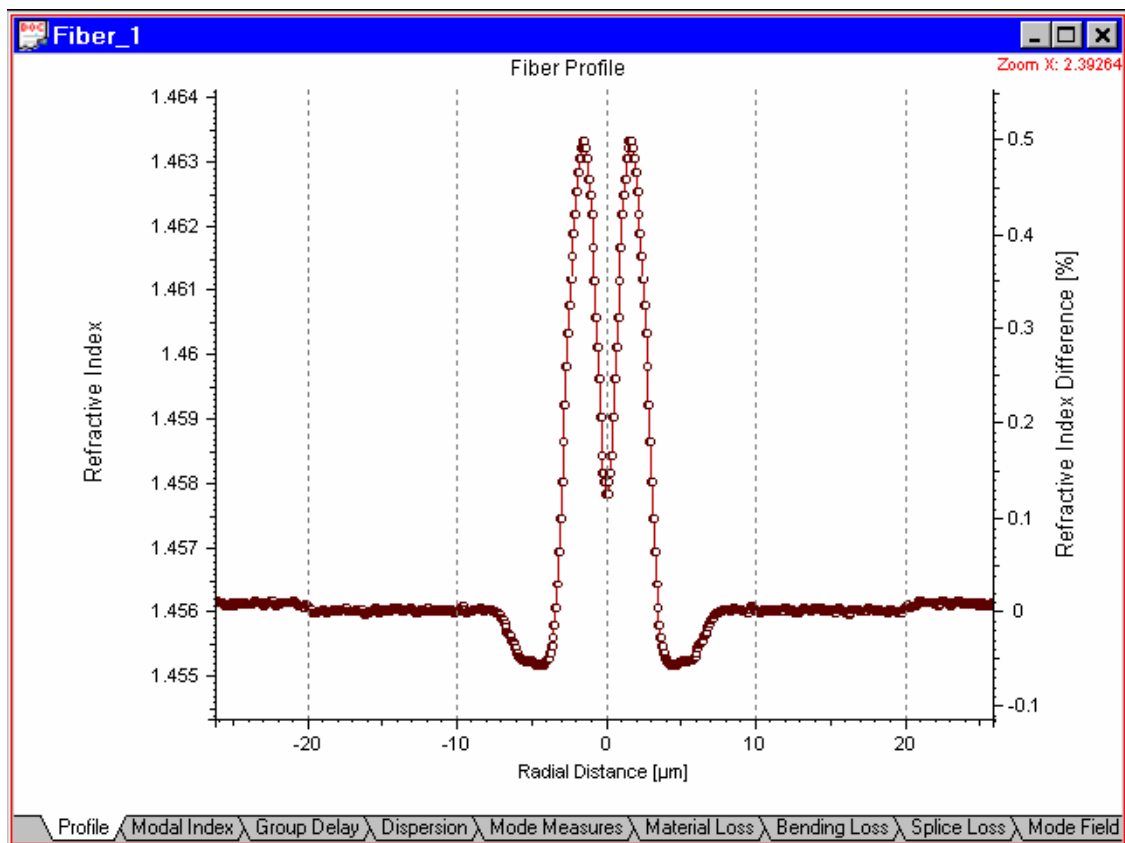
Output Views Reference

Profile view

The “Profile” view shows you the fiber index profile as defined in the “Fiber Profile” dialog box.

To access this view do one of the following steps:

- | Step | Action |
|------|--|
| 1 | Select the “Profile tab” in the “Views” window |
| 2 | Select “Views/Profile” on the “View” menu |



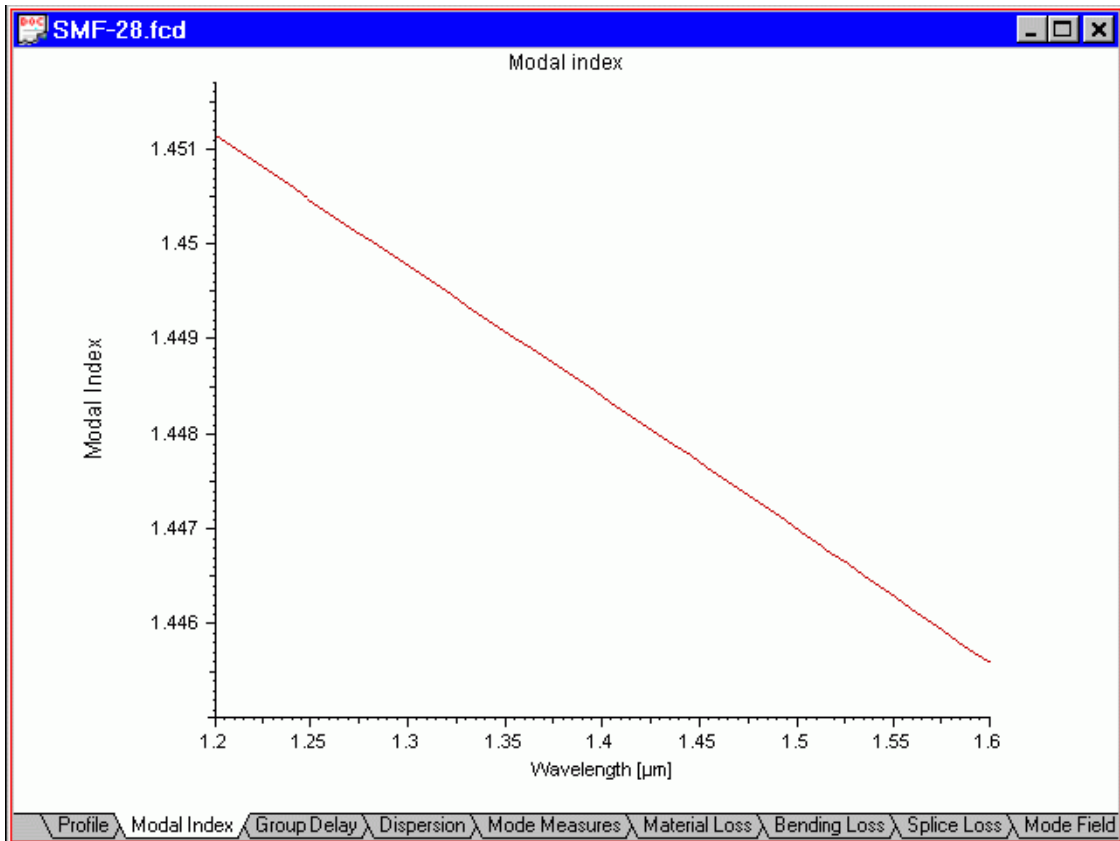
Modal Index view

The “Modal Index” view shows you the effective refractive index of the selected propagation mode vs. the scan parameter. The default scan parameter is the wavelength. You can change the scan parameter in the “Properties of Fundamental Mode” dialog box or in the “Properties of Higher Order Modes” dialog box.



To access this view do one of the following steps:

- | Step | Action |
|------|--|
| 1 | Select the “Modal Index” tab in the “Views” window |
| 2 | Select “Views/Modal Index” on the “View” menu |



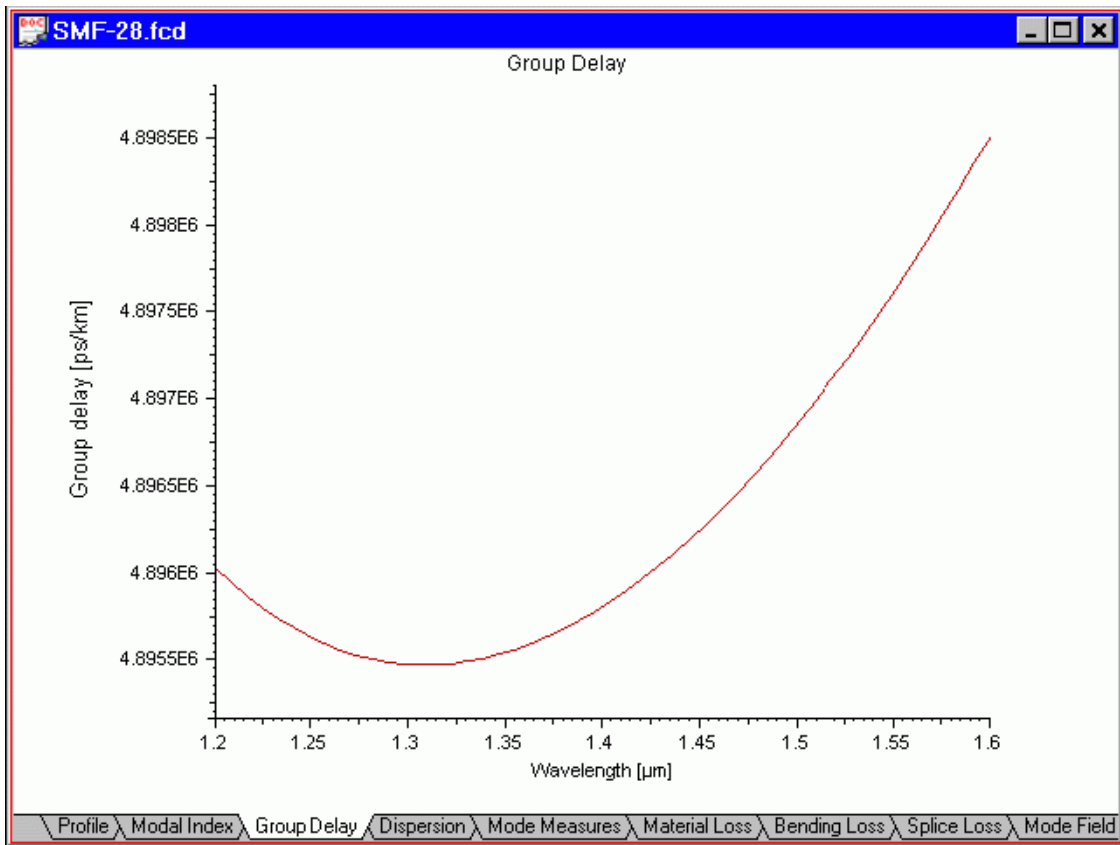
Group Delay view

The “Group Delay” view shows you the propagation group delay for the selected fiber mode vs. the scan parameter. The default scan parameter is the wavelength. You can change the scan parameter in the “Properties of Fundamental Mode” dialog box or in the “Properties of Higher Order Modes” dialog box.

To access this view do one of the following steps:

- | Step | Action |
|------|--|
| 1 | Select the “Group Delay” tab in the “Views” window |
| 2 | Select “Views/Group Delay” on the “View” menu |



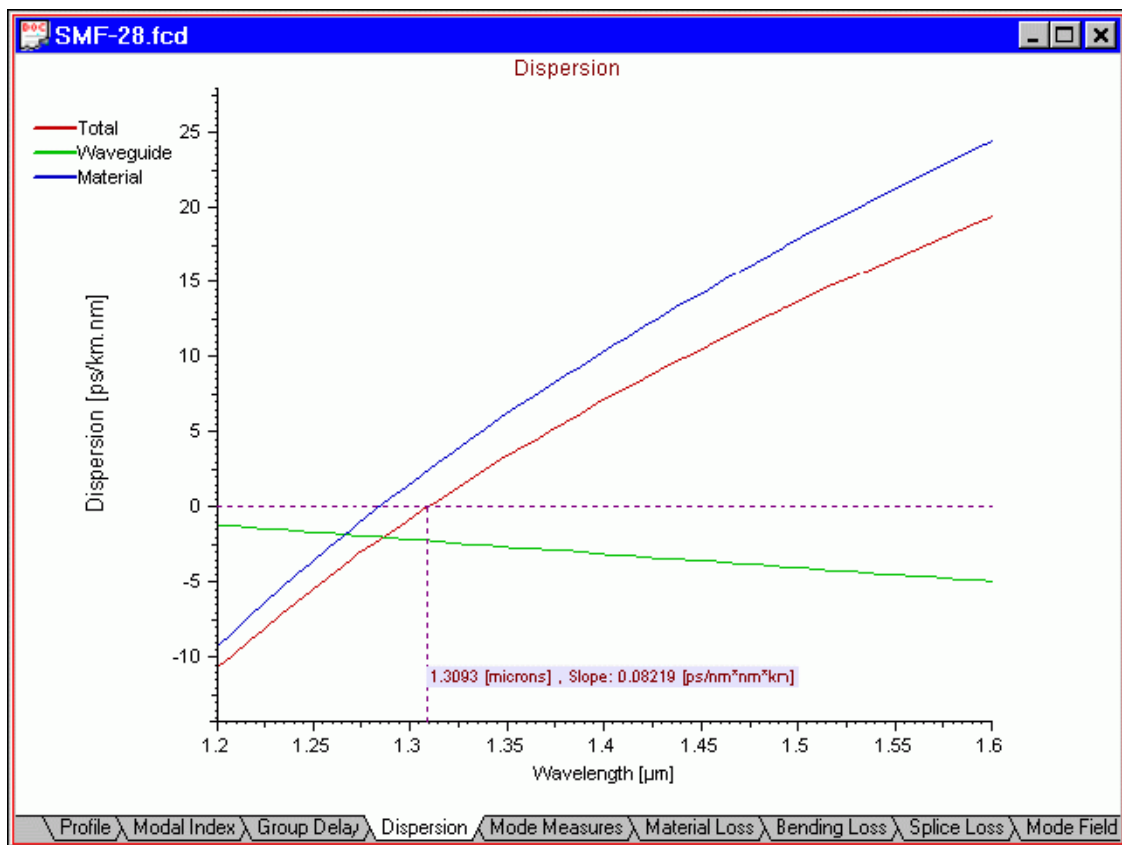


Dispersion view

The “Dispersion” view shows you the material, waveguide, and total dispersion characteristics vs. the scan parameter. The default scan parameter is the wavelength. You can change the scan parameter in the “Properties of Fundamental Mode” dialog box or in the “Properties of Higher Order Modes” dialog box.

To access this view do one of the following steps:

- | Step | Action |
|------|---|
| 1 | Select the Dispersion tab in the Views window |
| 2 | Select Views/Dispersion on the View menu |



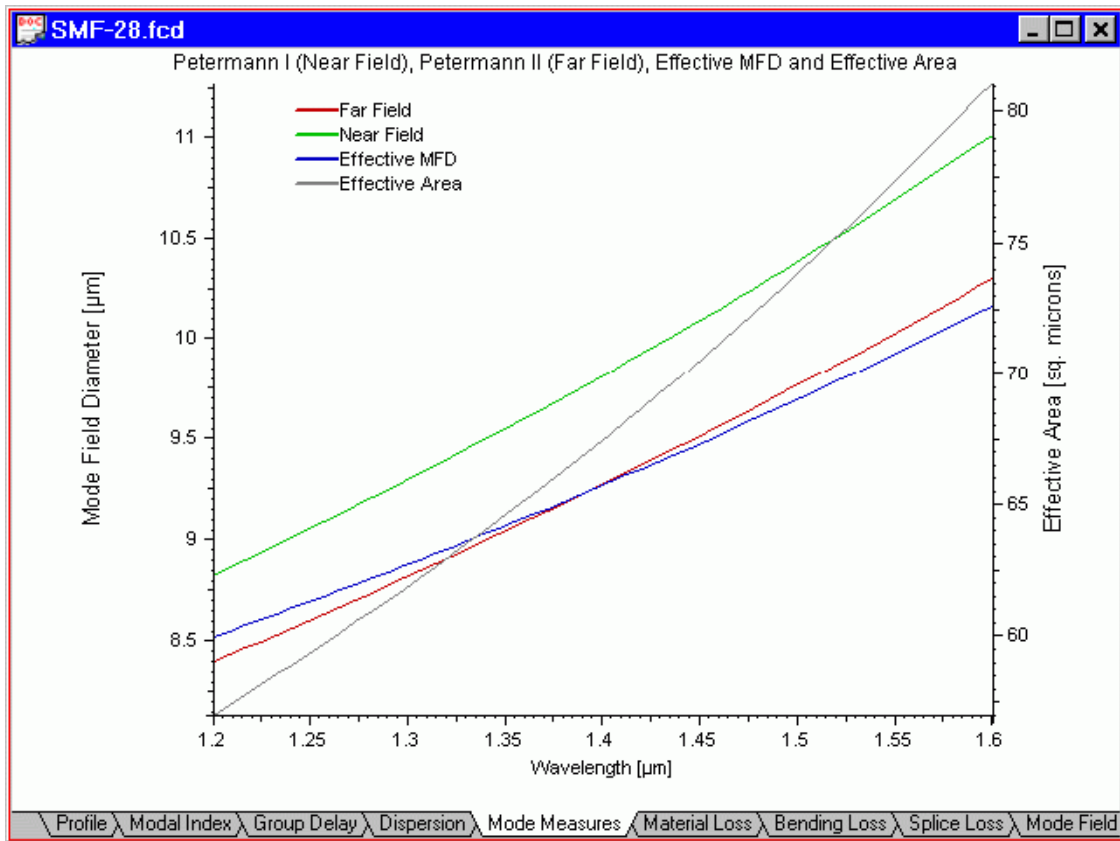
Mode Measures view

The “Mode Measures” view shows you the near-field, far-field and effective Mode Field Diameters (MFD) and the effective area of the fundamental mode vs. the scan parameter. The default scan parameter is the wavelength. You can change the scan parameter in the “Properties of Fundamental Mode” dialog box or in the “Properties of Higher Order Modes” dialog box.



To access this view do one of the following steps:

- | Step | Action |
|-------------|---|
| 1 | 1. Select the “Mode Measures” tab in the Views window |
| 2 | 2. Select “Views/Mode Measures” on the “View” menu |



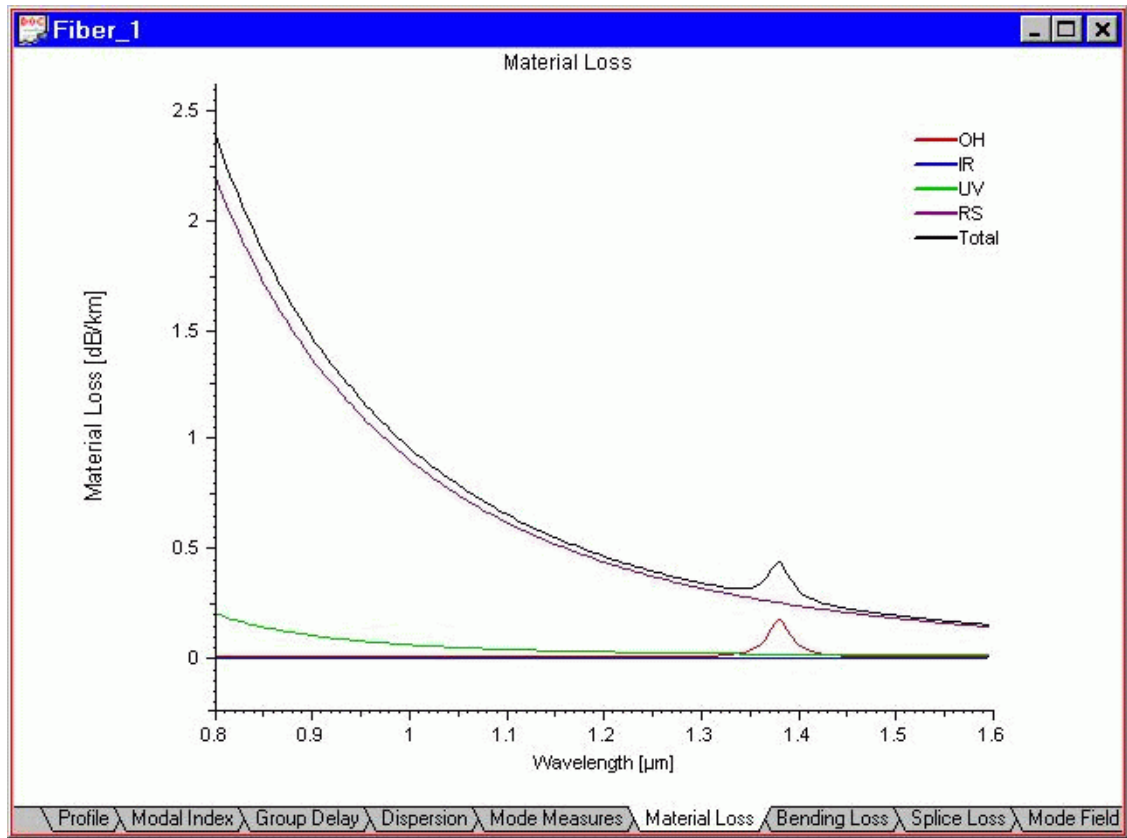
Material Loss view

The “Material Loss” view shows you the material loss characteristics vs. wavelength. The loss is defined according to four models in the “Material Loss” dialog box, as well as the total material loss curve.

To access this view do one of the following steps:

- | Step | Action |
|-------------|--|
| 1 | Select the “Material Loss” tab in the Views window |
| 2 | Select “Views/Material Loss” on the “View” menu |



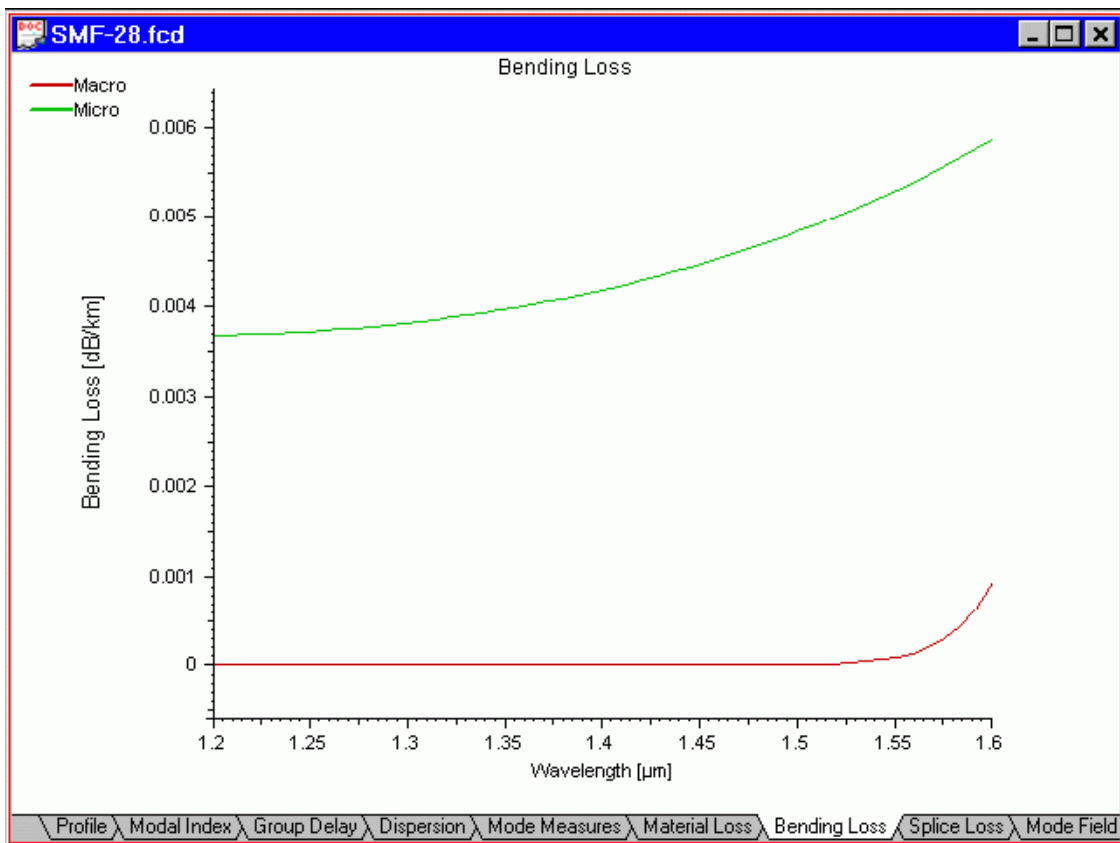


Bending Loss view

The “Bending” Loss view shows you the microbending and macrobending fiber loss vs. the scan parameter. The default scan parameter is the wavelength. You can change the scan parameter in the “Properties of Fundamental Mode” dialog box.

To access this view do one of the following steps:

- | Step | Action |
|------|---|
| 1 | Select the “Bending Loss” tab in the “Views” window |
| 2 | Select “Views/Bending Loss” on the “View” menu |



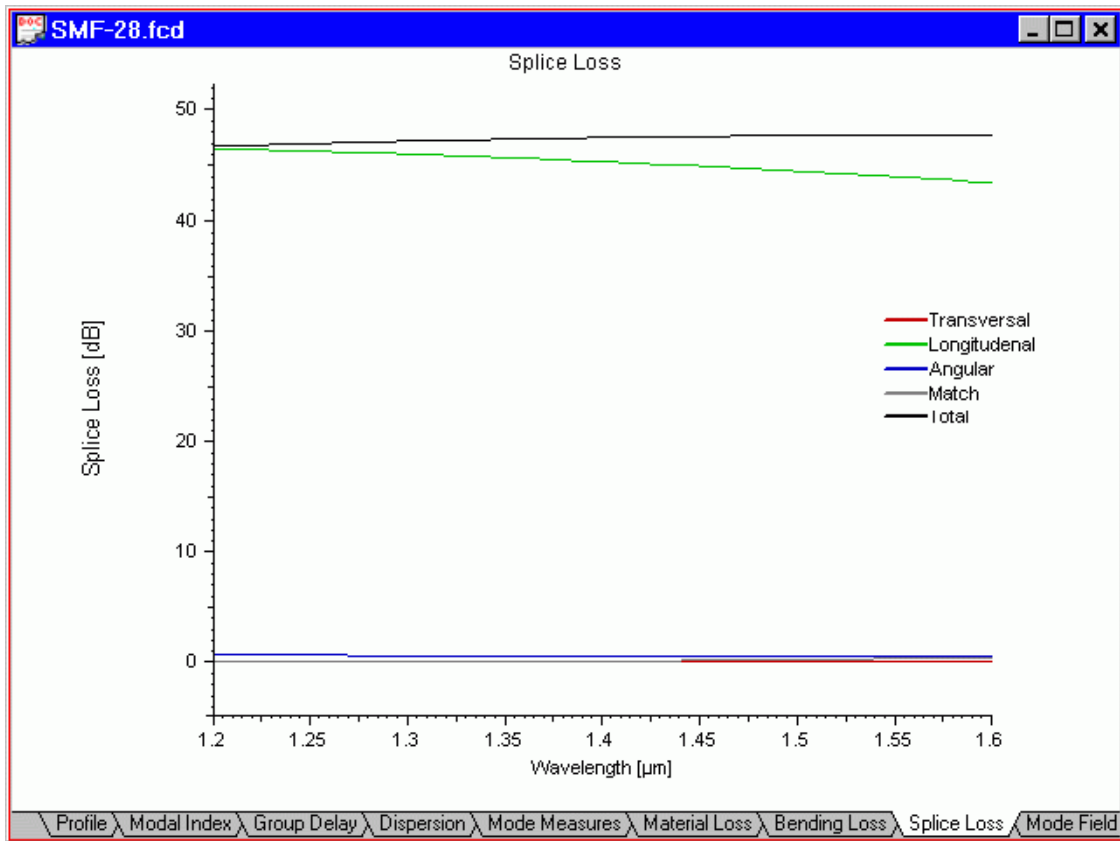
Splice Loss view

The “Splice Loss” view shows you the transversal, longitudinal, and angular misalignment loss, as well as the mode match and total splice loss vs. the scan parameter. The default scan parameter is the wavelength. You can change the scan parameter in the “Properties of Fundamental Mode” dialog box.



To access this view do one of the following steps:

- | Step | Action |
|------|--|
| 1 | Select the "Splice Loss" tab in the "Views" window |
| 2 | Select "Views/Splice Loss" on the "View" menu |



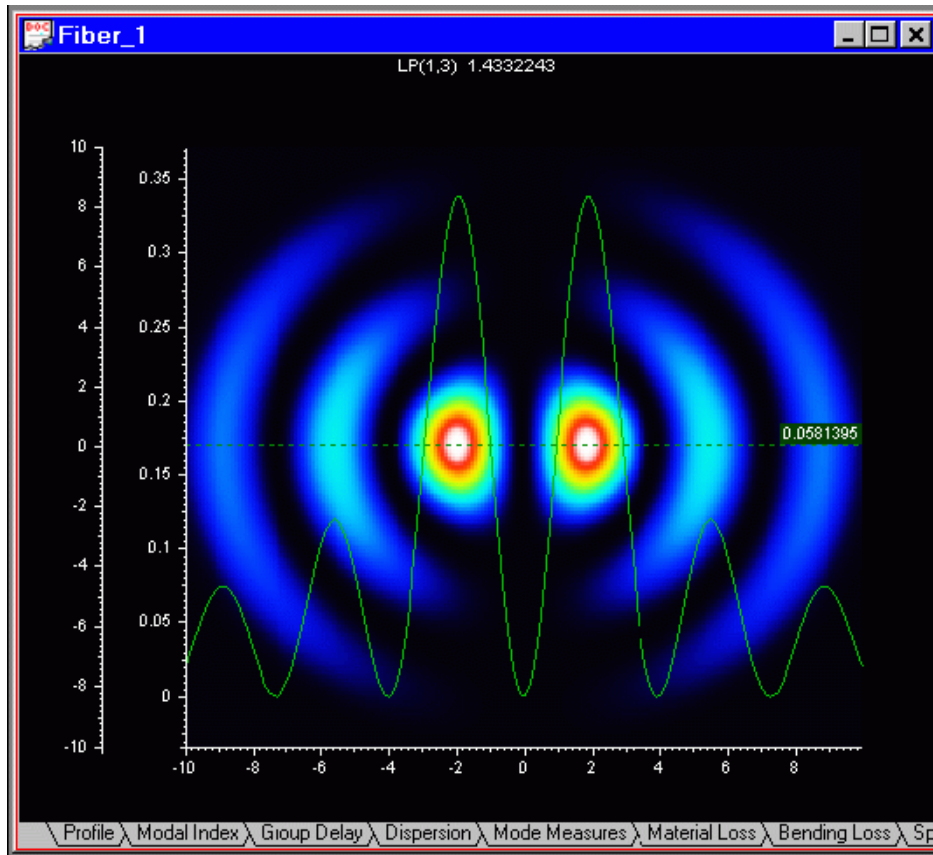
Mode Field view

The "Mode Field" view shows you a topographic plot of the mode field. The displayed mode is the one selected in the Modes dialog box. You can change the display mesh in the Global Settings dialog box. Also a X- or Y-cuts (or both) of the mode are shown.

To access this view do one of the following steps:

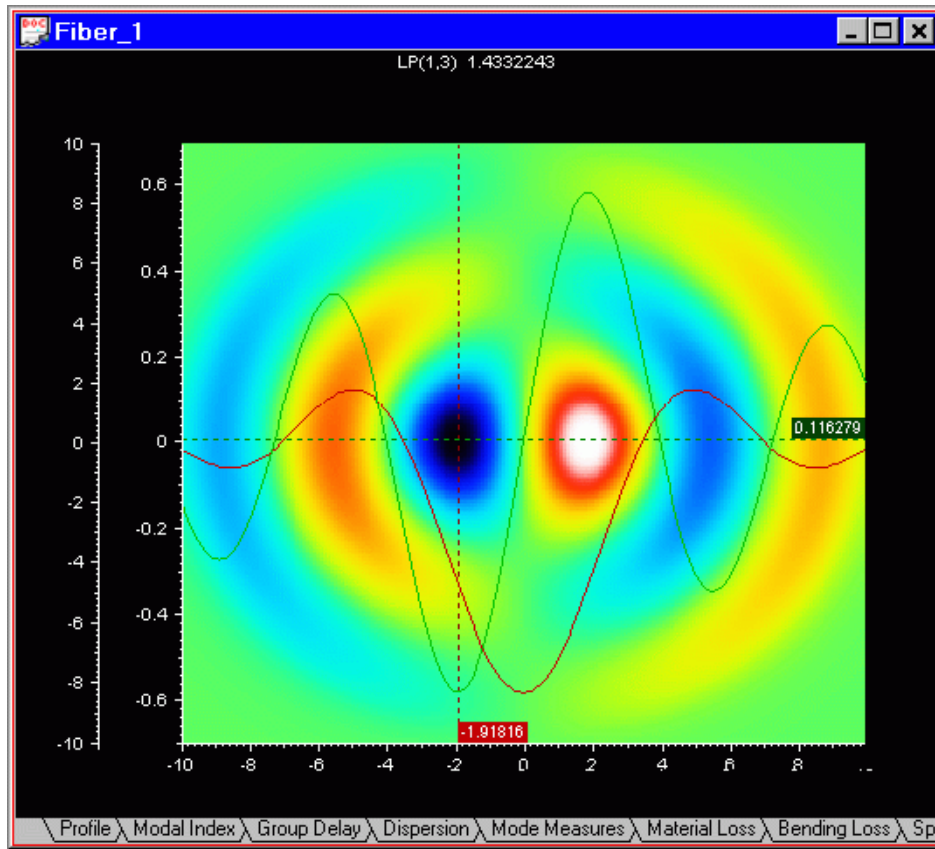
- | Step | Action |
|------|---|
| 1 | Select the "Mode Field" tab in the "Views" window |
| 2 | Select "Views/Mode Field" on the "View" menu |





If the option "Amplitude", instead of "Intensity" has been selected from the right-button context menu "Graph Properties", then the "Mode Field" displays a topological color-coded pattern and 2D X- and Y-cut cross sections of the amplitude of the same field, as shown below:





Birefringence view

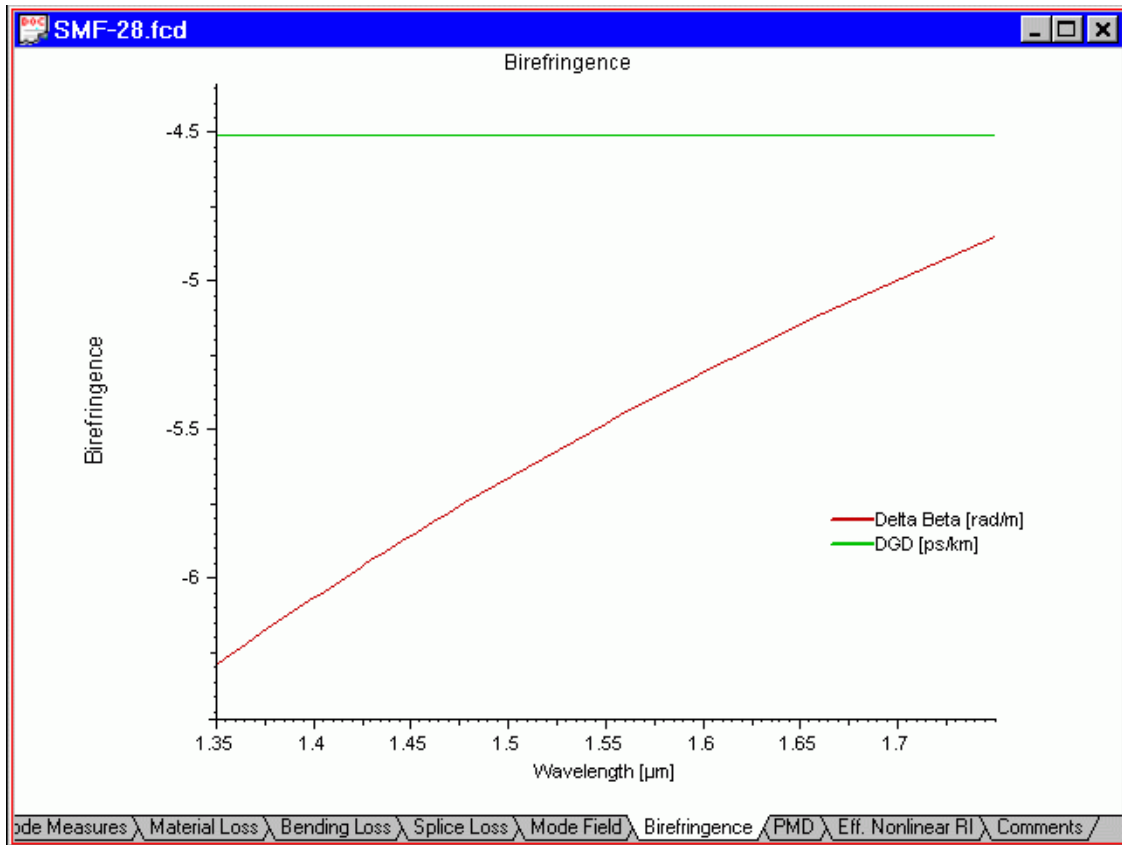
The “Birefringence” view shows you plots of:

- Delta Beta - Difference between the propagation constants of the two orthogonally polarized modes.
- DGD - Differential Group Delay (DGD) due to fiber birefringence vs. wavelength.

To access this view do one of the following steps:

- | Step | Action |
|------|--|
| 1 | Select the “Birefringence” tab in the “Views” window |
| 2 | Select “Views/Birefringence” on the “View” menu |





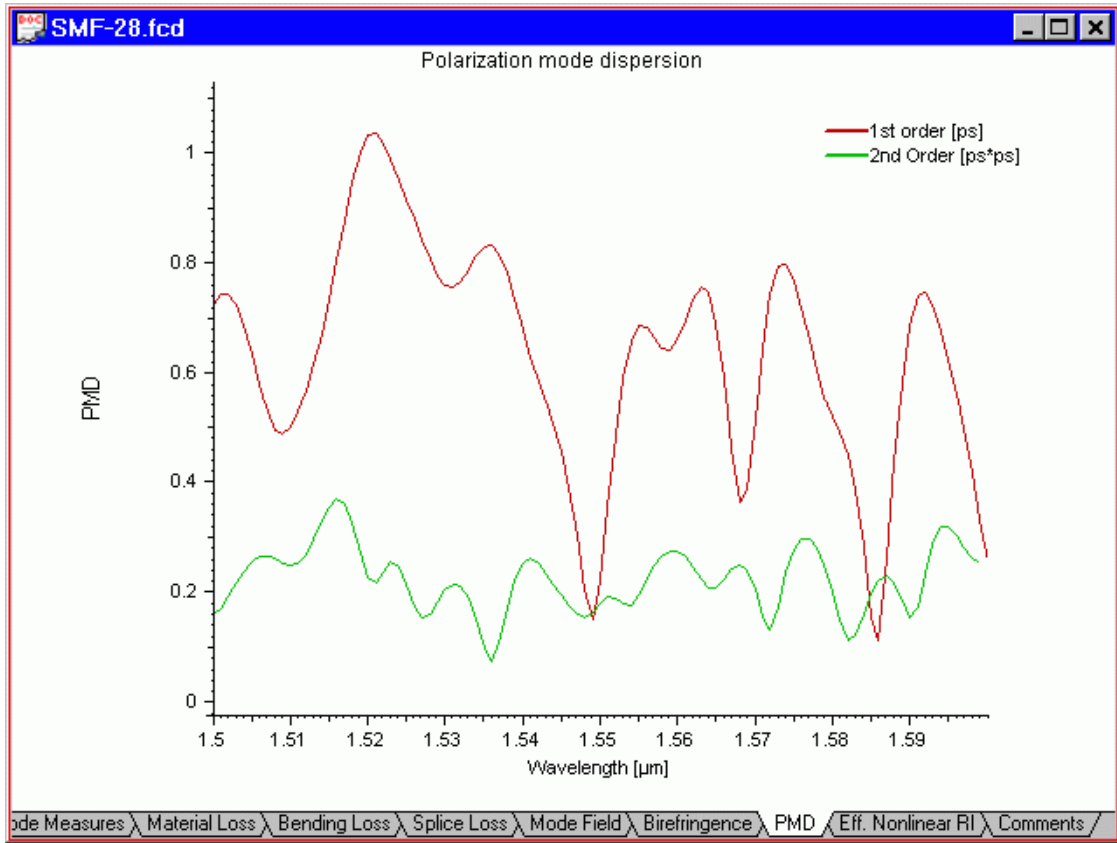
PMD view

The “PMD” view shows you the Polarization Mode Dispersion (PMD) of the first and second orders vs. wavelength.

To access this view do one of the following steps:

- | Step | Action |
|------|--|
| 1 | Select the “PMD” tab in the “Views” window |
| 2 | Select “Views/PMD” on the “View” menu |





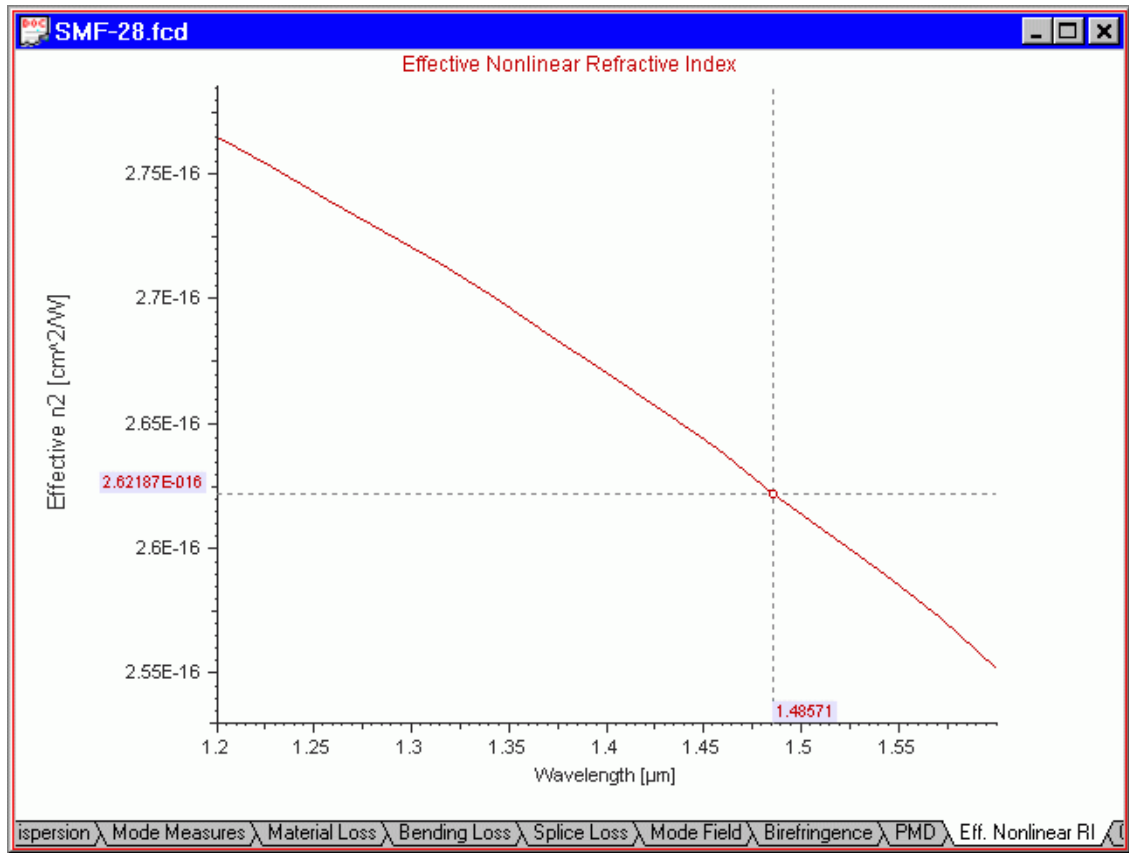
Effective Nonlinear Refr. Index view

This view shows you the eff. nonlinear refr. index of the fiber as determined by the nonlinearity of the bulk materials and the degree of confinement.

To access this view do one of the following steps:

Step	Action
1	Select the "Eff. Nonlinear RI" tab in the "Views" window
2	Select "Views/Effective Nonlinear Refr. Index" on the "View" menu







Appendix A - Script Language Reference

Overview of Script Language

The script language OptiFiber uses is a programming language based on the BASIC language syntax. You use the script language to define the fiber profile, or material dispersion, for example. To start programming with the Script Language, you have to choose the User Defined option in OptiFiber dialog boxes.

The script language is described in the following reference sections:

- Variables, Arrays, and Operators: Variables, Arrays, Mathematical Operators, Boolean Operators, and Comparison Operators
- Commands and Statements: Commands and Statements, RETURN Command, IF Statement, ERROR Keyword, FIRSTTIME Keyword, Input Dialog Box, Example Input, and Example Ginput
- Predefined Constants: Mathematical Constants and Physical Constants
- Functions Library: Commonly Used Functions, Other Functions, Fresnel Integral, Gamma Function, Error Function, Bessel Functions, Chebyshev Polynomials
- Unit Conversions: Length Conversions, Temperature Conversions, Other Conversions

Variables, Arrays, and Operators

Variables

A variable name can be any string beginning with a character. You cannot use special characters and operators in the name. Some names are reserved for commands, predefined constants, and functions. Variable names are case sensitive. For example, 'a' is not the same as 'A', 'Pos' is not the same as 'pos' or 'POS'.

Examples:

Valid variable names: ***a, pos, lambda, width1***

Invalid variable names: ****a, _pi, IF, RETURN***

Note: Comment lines in the editing area are preceded by the double slash symbol //.

Arrays

You can use only one-dimensional arrays. You do not have to declare an array before using it. For the array index, you can use a positive or a negative integer. The usage format is ***array_name[index]***.



Examples:

A[2]

B[-3]

a[x]=x*2

Mathematical Operators

The script language supports the following standard mathematical operators (listed in decreasing priority):

- ^ power operator
- * multiplication operator
- / division operator
- + addition operator
- subtraction operator

Boolean operators

The script language supports the following standard Boolean operators:

- = 'equal to' operator
- < 'less than' operator
- > 'more than' operator
- & 'and' operator
- | 'or' operator

Examples:

A=b

A<b

B&c

C|d

Comparison operators

Comparison operators serve to establish relations between two objects. They can be combined, for example:

a<=b; a<>b; a=>b



Commands and Statements

Commands and statements

The script language has a set of commands and control statements. All command and statement names must be in upper case letters.

Examples:

IF is a command

If or **if** can be a variable, but is not a command

RETURN command

The RETURN keyword terminates execution of the program in which it appears and returns the control (and the value of expression, if given). Notice that if you don't specify RETURN in your program, the interpreter will return the value of expression in the last logical order. You usually use the RETURN command if your program uses IF – THEN commands.

Syntax: RETURN[expression]

Example 1:

A program with only one line (you don't have to specify RETURN):

```
sin(3)*24+13*(2+6)
```

returns 107.38688.

The same result is obtained from the program:

```
RETURN sin(3)*24+13*(2+6)
```

Example 2:

Consider the program:

```
cp = 100  
a = Length-x  
IF x<cp THEN  
RETURN x  
ELSE  
RETURN a
```

The above program returns x if x is less than 100. Otherwise, it returns Length-x if x is larger or equal than 100.



Example 3:

Let's modify the previous example, Example 2, as follows:

```
cp = 100
a = Length-x
IF x<cp THEN
  b = x
ELSE
  b = a
RETURN b
```

This example gives the same result as Example 2. The difference is that another variable **b** is used instead of returning the value of **a** directly.

IF statement

The IF statement controls conditional branching. The body of an IF statement is executed if the value of the expression is nonzero. The syntax for the IF statement has two forms.

Syntax: **IF expression THEN statement ELSE statement**

In both forms of the IF statement, the expressions, which can have any value, are evaluated, including all side effects.

In the first form of the syntax, if expression is nonzero (true), the statement is executed. If expression is false, statement is ignored. In the second form of syntax, which uses ELSE, the second statement is executed if expression is false. With both forms, control then passes from the If statement to the next statement in the program.

Examples:

The following are examples of the IF statement:

```
IF i > 0 THEN y = x / i ELSE x = i
```

In this example, the statement **y = x/i** is executed if **i** is greater than **0**. If **i** is less than or equal to **0**, **i** is assigned to **x**.

For nesting IF statements and ELSE clauses, use BEGIN – END to group the statements and clauses into compound statements that clarify your intent. If no BEGIN - END are present, the interpreter resolves ambiguities by associating each ELSE with the closest IF that lacks an ELSE.

```
IF i > 0 THEN           // Without BEGIN - END
  IF j > i THEN
    x = j
  ELSE
    x = i
```



The ELSE clause is associated with the inner IF statement in this example. If *i* is less than or equal to **0**, no value is assigned to *x*.

```

IF i > 0 THEN
BEGIN          /* With BEGIN - END */
IF j > i THEN
x = j
END
ELSE
x = i

```

The BEGIN - END enclosing the inner IF statement in this example makes the ELSE clause part of the outer IF statement. If *i* is less than or equal to **0**, *i* is assigned to *x*.

ERROR keyword

The ERROR keyword stands for a constant and returns the error code (if any). In case of a mathematical error, like division by zero or overflow, it will reset the error flag.

The constant returns the error code (if any) and in cases of mathematical errors (division by zero, overflow, etc.) resets the error flag. This allows you to detect any unexpected errors during calculation. The best example is to use the ERROR command in the IF-THEN-ELSE statement.

Example 1:

The following one-line program:

```
Length /x
```

results in the Error message: *Division by zero, b=Length/x?????*

This is, because initially *x* has been set to **0**.

Example 2:

Consider the program:

```

b=Length/x
IF ERROR THEN
b=100;
RETURN b

```

Now, whenever we have a mathematical error, *b* is set to **100** and the program will continue without the error message.

Note: ERROR is a constant, and you cannot assign any other value to it.



FIRSTTIME keyword

The FIRSTTIME keyword is a flag that indicates the first time internal run.

Example:

```
S =7
IF FIRSTTIME THEN
RETURN 100
RETURN x*s
```

Input dialog box

This dialog will appear if you use INPUT or GINPUT in User Defined Functions. It contains a single edit box.

Syntax:

```
INPUT variable
INPUT "string" variable
INPUT "string" variable = init value

GINPUT variable=init value
GINPUT "string" variable = init value
```

Example Input

Usage of INPUT is limited. Because in OptiFiber you use user defined functions usually in a loop, INPUT will ask you to input data every time you repeat the loop (usually more than 100 times). To avoid this and to avoid redundant programming (*IF FIRSTTIME THEN ...*), use the function GINPUT (general input), which will ask you for input data only the first time when you enter the loop.

```
INPUT variable
INPUT "string" variable
INPUT "string" variable = init value
```

Example:

```
b=1
MAX = 8
INPUT "Factorial of:" MAX
```

You will get the same effect if you use:

```
b=1
INPUT "Factorial of:" MAX = 8
```

You will be asked to type a value in the Fractional Of box in the Input window.

Note: The initialization of **MAX** before **INPUT** is not necessary. If you delete the line **MAX = 8**, the default value in the Input box will be **0**.

Example Ginput

GINPUT variable=init value

GINPUT "string" variable = init value

(general input)

Displays an Input window on the screen (text is optional).

If the whole program (User Defined Function) is running more than once in the logical (internal) block,

GINPUT will ask you to enter data only the first time the program runs.

Example:

If you define the following user function:

s=4

tanh(s*(x/Length))*(tanh (s*(1-x/Length)))

then the shape of the above function is controlled by the s parameter (assuming that x is a running

variable).

Now, if you want to test different shapes, with different s values, you will need to change the s value for each calculation. Instead of going through all dialog boxes and buttons to reach the User Function dialog box, whenever you want to change "s".

Here comes the advantage of the GINPUT. You can use the **GINPUT** function:

GINPUT "Input Shape parameter" s=4

tanh(s*(x/Length))*(tanh (s*(1-x/Length)))

You will be asked to input different "s" values each time you press the Calculation button. Thus, you will be able to try different function shapes very quickly and easily.



Predefined Constants

Mathematical constants

pi 3.14159265358979323846

e 2.71828182845904523536

Physical constants

Symbol	Value	Units	Meaning
_c	2.9979e8	m/s	Speed of light in free space
_e	8.8542e-12	F/m	Permittivity in free space
_mi	4*pi*10e-7	H/m	Permeability in free space
_q	1.60219e-19	C	Elementary charge
_me	9.1095e-31	kg	Free electron mass
_u	1.660531e-27	kg	Atomic mass unit
_mp	1.672614e-27	kg	Proton rest mass
_mn	1.674920e-27	kg	Neutron rest mass
_eV	1.60219e-19	J	Energy unit (electron-volt)
_h	6.626e-34 J	s	Planck constant
_hr	1.05459 e-34	Js	Reduced Planck Constant
_lc	2.4263096e-12	m	Compton wavelength of electron
_Ry	13.6058	eV	Rydberg energy
_ri	1.09737312e7	1/m	Rydberg constant
_kT	25.853	meV	Thermal energy
_NA	6.022045e23	1	Avogadro number
_f	9.648 6e4	C/mol	Faraday constant
_a	7.297351e-3	1	Fine structure constant
_a0	5.291771e-11	m	Bohr radius
_re	2.817939e-15	m	Electron radius
_mb	9.274096e-24	J/T	Bohr magnetron
_kB	1.3807e-23	J/K	Boltzmann constant
_sb	5.66961e-8	1	Stefan-Boltzmann constant



Functions Library

Commonly used functions

<code>sin(radian)</code>	sine
<code>asin({0..1})</code>	radian
<code>sinh(x)</code>	hyperbolic sine of x
<code>cos(radian)</code>	{0..1}
<code>acos({0..1})</code>	radian
<code>cosh(x)</code>	hyperbolic cosine of x
<code>tan(radian)</code>	{0..inf}
<code>atan({0..1})</code>	radian
<code>exp(x)</code>	e^x
<code>ln(x)</code>	log in base e
<code>log(x)</code>	log in base 10
<code>deg(rad)</code>	radians into degrees
<code>rad(deg)</code>	degrees into radians
<code>fact(x)</code>	factorial x!
<code>sqrt(x)</code>	square root of x

Other functions

`min(a,b)` =a if $a < b$ else b

`max(a,b)` =a if $a > b$ else b

`comb(n, k)`= number of combinations for k object, n - total number of objects ($n \geq m$), return 0 if error

`perm(m, n)` =permutation mPn (0 if error)

`gcd(a, b)` = Greatest Common Divisor between a & b

`lcm(a, b)` = Largest Common Multiple between a & b

`frc(x)` = fractional part of 'x'

`int(x)` = integer part of 'x'

`angle(x,y)` Computes angle from Cartesian position (x,y), angle defined positive if $y > 0$ and negative if $y < 0$

`rand(MaxNum)` => Randomize {0..MaxNum}



Fresnel integral

fresnel_s(x) = Fresnel Integral SIN

fresnel_c(x) = Fresnel Integral COS

Evaluates the Fresnel integrals

$$S(x) = \int_0^x \sin\left(\frac{\pi}{2}t^2\right) dt \quad (27)$$

$$C(x) = \int_0^x \cos\left(\frac{\pi}{2}t^2\right) dt \quad (28)$$

f(x), g(x)

fresnel_f(x) = function f(x) related to the Fresnel Integral

fresnel_g(x) = function g(x) related to the Fresnel Integral

Evaluates the functions f(x) and g(x) related to the Fresnel integrals by means of the formulae

$$f(x) = \{1/2 - S(x)\} \cos(\pi x^2/2) - \{1/2 - C(x)\} \sin(\pi x^2/2) \quad (29)$$

$$g(x) = \{1/2 - C(x)\} \cos(\pi x^2/2) - \{1/2 - S(x)\} \sin(\pi x^2/2) \quad (30)$$

Gamma function

Computes the value of the gamma function at x



$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \quad (31)$$

gamma(x) Gamma Function

lgamma(x) Natural logarithm of Gamma Function, x - must be positive

Error function

erf(x) error function

erfc(x) complementary error function

Computes the error function erf(x) and Complementary error function erfc(x):

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad (32)$$

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt \quad (33)$$

When $x > 26$ then $\operatorname{erf}(x) = 1$ and $\operatorname{erfc}(x) = 0$

When $x < -5.5$ then $\operatorname{erf}(x) = -1$ and $\operatorname{erfc}(x) = 2$;

nexp_{erfc} computes $\exp(x^2) * \operatorname{erfc}(x)$

$$\operatorname{nexp}_{\operatorname{erfc}}(x) = \frac{2e^{x^2}}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt \quad (34)$$

i.e.

Inverse error function y(x):



inverf(x,minx)

Evaluates the inverse error function $y(x)$ where

$$x = \frac{2}{\sqrt{\pi}} \int_x^{y(x)} e^{-t^2} dt \quad (35)$$

x - it is necessary that $-1 < x < 1$

if $|x| > 0.8$ then value of x is not used in the procedure

minx if $|x| \leq 0.8$ then value minx is not used in the procedure

if $|x| > 0.8$ then minx has to contain the value of $1-|x|$.

In the case that $|x|$ is in the neighborhood of 1, cancellation of digits take place in the calculation of $1-|x|$

If the value $1-|x|$ is known exactly from another source, then minx has to contain this value, which will give better results.

Bessel functions

Bessel functions J

bessj0(x) - Bessel function $J_0(x)$ of the 1st kind of order 0

bessj1(x) - Bessel function $J_1(x)$ of the 1st kind of order 1

bessj [k] (x) - Bessel function $J_k(x)$ of the 1st kind in order k

Bessel functions Y (Weber's function)

bessy0(x) - Bessel function $Y_0(x)$ of the 2nd kind of order 0

bessy1(x) - Bessel function $Y_1(x)$ of the 2nd kind of order 1

bessy [k] (x) - Bessel function $Y_k(x)$ of the 2nd kind of order k

Modified Bessel functions I

bessi0(x) - Modified Bessel function $I_0(x)$ of the 1st kind of order 0

bessi1(x) - Modified Bessel function $I_1(x)$ of the 1st kind of order 1

bessi [k] (x) - Modified Bessel function $I_k(x)$ of the 1st kind of order k

Modified Bessel functions K

bessk1(x) - Mod. Bessel function $K_0(x)$ of the third kind of order 0



bessk1(x) - Mod. Bessel function $K_1(x)$ of the third kind of order 1

bessk [k] (x) - Mod. Bessel function $K_k(x)$ of the third kind of order k

Spherical Bessel functions

spbessj[k](x) => Spherical Bessel funct. $J_{k+0.5}(x)$

Bessel functions of the second kind (Neumann's functions)

neumann(a,x) - Neumann function $Y_a(x)$ of the 2nd kind of order a

neumann1(a,x) - Neumann function $Y_{a+1}(x)$ of the 2nd kind of order a

Chebyshev polynomials

chepol(n,x) - Computes the value of the Chebyshev polynomial $T_n(x)$

$$T_0(x) = 1, T_1(x) = x \tag{36}$$

$$T_i(x) = 2xT_{i-1}(x) - T_{i-2}(x), i = 2, \dots, n \tag{37}$$



Unit Conversions

Length conversions

ft_m(foot)	foot to meter
yd_m(yard)	yard to meter
in_m(inch)	inches to meter

Temperature conversions

c_k(celsius)	Celsius to Kelvin
fh_k(Fahrenheit)	Fahrenheit to Kelvin
fh_c(Fahrenheit)	Fahrenheit to Celsius
k_c(kelvin)	Kelvin to Celsius
c_fh(celsius)	Celsius to Fahrenheit
k_fh(kelvin)	Kelvin to Fahrenheit

Other conversions

gal_l gal_l(gallon)	gallon to liter
pt_l pt_l(pint)	pint to liter
oz_l oz_l(oz)	oz to liter
in3_l in3_l(cubInc)	cubic inch to liter
l_m3 l_m3(liter)	liter to cubic meter
pd_kg pd_kg(pound)	pound to kilogram
phe phe(wavelength[im])	calculate Photon energy [eV]



PREDEFINED CONSTANTS

NOTES:

Appendix B - Fiber Mode Solvers

Introduction

Many kinds of optical fiber can be described, or in the case of graded index fibers, approximated by, a series of concentric layers of loss-less dielectric. When the index contrast in the structure is small, it is common to use the scalar wave equation to obtain the linearly-polarized modes (LP modes). However, when the index contrast becomes larger, the LP approximation becomes inaccurate, and a full vector analysis is necessary [1]. Within any one of the concentric layers, the field components are all linear combinations of Ordinary and Modified Bessel functions, and the solution is a matter of matching the tangential field components of adjacent layers, leading to the solution of a linear system. There are some choices to make about the best way to arrange the linear system (see Ref. [2] for a complete treatment) but probably the best choice for a general, quick algorithm is the method of Yeh and Lindgren [3]. The method has intuitive appeal in its similarity to the transfer matrix method used for the analysis of planar waveguides [4]. Both methods use a matrix to express the fields at one side of a layer given their values at the other side, and the whole structure is then characterized by cascading the layers by matrix multiplication. For vector fields in fibers, there is no natural separation into TE and TM polarization, so one must include the two tangential components for both electric and magnetic field simultaneously. In total there are four transverse components at the layer boundaries, so the transfer matrix in fiber is a 4x4 matrix, instead of 2x2.

The method used by the Optiwave fiber mode solvers is different from the previous works in three ways. The 4x4 matrix method for vector modes in fibers is implemented with these improvements to make the algorithm faster in execution time, and more reliable in the finding of modes, particularly in cases where the modes are almost degenerate. The first improvement involves a reformulation of the basic equations to make a real-valued numerical implementation. Since it is loss-less modes on a fiber of loss-less material that is being sought, there is no reason to include complex numbers in the formulation. Real-valued implementation uses less computer resources. Second, the complete transfer across one layer boundary requires a matrix inverse. It is better to find this inverse analytically, rather than rely on numerical inversion at each stage. The layer matrix can be decomposed into two 4x4 matrices, and the new matrices are of a form where it is easy to find the inverse by inspection, thereby finding the analytic solution to the original inversion problem. Third, it is usual to construct the dispersion function (the zeros of which are located at the modal indices) as the determinant of the 4x4 matrix system. While this is theoretically correct, it is not the most intuitive prescription. Worse, the determinant



is not the most convenient construction for locating the zeros, particularly in the case where two zeros are very close to each other. Optiwave uses an eigen-value analysis that splits the dispersion function into two functions. This splitting resolves the almost degenerate pairs and helps the simple-minded computer algorithms to find the zeros of the dispersion function (i.e. the modes) more reliably.

Real-valued formulation

The time independent Maxwell curl equations with a positive time convention ($e^{j\omega t}$) are

$$\nabla \times \mathbf{E} = -j\omega\mu_0\mathbf{H} \quad \nabla \times \mathbf{H} = j\omega\varepsilon_0\varepsilon\mathbf{E} \quad (1)$$

and the divergence equations are

$$\nabla \cdot (\varepsilon\mathbf{E}) = 0 \quad \nabla \cdot \mathbf{H} = 0 \quad (2)$$

The factor j does not suit the current purpose, so make the substitution

$$\mathbf{h} = -j\eta_0\mathbf{H} \quad (3)$$

where $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$ is the free space impedance, so that \mathbf{h} and \mathbf{E} have the same units. Then

$$\nabla \times \mathbf{E} = k\mathbf{h} \quad \nabla \times \mathbf{h} = k\varepsilon\mathbf{E} \quad (4)$$

where $k = \omega\sqrt{\mu_0\varepsilon_0}$. Eliminating the \mathbf{h} gives the electric wave equation

$$\nabla \times \nabla \times \mathbf{E} - k^2\varepsilon\mathbf{E} = 0 \quad (5)$$

Debye Potential

For finding electromagnetic fields in a cylindrical geometry it is convenient to use cylindrical coordinates r , θ and z , and Debye potentials parallel to the axis of rotation,

$\hat{\mathbf{z}}$ [2]

$$\mathbf{E} = \nabla \times (\hat{\mathbf{z}}\psi) + \frac{1}{k\varepsilon}\nabla \times \nabla \times (\hat{\mathbf{z}}\varphi) \quad (6)$$

$$\mathbf{h} = \nabla \times (\hat{\mathbf{z}}\varphi) + \frac{1}{k}\nabla \times \nabla \times (\hat{\mathbf{z}}\psi) \quad (7)$$

It is supposed that the permittivity is constant in the region in which the above equations apply. The fibers are defined as a series of concentric layers of constant dielectric, so for the fiber mode solver, the region is the annulus between the layer boundaries. Equation 6 and Equation 7 are applied in a piecemeal way. Strictly speaking, the ψ , φ and ε should have subscripts to indicate to which layer the solution applies, but they are dropped here to simplify the representation. The complete solution for the multilayer fiber will be constructed by using a separate pair of functions for each layer, and by matching the tangential field components at the layer boundaries

The divergence of the curl of any vector field is identically zero. Therefore the choice of (6) and (7) to represent the electric and magnetic fields means that the divergence equations (2) will automatically be satisfied. In the remainder of this section, we show that if the two potentials ψ and φ are solutions to the scalar Helmholtz equation, then (6) will be a solution to the Maxwell wave equation (5), at least within any given layer. In subsequent sections, the particular solution for the mode will be found by observing the boundary conditions imposed by physical considerations on \mathbf{E} and \mathbf{h} .

Suppose ψ is a continuous function of position that satisfies the Helmholtz equation in 3 dimensions

$$\nabla^2 \psi + k^2 \varepsilon \psi = 0 \quad (8)$$

Consider the following equation, true for any ψ satisfying (9) in a region of constant permittivity.

$$\nabla[\nabla \cdot (\hat{\mathbf{z}}\psi)] - \nabla^2(\hat{\mathbf{z}}\psi) - k^2 \varepsilon \hat{\mathbf{z}}\psi = \nabla \frac{\partial \psi}{\partial z} \quad (9)$$

Associate the first two terms together and apply the vector identity

$$\nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A} = \nabla \times \nabla \times \mathbf{A} \quad (10)$$

to get

$$\nabla \times \nabla \times (\hat{\mathbf{z}}\psi) - k^2 \varepsilon \hat{\mathbf{z}}\psi = \nabla \frac{\partial \psi}{\partial z} \quad (11)$$

The right hand side of (11) is a gradient of a scalar function, so the curl of the left hand side must be zero. take the curl of (11)

$$\nabla \times \nabla \times \nabla \times (\hat{\mathbf{z}}\psi) - k^2 \varepsilon \nabla \times (\hat{\mathbf{z}}\psi) = 0 \quad (12)$$

and define \mathbf{E} by the first term of (6). With \mathbf{E} defined this way, the Maxwell electric wave equation (5) follows, and therefore this \mathbf{E} is a possible solution for electric field.

Solutions defined from the ψ function solely (that is to say, solutions with $\varphi = 0$), will have electric fields of the form

$$\mathbf{E} = \nabla \times (\psi \hat{\mathbf{z}}) = \frac{\hat{\mathbf{r}}}{r} \frac{\partial \psi}{\partial \theta} - \hat{\theta} \frac{\partial \psi}{\partial r} \quad (13)$$

from which we can see there is no longitudinal (z) component to the electric field, i.e. these are transverse electric fields. The magnetic field associated with these transverse electric fields is constructed from the first Maxwell curl equation in (4):

$$\mathbf{h} = \frac{1}{k} \nabla \times \nabla \times (\hat{\mathbf{z}} \psi) \quad (14)$$

which is the second term of (7).

The same sequence (7) - (11) can be applied to the φ function to give transverse magnetic fields, and the electric components of these are given as the second term of (6). A linear superposition of transverse magnetic and transverse electric fields will give solutions that are neither transverse magnetic nor transverse electric. In fact, most modes of the fiber are of this hybrid kind. In the hybrid case, equations (6) and (7) are used as written, and the relative value of the ψ and φ is now important, since it is a specific linear combination that matches the boundary conditions at the layer boundaries.

Separation of Variables

The potentials themselves are solutions of the scalar Helmholtz equation, and the particular solution is found by observing the boundary conditions imposed by physical considerations on \mathbf{E} and \mathbf{h} . The potentials are supposed to form modes, so a solution where the variables are separated is appropriate

$$\psi(r, \theta, z) = \psi_v(r) \exp[j(v\theta - \beta z)] \quad (15)$$

and a similar expression applies for the other Debye potential, φ . The Helmholtz equation (8) is expanded in cylindrical co-ordinates, and then (15) is substituted. For regions where ε is constant, the radial functions follow the Ordinary or Modified Bessel equation, and so the solutions are linear combinations of Bessel functions of integer order v . In any given layer,

$$\varphi_v(r) = AJ_v(ur) + BY_v(ur) \quad \psi_v(r) = CJ_v(ur) + DY_v(ur) \quad (16)$$



where $u = \sqrt{k^2 \varepsilon - \beta^2}$. In layers where the propagation constant squared is larger than $k^2 \varepsilon$, the Bessel functions J and Y are replaced by the Modified Bessel functions I and K , respectively.,

$$\varphi_\nu(r) = AI_\nu(wr) + BK_\nu(ur) \quad \psi_\nu(r) = CI_\nu(ur) + DK_\nu(ur) \quad (17)$$

where $w = \sqrt{\beta^2 - k^2 \varepsilon}$. Equations (15), (16), and (17) are substituted in (6) and (7) to find the electromagnetic fields. It is the tangential components θ and z that are needed explicitly, since it is the tangential components of the electric and magnetic fields that should match at layer boundaries. These field components are related to the coefficients A , B , C , and D by a 4x4 matrix

$$\mathbf{f} = \begin{bmatrix} E_z \\ h_\theta \\ h_z \\ E_\theta \end{bmatrix} = \begin{bmatrix} u^2 J_\nu(ur)/k\varepsilon & u^2 Y_\nu(ur)/k\varepsilon & 0 & 0 \\ -u J'_\nu(ur) & -u Y'_\nu(ur) & n\nu J_\nu(ur)/r & n\nu Y_\nu(ur)/r \\ 0 & 0 & u^2 J_\nu(ur)/k & u^2 Y_\nu(ur)/k \\ n\nu J_\nu(ur)/\varepsilon r & n\nu Y_\nu(ur)/\varepsilon r & -u J'_\nu(ur) & -u Y'_\nu(ur) \end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} \quad (18)$$

where $n = \beta/k$ is the modal index, and the common factor $\exp[j(\nu\theta - \beta z)]$ is suppressed. In layers where the propagation constant squared is larger than $k^2 \varepsilon$, the Bessel functions J and Y are replaced by the Modified Bessel functions I and K , respectively, and the u is replaced by w .

A similar equation to (18) applies in adjacent layers, with different constants A , B , C , D . Given the constants in one layer, the constants in the adjacent layer can be found by solving the linear system created by the field matching condition. The \mathbf{f} found by the two matrices should be the same field vector at the boundary between layers. The difference between this formulation and that in Ref. [2] and [3] is that this formulation uses real numbers only.

Solution of the linear system

The order of the components in the vector \mathbf{f} is chosen to help factor the matrix in (9) into two matrices as $\mathbf{Ff} = \mathbf{Dc}$ where $\mathbf{c} = [A, B, C, D]^T$,

$$\mathbf{F} = \begin{bmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & -1 & n\nu k/ru^2 & 0 \\ 0 & 0 & 1 & 0 \\ n\nu k/ru^2 & 0 & 0 & -1 \end{bmatrix} \quad (19)$$

$$\mathbf{D} = \begin{bmatrix} u^2 J_v/k & u^2 Y_v/k & 0 & 0 \\ u J_v & u Y_v & 0 & 0 \\ 0 & 0 & u^2 J_v/k & u^2 Y_v/k \\ 0 & 0 & u J_v & u Y_v \end{bmatrix} \quad (20)$$

The advantage of this factoring is that it is easy to find the expressions for \mathbf{F}^{-1} and \mathbf{D}^{-1} . \mathbf{F}^{-1} is found by two row reductions and \mathbf{D}^{-1} by inverting the 2x2 matrices in the block diagonal. These matrices are required to find the coefficients in the next layer. If \mathbf{c}_m are the coefficients in the m -th layer, then the coefficients in the next layer is found from the matrix product,

$$\mathbf{c}_{m+1} = \mathbf{D}_{m+1}^{-1}(r_m) \mathbf{F}_{m+1}(r_m) \mathbf{F}_m^{-1}(r_m) \mathbf{D}_m(r_m) \mathbf{c}_m \quad (21)$$

The use of the factored matrix means four matrix multiplications instead of two are required to cross the boundary, but it avoids having to find the matrix inverse numerically.

Dispersion equation

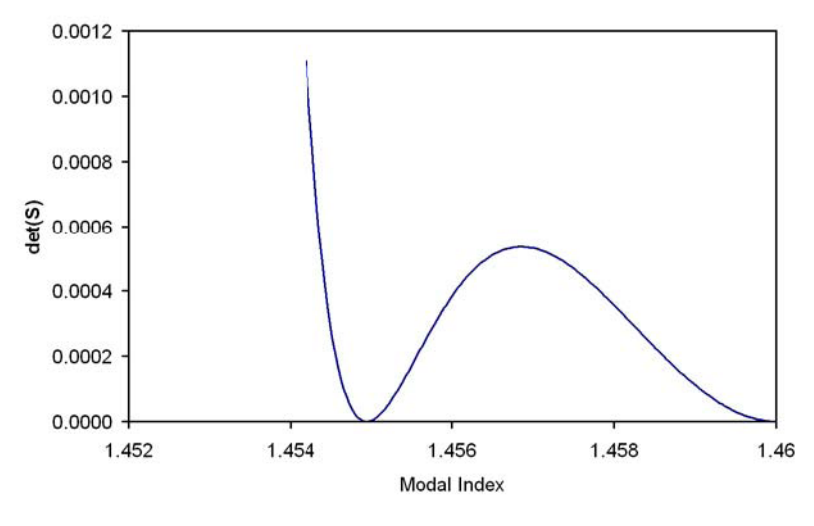
The matrix to describe the whole multilayer can be written as one 4x4 matrix, the product of all layers, one layer of which is shown in (21). The dispersion equation is usually constructed by setting the determinant of this 4x4 matrix product to 0, but this is not a good choice from the numerical point of view. In the limit of low index contrast, the modal indices can be very close to each other, making them hard to find by numerical methods, which tend to skip over closely spaced zeros. A more convenient condition comes from using rectangular matrices at the first and last layers, which are special cases. In the first layer, which contains $r = 0$, coefficients B_0 and D_0 must be zero, so the first matrix, \mathbf{D}_0 , is 4 x 2 consisting of the first and third columns of the \mathbf{D} matrix in (20). Similarly, in the last layer, it is the coefficients A_M and C_M that must go to zero in (17), since those contain solutions I_v with unphysical growth. The last matrix \mathbf{D}_M^{-1} will be of size 2 x 4, and consist of the first and third rows of \mathbf{D}^{-1} . The product of all these matrices will be of size 2x2, which we call $\mathbf{S}(n)$. (The dependence on n is written explicitly since it is the modal index to be found). A mode is obtained at a modal index n when a non-trivial solution is found to,

$$\mathbf{0} = \mathbf{S}(n) \begin{bmatrix} A_0 \\ C_0 \end{bmatrix} \quad (22)$$

The condition $\det(\mathbf{S}) = 0$ is sufficient for a non-trivial solution. However this condition can be inconvenient for the case of certain modes of the low index contrast fiber. For example, consider a step index fiber with radius $2 \mu\text{m}$, having a core index of 1.46 and a cladding of 1.45. For order zero ($v = 0$), the determinant of \mathbf{S} will vary with the modal index n as shown in Figure 1.



Figure 1 The determinant of the system matrix vs. the modal index. Step index fiber with radius $2 \mu\text{m}$, core index of 1.46, and a cladding of 1.45. The optical wavelength is $0.5 \mu\text{m}$, and the order $\nu = 0$.



It is difficult to find the zero for curves of this type. The position of the zero is easily passed over in the initial search for zero crossings. The shape of the curve in the region of the zero is very nearly quadratic, so the best solution is to split the determinant function into a product of two functions. In that case, the zeros can be found by looking for zero crossings of the two functions separately. Suitable functions can be found by considering the vector $[A_0, C_0]^T$, as an eigenvector of \mathbf{S} with eigenvalue, λ equal to 0. The eigenvalues of $\mathbf{S}(n)$ are ,

$$\lambda_1(n) = T/2 + \sqrt{T^2/4 - \det(\mathbf{S})} \quad \lambda_2(n) = T/2 - \sqrt{T^2/4 - \det(\mathbf{S})} \quad (23)$$

Where $T = S_{11} + S_{22}$. The determinant of a matrix is equal to the product of its eigenvalues, so the product $\det(\mathbf{S}(n)) = \lambda_1(n)\lambda_2(n)$ is a factoring convenient for the zero finding task. A mode exists when either $\lambda_1(n) = 0$ or $\lambda_2(n) = 0$. The advantage of searching for zeros of the two functions (23) is that the functions $\lambda_1(n)$ and $\lambda_2(n)$ have zeros that are widely spaced apart, and are more easily found than the zeros of the single determinant function.



Figure 2 Plot of the eigenvalues and determinant vs modal index.

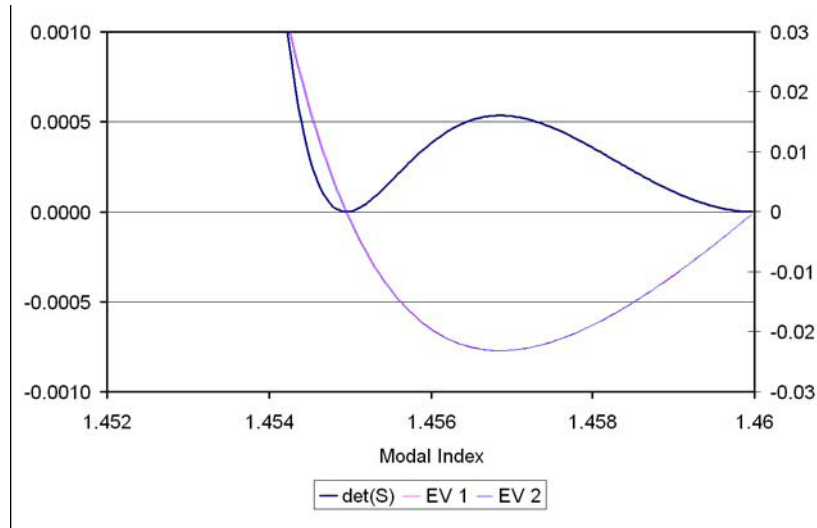
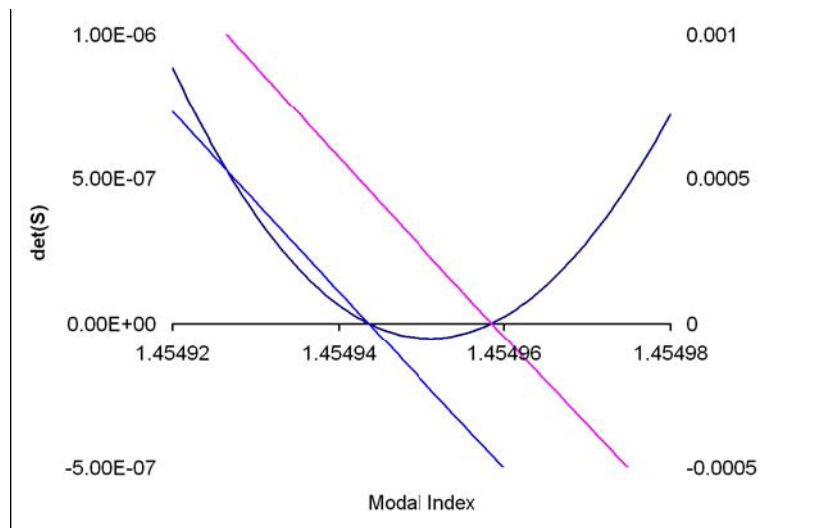


Figure 3 Expanded view of the zero crossing region



LP Modes

Linearly Polarized modes can be found with the same style of approach as above, by a transfer matrix analysis of multilayer fibers. In the LP analysis, the initial excitation is assumed to have a linear polarization, and so a modal analysis supporting only one field component is used. It can be shown this is a good approximation for fibers with low refractive index contrast, as shown below.

Consider again the wave equation of (5), but this time use the vector identity (10) directly on the electric wave equation instead of introducing the Debye potential. The result is

$$\nabla^2 \mathbf{E} - \nabla(\nabla \cdot \mathbf{E})\mathbf{E} + k^2 \varepsilon \mathbf{E} = 0 \quad (24)$$

From the Maxwell divergence equation (2)

$$0 = \nabla \cdot (\varepsilon \mathbf{E}) = \mathbf{E} \cdot \nabla \varepsilon + \varepsilon(\nabla \cdot \mathbf{E}) \quad (25)$$

so that

$$\nabla^2 \mathbf{E} + k^2 \varepsilon \mathbf{E} + \nabla \left(\mathbf{E} \cdot \frac{\nabla \varepsilon}{\varepsilon} \right) = 0 \quad (26)$$

In the case of low index contrast waveguides, such as are found in most optical fibers, the last term in (26) is negligible. The last term is the only one that contributes to coupling among the field components of the electric field, so if this term is neglected, the model will be a polarization preserving model. If the excitation was a linear polarization parallel to the X axis, the model could be further simplified by considering only the X component of (26). This shows that for the LP model, the governing equation for the field is the Helmholtz equation (8) applied to the field component E_x .

The solution for LP modes is constructed in a similar way as for the vector modes. The E_x is constructed in each layer as a linear combination of Bessel functions (16) and (17), except this time only two coefficients, A_1 and B_1 , are required, since only one function needs to be constructed. The physical consideration at the layer boundaries is the continuity of E_x and its derivative. The two conditions are related to the two coefficients A and B for each layer by 2x2 matrices. The modes are found by setting up a calculation that assumes $A_1 = 1$ and $B_1 = 0$ for the first (inner most) layer, and then calculating the coefficients in each subsequent layer by matrix manipulations. The last layer has the condition that the coefficient (A_M) of the Bessel function I_ν must be zero, since this Bessel function is not bounded at infinity. This last coefficient is a function of the order ν and the modal index n , so the modes are found by finding the zeros of $A_M(n)$.



References

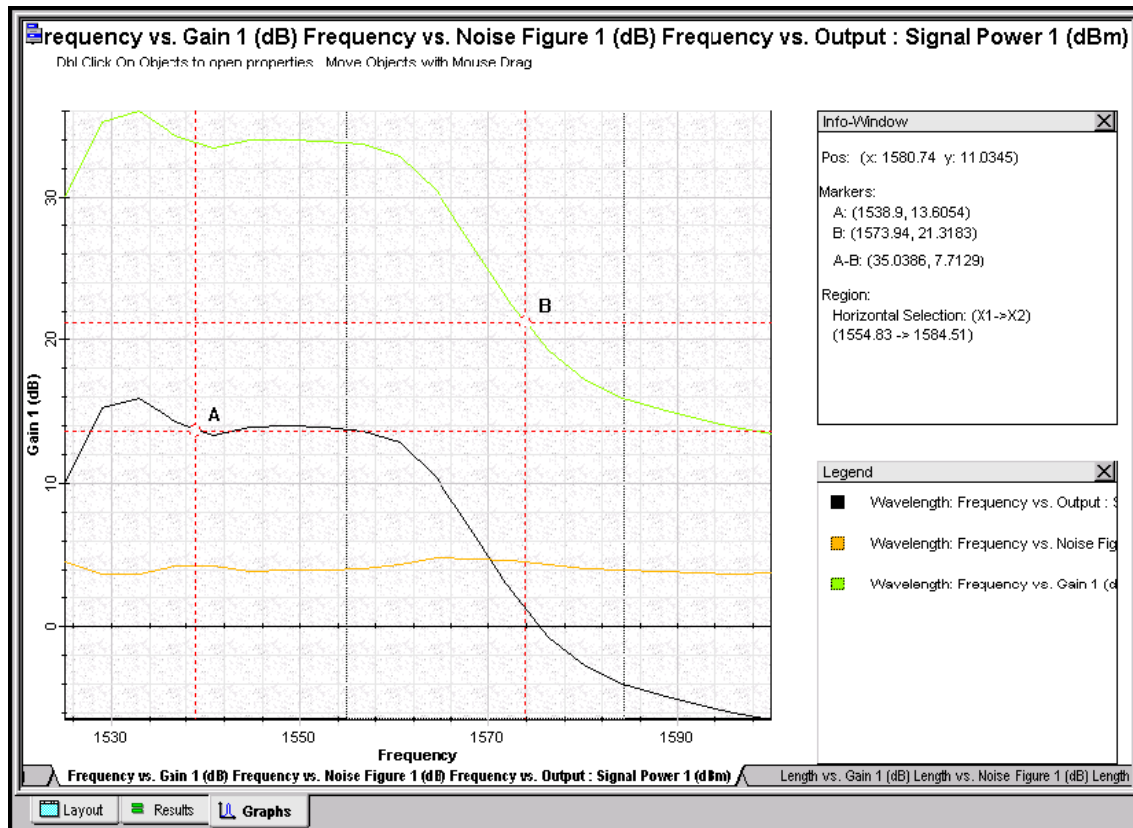
- [1] K. Okamoto, *Fundamentals of Optical Waveguides*, (Academic Press, San Diego, 2000).
- [2] C. Tsao, *Optical Fibre Waveguide Analysis*, (Oxford University Press, 1992), Part III
- [3] C. Yeh and G. Lindgren, "Computing the propagation characteristics of radially stratified fibers: an efficient method", *Applied Optics* 16(2) p483-493 (1977)
- [4] J. Chilwell and I. Hodgkinson, "Thin-films field-transfer matrix theory of planar multilayer waveguides and reflection from prism-loaded waveguide", *Journal of the Optical Society of America A*, 1 p742-753 (1984)



Appendix C - Opti2D Graph Control

The Graph control is a versatile, powerful easy-to-use tool for observing data (see [Figure 4](#)). This section gives a brief description of some of the 2D graph control features and an explanation of how to use them.

Figure 4 Opti2D Graph Control



User interface features

Features	Description
Large data handling capabilities	Opti2D Graph control is capable of handling millions of points.
Optimized drawing	Even with a large number of data points, Opti2D Graph Control is optimized to allow for smooth tracing and panning of graphs.
Moveable information windows	Moveable information windows allows for placement of the windows in the most convenient location in the graph window.
Crosshair	Visible cross to make seeing trace points easier.
Graph toolbox	The popup Graph toolbox allows easier access to the viewing/organizing/editing capabilities of the Opti2D Graph tool.
Graph Menu button	The Graph menu button allows you to access a full list of functionality associated with the graphs and their data.

Information windows

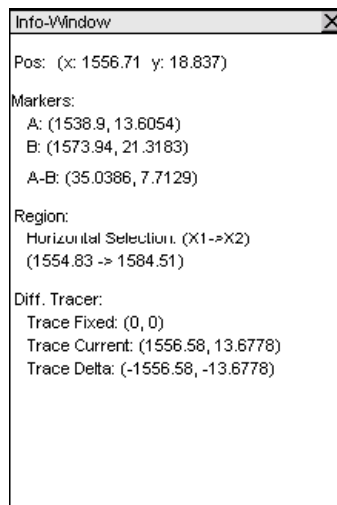
There are two main windows visible on the main display:

- [Info-window](#)
- [Info-Window settings dialog box](#)

Both can be launched using the [Graph menu](#) or [Graph tools](#).

Info-window

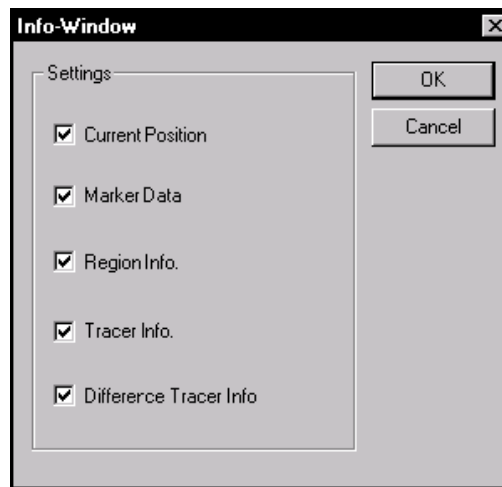
Figure 5 Info-window



When you access the Info-window, it displays in the work area of the graph view. By default, it displays the current position (in data-base coordinates) of the cursor. When you add marker, tracers, and regions, the Info-Window expands to show the details of these components.

When you use the Select tool, if you double click in the window, the Info-Window properties dialog displays (see [Figure 6](#)).

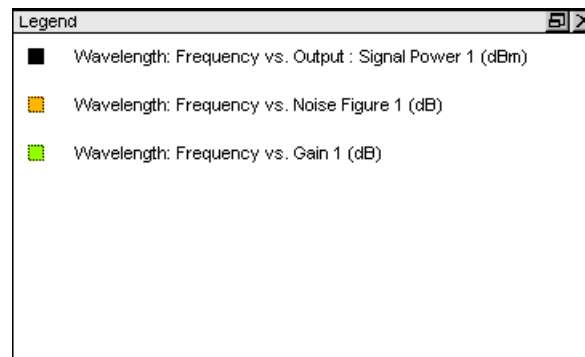
Figure 6 Info-Window settings dialog box



Legend

You can switch the Legend on and off using the Legend tool in the Graph toolbox, or the Graph menu. The Legend displays a list of all the curves displayed in the graph with the corresponding line color that is used to display those curves (see [Figure 7](#)). Use the Minimize/Maximize button to change the display of the Legend, or close the Legend by using the Close button.

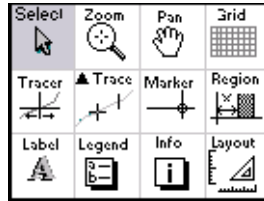
Figure 7 Legend






Graph toolbox






To access the Graph toolbox, right-click in the graph view. Most graph editing/viewing/organizing capabilities are accessible using the toolbox (see [Figure 8](#)).

Figure 8 Popup Graph Toolbox







Graph tools

File menu item	Toolbar button	Description
Select		<p>Allows you to manipulate and move most of the objects on the Graph.</p> <p>Note: To edit the properties of an object, double-click the object in the graph view.</p>
Zoom		<p>Zoom in: You can select a rectangular region, or click in the graph view for proportional zoom in.</p> <p>Extra features:</p> <ul style="list-style-type: none"> • Zoom out: Hold Ctrl and click to perform a zoom out. • Reset Zoom Level: Double-click in the graph view to return to the default Zoom level.
Pan	If 	<p>Allows you to pan from side to side in the graph display to see parts of the graph that may not be visible at the existing Zoom level or resolution.</p> <p>To pan, click to grab the display, and move the cursor from side to side.</p> <p>Extra Features:</p> <ul style="list-style-type: none"> • If you press Ctrl while panning the graph display, accelerated pan is engaged, which makes the pan much faster. This feature is useful when you work under a high zoom factor.

File menu item	Toolbar button	Description
Grid		Allows you to turn the grid lines on/off. Click on the Grid tool to toggle the grid lines.
Tracer		Allows you to select a curve and trace over it while viewing the exact positional values on the curve in the Info Window. To select a different curve, double click in graph view. Extra Features: <ul style="list-style-type: none"> You can freeze the tracer by pressing Ctrl. Click to place a marker on the curve at that position. Press Shift and drag the cursor to put the tracer into a high-resolution trace that iterates through each element in the source data array. This allows for a very detailed scan of the data and to find peaks that the standard trace may omit.
Trace		Allows you to select a curve and trace over it while viewing the exact positional values on the curve in the Info Window. The Difference Tracer differs from the Tracer tool because it allows you to create a second tracer to compare values on either the same curve or on different curves. To select the next curve, double click on the curve in the graph view. Extra Features: <ul style="list-style-type: none"> By Pressing the Control Key the tracer will freeze in its present position. Then by pressing the left mouse button a marker will be placed on that position on the curve. By pressing the shift key and dragging the mouse the tracer jumps into a high-resolution trace that iterates through each element into the source data array. This allows for a very detailed scan of the data and to find peaks that the standard trace may omit.
Marker		Allows you to place markers in the active graph view. The markers can be horizontal, vertical or both. The position of the markers is displayed in the Info Window.
Region		Allows you to select a horizontal, vertical or rectangular region in the active graph view. The coordinates of the selection are displayed in the Info Window.



APPENDIX C - OPTI2D GRAPH CONTROL

File menu item	Toolbar button	Description
Label		Allows you to place customized labels in the active graph view.
Legend		Allows you to toggle the Legend on and off within the active graph view.
Info		Allows you to toggle the Info-Window on and off within the active graph view.
Layout		Allows you to reset the layout and place all windows in their default positions.

Graph menu

To open the **Graph** menu, click the blue icon at the top left corner of the **Graph** view (see [Figure 9](#)).

Figure 9 Graph Menu



Graph Menu button

The Graph Menu button is in the top left corner of the graph view.

Tools

The tools available from the Graph menu include:

- • [Select](#)
- • [Zoom](#)
- • [Pan](#)
- • [Grid](#)
- • [Tracer](#)
- • [Difference Tracer](#)
- • [Marker](#)
- • [Region](#)
- • [Label](#)

Windows

The information windows available in the Graph Menu include:

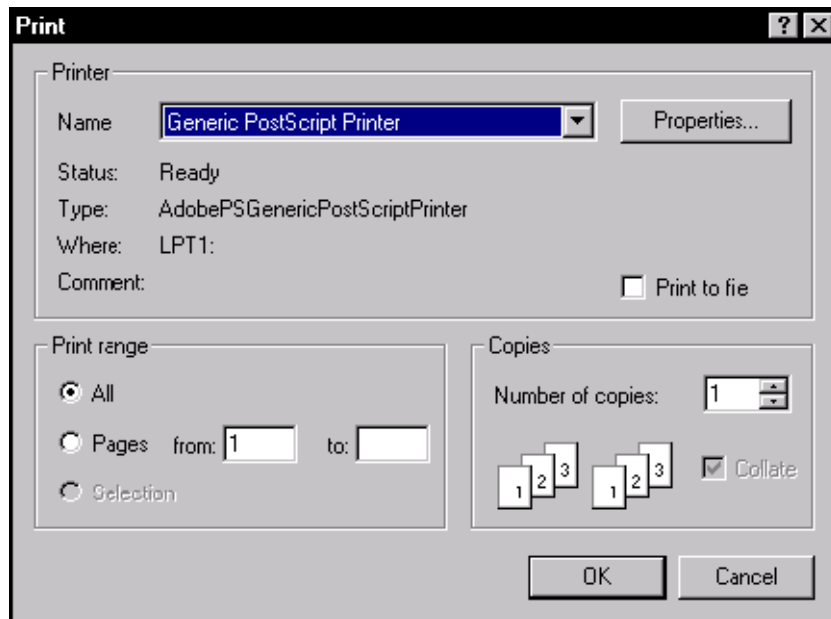
- [Legend](#)
- [Info Window](#)
- [Reset Layout](#)

Printing and exporting files

Print

Opens the **Print** dialog box and allows you to print an image of the active graph view (see [Figure 10](#)).

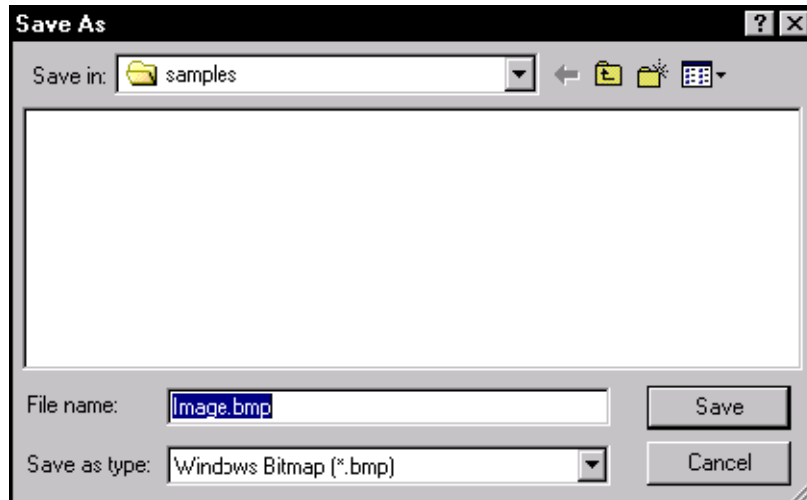
Figure 10 Print dialog box



Print to BMP file

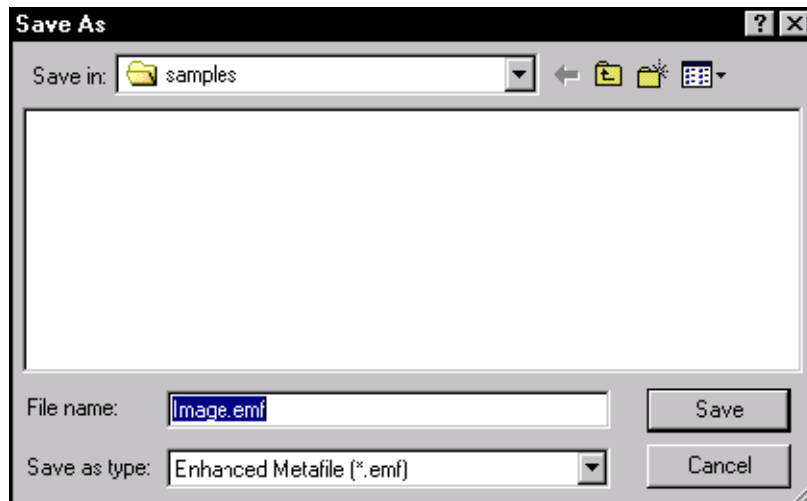
Exports an image of the active graph view to a file in **.bmp** format using the **Save As** dialog box (see [Figure 11](#)).

Figure 11 Print to BPM File

**Print to EMF file**

Exports an image of the active graph view to a file in **.emf** format using the **Save As** dialog box (see [Figure 12](#)).

Figure 12 Print to EMF File

**Copy image to clipboard**

Copies an image of the active graph view to the clipboard.

Utilities

Tool setup

Allows you to modify the properties of some of the tools.

Note: The tool property dialog only launches if the active tool allows settings to be changed.

Set Active Display

Allows you to select the active display. [For more information, see “Displays” on page 231.](#)

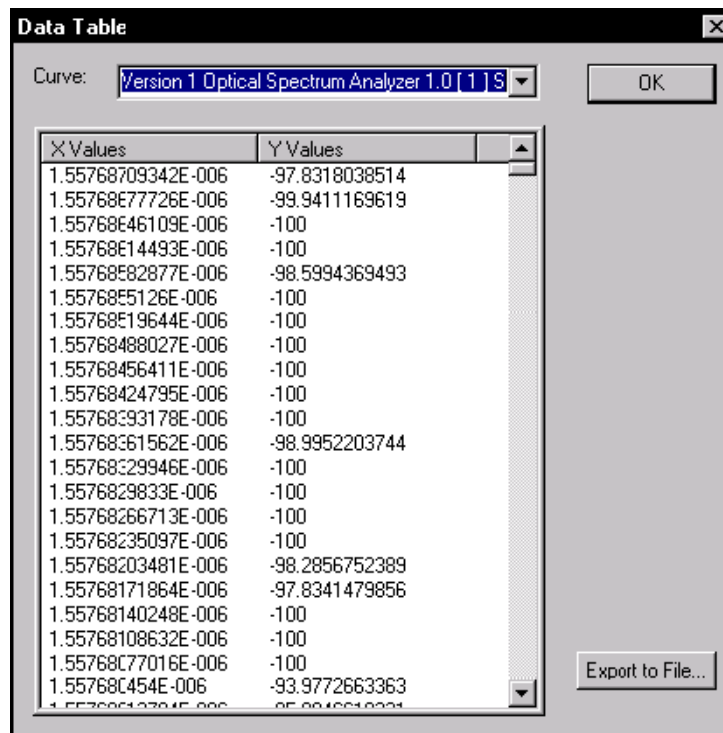
Properties

Allows you to launch the Graph Properties dialog. [For more information, see *For more information, see “Graph display” on page 232.*](#)

Table of Points

Launches a dialog box that displays a list of all the curves on the graph control and displays the data coordinates of those curves. It also allows you to export the data points to a text file (see [Figure 13](#)).

Figure 13 Data Table dialog box



Help

Launches a help dialog box specifically related to the Opti2D Graph Control.

Import Curve

Allows you to import a curve from a text file. The file must be in the format below.

X1 (tab) Y1

X2 (tab) Y2

Etc...

Ex:

// (Beginning of file) (this line should not be in the file)

123.23 123.45

123.24 124.55

123.25 555.5

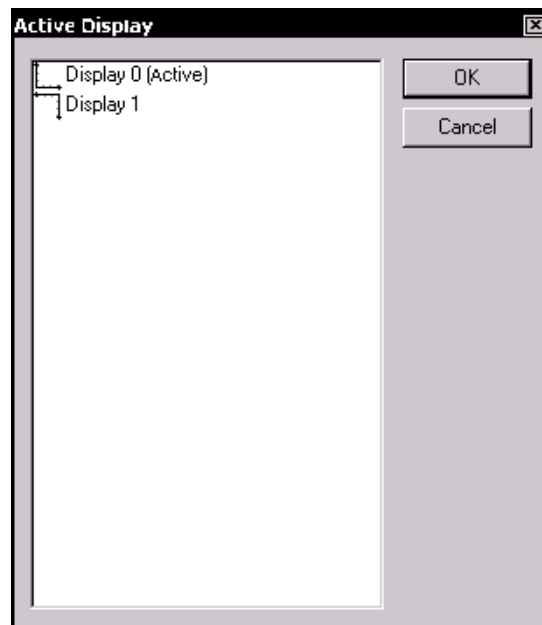
123.26 222.22

//(End of file) (this line should not be in the file)

Displays

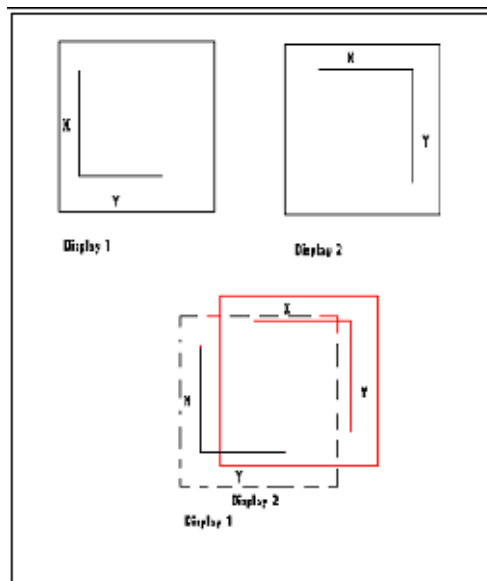
The graph is made up of layered displays. Each display has a pair of axes. By default, the control contains one display with Axis X on the bottom of the display and Axis Y on the left. In the case of complex graphs that require more than one pair of axes, more than one display exists (see [Figure 14](#)).

Figure 14 Active Display dialog box



Any objects that you place on the graph are placed on the active graph view. Therefore, if you place a marker on the graph and Display 1 is active, the new marker is based on the coordinate system of Display 1. If you want to add a marker on Display 2, you must select the main menu in the Graph menu. This launches the Graph Display dialog, which permits you to select a different display. In complex graphs, the displays are layered one on top of the other (see [Figure 15](#)).

Figure 15 Graph display



Graph Properties dialog

The Graph Properties dialog allows you to manage properties of the graph.

The Graph Properties dialog tabs include:

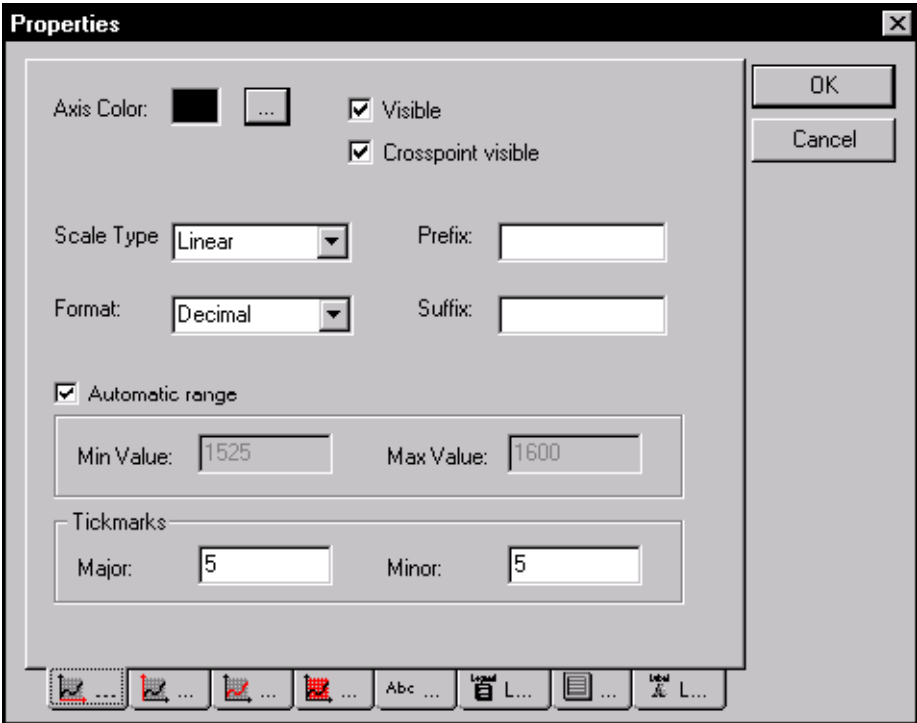
- [X-Axis](#)
- [Y-Axis](#)
- [Properties dialog box-Y-Axis tab](#)
- [Grid](#)
- [Fonts](#)
- [Legend](#)
- [Properties dialog box-Legend tab](#)
- [Label Management](#)

X-Axis

The X-Axis Tab allows you to set properties of the X-axis (see [Figure 16](#)).



Figure 16 Properties dialog box-X-Axis tab



The values in **Scale Type** can be:

- Linear
- Logarithmic
- DB

The values in **Format Value** can be:

- Decimal: simple decimal values (1000.0, 2000.0, 3000.0)
- Exponential: exponential notation (1.0-e3, 2.0-e3, 3.0-e3)
- Engineering: engineering notation (1k, 2k, 3k)
- Scientific: scientific notation (1.0 x 10³, 2.0 x 10³, 3.0 x 10³)

Prefix: You can place a prefix string before each of the scale values.

Suffix: You can place a suffix string after each of the scale values (e.g. 1000.0 nm)

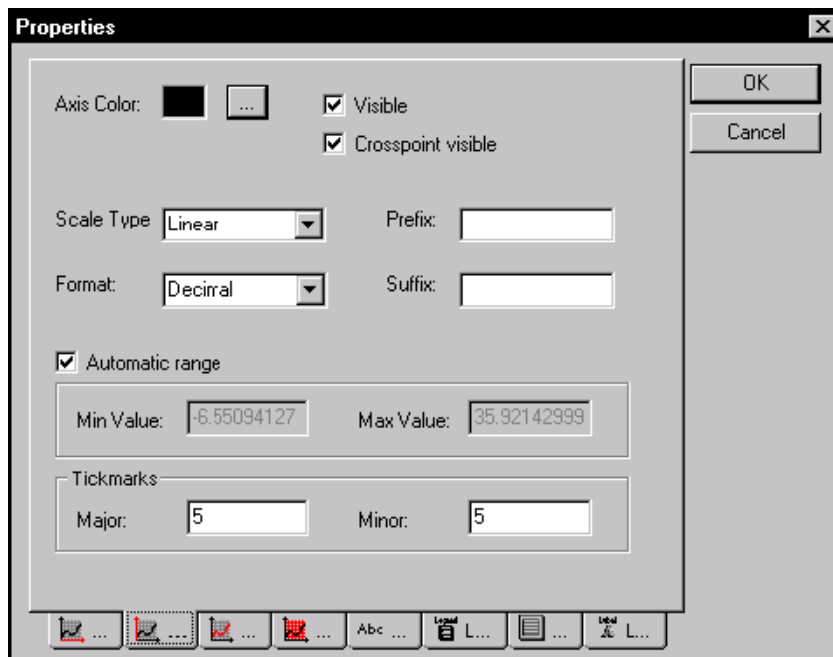
Automatic Range, Min Value, Max Value: You can check Automatic Range, which sets the range according to the curves in the displays, or force the axis range to certain values.

Tickmarks: You can set the number of major and minor tick marks on the Axis.

Y-Axis

The Y-Axis Tab allows you to set properties of the Y-axis (see [Figure 17](#)). To see descriptions of the Y-Axis dialog fields, see “X-Axis” on page 196.

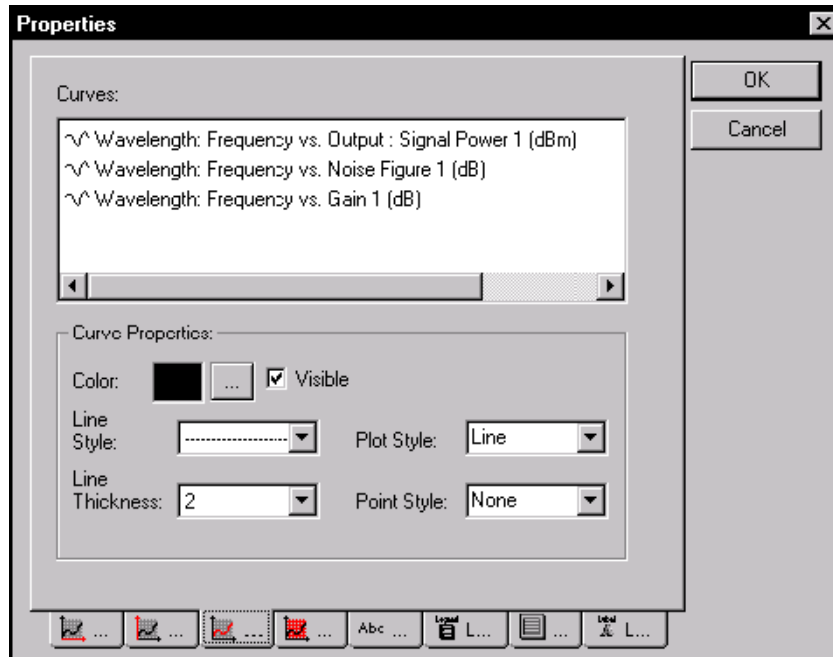
Figure 17 Properties dialog box-Y-Axis tab



Curve

The Curve tab allows you to set various properties of the curves that are added to the control (see [Figure 18](#)).

Figure 18 Properties dialog box-Curves tab



Curve List: Displays all of the curves on the active display.

Curve Properties

Color: Allows you to choose the color of the selected curve.

Line Style: Allows you to select the line style of the selected curve.

Plot Style: Allows you to select the plot style.

The values in **Plot Style** can be:

- Point
- Line
- Segment Left
- Segment Right
- Segment Center
- Step Left
- Step Right
- Drop Line



Line Thickness: Allows you to select the thickness of the currently plotted curve line. Values range from 1 to 8.

Point Style: Allows you to select the style in which each point on the curve will be drawn.

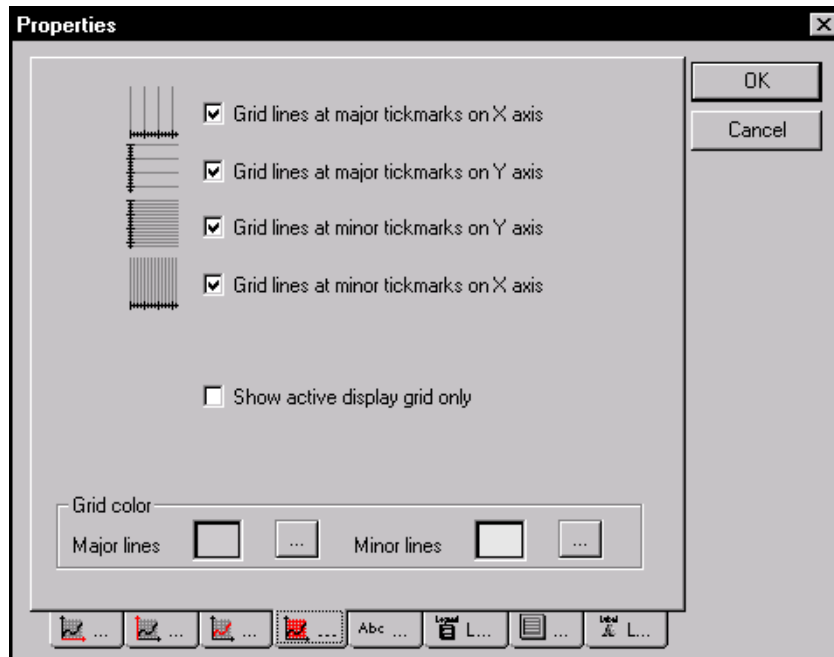
The values in **Point Style** can be:

- None
- Circle
- Square
- Diamond
- Cross

Grid

The **Grid** tab allows you to select which of the grid lines on the display are visible, and what color they are to be displayed in (see [Figure 19](#)).

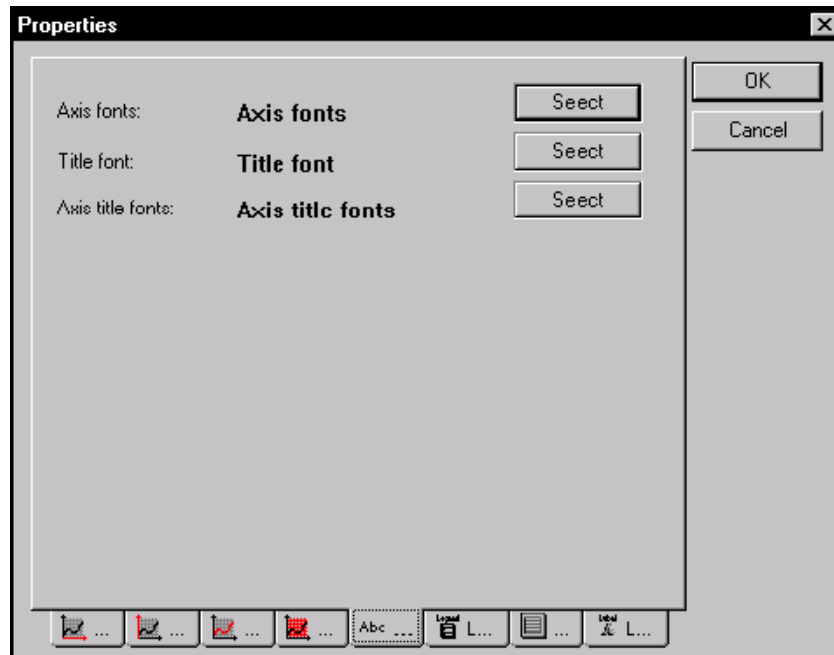
Figure 19 Properties dialog box-Grid tab



Fonts

The Font Tab allows you to select the fonts used for displaying titles and axis values. (see [Figure 20](#)).

Figure 20 Properties dialog box-Fonts tab

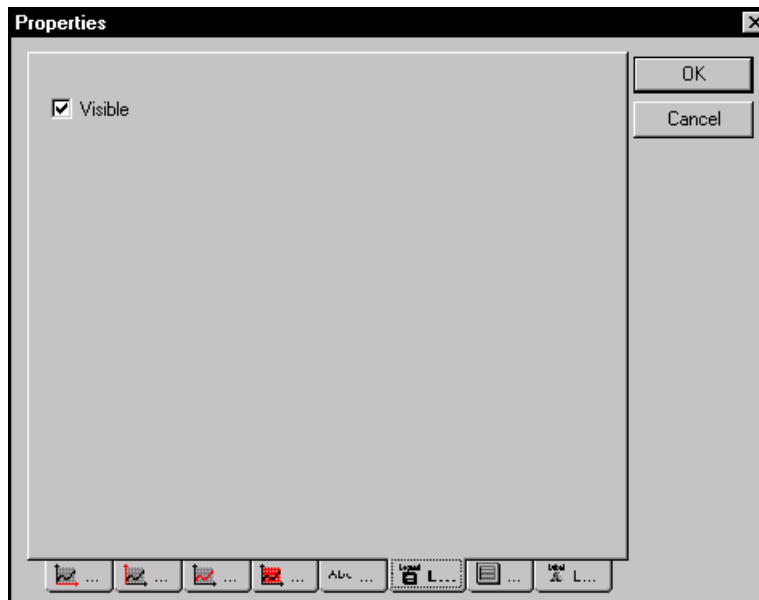


Legend

Legend tab simply has a toggle for the **Legend Visible/Invisible**. More features will become available in the future (see [Figure 21](#)).



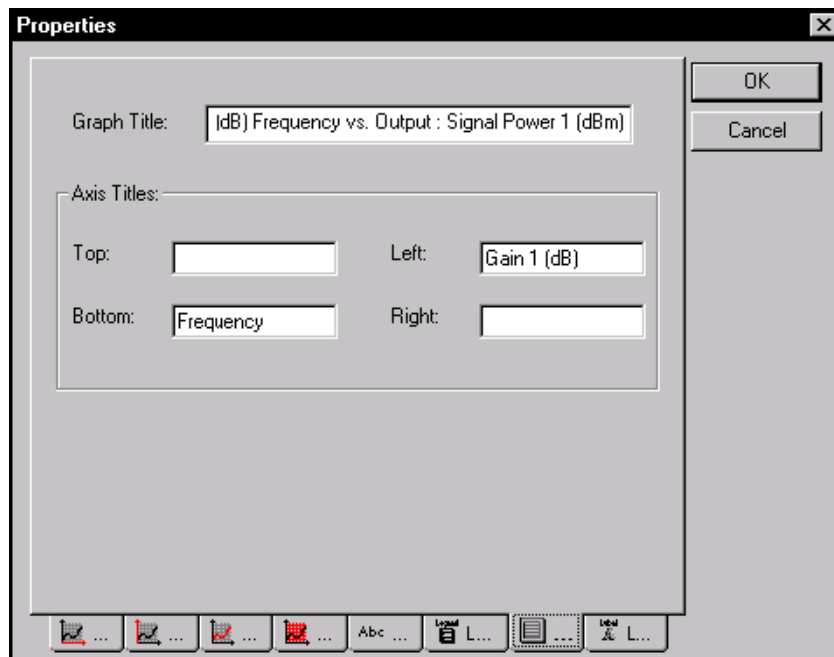
Figure 21 Properties dialog box-Legend tab



Graph

The **Graph** tab is used for editing the titles of any axis as well as the graph title itself (see [Figure 22](#)).

Figure 22 Properties dialog box-Graph tab

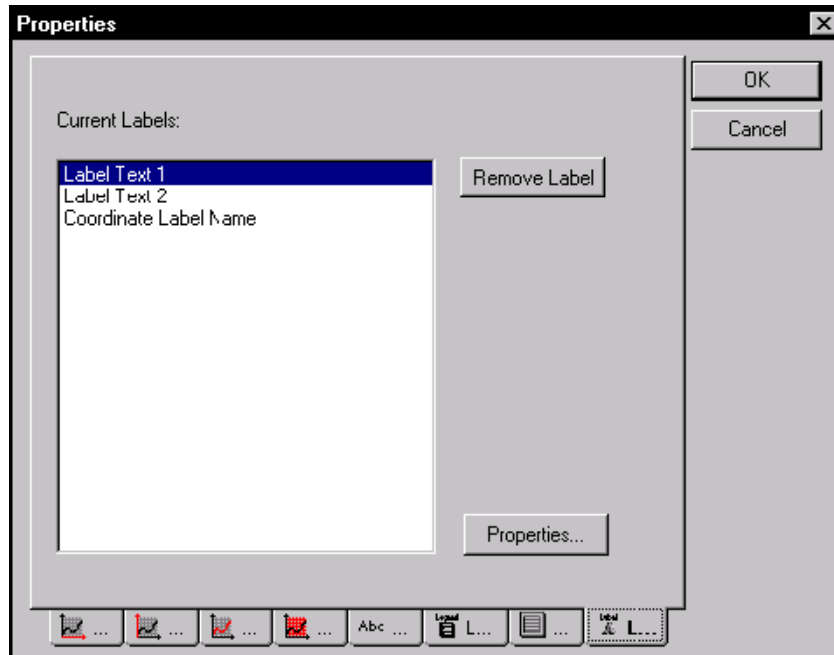


Label Management

The **Label Management** tab allows you to remove and edit labels on the graph. You can also access the Label Management function using the **Label** tool in the **Graph toolbox** (refer to [Figure 23](#)).

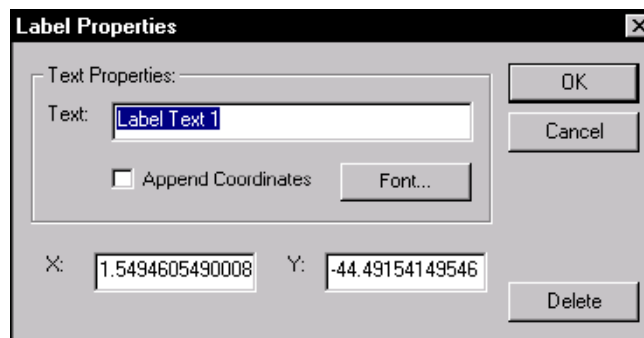
Note: For removing a large number of labels or labels that may have been positioned at coordinates that are not in the viewable area, it is easier to remove or edit them using the Label Management tab, because of the multiple selection feature.

Figure 23 Properties dialog box-Label Management tab



Use the **Label Properties** dialog box to edit the name or coordinates of the selected label (see [Figure 24](#)).

Figure 24 Label Properties dialog box



Appendix D - File Formats

Generic file format

The Generic file format is a text format that consists of three data columns, X, Y, and Z, separated by space (see [Table 1](#)).

Note: This format is one of the export formats. It is not supported by any of the viewers.

Table 1: Generic file format

X	Y	Z
1	1	1
X	Y	Z
2	2	2
X	Y	Z
3	3	3
..
.	.	.
X	Y	Z
N	N	N

Data file formats

Optiwave software uses the text data format for saving the simulation results and reading user defined fields and index of refraction distributions:

- Real Data 2D File Format: BCF2DPC
- Real Data 3D File Format: BCF3DPC
- Complex Data 2D File Format: BCF2DCX
- Complex Data 3D File Format: BCF3DCX
- User Refractive Index Distribution File Format



Optiwave software uses several different formatted text files for reading and saving optical fields and index of refraction distributions.

Real Data 2D File Format: BCF2DPC

Applies to input and output files that contain real data as text. The file contains the file header, number of data points, and the real x and y data points:

```
BCF2DPC      file header (this string is used to identify the file type)
N            number of data points
X1 Y1       first x and y data separated by space
X2 Y2       second x and y data point
.
.
.
XN YN       last x and y data point
```

Files that follow the BCF2DPC format

- Output files in 2D: [*.rpd], [*.poi]
- Output files in 3D: [*.rpd], [*.poi]

Example: Power overlap integral output file in 2D [*.poi]

In this example, a Gaussian input field is propagated in a Linear Waveguide from the starting distance 0.000000E+000 to the end distance 1.000000E-001. The propagating field is overlapped with the starting field, giving the power overlap value 1.000000E+000 at the start and the value 4.034535E-001 at the end of propagation. The number of displays in the Global Data dialog box is 30, while the actual number of saved data points is 31. This is, because the file contains also the power overlap value at the start of propagation in addition to 30 values from the propagation.

```
BCF2DPC      file header
31           number of data points
0.000000E+000  start distance and power overlap at start
1.000000E+000
3.3300000E-003  3.558430E-001  distance and power overlap
6.670000E-003  3.663763E-001  distance and power overlap
.
```



.
 .
 9.333000E-002 4.039581E-001 distance and power overlap
 9.667000E-002 4.038129E-001 distance and power overlap
 1.000000E-001 4.034535E-001 end distance and power overlap

Real Data 3D File Format: BCF3DPC

This format applies to input and output files that contain real data as text. The file contains the file header, number of x and y data points, minimum and maximum values of x, y and z, and the real z(x,y) data points. The data points are presented in one column with the order determined by scanning the x and y coordinates.

BCF3DPC	file header
NX NY	number of x and y data points
XMIN XMAX	minimum and maximum x values
YMIN YMAX	minimum and maximum y values
ZMIN ZMAX	minimum and maximum z values
Z1	real z data point with coordinates (xmin, ymin)
Z2	real z data point with coordinates (xmin+dx, ymin)
Z3	real z data point with coordinates (xmin+2dx, ymin)
.	
ZNX	real z data point with coordinates (xmax, ymin)
ZNX+1	real z data point with coordinates (xmin, ymin+dy)
.	
.	
ZN	last real z data point with coordinates (xmax, ymax), where N=NXxNY

where $dx = (xmax-xmin)/(nx-1)$ and $dy = (ymax-ymin)/(ny-1)$.

Files that follow the BCF3DPC format

- Output files in 2D: [*.amp], [*.pha], [*.rri]
- Output files in 3D: [*-x.amp], [*-y.amp], [*-x.pha], [*-y.pha], [*-x.rri], [*-y.rri]

For more information, see [Data file formats](#).



Example: Real refractive index in 2D [*.rri]

In this example, the transverse mesh extends from -5.000000E+000 to 5.000000E+000 microns. The propagation distance extends from 0.000000E+000 to 1.000000E-001 millimeters. A Linear Waveguide with refractive index 1.5 is laid out on a wafer with the index 1.3. The number of mesh points is 100 and the number of displays in the Global Data dialog box is 30. The actual y number of saved index x distributions is 31. This is, because the file contains also the index distribution at the start of propagation in addition to 30 values from the propagation.

BCF3DPC		file header
100 31		number of x and y data points
-5.000000E+000	5.000000E+000	minimum and maximum transverse mesh values
0.000000E+000	1.000000E-001	minimum and maximum distance
0.000000E+000	1.000000E+000	unused values added to conform to the format
		Note: Optiwave software adds a line of default values 0 and 1 to conform this format.
1.300000E+000		real z data point with coordinates (xmin, ymin)
1.300000E+000		
1.300000E+000		
.		
.		
.		
1.300000E+000		
1.300000E+000		
1.300000E+000		

Complex Data 2D File Format: BCF2DCX

This format applies to input and output files that contain complex number data as text. The file contains the file header, number of data points, mesh width, and the complex z data points:

New format

BCF2DCX 3.0	file header
N	number of data points
Xmin Xmax	minimum and maximum of x values
Z1	first complex data point
Z2	second complex data point
.	
.	
.	
ZN	last complex data point

Files that follow the BCF2DCX format

- Output files in 2D: [*.f2d]

For more information, see [Data file formats](#).

Example: Complex field (end of propagation) in 2D [*.f2d]

In this example, the number of data points, that is, the number of mesh points is 100. The transverse mesh extends from $-5.000000E+000$ to $5.000000E+000$ microns giving the mesh width $1.000000E+001$ microns.

```
BCF2DCX
100
1.000000E+001          3.000000E+001
-1.625361825110615E-003, -4.389245939619818E-004
-1.509141347436203E-003, -5.157781413025380E-001
1.396612427100470E-003,  5.882450646580990E-004
.
.
.
1.396612427102228E-003, -5.882450646589938E-004
-1.509141347437384E-003, -5.157781413024150E-004
```

-1.625361825110870E-003, -4.389245939610474E-004

Complex Data 3D File Format: BCF3DCX

This format applies to input and output files that contain complex data as text. The file contains the file header, number of x and y data points, mesh widths in x and y, and the complex $z(x,y)$ data points. The data points are presented in one column with the order determined by scanning the x and y coordinates.

New format

BCF3DCX 3.0	file header
NX NY	number of x and y data points
Xmin Xmax Ymin Ymax	minimum and maximum x and y values
Z1	complex number z data point with coordinates (xmin, ymin)
Z2	complex number z data point with coordinates (xmin+dx, ymin)
Z3	complex number z data point with coordinates (xmin+2dx, ymin)
.	
ZNX	complex number z data point with coordinates (xmax, ymin)
ZNX+1	complex number z data point with coordinates (xmin, ymin+dy)
.	
.	
ZN	last complex number z data point with coordinates (xmax, ymax), $N=NX \times NY$

where $dx = (x_{max} - x_{min}) / (nx - 1)$ and $dy = (y_{max} - y_{min}) / (ny - 1)$.

Example: Complex field (end of propagation) in 3D [*f3d]

In this example, the number of data points is 100 and equals to the number of mesh points. The transverse mesh extends from $-5.000000E+000$ to $5.000000E+000$ microns giving the mesh width $1.000000E+001$ microns.

```
BCF3DCX    3.0
100      100
```



1.000000E+001 1.100000E+001 2.000000 E+001 3.000000 E+001

-4.582487025358980E-004, -2.411965546811583E-002

1.813879122411751E-004, -2.322439514101689E-002

8.864140535377826E-004, -2.245463661588051E-002

.

.

.

-1.004141897700716E-002, 7.709994296904761E-003

-9.736326254112302E-003, 8.732395427319460E-003

-9.270032367315658E-003, 9.686774052240091E-003

Files that follow the BCF3DCX format

- Output files in 3D: [*.f3d]

For more information, see [Data file formats](#).



User Refractive Index Distribution File Format

UPI2DRI 3.0	file header
NPM	number of points in mesh
XMIN XMAX	min and max mesh points
Z1	first complex number data point
Z2	second complex number data point
.	
.	
.	
ZN	last complex number data point

Example

```

UPI2DRI 3.0
500
-50 50
1.4910000000000000E+000, 0.0000000000000000E+000
1.4910000000000000E+000, 0.0000000000000000E+000
.
.
.
1.4910000000000000E+000, 0.0000000000000000E+000
    
```

Default format for 3D Refractive Index Distribution

UPI3DRI 3.0	file header
NPMX NPMY	number of points in mesh in X and Y
Xmin Xmax Ymin Ymax	min and max mesh points in X and Y
Z1	first complex number data point
Z2	second complex number data point
.	

```

.
.
ZN                                last complex number data point

```

Example

```

UPI3DRI 3.0
151 121
-7.5 7.5 -3 3
3.3000000000000000E+000, 0.0000000000000000E+000
3.3000000000000000E+000, 0.0000000000000000E+000
.
.
.
3.2500000000000000E+000, 0.0000000000000000E+000

```

Reading User Refractive Index Files

During the propagation, the Optiwave software simulator reads the index distribution file in a step by step manner. The information for reading the user data file is provided by the Device Layout Designer and it concerns the number of mesh points and the extent of the User Defined File Region.

If the refractive index distribution as defined by the properties of the region is independent of the propagation distance (i.e. constant), then the simulator reads the index data only once, for the first step of propagation in the region and uses the same data for every step in that region.

If the refractive index distribution is defined as propagation dependent, then the propagation enters the User Defined File Region, the program reads index of refraction data for each propagation step. The number of lines that is read at one step is equal to the number of transverse mesh points.

For more information, see [Data file formats](#).

Complex Data 3D Vectorial File Format: BCF3DCXV

This format applies to input and output files that contain vectorial complex data. The file contains the file header, number of x and y data points, mesh widths in x and y, and the complex $z(x,y)$ data points both for E_x and E_y field components. The data points are presented in one column with the order determined by scanning the x and y coordinates.

APPENDIX D - FILE FORMATS

BCF3DCXV	file header
Nx Ny	number of x and y mesh points
Xmin Xmax Ymin Ymax	minimum and maximum X and Y coordinates
Za1	complex field (Ex field component) at point with coordinates (xmin, ymin)
Za2	complex field (Ex field component) at point with coordinates (xmin+dx, ymin)
Za3	complex field (Ex field component) at point with coordinates (xmin+2dx, ymin)
.	
ZaNx	complex field (Ex field component) at point with coordinates (xmax, ymin)
ZaNx+1	complex field (Ex field component) at point with coordinates (xmin, ymin+dy)
.	
.	
ZaN (N=Nx*Ny)	complex field (Ex field component) at point with coordinates (xmax, ymax)
Zb1	complex field (Ey field component) at point with coordinates (xmin, ymin)
Zb2	complex field (Ey field component) at point with coordinates (xmin+dx, ymin)
Zb3	complex field (Ey field component) at point with coordinates (xmin+2dx, ymin)
.	
ZbNx	complex field (Ey field component) at point with coordinates (xmax, ymin)
ZbNx+1	complex field (Ey field component) at point with coordinates (xmin, ymin+dy)
.	
.	



ZbN (N=Nx*Ny) complex field (Ey field component) at point with coordinates (xmax, ymax)

where N=Nx*Ny, dx=(xmax-xmin)/(Nx-1), and dy=(ymax-ymin)/(Ny-1).

Note: The total number of data points is twice the number of the total mesh points Nt=2*N.

Path Monitoring File Format

The sample is provided (*.mon):

BCF2DPM

Npts NPath	Number of data points (lines) and number of paths			
[Distance]	[Path 1]	[Path 2]	[Path 3]	...[Path NPath] text discriptor
XCoord 1	P1val1	P2val1	P3val1 PNPathval1
XCoord 2	P1val2	P2val2	P3val2 PNPathval1
...				
XCoord Npts	P1valNpts	P2valNpts	P3valNpts PNvalNpts

Power In Output Waveguides File Format

The sample is provided (*.piw)

BCF2DMC

NPts WGN	Number of data points (lines) and number of waveguides			
[Wavelen]	[WG1]	[WG2]	[WG3] [WGWGN] text descriptor
XCoord1	P1val1	P2val1	P3val1 PWGNval1
XCoord2	P1val2	P2val2	P3val2 PWGNval2
...				
XCoordNPts	P1valNPts	P2valNPts	P3valNPts PWGNvalNPts





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