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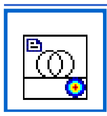
Measured-Index Multimode Fiber



This component is a general-purpose multimode fiber with user-defined or alpha profile refractive index profile. It is a spatially dependent component that models the transverse field profiles and propagation constants for each mode supported by the fiber.

Ports

Name and description	Port type	Signal type	Supported Modes
Input	Input	Optical	Sampled signals
Output	Output	Optical	

Parameters

Main

Name and description	Default value	Default unit	Units	Value range
Length Defines the fiber length	1	km	m, km	[0, 100000]
Attenuation Defines the fiber attenuation	2.61	dB/km		[0, 1e+101]

Fiber Profile

Name and description	Default value	Default unit	Units	Value range
Reference wavelength (profile)	850	nm		[100, 2000]

Refractive index profile Defines whether to calculate the fiber profile based on the alpha setting or measured data	Alpha profile			[Alpha profile, Measured]
OptiFiber file format Defines whether to load a file generated by OptiFiber or not	NO			[YES, NO]
Filename The filename with the refractive index profile	Index.txt			
Core radius Defines the fiber core radius	25	um		[1, 100]
Cladding thickness Defines the thickness of the cladding	10	um		[1, 10000]
Refractive index peak The peak value of the refractive index for the profile	1.462			[1, 2]
Use index contrast Determines whether to use the index contrast or the cladding index	NO			[YES, NO]
Refractive index cladding The filename with the refractive index profile	Index.txt			
Refractive index contrast The delta parameter of the refractive index for the profile	1	%		[0.01, 10]
Alpha The alpha parameter for the index profile	2			[1, 1e10]
Number of radial steps The number of steps for the refractive index profile	1000			[10, 10000]

Material Properties

Name and description	Default value	Default unit	Units	Value range
Include material properties Defines whether material properties are take into consideration in the delay calculationt	NO			[YES, NO]
Host material Defines the fiber host material	Pure silica			Pure silica, 1.0% fluoride-doped silica,

				3.0% B2O3-doped silica, 3.1% germania-doped silica, 9.1% P2O5-doped silica, Pure fused GeO2, Pure P2O5, Pure silica, ZBLAN
Host filename File containing the Sellmeier coefficients	HostIndex.txt			
Dopant+ material Defines the fiber material that has higher index due to an index-rising dopant.	3.1% germania-doped silica			Pure silica, 1.0% fluoride-doped silica, 3.0% B2O3-doped silica, 3.1% germania-doped silica, 9.1% P2O5-doped silica, Pure fused GeO2, Pure P2O5, Pure silica, ZBLAN
Dopant+ filename File containing the Sellmeier coefficients	DopantIndex.txt			
Dopant- material Defines the fiber material that has lower index due to an index decreasing dopant.	1.0% fluoride-doped silica			Pure silica, 1.0% fluoride-doped silica, 3.0% B2O3-doped silica, 3.1% germania-doped silica, 9.1% P2O5-doped silica, Pure fused GeO2, Pure P2O5, Pure silica, ZBLAN
Dopant- filename File containing the Sellmeier coefficients	DopantIndex.txt			

Chromatic Dispersion

Name and description	Default value	Default unit	Units	Value range
Include chromatic dispersion Defines whether chromatic dispersion effects are included or not	NO			[YES, NO]
Reference wavelength Dispersion and dispersion slope are provided at this reference wavelength	820	nm		[100, 2000]
Use Sellmeier approximations Defines whether Sellmeier approximations are used or not	YES			[YES, NO]
Zero dispersion wavelength The wavelength where the dispersion is zero. The zero dispersion slope is also provided at this wavelength.	1354	nm		[100, 2000]
Zero dispersion slope The dispersion slope at the zero dispersion wavelength	0.097	ps/(nm^2.km)		[-1e+100, 1e+100]
Dispersion Dispersion at the reference wavelength	–100	ps/(nm.km)		[-1e+100, 1e+100]
Dispersion slope Dispersion slope at the reference wavelength	0.5	ps/(nm^2.km)		[-1e+100, 1e+100]

Numerical

Name and description	Default value	Default unit	Units	Value range
User defined wavelength Defines whether to calculate the mode solver at a user defined wavelength or not	NO			[YES, NO]
Solver wavelength Mode solver is calculated at this wavelength	820	nm		[100, 2000]
Modal attenuation Defines whether to load a file with modal attenuations or no	NO			[YES, NO]
Attenuation filename The filename with the refractive index profile	Attenuation.dat			

Relative delay Defines whether the differential mode delay is absolute or relative	YES			[YES, NO]
Const. mode power dist. Defines whether to generate a constant mode power distribution (MDP) or not	NO			[YES, NO]
Modal delay Defines whether to calculate the differential mode delay using Wentzel-Kramers-Brillouin (WKB) or not	Effective index diff.*			[Effective index diff., Wentzel-Kramers-Brillouin, Variation principle]
LP(m,n) max. The maximum LP mode index value when the mode solver is searching for modes	20, 10			[0, 1000]
Min. signal power The minimum signal power for a given mode. Modes will not be attached to signals with power lower than this value.	-100	dBm		[-1e+100, 0]
Mode solver	LP			LP, OptiFiber
Solver tolerance	1e-014			[1e-100, 0.1]
Solver step size	1.5e-005			[1e-100, 1]
Solver sample rate	25	1/um		[10, 1000]
Generate overfilled launch Defines whether to generate an overfilled fiber launch or not	NO			[YES, NO]
Generate report Defines whether to generate a report with the attributes of the fiber	YES			[YES, NO]
Report The summary of fiber attributes, including number of modes, coupling coefficients and delays				

Graphs

Name and description	Default value	Default unit	Units	Value range
Calculate graphs Defines whether to calculate graphs or not during simulation	NO			[YES, NO]

Calculate graphs on OK Defines whether to calculate graphs after clicking on the component properties OK button	NO			[YES, NO]
Format Defines whether to calculate the graphs using rectangular or polar format	Power Phase			[Power Phase, Real Imag]
Wavelength The reference wavelength for the graphs	820	nm		[100, 2000]
LP(m,n) The LP mode index for the individual radial and mode profile graphs	0, 1			[0, 1000]
Radial graphs Defines whether to calculate the radial graphs	YES			[YES, NO]
Mode number graphs Defines whether to calculate the mode number graphs	YES			[YES, NO]
Spatial profile graphs Defines whether to calculate the spatial profile graphs	NO			[YES, NO]
Spatial overfilled graphs Defines whether to calculate the spatial overfilled graphs	NO			[YES, NO]
Fiber bandwidth cut-off Defines the point at which to calculate the fiber bandwidth-distance product (MHz-km)	3	dB	dB	[0, 100]

Simulation

Name and description	Default value	Default unit	Units	Value range
Enabled Determines whether or not the component is enabled	YES			[YES, NO]

Graphs

Name and description	X Title	Y Title
Refractive index profile (reference wavelength)	Radius (m)	Refractive index
Refractive index profile (test wavelength)	Radius (m)	Refractive index
LP[m,n] index array - m	Mode number	m

LP[m,n] index array - n	Mode number	n
Group delay	Mode number	Group delay (ps/km)
Group delay relative	Mode number	Group delay relative (ps/km)
Effective index	Mode number	Effective index
Fiber transfer function	Frequency (GHz)	Abs (Transfer function) (dB)
Radial profile - individual a	Radius (m)	Intensity
Radial profile - individual b	Radius (m)	Phase (rad)
Spatial profile - individual a	X (m)	Y (m)
Spatial profile - individual b	X (m)	Y (m)
Spatial profile - overfilled a	X (m)	Y (m)
Spatial profile - overfilled b	X (m)	Y (m)
Modal power distribution	Mode number	Power coupling

Results

Name and description	Units
Highest index in profile @ reference wavelength	
Lowest index in profile @ reference wavelength	
Refractive index contrast @ reference wavelength	%
Highest index in profile @ solver wavelength	
Lowest index in profile @ solver wavelength	
Refractive index contrast @ solver wavelength	%
Refractive index: Base (solver wavelength)	
Refractive index: Dopant+ (solver wavelength)	

Refractive index: Dopant- (solver wavelength)	
Sellmeier amplitude A(1) - Base	
Sellmeier resonance L(1) - Base	micron
Sellmeier amplitude A(2) - Base	
Sellmeier resonance L(2) - Base	micron
Sellmeier amplitude A(3) - Base	
Sellmeier resonance L(3) - Base	micron
Sellmeier amplitude A(1) - Dopant+	
Sellmeier resonance L(1) - Dopant+	micron
Sellmeier amplitude A(2) - Dopant+	
Sellmeier resonance L(2) - Dopant+	micron
Sellmeier amplitude A(3) - Dopant+	
Sellmeier resonance L(3) - Dopant+	micron
Sellmeier amplitude A(1) - Dopant-	
Sellmeier resonance L(1) - Dopant-	micron
Sellmeier amplitude A(2) - Dopant-	
Sellmeier resonance L(2) - Dopant-	micron
Sellmeier amplitude A(3) - Dopant-	
Sellmeier resonance L(3) - Dopant-	micron
Sellmeier amplitude A(1) - Dopant-	
Bandwidth	MHz-km

Technical background

This component is a general-purpose multimode fiber with a user-defined or alpha profile index. The user should provide the fiber refractive index as an input file.

The main result of the fiber calculation is the spatial profile, coupling coefficients and the time delay for each mode. The final solution for the output field of the combined temporal and spatial properties of the fiber for *N* number of modes is:

$$E_{out}(r,\phi,t) = \sum_{i=1}^{N}[c_i E_{in}(t-\tau_i)]E_i(r,\phi) \qquad (1)$$

where E_{in} is the signal input field, c_i is the coupling coefficient between the fiber modes and the spatial profile if the input field and E_i is the fiber mode for each index *i*. If the power of $(c_i.E_{in})$ is below the parameter *Min. signal power,* the signal *i* is discarded.

The component has a numerical mode solver that will calculate the *LP(m,n)* modes and the propagation constants. The parameter *LP(m,n)* max. defines the maximum order for the radial and azimuthal indexes *m* and *n* when searching for fiber modes. The signal center frequency for the mode solver depends on the center frequency of the input signal. The user can force the mode solver to work at a user defined wavelength by enabling parameter User defined wavelength.

The parameter *OptiFiber file format* defined whether the refractive index file was generated by Optiwave OptiFiber[2] (or *Fiber_CAD*) software tool. The refractive index file format is a list with the radial position from the center of the fiber to the clad, and the real value of the refractive index. The radial position should be provided in microns:

Figure 1 File with fiber profile, radius (first column) should be given in microns

```
2.500000e-001 1.414200e+000
5.000000e-001 1.414197e+000
7.500000e-001 1.414191e+000
1.000000e+000 1.414183e+000
1.250000e+000 1.414171e+000
1.500000e+000 1.414157e+000
1.750000e+000 1.414140e+000
2.000000e+000 1.414120e+000
2.250000e+000 1.414098e+000
2.500000e+000 1.414072e+000
2.750000e+000 1.414044e+000
3.000000e+000 1.414013e+000
3.250000e+000 1.413979e+000
3.500000e+000 1.413942e+000
3.750000e+000 1.413903e+000
4.000000e+000 1.413860e+000
4.250000e+000 1.413815e+000
4.500000e+000 1.413767e+000
4.750000e+000 1.413716e+000
5.000000e+000 1.413662e+000
.
.
.
```

IMPORTANT: the first radial position should be different from zero.

If the OptiFiber format is enabled, the file should also include the header and the number of radial points (Figure 2).

Figure 2 File with fiber profile using OptiFiber format, radius (first column) should be given in microns

```
FIBERCAD
101
2.500000e-001 1.414200e+000
5.000000e-001 1.414197e+000
7.500000e-001 1.414191e+000
1.000000e+000 1.414183e+000
1.250000e+000 1.414171e+000
1.500000e+000 1.414157e+000
1.750000e+000 1.414140e+000
2.000000e+000 1.414120e+000
2.250000e+000 1.414098e+000
2.500000e+000 1.414072e+000
2.750000e+000 1.414044e+000
3.000000e+000 1.414013e+000
3.250000e+000 1.413979e+000
3.500000e+000 1.413942e+000
3.750000e+000 1.413903e+000
4.000000e+000 1.413860e+000
4.250000e+000 1.413815e+000
4.500000e+000 1.413767e+000
4.750000e+000 1.413716e+000
5.000000e+000 1.413662e+000
.
.
.
```

There are two main results of this calculation, the time delay associated with each mode, and the coupling coefficient between the input spatial fields and each of the spatial fiber modes. Additionally, the user can provide a file with the modal attenuation. The modal attenuation file format is a list with the *m* and *n* mode index and the attenuation in dB/km for polarizations X and Y:

Figure 3 Modal attenuation file

```
0     1     0       0
0     2     500000  500000
1     1     2000    2000
-1    1     2000    2000
```

For illustration purposes, in the file above, 4 modes will be attenuated: $LP_{0,1}$, $LP_{0,2}$, and $LP_{-1,1}$. The first mode will be attenuated by 0 dB/km for both polarizations. The next mode will be attenuated by 500000 dB/Km. The remaining two modes will be attenuated by 2000 dB/km.

The propagation constant β is used to calculate the time delay per mode. There are three options to calculate the delay. The first option uses the Wentzel-Kramers-Brillouin method:

$$\tau_{m,n} = \frac{Ln_1}{2c}\left(\frac{n_1}{N_{eff_{m,n}}} - \frac{N_{eff_{m,n}}}{n_1}\right)$$

$$N_{eff_{m,n}} = \frac{\beta_{m,n}}{k_0} \qquad (2)$$

$$k = \frac{2\pi}{\lambda_0}$$

where n_1 is the peak value of the refractive index, L is the fiber length, c is the speed of light and λ_0 is the center wavelength.

The second method is to apply the derivative of the effective index directly to calculate the delay:

$$\tau_{mn} = \frac{L}{c}\left(N_{eff_{mn}} - \lambda_0 \frac{dN_{eff_{mn}}}{d\lambda_0}\right) \quad (3)$$

The derivative method includes the material dispersion in the calculation if the material properties field is enabled. The following adjustments are applied to the fiber refractive index profile:

$$\text{If } n > n_b \text{ then } n_{adj} = \sqrt{n_b^2(\lambda_\Delta) + \frac{n^2(\lambda) - n_b^2(\lambda)}{n_{d+}^2(\lambda) - n_b^2(\lambda)} \times (n_{d+}^2(\lambda_\Delta) - n_b^2(\lambda_\Delta))}$$

$$\text{If } n < n_b \text{ then } n_{adj} = \sqrt{n_b^2(\lambda_\Delta) - \frac{n_b^2(\lambda) - n^2(\lambda)}{n_b^2(\lambda) - n_{d-}^2(\lambda)} \times (n_b^2(\lambda_\Delta) - n_{d-}^2(\lambda_\Delta))}$$

where n_b, n_{d+}, n_{d-} are the Sellmeier refractive indices for the base, dopant plus and dopant minus materials; respectively, λ is the mode solver reference wavelength, and λ_Δ is the offset wavelength (~0.01 nm) used to calculate the modal delay times.

The third method is to apply the variation principle to calculate the delay, avoiding the numerical errors of the derivative:

$$\tau_{m,n} = \frac{\frac{k}{\beta c}\iint N_{n,m}{}^2(x,y)E_i{}^2(x,y)dxdy}{\iint E_i{}^2(x,y)dxdy}$$

The coupling coefficient is calculated according to:

$$c_i = \int_0^{2\pi}\int_0^{\infty} E_{in}(r,\phi)E_i^*(r,\phi)rdrd\phi \quad (8)$$

where E_i is the spatial profile for each *m,n* mode, including the *sin* and *cosine* factors, and E_{in} is the spatial input field.

The user can also generate a constant mode power distribution (MPD). In this case the coefficients will be constant. Enabling the parameter *Generate overfilled launch* can generate an overfilled launch mode.

After the calculation, the parameter *Report* will have a list of the modes, coupling coefficients, and delays for each mode and polarization.

Another advanced feature of this model is the graph calculations.

By enabling the parameter *Calculate graphs*, the user can see the results from the analytical mode solver. The results can include the mode index number for the calculated modes, the effective index, delays, power coupling, the refractive index profile, and spatial and radial profiles for the individual and overfilled mode.

The fiber model also includes the chromatic dispersion effects. If chromatic dispersion is enabled, the user can specify the value of the dispersion and dispersion slope, as well as Sellmeier approximations.

The parameter *Use Sellmeier approximations* defines whether to calculate dispersion and slope from the Sellmeier approximations[3]:

$$D = \frac{S_0}{4}\left(\lambda_r - \frac{\lambda_0^4}{\lambda_r^3}\right) \quad (9)$$

$$S = \frac{S_0}{4}\left(1 + 3\frac{\lambda_0^4}{\lambda_r^4}\right) \quad (10)$$

Material parameters

The Material Properties tab allows the specification of the material dispersion model based on the Sellmeier theory. The fiber uses six Sellmeier coefficients, three wavelengths and three amplitudes, to define the dispersion curve.

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

Where n is the wavelength-dependent refractive index, A_1, A_2, and A_3 are the Sellmeier amplitudes, and λ_1, λ_2 and λ_3 are the Sellmeier resonance wavelengths.

The material properties are internally defined based on the type of material selected (see Table 2, "Sellmeier coefficients for various host and dopant materials," on page 460) or, when "User defined" is selected, by a file containing the Sellmeier coefficients for that material. The file format must be similar to the following example

Figure 4 Material properties file

```
0.0684043 0.6961663
0.1162414 0.4079426
9.896161  0.897479
```

Where the first column presents the wavelength Sellmeier coefficients and the second one the Sellmeier amplitude coefficients.

Table 2 Sellmeier coefficients for various host and dopant materials

Material							

	A_1	A_2	A_3	$Lambda_1$	$Lambda_2$	$Lambda_3$
1% fluoride doped silica	0.69325	0.3972	0.86008	0.06723987	0.11714009	9.7760984
3% B_20_3 doped silica	0.6935408	0.4052977	0.9111432	0.0717021;	0.1256396	9.896154
3.1% Germania doped silica	0.7028554	0.4146307;	0.897454;	0.0727723	0.11430853;	9.8961609;
9.1% P_2O_5 doped silica	0.91914	0.67072	0.5696	0.11921	0.00256	6.50697
GeO_2 pure fused	0.80686642	0.71815848	0.85416831	0.06897261	0.1539661	11.841931
P_2O_5 pure	0.91914	0.67072	0.5696	0.11921	0.00256	6.50697
Silica pure	0.6961663	0.4079426	0.897479	0.0684043	0.1162414	9.896161
ZBLAN	1.168	2.77	0.0	0.0954	25	11.841931

Alpha profile

When using the alpha profile the following index profile is used[4]:

$$n(r) = n_{peak} \cdot \left(1 - \Delta \cdot \left[\frac{r}{a}\right]^{\alpha}\right) \qquad \text{for } r < a$$

$$n(r) = n_{peak} \cdot (1 - \Delta) = n_{cladding} \quad \text{for } (r \geq a)$$

where *a* is the core radius, Δ is the index contrast, and α is the alpha profile value

References

[1] A. Ghatak, K. Thyagarajan, Introduction to Fiber Optics, Cambridge University Press, New York, NY, 1998.

[2] OptiFiber 1.5 documentation, Optiwave Corporation, www.optiwave.com.

[3] G.D. Brown, "Bandwidth and Rise Time Calculations for Digital Multimode Fiber-Optic Data Links", Journal of Lightwave Technology, VOL. 10, NO 5, May 1992, pp. 672-678.

[4] Govind P. Agrawal, Fiber-Optic Communication Systems, 4th Edition, Wiley, Hoboken, NJ, 2010.

Notes:

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