WDM Phasar

Technical Background and Tutorials

Phased Array WDM Device Design Software

Version 2.0 for Windows®

Optiwave
DESIGN SOFTWARE

WDM_Phasar

Technical Background and Tutorials

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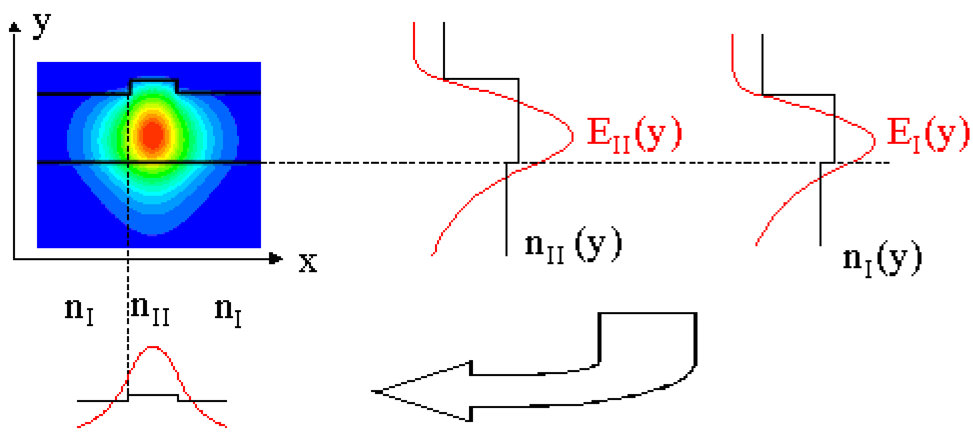
Effective Index method

Among the numerical and approximate methods in waveguide analysis, the effective-index method (EIM) is probably the most popular method for analysing integrated optical devices. The basic idea of the method is to replace the structure found in the transverse plane (a rectangular waveguide or rib waveguide) by an equivalent one dimensional slab with effective refractive indices. This transformation reduces the two-dimensional transverse cross-section of the device refractive index to a one-dimensional one. Therefore, there are two steps in the Effective Index Method (EIM). The first step is to find the fundamental modal index of the waveguide along the y-axis (perpendicular to the propagation) and the second is to analyse the resulting 2D structure (x axis and the propagation direction z) using the 2D Beam Propagation Method (BPM). The following diagram illustrates these two steps.

Figure 1 Effective Index Method — two steps



Note that the sense of the principal direction changes from the first to the second step. Therefore the simulations for the first and second steps should be done with the opposite polarization (TE or TM). The following table describes the polarization condition in the EIM, depending on the initial polarization.

IF initial polarization state	TE	TM
THEN		
Effective index: Step 1 (modal) along Y	TE	TM
Effective index: Step 2 (BPM 2D) in X–Z	TM	TE

As only the solutions for slab waveguides are required, the EIM is significantly more efficient in terms of CPU time than the full 3D methods that solve the waveguide structure directly. The effective index method works very well for weakly guiding devices and when the modes of the waveguides are in the far-from-cutoff region. The effective index method can be applied both for mode solving and beam propagation simulations. Among the most popular introductory references regarding the EIM are:

[1] Marcuse, D., "Theory of Dielectric Optical Waveguides, Second Edition," Boston, Academic Press, 1991.

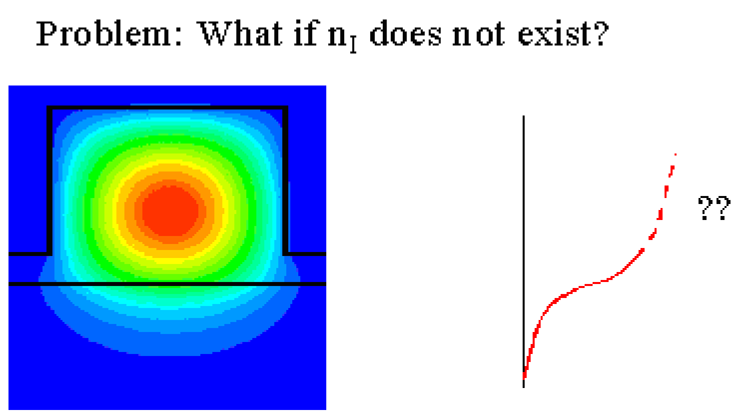
[2] Chiang, K. S., "Review of numerical and approximate methods for the modal analysis of general optical dielectric waveguides," Optical and Quantum Electronics, vol. 26, 1994, pp. S113-S134, Sections 7.2 and 7.3.

The WDM_Phasar software package is based on the EIM. The program combines the advantages of the 2D Beam Propagation Method (BPM), mode solving, and waveguide bend loss simulations in a comprehensive way to analyse Phased Array Wavelength Division (De)Multiplexers (Phasar Arrays).

Weighted Index Method

The effective index method is useful for reducing the complexity of the calculations by eliminating one of the transverse axes. However, a problem occurs when the conditions in the cladding do not allow a guided mode. This condition is likely to occur in buried waveguides, or rib waveguides where the majority of the light energy is confined to the rib. In these cases, matching the boundary conditions of the mode profile in the cladding substrate will make it impossible to match the boundary conditions in the cover layer, as illustrated below:

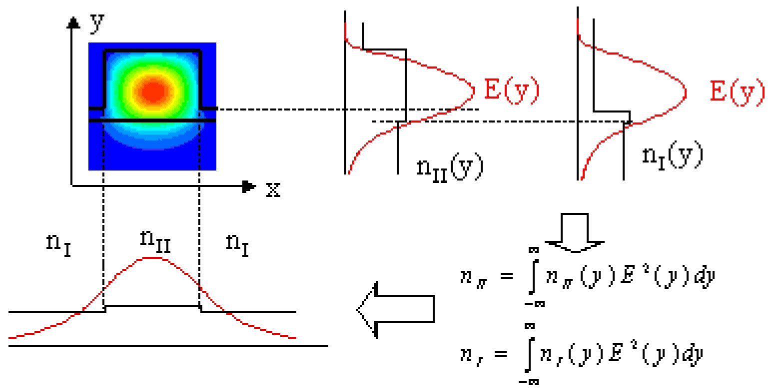
Figure 2 Problem — what if n_I does not exist?



The whole idea of EIM is to match these vertical modes at the boundaries of the rib, so the simple implementation of the EIM will fail if no such vertical mode exists in the cladding layers outside the rib.

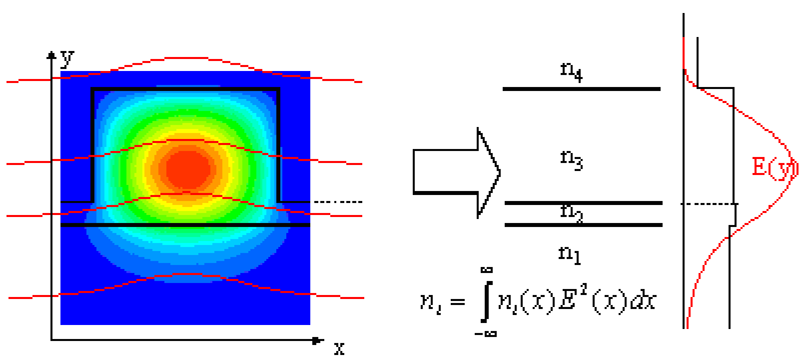
In the WIM (Weighted Index Method), the same basic idea of the EIM is used: to replace the rectangular structure by an equivalent slab. The difference is in the way the effective indices of the slab are defined. In the WIM, a one dimensional field profile is found from the centre line of the rib. This profile is then used as a weighting function applied to the refractive index distribution found outside the rib. These two slab indices are then used in an equivalent horizontal index distribution to make up a horizontal field distribution. This first step of the WIM is illustrated below.

Figure 3 WIM — first step



The WIM is an iterative method. At the end of the steps described above, the horizontal field distribution can be used as a weighting function for the horizontal layers in the rib. This leads to a new definition of the vertical layers, different from the values on the centre line which were used in the first step. Using these new values for the horizontal layers, a new vertical field distribution is defined, which will define new weights for the vertical (effective slab) layers, as shown below

Figure 4 New weights for vertical layers



In this way a loop begins, and after a few iterations the loop converges. It is the values of the indices after convergence that are used in the WIM.

The utility of EIM and WIM for WDM_Phasar is that they implement the basic idea of the effective index (to replace the 2D picture of the transverse plane with a 1D model). The advantage of the WIM over EIM is that WIM may be used for a greater range of waveguide structures. Furthermore, in the case where the light energy is more confined to the rib, the numerical value of the modal index calculated by WIM is more accurate. See the following references for more details on WIM

References

[1] Kendall, P.C. et al, "Theory for calculating approximate values for the propagation constants of an optical rib waveguide by weighting the refractive indices", IEE Proceedings, 134(8), p699-702 (1987)

[2] Benson, T.M. and Kendal, P.C., "Variational techniques including effective and weighted index methods", in Progress in Electromagnetics Research, No. 10, (EMW Publishing, Cambridge, Massachusetts, USA, 1995)

Notes

BPM 2D

The EIM reduces real three-dimensional (3D) waveguide devices like phasar arrays to two-dimensional (2D) structures. The BPM solving engine simulates the light propagation in the 2D device. The simulation process is a step-by-step propagation in the direction defined as the propagation direction, Z. Since the geometry of the phasars (especially the Dense WDM devices) can be very complicated, a global propagation direction cannot be defined. Moreover, the BPM algorithms have limitations in the analysis of waveguides whose path has a large tilt angle with respect to the propagation direction. Therefore, the BPM has been used to simulate only some parts of phasars. BPM is still used in the slab (Free Propagation) regions, the input/output channels and the array waveguides in the sections where the coupling cannot be neglected.

In the BPM simulations, we consider only monochromatic light that is described by an electromagnetic wave with a single frequency. The optical waveguides and waveguide devices are defined by a spatial distribution of the refractive index.

The propagation of the coherent field E(x,z) is governed by the 2D Helmholtz equation. In actual simulations, we use paraxial or wide-angle approximations to the Helmholtz equation.

The following is the paraxial Fresnel equation that is an approximation of the Helmholtz equation, valid for small angles of propagation:

$$\frac{\partial}{\partial z}E(x,z) = \frac{i}{2kn_{ref}}PE(x,z) \tag{1}$$

The Fresnel equation is expressed with the help of the paraxial propagator P. This propagator P can be formulated as scalar, or vector with a reference to polarization corrections.

The paraxial scalar propagator in 2D is:

$$PE(x,z) = \frac{\partial^2}{\partial x^2}E(x,z) + k^2(n^2 - n_{ref}^2)E(x,z) \tag{2}$$

where k is the vacuum wavenumber, n (x,z) is the refractive index distribution, and n_{ref} is the reference index.

The following is a vectorial propagator, which has polarization corrections due to dielectric interfaces:

$$PE(x,z) = \frac{\partial^2}{\partial x^2}E(x,z) + k^2(n^2 - n_{ref}^2)E(x,z) + \frac{\partial}{\partial x}\left[\frac{1}{n^2}\frac{\partial}{\partial x}(n^2 E(x,z))\right] \tag{3}$$

For wide angles of propagation, the model is improved by adding corrections based on Padé approximations. Solvers based on higher Padé approximations also allow for simulations of structures with larger refractive index contrast. The wide-angle equations are built with the help of the propagator P.

The Wide-Angle Padé(1,1) propagation equation in 2D is the following:

$$\frac{\partial}{\partial z}E(x,z) = \frac{i}{2kn_{ref}}\left[1 + \frac{P}{4k^2 n_{ref}^2}\right]^{-1} PE(x,z) \tag{4}$$

The Wide-Angle Padé(2,2) propagation equation in 2D is the following:

$$\frac{\partial}{\partial z}E(x,z) = i\left[\frac{3P}{4k^2 n_{ref}^2} + \frac{P^2}{16k^4 n_{ref}^4}\right]^{-1}\left[\frac{1}{2kn_{ref}} + \frac{P}{4k^3 n_{ref}^3}\right]^{-1} PE(x,z) \tag{5}$$

Finite-Difference Method

The above listed paraxial Fresnel equation and the Wide-Angle Padé propagation equations can be solved using different numerical approaches. Our BPM was built in the frame of the Finite-Difference Method (FDM). The refractive index distribution of the device and the propagating optical field should be discretized in both transverse and longitudinal directions. A central difference numerical scheme is used to represent the derivatives with respect the transverse co-ordinate x and a Crank-Nicolson method is employed for the propagation. The propagation is performed in a step-by-step fashion.

In the transverse direction, the solution domain is bounded by the mesh window. In the propagation direction, the domain is limited by start and end propagation distances. We impose the optical field at the start position, while the BPM finds the field at other distances. Boundary conditions are used for finding the field at the transverse boundaries. A physical condition that allows the optical field to radiate out from the computational domain is called the transparent boundary condition, or TBC.

References

[1] Yevick, D., "A Guide to Electric Field Propagation Techniques for Guided-Wave Optics", Optical and Quantum Electronics, vol. 26, 1994, pp. S185-S197.

[2] Hadley, G. R., "Wide-angle beam propagation using Padé approximant operators", Optics Letters, vol. 17, No. 20, 1992, pp. 1426-1428.

[3] Hadley, G. R., "Transparent Boundary condition for the beam propagation method", IEEE J. Quantum Electronics, vol. 28, No. 1, 1992, pp. 363-370.

Notes

Slab Waveguide Modes

The TE and TM modes of a slab waveguide can be determined by solving the eigenvalue equation for the corresponding polarization. Later the nonzero-field component distributions can be found. The slab waveguide modes are the modes of the one-dimensional structure obtained via the Effective Index Method. More details about the slab mode solving are given in the chapter describing the Wizard Tool features.

Phase Accumulation

The phase accumulation is an important process responsible for the tilt of the phase front in the array of waveguides. The light signal at the end of the k-th waveguide in the array can be described by the complex amplitude A^k:

$$A^k = A_o^k \exp[-i\varphi_o + i\beta(f)L_k] \tag{6}$$

Where A_o^k *is the initial signal amplitude,* φ_o *is the initial phase,* L_k *is the length of the* k^{-th} *waveguide, and* $\beta(f)$ *is the modal index of the propagation (TE or TM mode).*

The neighbour waveguides in the array have a certain length difference designed in such a way to produce a phase difference which is some multiple of 2π for the central frequency f_c:

$$\beta(f_c)L_{k+1} = \beta(f_c)(L_k + \Delta L) = \beta(f_c)L_k + 2\pi m \tag{7}$$

where m is the order of the array. Therefore, after propagation through the array, there will be no tilt of the phase front.

If the signal frequency (f) is different from the central one f_c, there will be a frequency dependent phase accumulation $\psi(f)$ for each waveguide from the array:

$$\beta(f)L_{k+1} = \beta(f)(L_k + \Delta L) = \beta(f)L_k + 2\pi m + \psi(f) \tag{8}$$

After propagation through the array, the phase difference between the signals in the array will result in a frequency (wavelength) dependent tilt of the phase front before the propagation starts in the output free propagation region. This tilt will be responsible for the shift of the position of the signal in the focal plane as the wavelength changes.

Power Overlap Integral

The power overlap integrals provide very important information. First, they show how much power from a propagating light signal with any distribution can be coupled to a given guided mode of a waveguide. Second, the overlap integrals provide important information about the cross-talk level. More details about the Power Overlap Integral are given in the section describing the cross-talk level estimation in the Chapter regarding the Wizard Tool.

Waveguide Bend Loss

When guided light goes around a bend, the phase front will need to move more quickly at the outside of the bend than the inside. Following this trend to greater radii will lead to a point where the phase velocity of the guided mode is equal to the velocity of unguided light in the substrate. The matching of velocities here makes the opportunity for the guided light to couple to unbound radiation modes. This mode conversion is the physical origin of optical loss on bent waveguides. Since a typical Dense Wavelength Division (De) Multiplexer with Phased Array geometry employs a number of waveguides with an arc shape, the simulation of the bend loss is an important part of the device analysis. There are many methods to evaluate the bend loss, which include the BPM with or without conformal mapping of the refractive index. The method implemented in the WDM_Phasar simulator is a trade-off approach, which combines very high simulation speed with a reasonable accuracy. This method has been described in

[1] Marcuse D., "Bending Losses of Asymmetric Slab Waveguides", The Bell System Technical Journal, vol. 50, (1971), pp. 2551-2563.

According to the above-listed reference, if an optical signal with input amplitude A_{in} propagates in a bend with radius of curvature R and length l, the output amplitude A_{out} will be given by:

$$A_{out} = A_{in} \exp(-\alpha l) \tag{9}$$

The loss coefficient a can be found from the following expression:

$$\alpha = \frac{\gamma s^2 \exp(\gamma d) \exp(-U)}{k^2 \beta (n_{co}^2 - n_{cl}^2)(d + 2/\gamma)} \tag{10}$$

Where:

$$U = \left\{ \frac{\beta}{\gamma} \ln\left[\frac{1 + \frac{\gamma}{\beta}}{1 - \frac{\gamma}{\beta}}\right] - 2 \right\} \gamma R$$

(11)

$$\gamma = (\beta^2 - n_{cl}^2 k^2)^{1/2}$$

(12)

$$s = (n_{co}^2 k^2 - \beta^2)^{1/2}$$

(13)

The rest of the parameters are:

d	waveguide width
n_{co}	core effective index
n_{cl}	cladding effective index
β	propogation constant of the unbent slab
k	wavenumber
R	radius of curvature of the bend

The way to evaluate the bend loss described above is applicable only when both conditions listed below are fulfilled:

(14)

$$\beta < n_{cl}k\left(1 + \frac{d}{2R}\right)$$

$$\beta > n_{cl}k\left(1 - \frac{d}{2R}\right)$$

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Propagation constant of bent waveguides

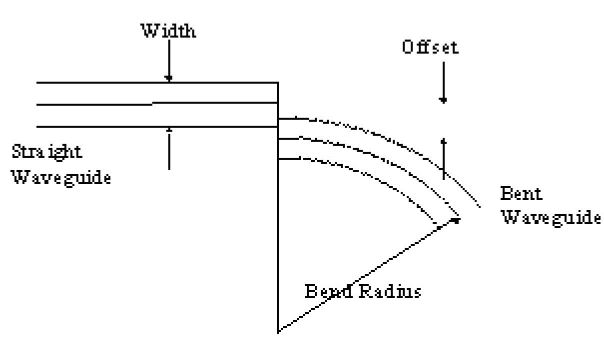
As mentioned in the previous section, light going around a bend must have a local phase velocity that increases with the radius. It is by advancing the phase at the outer radius that the direction of the propagation is modified. A suitable model of this situation is to compare with a straight waveguide which has a linear increase of refractive index superimposed on the waveguide refractive index profile. This perturbation to the refractive index distribution distorts the optical wave, and changes the propagation constant slightly. Since phasar devices use long bent waveguides having various bend radii, this small change in propagation constant might sometimes be significant to the final phase presented to the output coupler after the light passes through the phasar array. Therefore the change in propagation constant due to bending is included in WDM_Phasar. The change is estimated by a second order perturbation theory as described in the following paper:

[1] Garth, S.J., "Modes on a bent optical waveguide", IEE Proceedings, 134(4) Part J, p221-229 (1987)

Optimum Offset

In a bent optical waveguide, the outside of the bend has the higher phase velocity. Therefore in the perturbed index model of a bent optical waveguide, the side corresponding to the outside of the bend must have a higher index of refraction. The effect on the optical field is to shift the field toward the outside of the bend, in a way similar to the change in electronic wavefunction in response to the Stark Effect. The mismatch of the field shapes can lead to losses at the junction between straight and curved waveguides. These losses can be minimised by introducing an offset at these junctions, as shown below:

Figure 5 Introducing an offset at junctions



The value of the optimum offset is estimated by finding the maximum of the perturbed field. Within the approximations used in WDM_Phasar, waveguides set with this optimum offset have negligible losses at the junctions.

Bent/Straight Junction Loss

In the case where the optimum offset is not used, the waveguides are continuous across the bent/straight waveguide junctions, and some small loss can be expected from the mismatch of the shapes of the modal fields. To the approximation used in WDM_Phasar, the field of the bent waveguide is the same as the straight one, but only displaced according to the Optimum Offset as described in the above section. The calculation of the resulting loss is then the same as the calculation of crosstalk using overlap integrals, and WDM_Phasar estimates the junction loss in the same way.

Wizard Tool

The idea behind the Wizard is to provide a tool which will compute the basic geometric parameters of the Phasar, based on some requirements for the performance of the device. The most important requirements are: the maximum cross-talk level, maximum loss, channel spacing, and level of the transmitted power.

The evaluator consists of the following main modules:

- 2D Mode solving
- Crosstalk level
- Free propogation region
- Array waveguide length increment and order of the array
- Aperture width and the number of array waveguides

2D Mode solving

The fundamental TE and TM modes of a symmetric slab should be found first. This will determine the input/output waveguide minimum separation as well as the separation of the array waveguides. In this way a predefined maximum cross-talk level is ensured.

The eigenvalue equations for the TE and TM modes of a symmetric slab are, respectively:

$$\tan(ud/2) = \gamma/u$$

$$\tan(ud/2) = \frac{n_1^2}{n_2^2}\gamma/u \tag{15}$$

where the parameters involved are:

d	waveguide width
n_1	core effective index
n_2	cladding effective index

$$u = \frac{2\pi}{\lambda}(n_1^2 - n_{eff}^2)^{1/2}$$

(16)

$$\gamma = \frac{2\pi}{\lambda}(n_{eff}^2 - n_2^2)^{1/2}$$

(17)

n_{eff} modal (TE or TM) index

Cross-talk level

Using the modal fields and a predefined maximum crosstalk level (CT_{MAX}), the minimum separation between the centres of two neighbouring input/output channels (d_r) and two array waveguides (d_a) can be estimated. The crosstalk level in dB is related to the power overlap integral P_{over}:

$$CT(dB) = 10\log(P_{over})$$

(18)

The power overlap integral by itself can be defined as:

$$P_{over}(ds) = \frac{\left\{0.5\left[\int_{A\infty}(\vec{E}_1^* \times \vec{H}_2 + \vec{E}_2 \times \vec{H}_1^*)dA\right]\right\}^2}{\int_{A\infty}(\vec{E}_1 \times \vec{H}_1^* \cdot \vec{z})dA\int_{A\infty}(\vec{E}_2 \times \vec{H}_2^* \cdot \vec{z})dA}$$

(19)

where ds is the separation (d_r or d_a), E_1 and H_1 are transverse electric and magnetic components for the fundamental mode of the first waveguide that are different from zero (E_y and H_x for TE modes, and E_x and H_y for TM modes). E_2 and H_2 are the corresponding components for the fundamental mode of the second waveguide.

In the case of equivalent waveguides, the following relations are valid:

$$\vec{E}_2(x,ds) = \vec{E}_1(x+ds)$$
$$\vec{H}_2(x,ds) = \vec{H}_1(x+ds)$$

(20)

Based on the above formulae, one can find the minimum distance of separation ds_{min}, which will ensure a maximum crosstalk level CT_{MAX}.

Free propagation region

The minimum length of the free propagation region R_a^{min} can be estimated from the required value of the maximum acceptable access loss for the outer channel (or non-uniformity L_u).

$$R_a^{min} = \frac{s_{max}}{\theta_{max}}$$

(21)

where s_{max} is the co-ordinate of the outer receiver defined by:

$$s_{max} = \frac{N}{2} d_r$$

(22)

where N stands for the number of the output channels, and d_r is the separation distance between the two neighbouring channels defined above.

The maximum acceptable dispersion angle θ_{max} can be found using the Gaussian far-field approximation of the modal field.

$$\theta_{max} \approx \sqrt{\frac{1}{8.7} L_u \theta_o^2}$$

(23)

θ_o is the width of the fundamental modal field of a single waveguide from the phased array given by:

$$\theta_o = \frac{\lambda}{n_{FPR} w_e \sqrt{2\pi}} \tag{24}$$

The following parameters are involved in the formula above.

n_{FPR}	effective index of the free propagation region
w_e	effective width of the modal field given by the following expression:

$$w_e = \frac{\int_{-\infty}^{+\infty} E(x)^2 dx}{E_{max}^2} \tag{25}$$

where E(x) is the distribution of the modal field.

Array waveguide length increment and order of the array

The array waveguide length increment ΔL can be calculated based on the requirements for the dispersion D and the central operating frequency f_c .

The length increment is given by:

$$\Delta L = \frac{D f_c n_{FPR} \Delta\alpha}{\tilde{n}_g} \tag{26}$$

The dispersion $D = ds/df$ is the lateral displacement ds of the focal spot along the image plane per unit frequency change. The required dispersion can be found from the desired channel spacing Δf and the distance between the adjacent channels, d_r, as $D = d_r/\Delta f$.

The divergence angle $\Delta\alpha = d_a / R_a$ is the ratio between the distance between two waveguides d_a and the length of the free propagation region R_a. In the above formula, the group modal index that has been also involved is defined as:

$$\tilde{n} = n_g + f\frac{dn_g}{df} \tag{27}$$

where $n_g(f)$ is the modal index of the fundamental mode that is function of the frequency f.

The array order can be defined as:

$$m = \frac{\Delta L f_c n_g}{c} \tag{28}$$

Aperture width and the number of array waveguides

The angular half width θ_a of the array aperture can be determined from the requirements for the transmission power level assuming an equivalent to a Gaussian far field. The number of array waveguides N_a is then given by:

$$N_a = 2\theta_a R_a / d_a + 1 \tag{29}$$

Performance Calculator

The Performance Calculator is a tool for the fast evaluation of the performance of a WDM device. In a sense it is the opposite of the Wizard Tool, which computes the basic geometrical parameters of the Phasar based on some requirements for the performance of the device. The Performance Calculator, on the other hand, estimates the Phasar performance by taking into account the geometric and material parameters of the device.

Crosstalk level

Using the same approach as the one in the Wizard Tool, we can calculate the modal fields of two neighbouring output channels and find the overlap integral for a given distance of separation d_r. The maximum crosstalk level CT_{MAX} can be determined using Equation 18, where the power overlap integral is defined by Equation 19.

Dispersion

The dispersion D of the array is described as the lateral displacement of the focal spot along the image plane per unit frequency change:

$$D = \frac{ds}{df} = \frac{\tilde{n}_g \Delta L}{f_c n_{FPR} \Delta\alpha} \tag{30}$$

where, $\tilde{n}_g$ is the group modal index defined by Equation 27, $\Delta\alpha$ is the divergence angle, n_{FPR} is the slab effective index of the free propagation region, and f_c is the central frequency.

Phasar and modified Phasar order

The order of the phased array m can be found using Equation 28, and the modified order of the phased array m' can be defined as follows:

$$m' = m\frac{\tilde{n}_g}{n_g} \tag{31}$$

where n_g and $\tilde{n}_g$ are the effective index of the guided mode and the group modal index, respectively.

Nonuniformity

The nonuniformity L_u is defined as the intensity ratio (in dB) between the central channel and the outermost channel. Using a Gaussian-beam approximation for the intensity of the far-field we can find the following dependence for the nonuniformity.

$$L_u = -10.\log[\exp(-2\theta_{max}^2/\theta_0^2)] \tag{32}$$

where the angle corresponding to the outer channel θ_{max} *can be found from Equation 21, and* θ_0 *is the width of the equivalent Gaussian far-field given by Equation 24.*

Among the most detailed studies related to PHASAR design are listed in the references.

References

[1] Meint K. Smit and Cor van Dam, "PHASAR-Based WDM-Devices: Principles, Design and Applications", IEEE Journal of Selected Topics in Quantum Electronics, vol. 2, No. 2, pp. 236-250 (1996).

[2] Cor van Dam, "In P-based polarization independent wavelength demultiplexors", Ph.D. Thesis, Delft University of Technology, The Netherlands, (1997).

WDM_Phasar Tutorials

The best way to learn how to work with WDM_Phasar is to do the Tutorial lessons. By following the step-by-step instructions, you will see how quickly you can become a highly efficient WDM_Phasar user.

Although you can use WDM_Phasar to perform a huge variety of tasks, in these introductory lessons you will learn how do the following.

- Effective index calculations
- Design a WDM device using the Wizard Tool
- Edit the WDM Device geometry
- Use the tools for fast evaluation of the WDM device performance
- Perform a parameter scan
- Run advanced calculations

The WDM_Phasar tutorial contains the following lessons and examples.

Lessons

Examples

Notes

Lesson 1: Effective index calculations

In this lesson, you will use some of the options available in the Effective Index Calculator dialog box. You will learn to edit the default parameters of a multilayer ridge waveguide, to define the calculation parameters, and to perform the effective index calculations.

You will also learn how to calculate the modal indices of the guided modes and how to view the modal field distributions and the refractive index distribution of the waveguide.

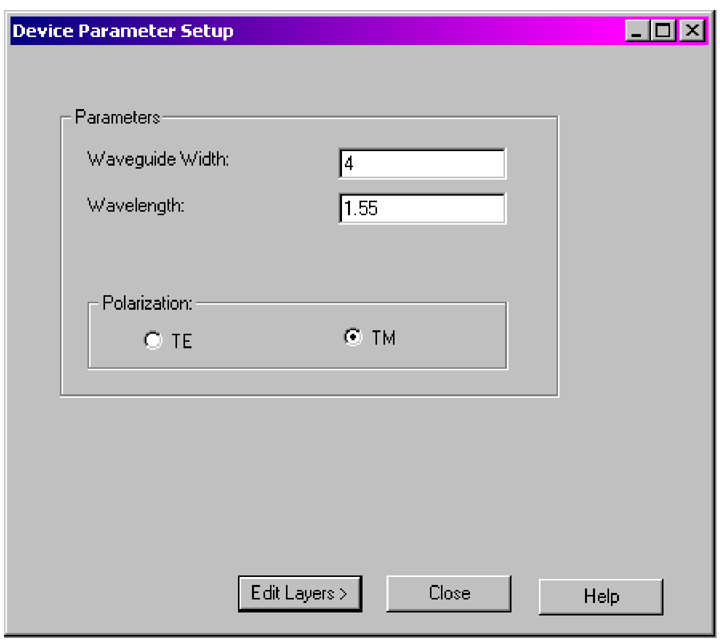
Opening a new project

The first thing you will do is to open a new project. Then, you will define the parameters for the layers of a multilayer ridge waveguide. You will double-click each of the layers (starting from the bottom to the top) and enter data for each layer in the Layer dialog box.

To open a new project, perform the following procedure.

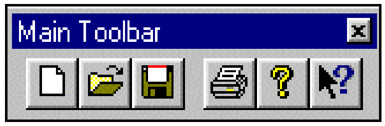
Step	Action
1	From the **File** menu, click **New**. *The Effective Index Calculator starts, and the first box in the sequence (Device Parameter Setup) appears (see Figure 1).*

Figure 1 Device Parameter Setup dialog box



- **TIP:** To open a new project, you can also click the New button (the first button on the **Main Toolbar** shown in Figure 2).

Figure 2 Main Toolbar

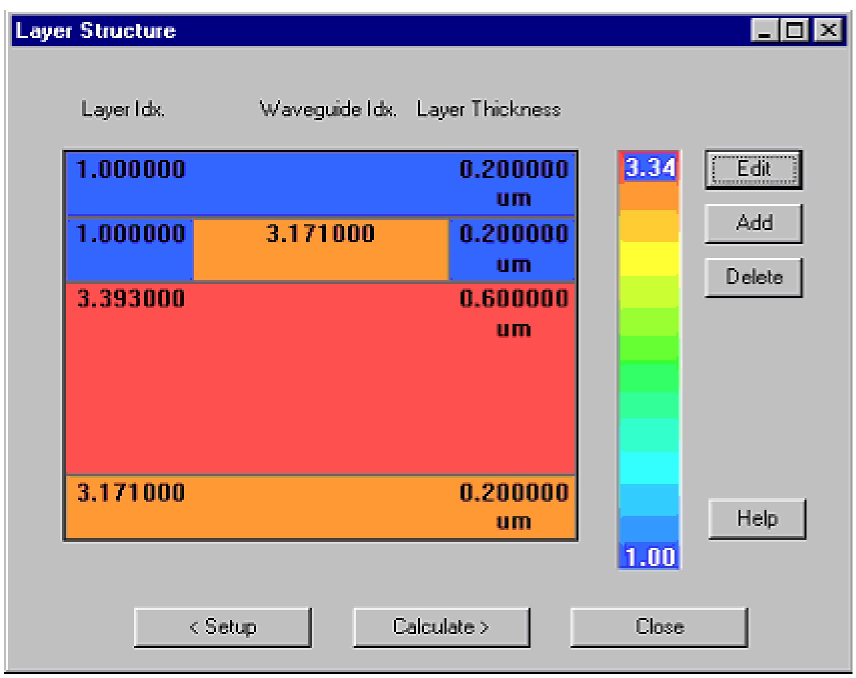


Defining the device parameters

To define the device parameters, perform the following procedure.

Step	Action
1	In the Device Parameters dialog box, type 1.5 in the Waveguide Width box.
2	In the Wavelength box, type 1.55.
3	In the Polarization section, enable the TE button.
4	Click the Edit Layers button to get to the next dialog box (see Figure 3).

Figure 3 Layer Structure dialog box



This dialog box presents a picture of the cross section (transverse plane) of the waveguide to be used in the phasar array. The substrate is at the bottom, and the superstrate (cover layer) is at the top. The thickness of the top and bottom layer is not important to the calculation, as they are assumed by the calculation engine to extend to infinity. They should be adjusted for the sake of convenient viewing only. The above Layer Structure dialog box shows an example of a rib waveguide.

In the Layer Structure dialog box, the widths and refractive indices of any layer can be changed by first selecting the layer with a single click and then clicking on Edit. (Double clicking on the layer will have the same effect.) Layers can be added or deleted by clicking on the appropriate button. You should modify the above example to model the waveguide you intend to use.

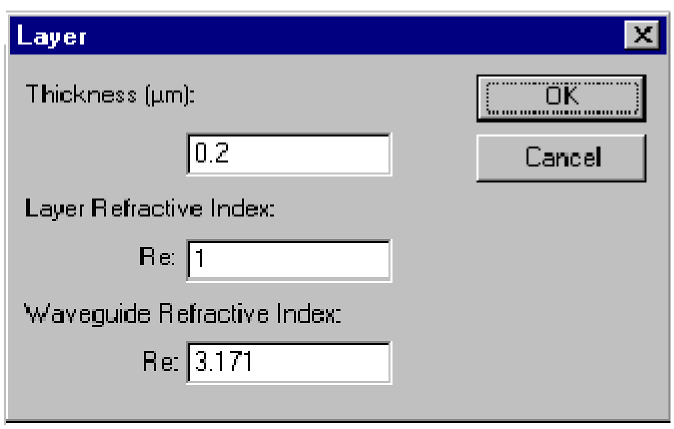
The above Layer Structure dialog box shows the default values supplied by the program. After you modify this structure, the program will automatically create an `.ini` file which will store the new structure you create. The next time you return to WDM_Phasar and run the Effective Index Calculator again, the latest structure you used will appear as the default.

Defining the parameters for a layer

To define parameters for a layer, perform the following procedure.

Step	Action
1	In the Effective Index Calculator dialog box, double-click the layer you want to modify.
2	In the Layer dialog box, type the desired thickness in the Thickness box (see Figure 4).

Figure 4 Layer dialog box



Step	Action
3	In the Layer Refractive Index section, type in the refractive index of the material in this layer. The layer section is the region outside the waveguide. For example, if this layer has been etched away, this value will be 1.00.
4	In the Waveguide Refractive Index section, type the refractive index of the material in the waveguide section in this layer. In the top and bottom layers, the waveguide is not allowed, and for these layers this section will appear grey. If the Waveguide Refractive Index is set equal to the Layer Refractive

Index, the waveguide will disappear in this layer, as in the third layer of the Layer Structure dialog box above.

5 Click the OK button to enter the new values and display the new structure in the Layer Structure dialog box.

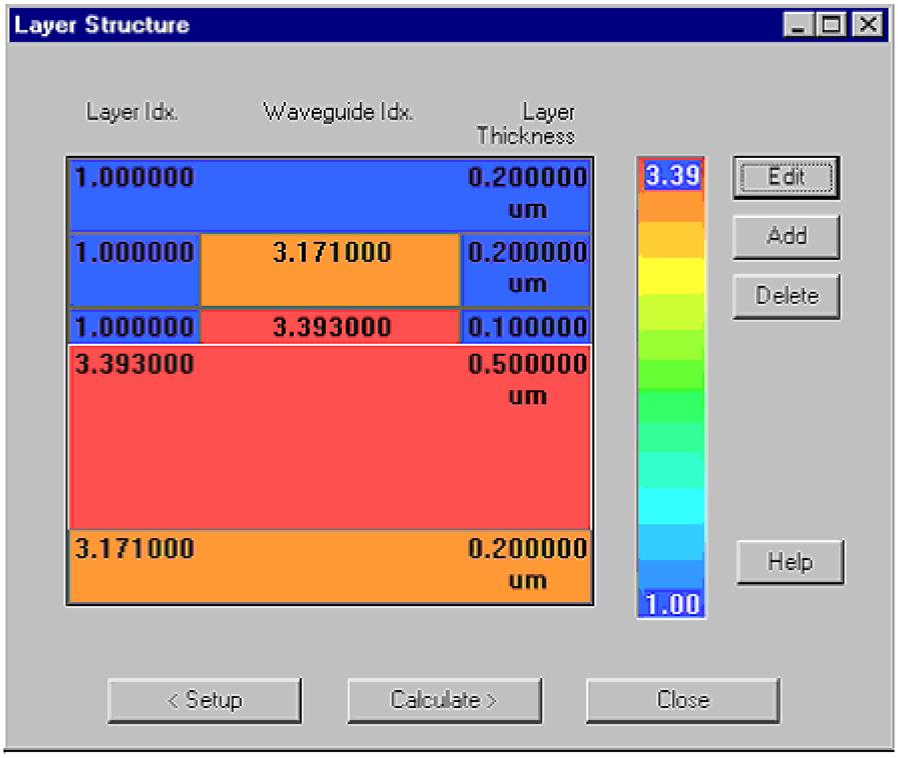
Adding a layer

The Layer Structure dialog box can also be modified by adding and deleting layers. For example, the effect of etching deeper into the wafer can be modelled by making the substrate layer thinner and adding another layer.

To add a layer, perform the following procedure.

Step	Action
1	In the Effective Index Calculator dialog box, click the layer which will be below the new layer.
2	Click Add
3	Click on the new layer, and then on Edit to modify the thickness and indices.
	After making the layer below thinner by 0.1 microns, the structure with the additional etching can be modelled (see Figure 5).

Figure 5 Layer structure with additional etching



Performing effective index simulations

In this step, you will perform effective index simulations using the Weighted Index Method of the waveguide you have designed. They will result in a transformation of the 2D waveguide refractive index into a 1D effective index distribution.

To perform the effective index simulations, perform the following action.

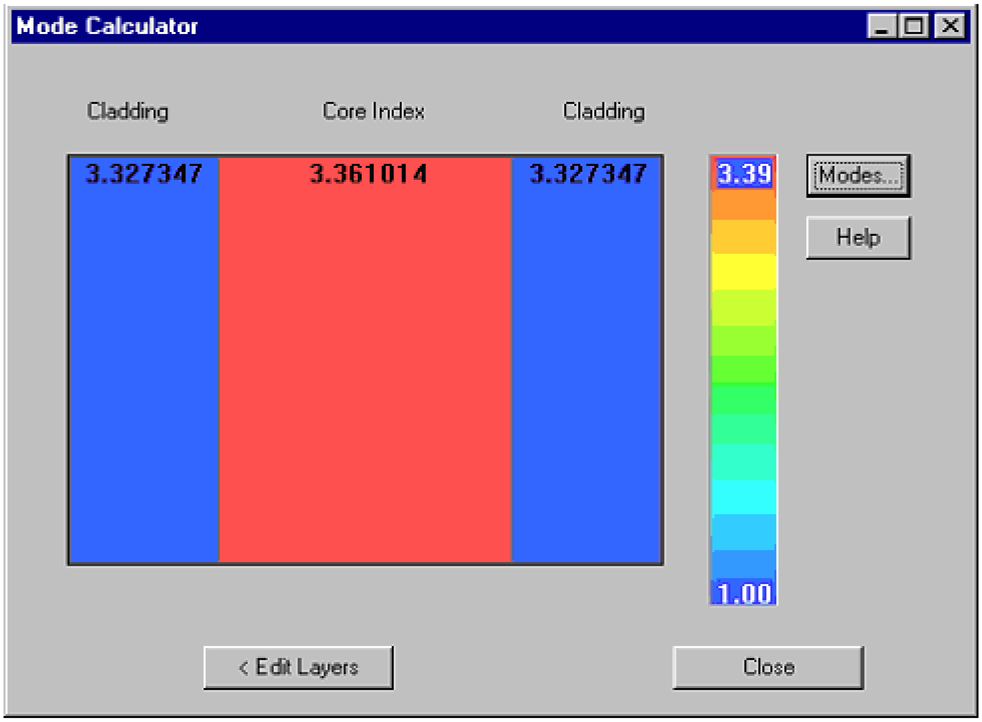
Action

- In the Layer Structure dialog box, click the Calculate button.

  Note: Notice that, after the effective index simulations, the waveguide structure has been transformed to a 1D effective index distribution. The data from the effective index simulation can be used directly in the WDM design as default parameters for the wafer and the waveguide. This means that you can press the Close button and go directly to Step 1 of Lesson 2.

If the structure shown in the first Layer Structure dialog box is used, the equivalent waveguide should look like the one in the picture below. The rib (or buried waveguide structure) is replaced by a symmetric slab guide (see Figure 6).

Figure 6 Waveguide



Showing results of the modal index calculation

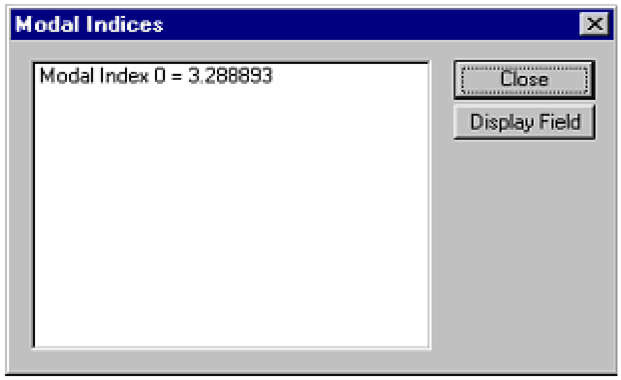
This step will show the result of the modal index calculation using the Weighted Index Method to find all the modes supported by the guiding structure. Then, you will learn how to display the modal field distribution and the refractive index distribution.

To find the modal indices of the guided modes, perform the following action.

Action

- In the Mode Calculator dialog box, click **Modes**.
  The Modal Indices dialog box appears (see Figure 7).

Figure 7 Modal Indices dialog box



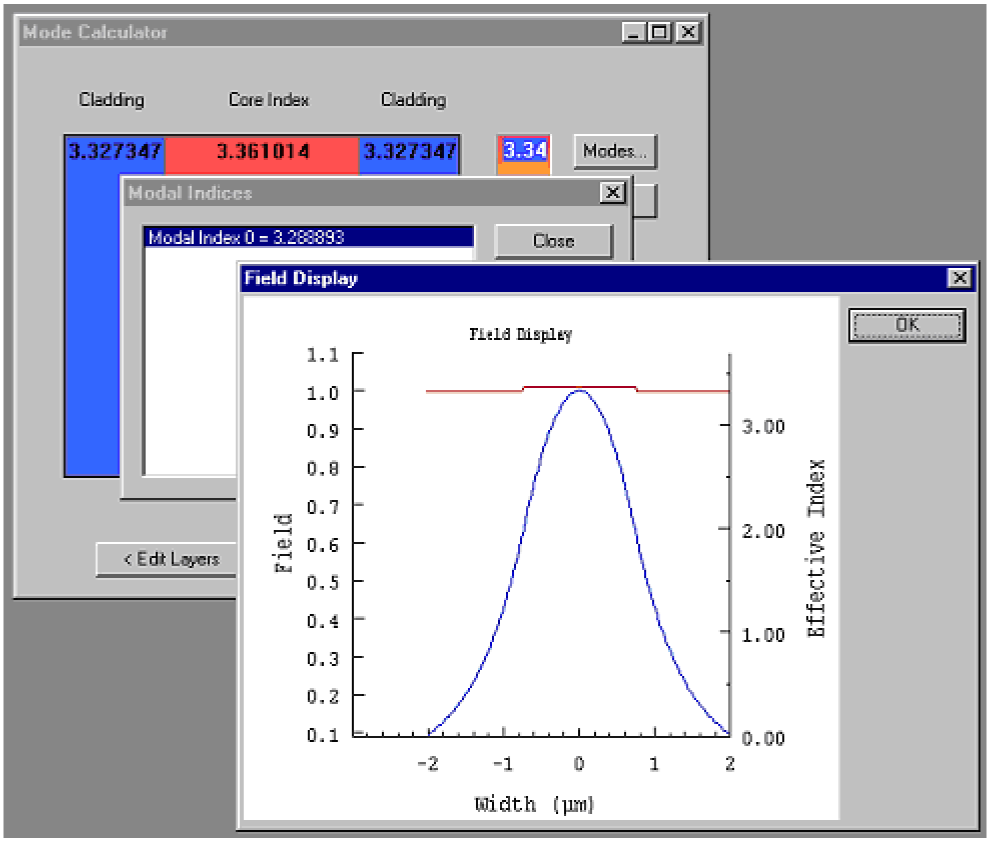
Note: In the Modal Fields dialog box, you see a list of the modal indices. Since the waveguide you have designed is **monomode**, there is only one item in the list.

Viewing the modal field distribution and effective index distribution

To view the modal field distribution and the effective index distribution, perform the following procedure.

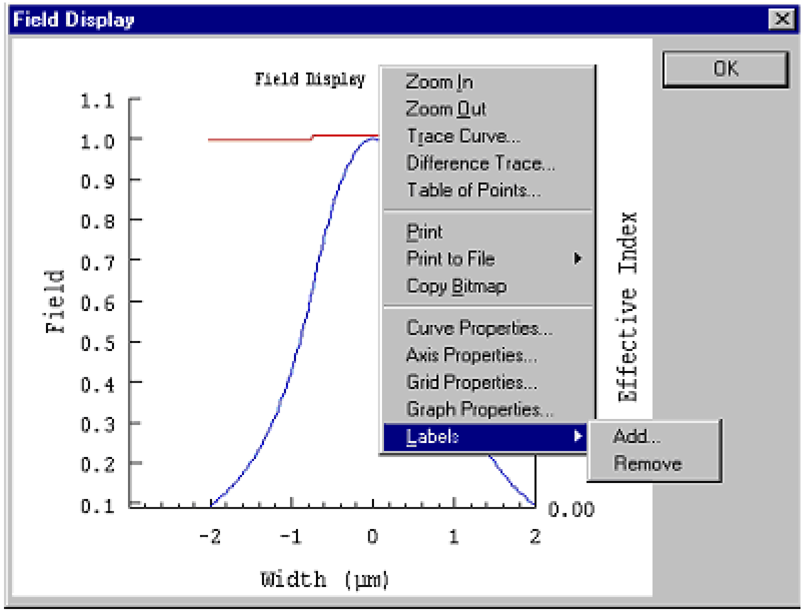
Step	Action
1	In the Modal Indices dialog box, click the mode in the list to select it.
2	Click the Display Field button. *At the end of this step, you should be able to view the modal indices of the waveguide, the modal field distribution, and the effective index distribution (see Figure 8).*

Figure 8 Modal field distribution and effective index distribution



3 A right mouse button click in the graph area of the Field Display dialog box will bring up a menu with more display options (see Figure 9). These options can be used to modify the display, get tabular data about the curves, modify colors, add grids, labels, or print the graph.

Figure 9 Display options



Notes

Lesson 2: Design a WDM device with the Wizard Tool

In this lesson, you will use the Wizard Tool to create a WDM device.

Closing dialog boxes to access the Initial Data dialog box

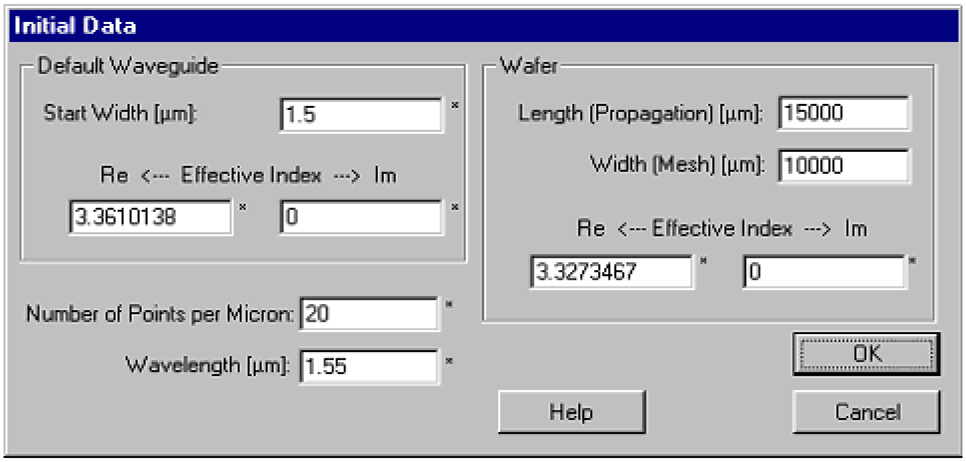
At the end of Lesson 1, you have opened the Effective Index Calculator dialog box, the Modal Fields dialog box, and the Field Display dialog box. In this step, you will close those dialog boxes to access the Initial Data dialog box in which you will further define the parameters of your WDM design and simulations.

Since you have already calculated the data regarding the effective indices and entered the waveguide width and the wavelength in the previous lesson, you will now enter only the data regarding the length and the width of the wafer and the number of points per micron for BPM simulations.

To enter data in the Initial Data dialog box, perform the following procedure.

Step	Action
1	Close the Field Display dialog box.
2	In the Modal Indices dialog box, click the Close button.
3	In the Mode Calculator dialog box, click the Close button. The Initial Data dialog box will appear *(see Figure 1)*.

Figure 1 Initial Data dialog box



4	In the Wafer section, type 15000 in the Length (Propagation) box.
5	In the Wafer section, type 10000 in the Width box.
6	In the Number Of Points Per Micron box, type 20.
7	Click the OK button. *At the end of this step, you should be able to see the Wafer work space on your screen .*

Creating a WDM device using the Device Wizard

In this step, you will use the Device Wizard command available in the Design menu of the WDM - Device Layout Designer dialog box. You will start creating a WDM device using the Wizard windows.

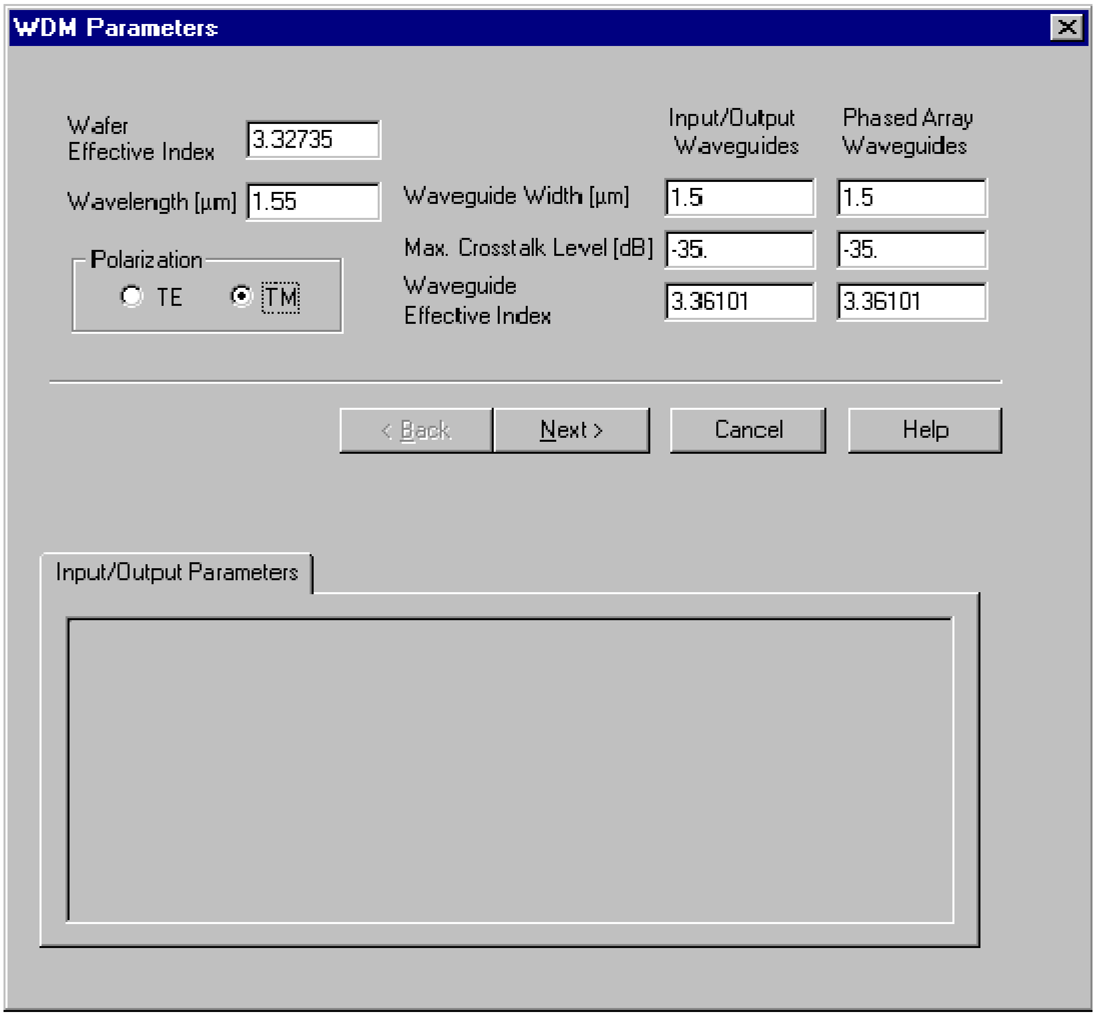
Defining the required polarization and crosstalk level

To define the required polarization and crosstalk level, perform the following procedure.

Step	Action
1	From the Design menu, click Device Wizard.
2	In the WDM Parameters dialog box, enable the TM button in the Polarization section. This is required because the effective index calculation (in the transverse plane) had a TE polarization, but the simulations of the array are in the epitaxial plane. Therefore the sense of direction is reversed, and the polarization is opposite (see the Technical Background section of the manual).
3	In the Maximum Crosstalk Level (dB) section, enter the value of -35 in the Input/Output Waveguides box and the Phased Array Waveguides box.
4	Click the Next button.

Note: Make sure that you have the same data entered in the WDM Parameters dialog box as the data in Figure 2.

Figure 2 WDM Parameters dialog box



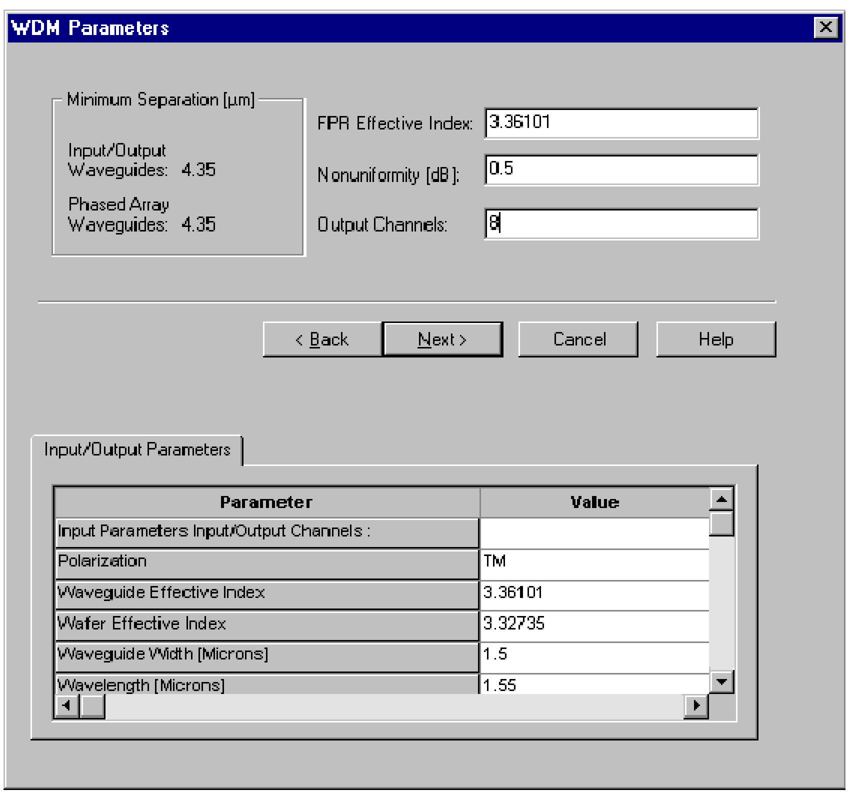
Define nonuniformity of output channels and the number of output channels

In this step, you will work in the next Wizard window. It contains data regarding the Minimum Waveguide Separation, which has been calculated on the basis of the Crosstalk Level requirements, and the waveguide modal properties defined in the previous window. At the bottom of this Wizard window, you will find information about the input/output parameters of the waveguides.

To enter output channels data, perform the following procedure.

Step	Action
1	In the Nonuniformity box, make sure the value entered is 0.5 (see Figure 3).
2	In the Output Channels box, type 8 (see Figure 3).
3	Click **Next**.
	Note: The Free Propagation Region Effective Index can be assigned a value which is different from the value for the Waveguide Effective Index. In this particular example, however, you are using the same value.

Figure 3 Changing nonuniformity and output channels

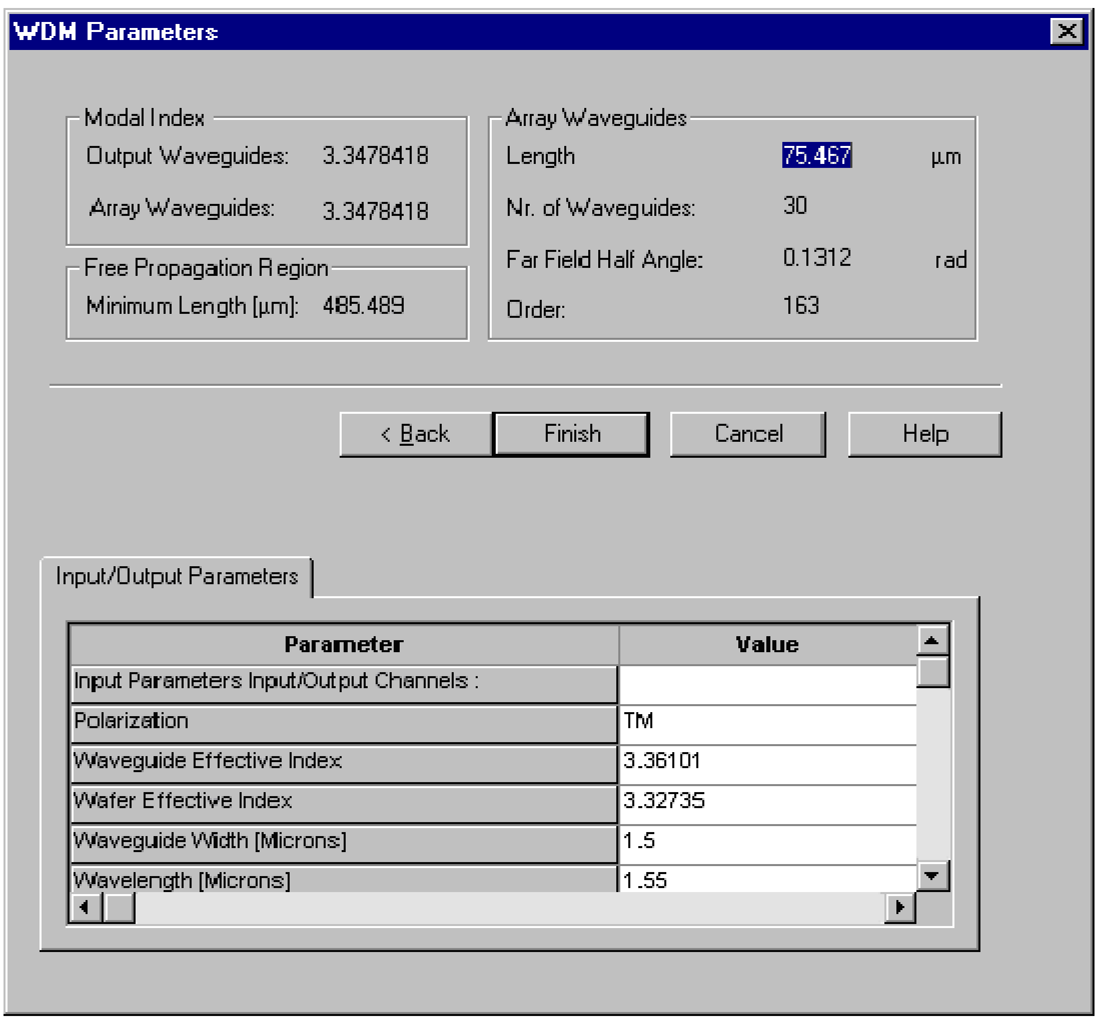


In this Wizard window, you can see the calculated results for the Minimum Length of the Free Propagation Region. The Minimum Length and the Far-Field-Half Angle values are displayed in the top section of the Wizard window. The calculation of those results is based on the requirements for the number of output channels, nonuniformity, and the waveguide and wafer parameters.

4 Press the Next button.

In the Wizard window in Figure __ , you see a summary of the most important WDM geometric and modal parameters that are calculated based on your requirements for waveguide and wafer properties, crosstalk level, polarization, number of output channels and nonuniformity. Array transmission and device dispersion.

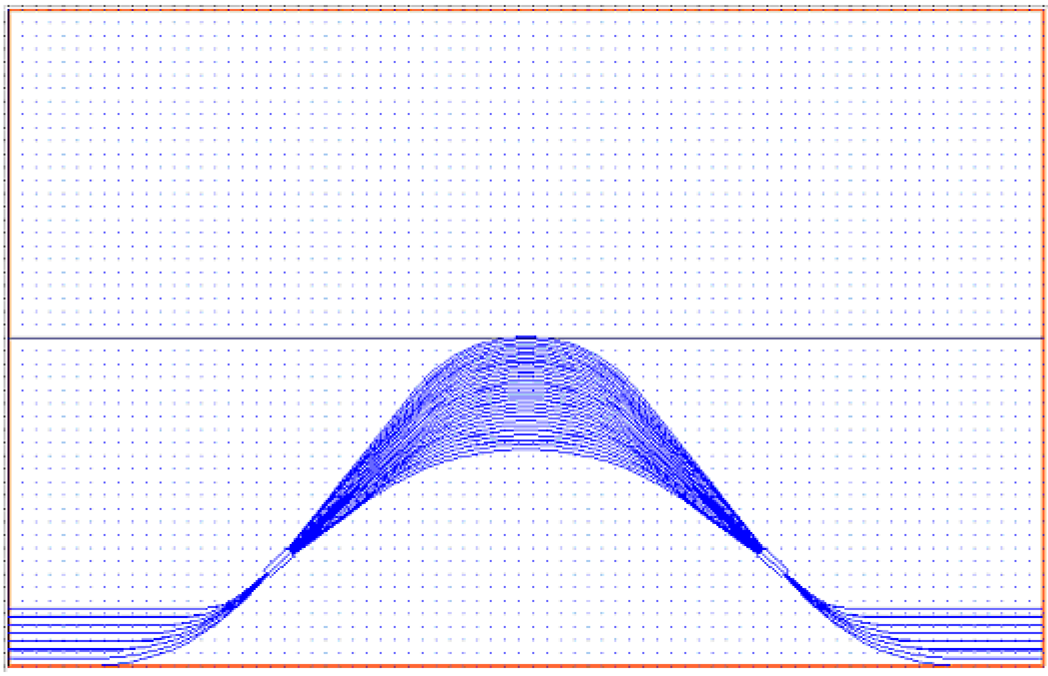
Figure 4 Summary of parameters



5 Click the Finish button.

At the end of this step, WDM_Phasar will display automatically the WDM device, shown in the picture below:

Figure 5   WDM device



This design can be saved using the File drop down menu. In the Samples directory of WDM_Phasar, this design is already saved as **`Lesson2.wdm`**.

Lesson 3: Editing the WDM device geometry

In this lesson, you will get acquainted with the options available in the WDM Device Properties dialog box. You can use this dialog box to edit the WDM Device geometric and material parameters. The WDM Device Properties dialog box contains seven tabs that allow you to view and define the parameters of the different components of the WDM device. For the parameter naming conversion, see Appendix I (WDM_Phasar Atlas).

To start this lesson where Lesson 2 ended, open the file **`Lesson2.wdm`**.

Using the WDM Device Properties dialog box

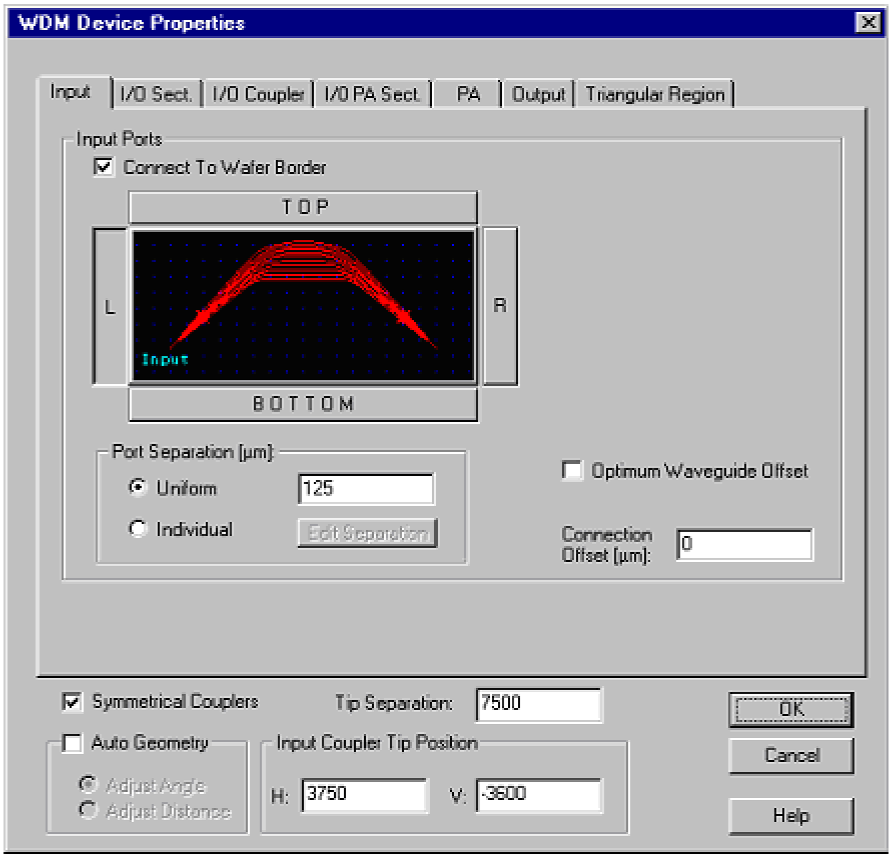
In this step, you will open the WDM Device Properties dialog box in which you can edit the input port parameters. In the Connection Offset box, you can define the distance between the wafer edge and the first waveguide centre; in the Port separation frame, you can define the distance between individual waveguide centres. There is also a check box to enable the use of Optimum Waveguide Offset. This feature can be used in the input, output, and phased arrays. When enabled, an offset is added at the junctions between straight and curved waveguides to minimize the radiation loss there. See the sections Propagation Constant of Bent Waveguides, Optimum Offset, and Bent/Straight Junction Loss in the Technical Background chapter of this manual for further details.

Accessing the WDM Device Properties dialog box

To access the WDM Device Properties dialog box, perform the following procedure.

Step	Action
1	Select the device by clicking in the wafer and dragging the cursor to enclose at least part of the device in a selection box.
2	From the Edit menu, click Properties. *By default, the Input tab is enabled, and you see the data entered in the boxes on the Input page.* ***Note:*** For the purposes of this lesson, you don't have to change the default values on the Input page (shown below).

Figure 1 WDM Device Properties — default values



Notice that the Symmetrical Couplers check box is enabled, that is, the Phased Array is symmetric and the Output Star Coupler is a mirror image of the Input Star Coupler. For more information about input ports, see Appendix 1 in this manual.

Parameters of the Input Selection of the Input coupler

In this step, you will access the parameters of the Input Section of the Input Coupler. On the I/O Section page, you can edit the following parameters:

- **Radius box** — Radius of the input surface of the Free Propagation Region
- **Number Of Waveguides box** — Number of waveguides
- **Minimum Waveguide Separation box** — Separation from one waveguide centre to the centre of the adjacent waveguide. These separations can be the same for all waveguides, or a non-uniform spacing can be specified.
- **Waveguide Length box** — Length of the I/O Section waveguide (the waveguide connected to the coupler)
- **Waveguide Effective Index boxes** — Real and the imaginary values. The waveguides need not have the same index.
- **Tapered Entry section (when enabled)** — Tapered start and end width and the length of

the tapers, as well as the type of taper.

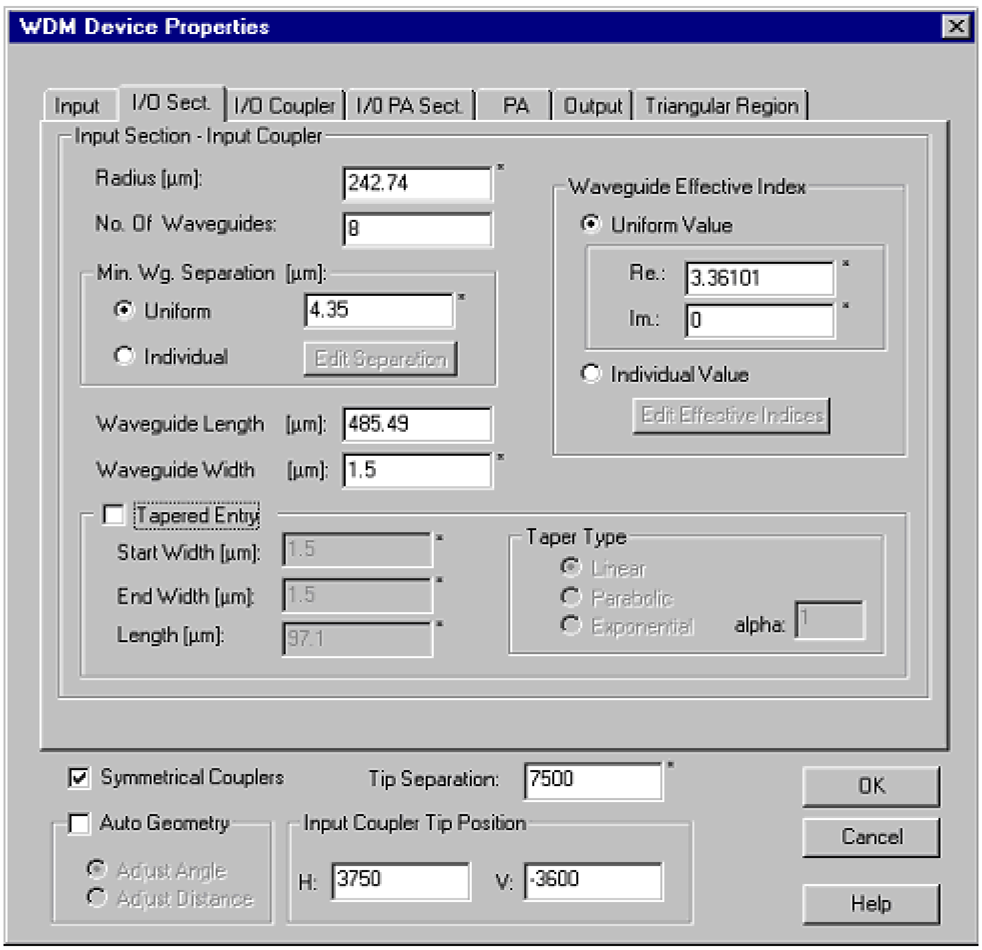
Accessing data on the I/O Section page

To access the data on the I/O Section page, perform the following action.

Action

- In the WDM Device Properties dialog box, click the I/O Section tab.

Figure 2 I/O Section tab



For the purposes of this lesson, you don't have to change the default values, shown on the picture above.

For more information, see the Input Section, Input Coupler section in Appendix I in the WDM_Phasar Parameter Atlas.

Input Star Couplers parameters

In this step, you will access the parameters of the Input Star Couplers. On the I/O Coupler page, you can edit the values of the Free Propagation Region of the Input Coupler. You can define the following parameters:

- **Tip Position boxes** — Position of the lower tip
- **Coupler Length box** — Length of the Free Propagation Region element
- **Orientation Angle box** — Angle between the horizontal axis and the central line of the Free Propagation Region
- **Angular Width box** — Angular opening of the Free Propagation Region seen from the Tip
- **Effective Index boxes** — Real and imaginary values

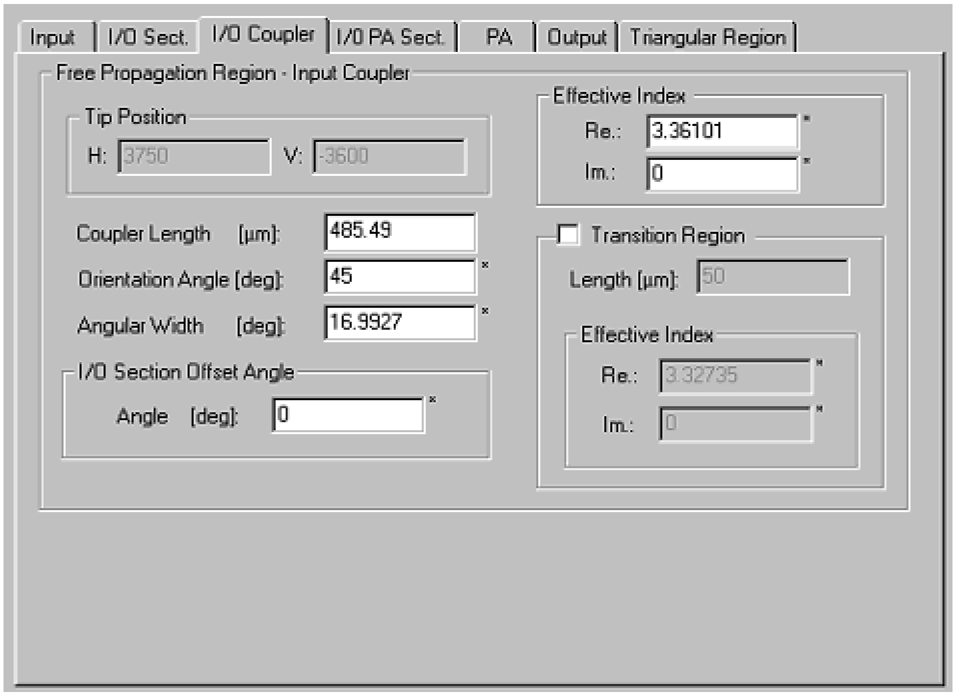
Accessing the data on the I/O Coupler page

To access the data on the I/O Coupler page, perform the following action.

Action

- In the WDM Device Properties dialog box, click the I/O Coupler tab.

Figure 3 I/O Coupler tab



For the purposes of this lesson, you don't have to change the values, shown of the picture above.

For more information, see the Input Coupler, Free Propagation Region section in Appendix I of the WDM_Phasar Atlas.

Parameters of the Phased Array Section of the I/O Coupler

In this step, you will access the parameters of the Phased Array Section of the Input/Output Coupler. On the I/O PA Section page, you can edit the following parameters:

- **Radius box** — Radius of the output surface to the Free Propagation Region
- **Number of Waveguides box** — Number of the waveguides
- **Minimum Waveguide Separation box** — Separation from waveguide centre to waveguide centre (see Appendix 1)
- **Waveguide Length box** — Length of the phased array waveguide connected to the coupler (see Appendix 1)
- **Waveguide Width box** — Width of the waveguide
- **Waveguide Effective Index boxes** — Real and the imaginary values
- **Tapered Entry section (when enabled)** — Tapered start and end width and the length of the tapers

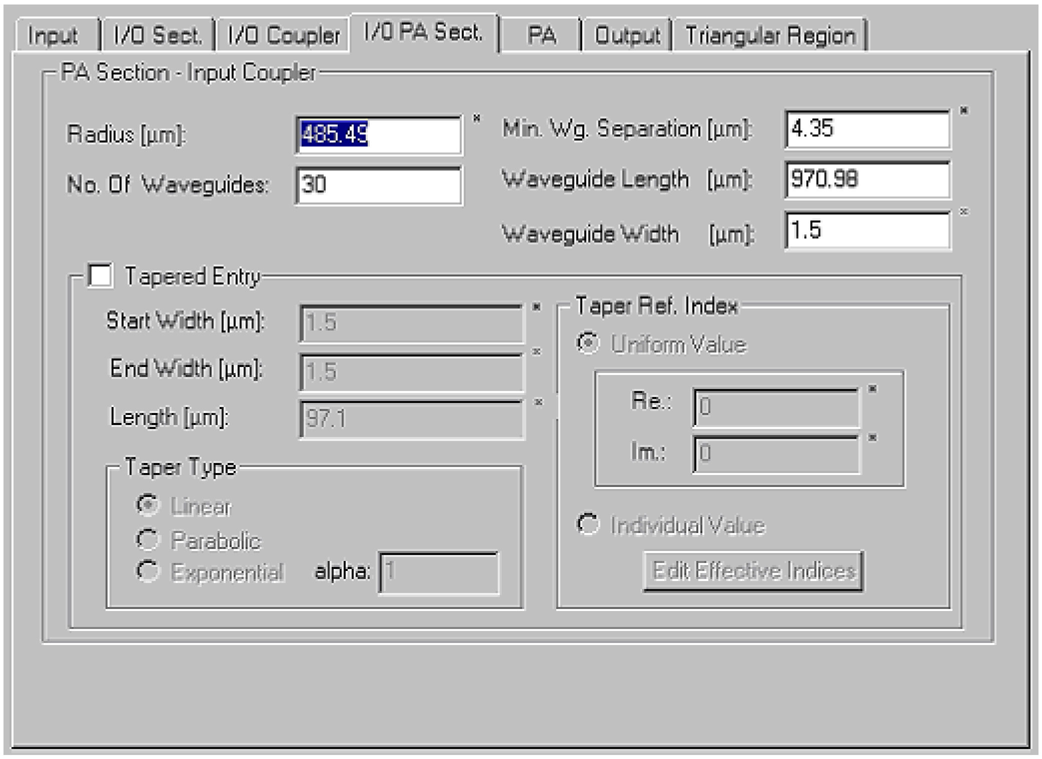
Accessing the data on the I/O PA Section page

To access the data on the I/O PA Section page, perform the following procedure.

Action

- In the WDM Device Properties dialog box, click the I/O PA Section tab.

Figure 4 I/O PA Section tab



For the purposes of this lesson, you don't have to change the default values, shown on the picture above.

For more information, see the Phased Array Section, Input Coupler section in Appendix I of the WDM_Phasar Atlas.

Phased Array Section parameters

In this step, you will access the parameters of the Phased Array Section. On the PA page, you can edit the following parameters:

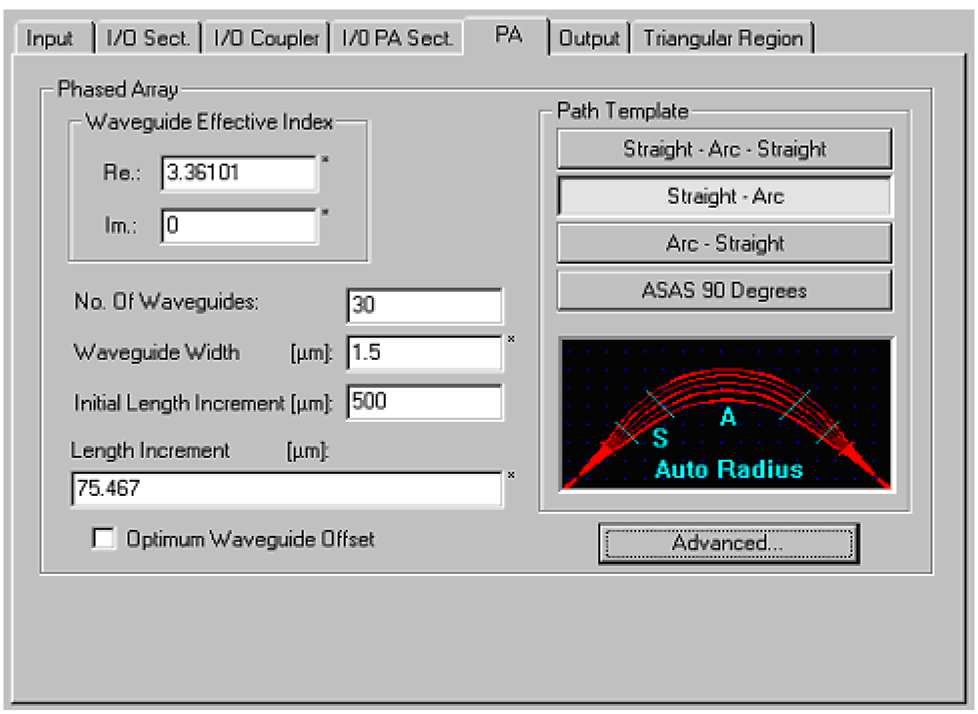
- **Waveguide Effective Index boxes** — Real and the imaginary values
- **Number of Waveguides box** — Number of the waveguides
- **Waveguide Width box** — Width of the waveguide
- **Length Increment box** — Length increment with respect to the previous path
- **Initial Length Increment box** — Difference between the distance between the couplers and the length of the first path.

To access the data on the PA page, perform the following action.

Action

- In the WDM Device Properties dialog box, click the PA tab.
  The buttons in the Path Template section allow you to use any of the four templates.

Figure 5 PA tab



For the purposes of this lesson, you don't have to change the data on the PA page, shown on the picture above.

For a detailed description of the Phased Array, see the Phased Array Section, Input Coupler section in Appendix I of the WDM_Phasar Atlas.

For more information about using the path templates, see Appendix II of the WDM_Phasar Atlas.

Output Port parameters

In this step, you will access the parameters of the Output Ports. On the Output page, you can edit the following parameters:

- **Connection Offset box** — Distance from the edge of the wafer to the centre of the first port waveguide
- **Port Separation frame** — Difference between centres of the waveguides. The separation can be a uniform or non uniform spacing.

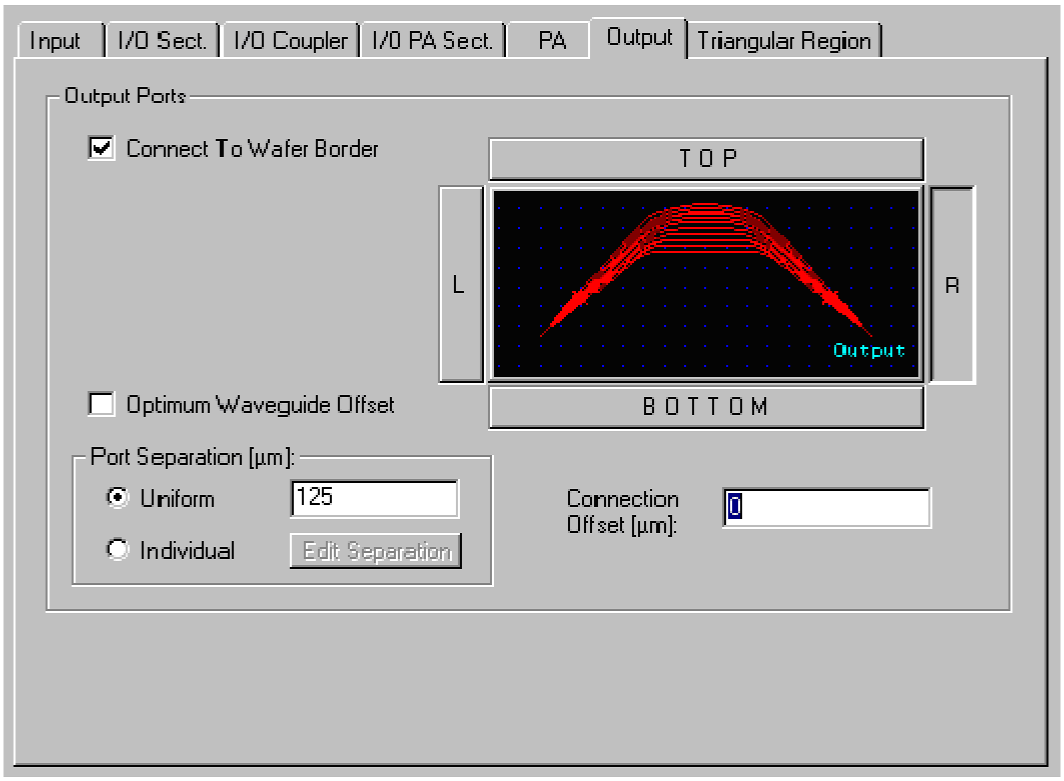
Accessing data on the Output page

To access the data on the Output page, perform the following action.

Action

- In the WDM Device Properties dialog box, click the Output tab.

Figure 6 Output tab



For the purposes of this lesson, you don't have to change the default data on the Output page, shown on the picture above.

For a detailed description of the output ports, see the Output Ports section in Appendix I of the WDM_Phasar Parameter Atlas.

Notes

Lesson 4: Tools for fast evaluation of WDM device performance

In this lesson, you will learn how to use the following tools for fast evaluation of the WDM device performance: Device Statistics, Statistics Monitor, and Performance Calculator.

Commands available in the Performance menu

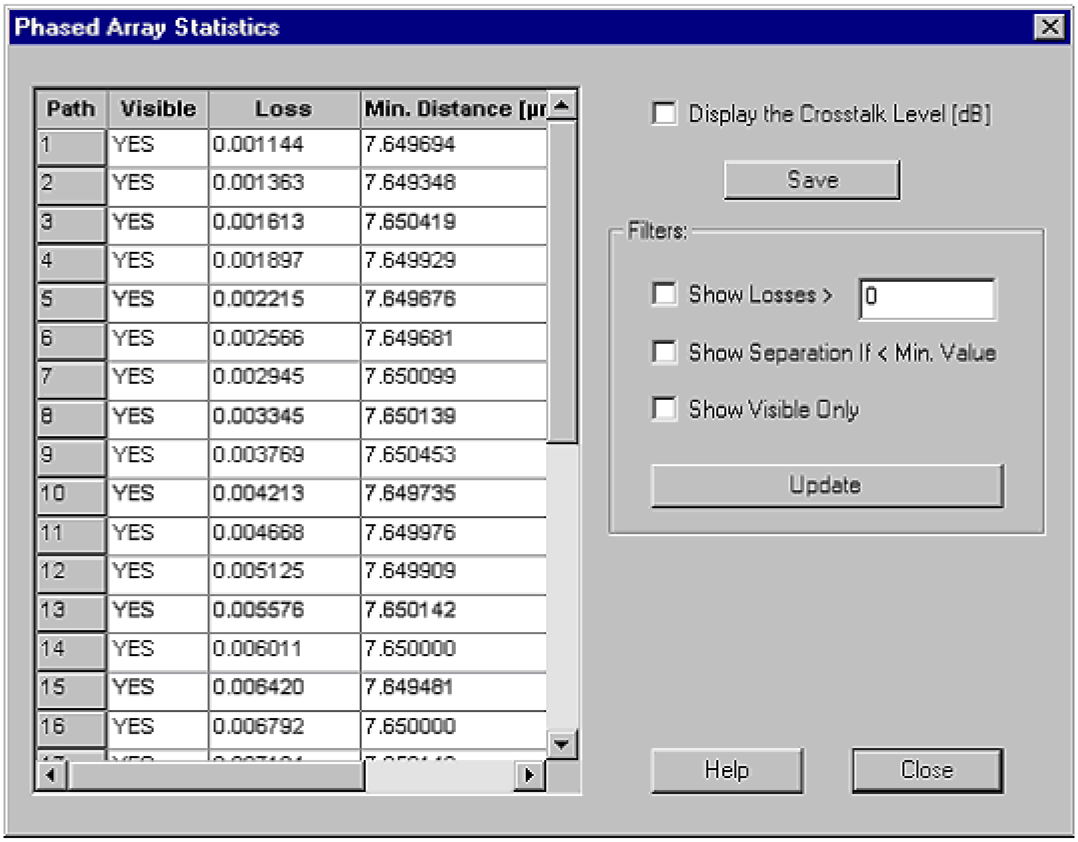
In this step, you will access the statistics information regarding the Phased Array, the Input Array, and the Output Array by using the commands available in the Performance menu.

Accessing the Phase Array statistics

To access the Phased Array statistics, perform the following procedure.

Step	Action
1	Make sure the device is selected.
2	From the Performance menu, click Device Statistics, Phased Array. After the calculation of the Phased Array is completed, the Phased Array Statistics dialog box appears. The statistics for the Phased Array are shown. The first column shows if the geometry allowed the waveguide path to be drawn. The second estimates the losses in the path from bending and junctions. The last shows the closest the waveguide gets to a neighbor while in the Phased Array. This does not include the Phased Array Section near the couplers (see the WDM Atlas for the precise definition of these terms).
3	In the Phased Array Statistics dialog box, enable the Display The Crosstalk Level check box. WDM Phasar recalculates the exact maximum Cross-talk level that corresponds to the given minimum separation distance.

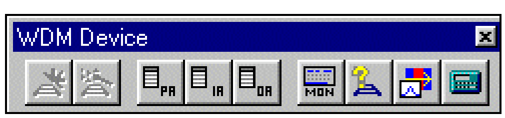
Figure 1 Phased Array Statistics dialog box



4 Click the Close button.

- **TIP:** To access the Phased Array Statistics dialog box, you can also click the PA Stats button on the WDM Device toolbar (the third button on the toolbar shown below).

Figure 2 WDM Device toolbar — PA Stats button



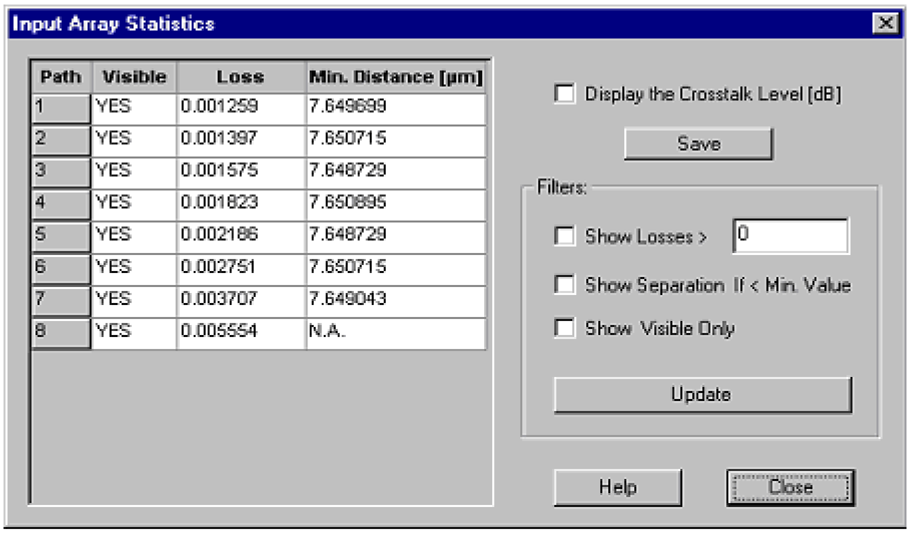
Accessing the Input Array statistics

To access the Input Array statistics, perform the following procedure.

Step **Action**

1 From the Performance menu, click Device Statistics, Input Array.

Figure 3 Input Array Statistics dialog box



2 Click the Close button.

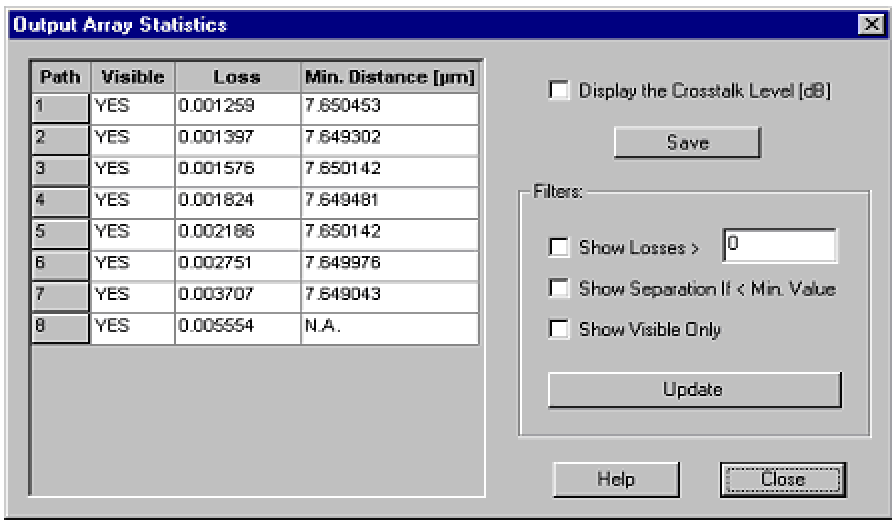
- **TIP:** To access the Input Array Statistics dialog box, you can also click the IA Stats button on the WDM Device toolbar (the fourth button on the toolbar shown below).

Accessing the Output Array statistics

To access the Output Array statistics, perform the following procedure.

Step	Action
1	From the Performance menu, click Device Statistics, Output Array.

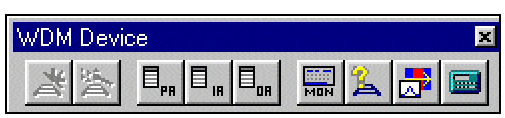
Figure 4 Output Array Statistics dialog box



2	Click the Close button.

- **TIP:** To access the Output Array Statistics dialog box, you can also click the OA Stats button on the WDM Device toolbar (the fifth button on the toolbar shown below).

Figure 5 WDM Device toolbar — OA Stats button



Summary of calculated parameters

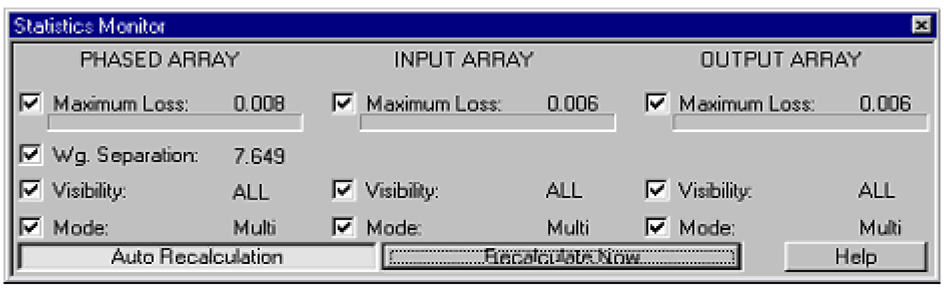
In this step, you will get a summary of calculated parameters of the Phased Array, the Input Array, and the Output Array. You will accomplish this by using the Statistics Monitor dialog box.

Obtaining a summary of device statistics

To obtain a summary of the device statistics, perform the following procedure.

Step	Action
1	From the Performance menu, click Statistics Monitor. *The Statistics Monitor dialog box appears (see Figure __).*

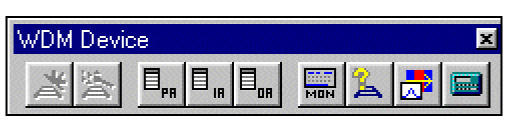
Figure 6 Statistics Monitor dialog box



Step	Action
2	Click the Recalculate Now button. *The Statistics Monitor displays an information summary regarding the Phased, Input, and Output Arrays.*
3	Close the Statistics Monitor dialog box. ***Note:*** If the Auto Recalculation button is enabled, WDM_Phasar will recalculate the parameters that are selected whenever related parameters from the WDM device are changed.

- **TIP:** To access the Statistics Monitor dialog box, you can also click the Stats Monitor button on the WDM Device toolbar (the sixth button on the toolbar shown below).

Figure 7 WDM Device toolbar — Stats Monitor button



Compute the performance characteristics of the device

In this step, you will use the Performance Calculator to compute the performance characteristics of the device. In the Performance Calculator dialog box, you will find a summary of the most important geometric, material, and modal properties of the WDM device.

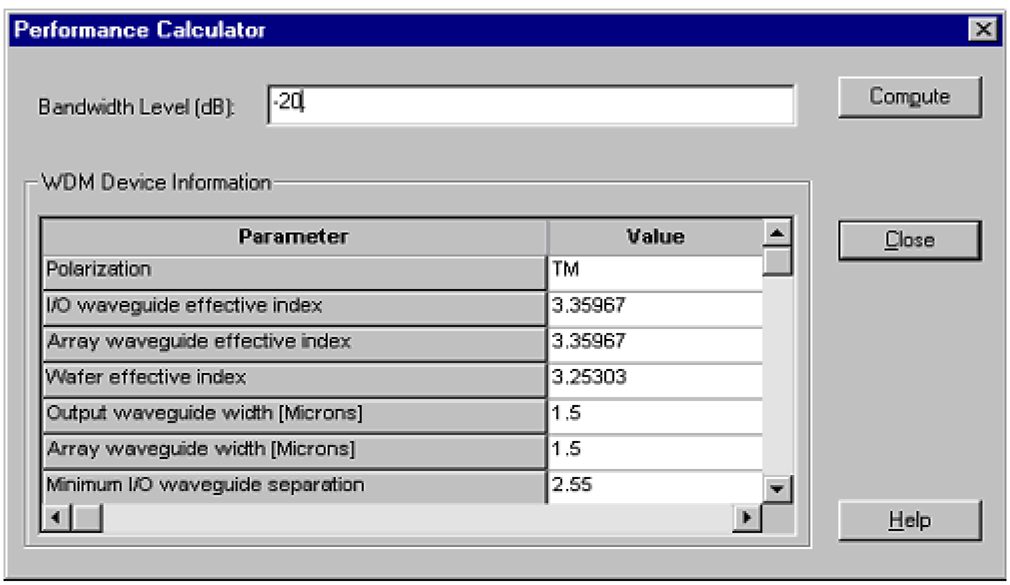
You will also calculate the most important performance characteristics of the device--Phasar Order, Dispersion, Free Spectral Range, Channel Nonuniformity, Spacing, Bandwidth, and Diffraction Loss — which will be displayed in the Results dialog box.

Calculating the device performance characteristics

To use the calculate the device performance characteristics, perform the following procedure.

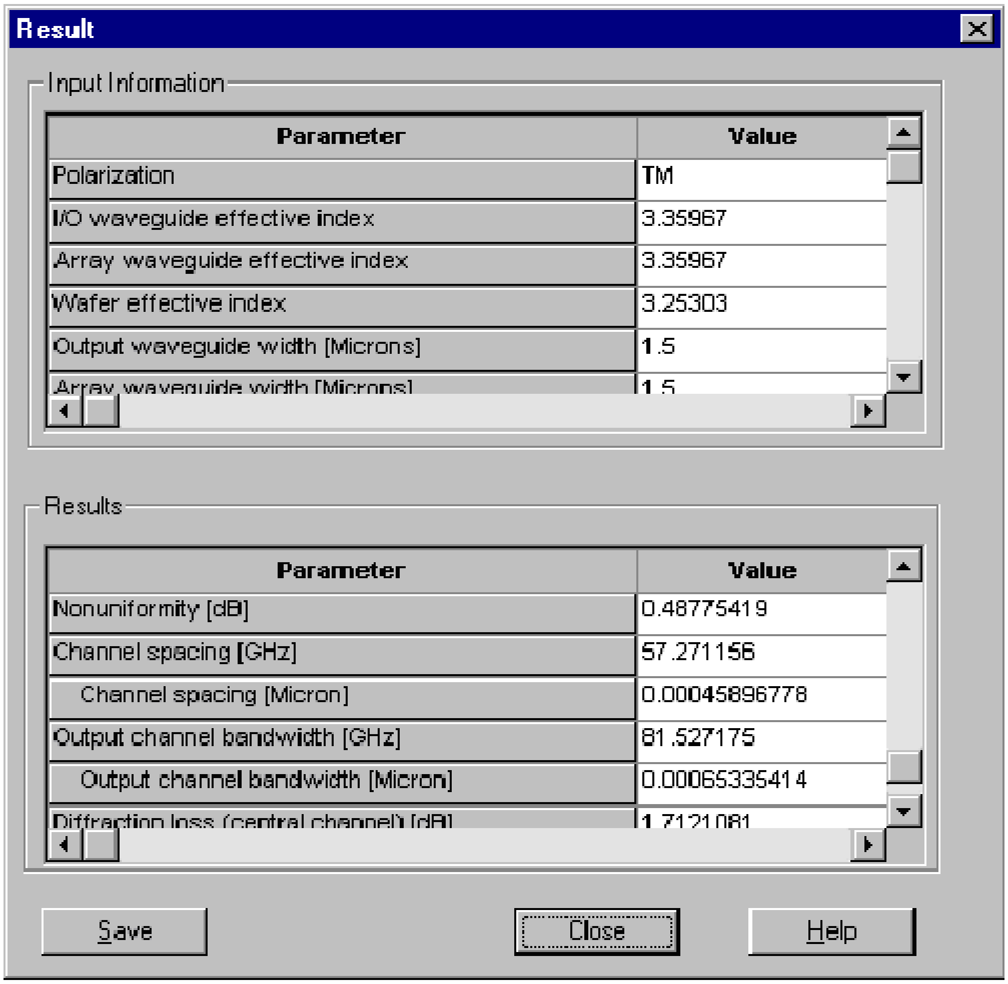
Step	Action
1	From the Performance menu, click Performance Calculator.
2	The Bandwidth Level is used to define the widths of channels. To report 3 dB levels, enter -3 in this box. -20 defines the widths for a 20 dB level.

Figure 8 Performance Calculator dialog box



Step	Action
3	Click the Compute button. *After the calculation is performed, the Result dialog box appears. It provides a summary of all input information and a summary of the calculation results of that information.*

Figure 9 Result dialog box



4 To save the calculation results, click the Save button.

5 In the Save As dialog box, choose a folder where you want to save the information and type a name in the File Name box.

6 Click the Save button to save the results and close the Save As dialog box.

7 Click the Close button to close the Result dialog box.

8 Click the Close button to close the Performance Calculator dialog box.

Notes

Lesson 5: BPM simulation

In this lesson the light passing through the phasar array will be simulated for a fixed wavelength.

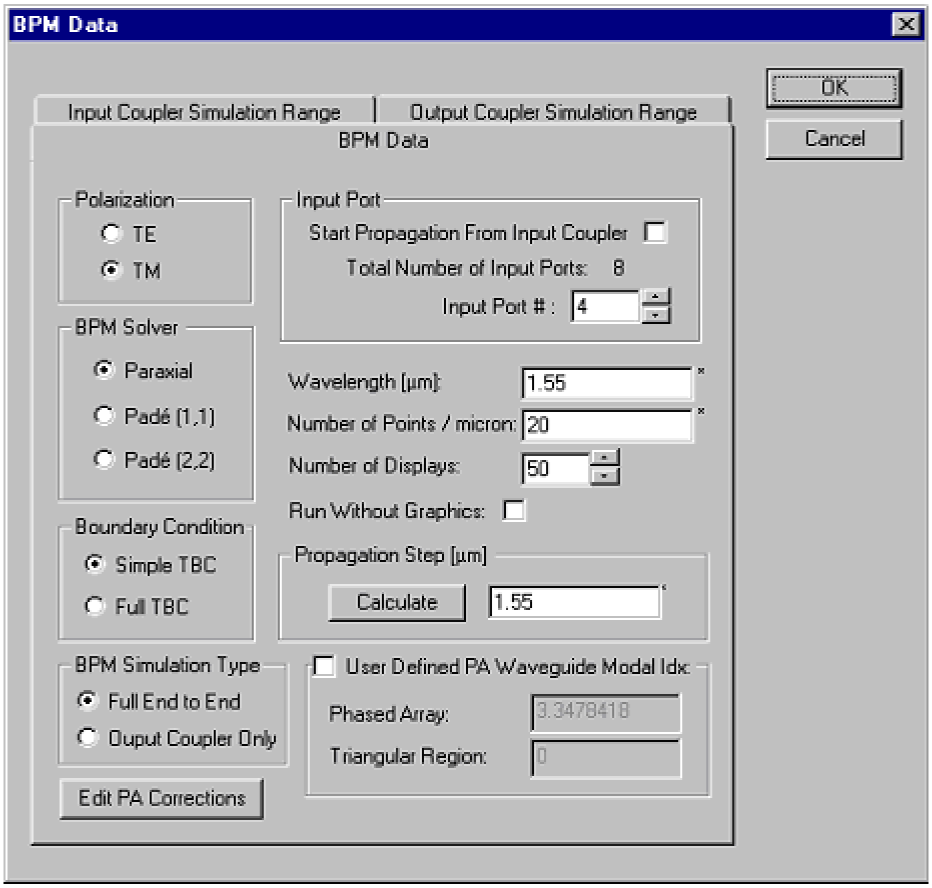
Define parameters to control BPM simulation

In this step, you will define the parameters to control the BPM simulation of the input and output couplers.

Setting the BPM parameters

To set the BPM parameters, perform the following procedure.

Step	Action
1	From the Simulation menu select BPM Data.



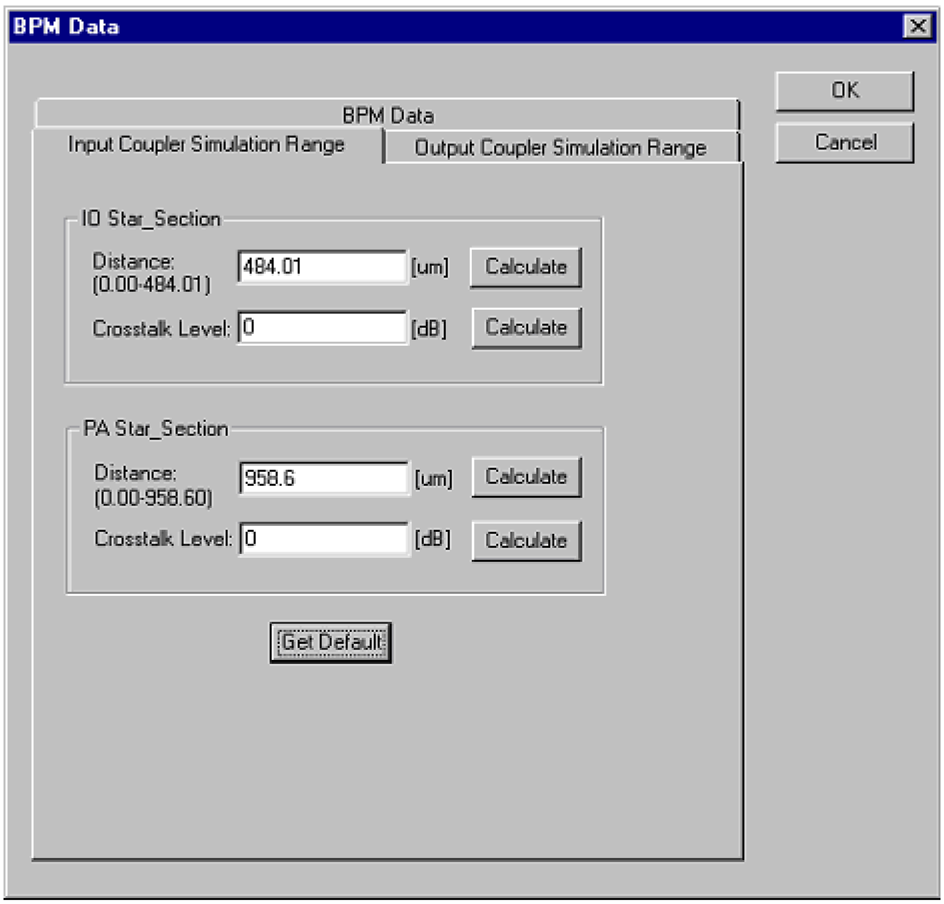
Step	Action
2	Set the polarization to TM.
3	In the number of displays box, type 50.
4	In the propagation step box, type 1.55.
5	In the Input Port frame, select which port you would like the input light to enter the device (4).
6	Select the wavelength of light for this simulation (1.55 mm).

Setting the input and output coupler simulation range

To set the input and output coupler simulation range, perform the following procedure.

Step	Action
1	From the Simulation menu select BPM Data.
2	Select the Input Coupler Simulation Range tab.

Figure 10 BPM Data — Input Coupler Simulation Range tab



Step	Action
3	Click on the Get Default button to set the input range to the maximum extent possible.
4	Repeat step 3 for the Output Coupler Simulation Range.
5	Click OK to close the box.
	A shorter distance will reduce the execution time of the simulation. Pressing Calculate next to the Crosstalk level box will show the expected level of crosstalk between waveguides at this point, based on an estimate from an overlap integral. The distance should be set large enough that coupling can be neglected outside the region of BPM simulation.

Clicking on Calculate next to the Crosstalk Level will show the result of the overlap integral with the distance shown in the corresponding Distance box.

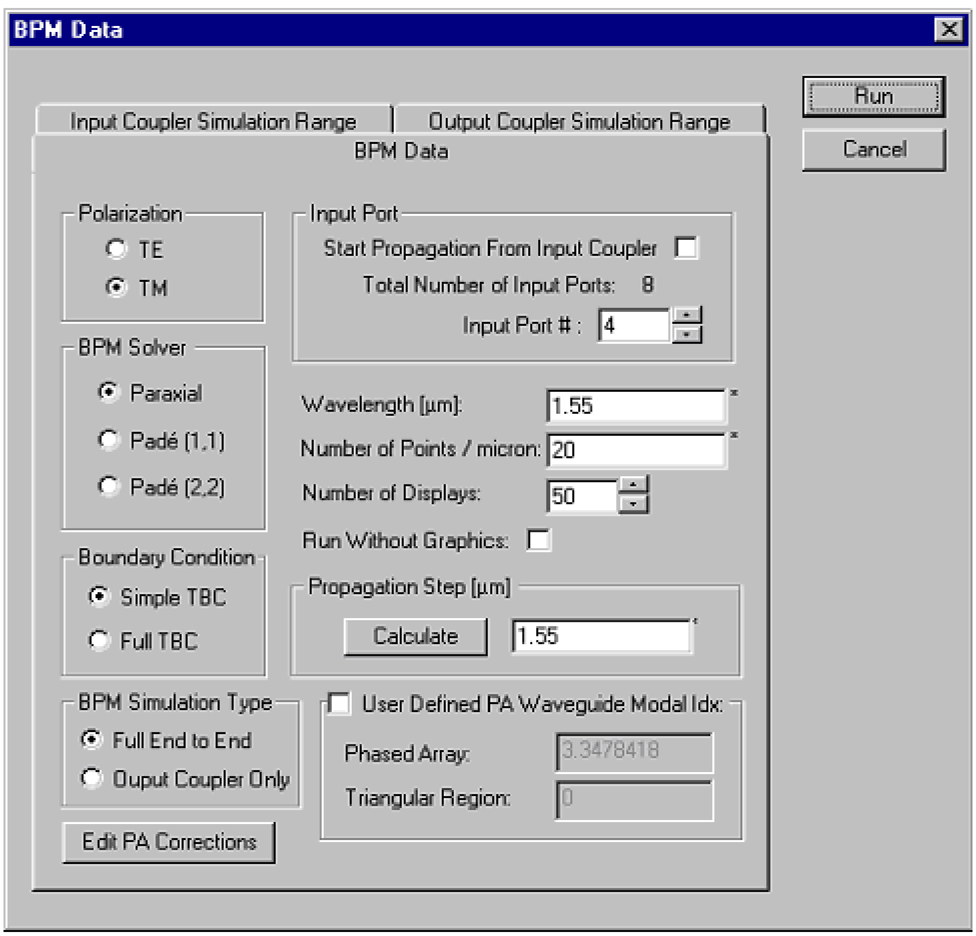
It is possible to use this feature in the opposite direction, you can type a value into Crosstalk level (between -10 and -200 dB), and click on the Calculate button next to the Distance box. The computer will then calculate (approximately) the corresponding distance.

Running the simulation and view the results

In this step, you will run the simulation and view the results. To run the simulation, perform the following procedure.

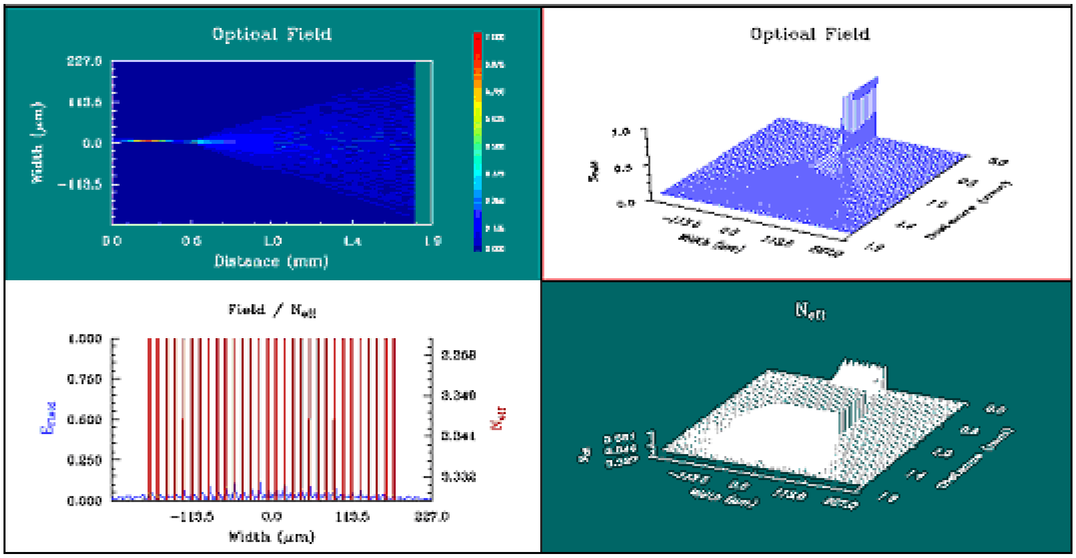
Step	Action
1	From the Simulation menu select Calculate.

Figure 11 BPM Data dialog box — calculate



Step	Action
2	Click on Run to start the simulation. The simulator will pop up the following windows which will display the fields as the calculation progresses.

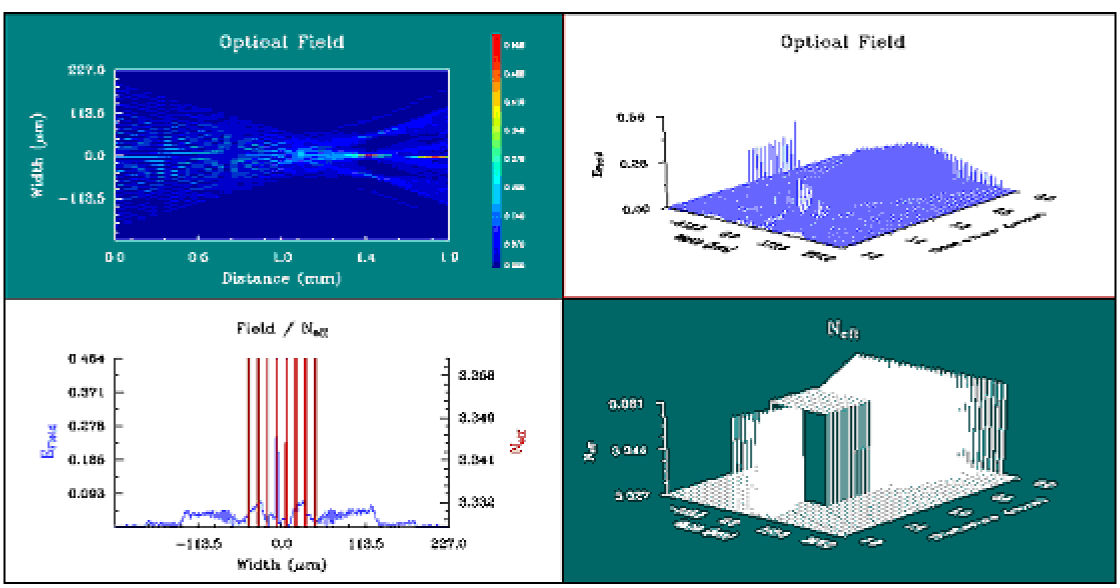
Figure 12 Calculation — progress



The top left quadrant displays a topographical view of the optical field. The top right quadrant displays a 3D view of the optical field. The bottom left quadrant displays a cross-sectional view of the effective index distribution (in red) and the field distribution (in blue). The bottom right quadrant displays a 3D view of the effective index.

After the calculation is finished, the windows show the light after crossing the output coupler.

Figure 13 Calculation — light after crossing the output coupler



After the simulation is finished, any of these windows can be expanded to fill the whole window by selecting the desired window and pressing F2. Click the right mouse button to pop up a menu with further display options.

Lesson 6: Parameter scanning

In Lesson 6, you are going to define parameters for scanning. You will assign the range of the parameter values and the number of simulation steps. Any parameter marked with an asterisk in the dialog boxes can be scanned. In this example, the wavelength is assigned as the scan variable, and the power in each output port is plotted as a function of wavelength at the input port. In this way the device can be evaluated as a multiplexer/demultiplexer.

Define the initial value of the parameter

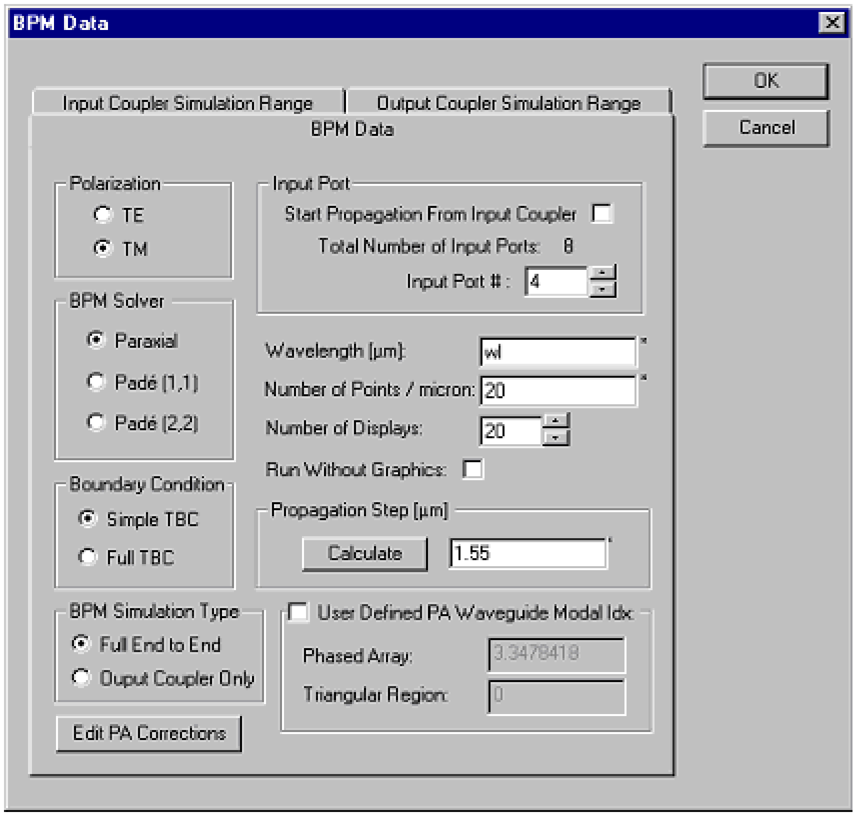
In this step, you will define the initial value of the parameter to be scanned by using the BPM Data dialog box. More specifically, you are going to scan the wavelength which is crucially important for the analysis of the performance of a (de) multiplexer. In this step, instead of a fixed value, you will define a variable name ("wl") for the wavelength.

Entering the initial value of the parameters to be scanned

To enter the initial value of the parameters to be scanned, perform the following procedure.

Step	Action
1	From the Simulation menu, click BPM Data.
2	In the BDM Data dialog box, type "wl" in the Wavelength box.

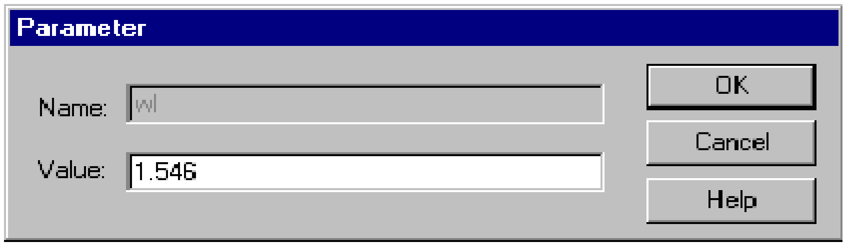
Figure 1   BPB Data dialog box — wavelength



3 Click the OK button to open the Parameter dialog box.

4 In the Parameter dialog box, type 1.546 in the Value box.

Figure 2 Parameter dialog box



5 Click the OK button to close the Parameter dialog box and the BPM Data dialog box. This sets the starting value of the scanned parameter.

Define the number of simulation steps and end value

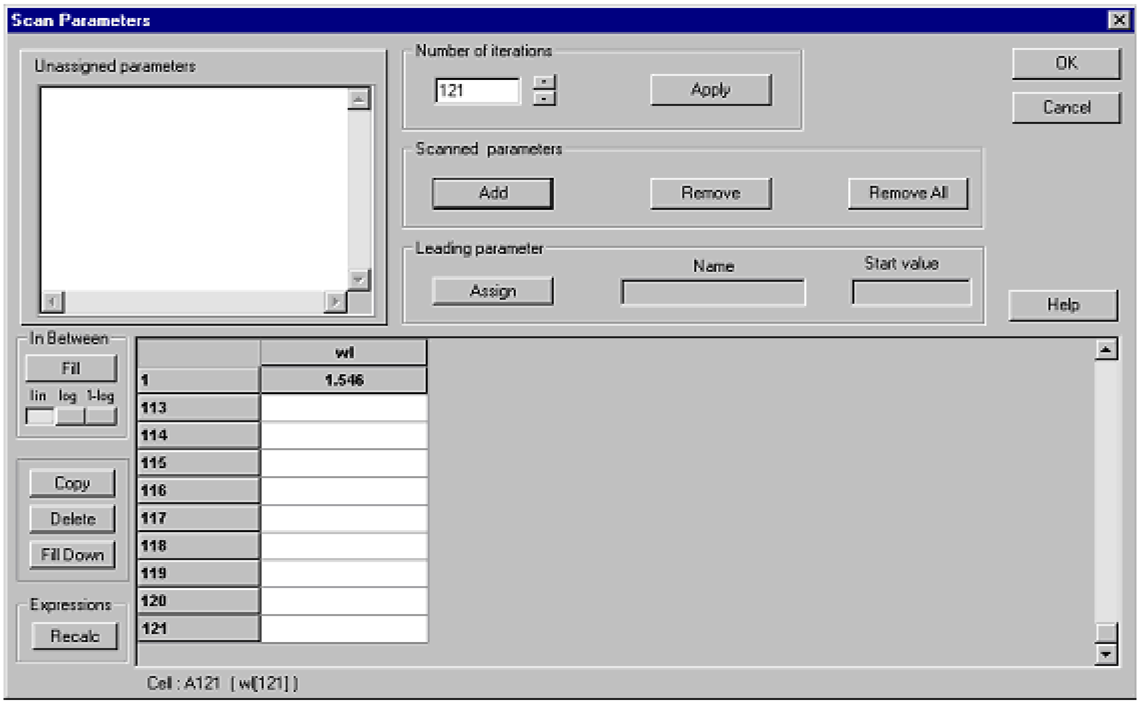
In this step, you will further define the number of simulation steps and the end value of the parameter.

Defining parameters

To define parameters in the Scan Parameters dialog box, perform the following procedure.

Step	**Action**
1	From the Simulations menu, click Scan Parameters.
2	In the Scan Parameters dialog box, double-click the name of the parameter that appears in the Unassigned Parameters box. *The parameter is added to the first column in the bottom section of the dialog box.*
3	In the Number Of Iterations section, type 121 in the box.
4	Click the Apply button.

Figure 3 Scan Parameters dialog box



Define parameter values and assign a leading parameter

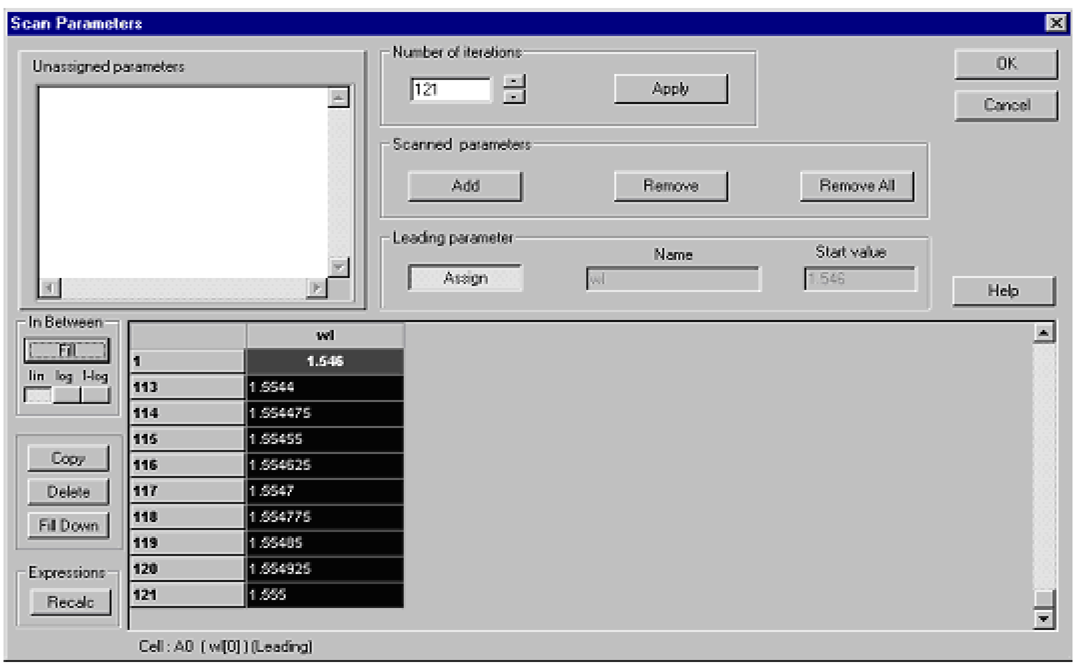
In step 3, you are going to define parameter values and assign a leading parameter. The leading parameter is the one which will be used on the x-axis when the results are plotted. (You can, if you like, make other variables vary with the leading one).

Defining the wavelength parameters

To define the wavelength parameters to be scanned, perform the following procedure.

Step	Action
1	In the Scan Parameters dialog box, scroll down using the mouse until you get to row #121.
2	In the column next to 121, type 1.555.
3	Click the top of the "wl" column to select it.
4	Click the Fill button to fill up the table with equidistant values between 1.546 and 1.555 in 121 iteration steps.

Figure 4 Scan Parameters dialog box — Fill table

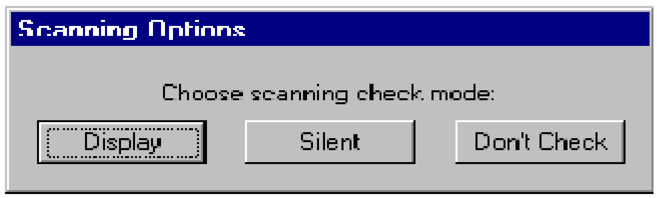


Assigning a leading parameter

To assign a leading parameter, perform the following procedure.

Step	Action
1	In the Scan Parameters dialog box, click the Assign button to assign the parameter "wl" as the leading parameter.
2	Click the OK button to open the Scanning Options dialog box.

Figure 5 Scanning Options dialog box



Step	Action
3	In the Scanning Options dialog box, click the Don't Check button. ***Note:*** If you scan a geometric parameter, you may encounter ranges in which the device does not exist, due to the constraints of geometry. You can use the Display button and the Silent button in the Scanning Options dialog box for a preview when you want to scan a geometric parameter.

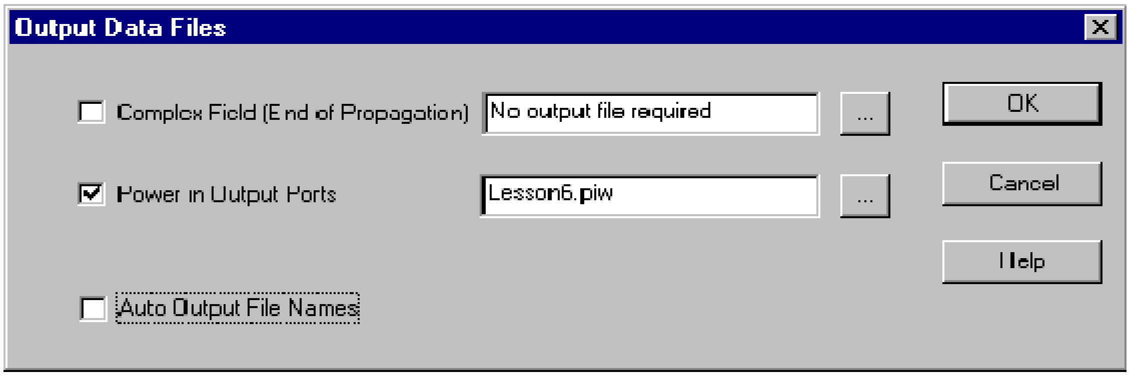
Define simulation results to save

In step 4, you are going to define which simulation results will be saved.

To define the output data files in which the simulation results will be saved, perform the following procedure.

Step	Action
1	From the Simulation menu, click Output Data Files. *The Output Data Files dialog box appears (see Fig __).*

Figure 6 Output Data Files dialog box



2	In the Output Data Files dialog box, enable the Power In Output Ports check box.
3	Disable the Auto Output File Names checkbox.
4	Click the OK button. The data about the power in the output ports will now be sent to the file shown in the box, in ascii format.

Set up parameters for full scanned simulation

In this step, you will set up the parameters for the full scanned simulation. Then, you are going to run the simulation.

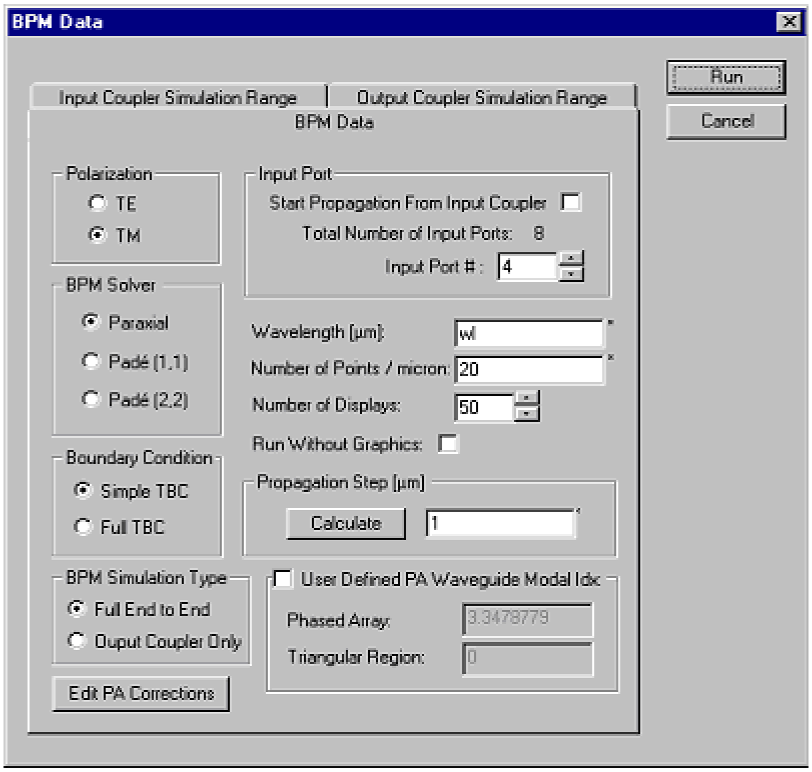
Note: You may want to let your computer do this calculation overnight, or some time when the processor is not in high demand.

Running the scanned simulation

To run the scanned simulation, perform the following procedure.

Step	Action
1	From the Simulation menu, click Calculate.
2	In the Number Of Displays box, type 50.
3	In the Propagation Step section, type 1.

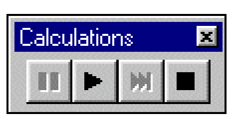
Figure 7 BPM Data dialog box — calculation



4 Click the Run button.
The WDM Device Simulator dialog box appears.

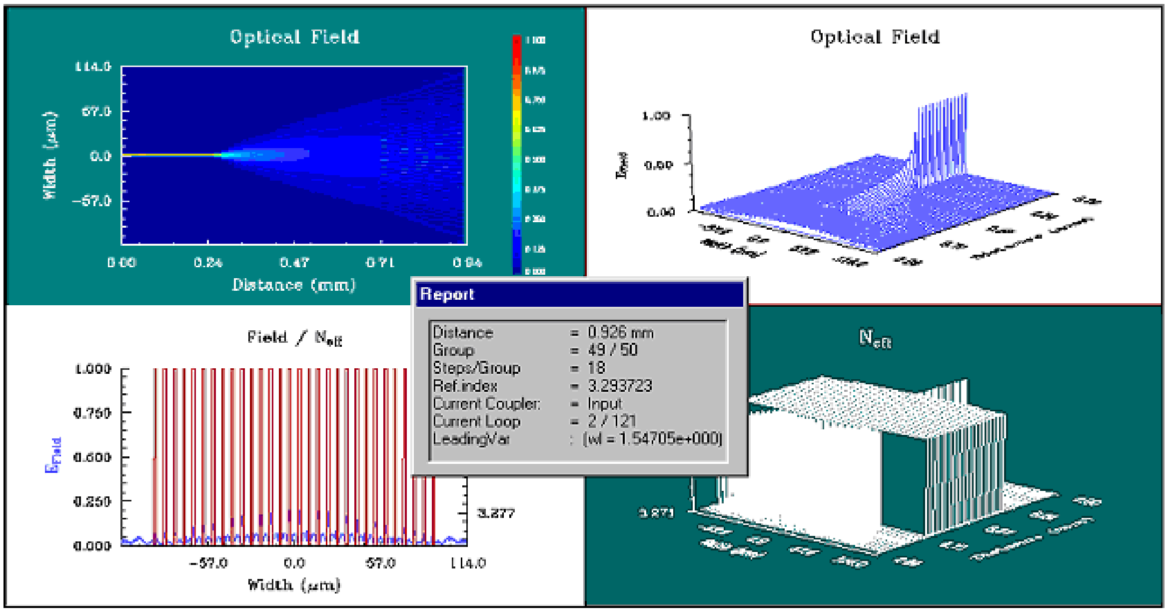
Note: You can stop the calculations at any time by pressing the Pause Calculation button (the first button on the Calculations toolbar). To resume the calculations, press the Resume The Actual Calculations button (the second button on the Calculations toolbar).

Figure 8 Calculations toolbar



At the end of this step, the following run time graphics appear which are displayed in four quadrants:

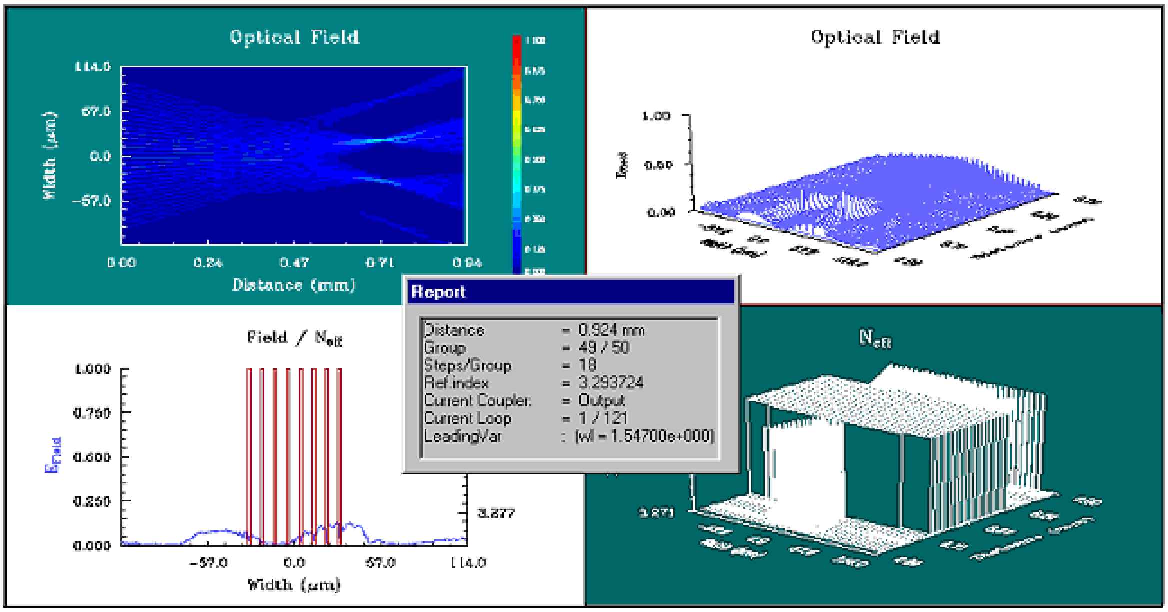
Figure 9 Run time graphics



The top left quadrant displays a topographical view of the optical field; the top right quadrant displays a 3D view of the optical field; the bottom left quadrant displays a cross-sectional view of the effective index distribution (in red) and the field distribution (in blue); the bottom right quadrant displays a 3D view of the effective index. The Report box you see in the middle displays some of the most important parameters during the simulations.

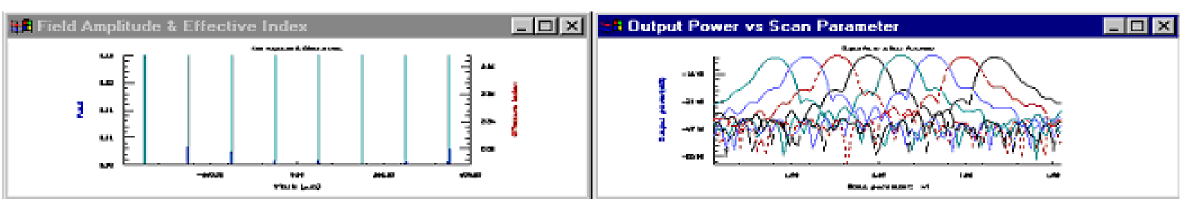
In the next stage of the simulation process, the quadrants on the screen display the same information about the propagation in the Output Coupler.

Figure 10 Propagation in the Output Coupler



At the end of the first run (for the first wavelength), two more graphics will appear at the bottom of the WDM_Device Simulator dialog box, as shown below.

Figure 11 End of first run

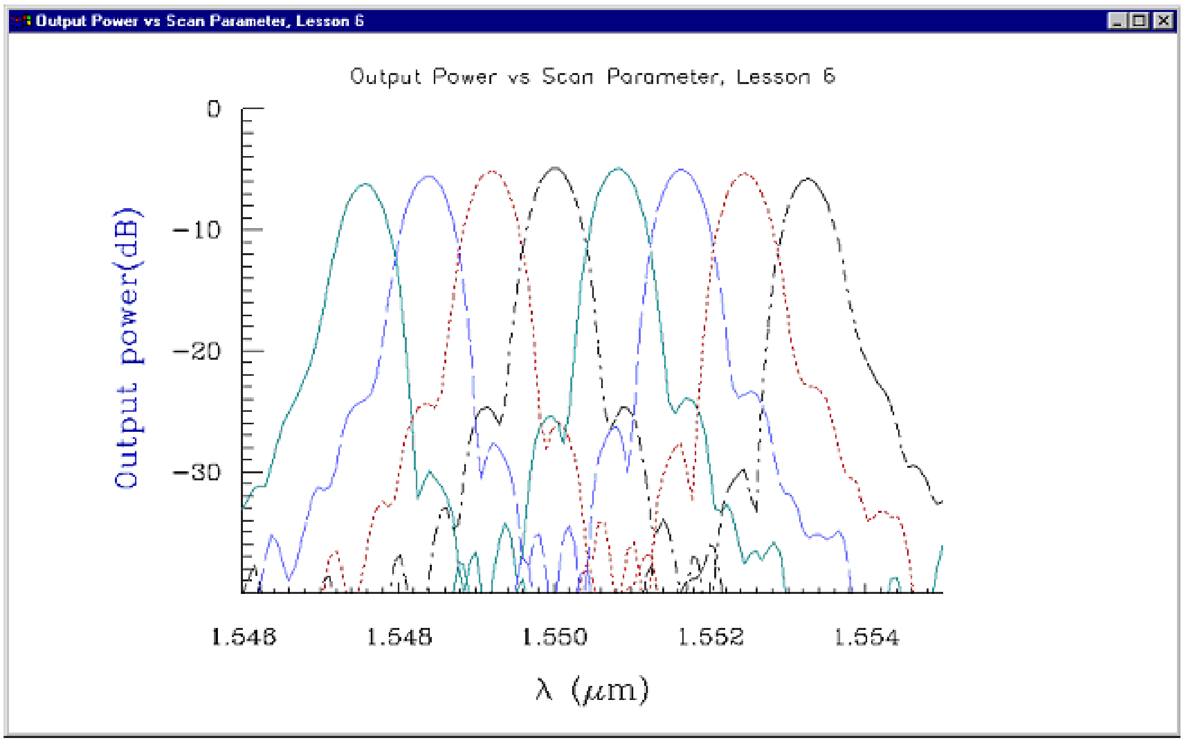


The left-hand quadrant (Field Amplitude & Effective Index) shows the effective index and the field distributions in the end of the propagation for all eight channels; the right-hand quadrant (Output Power VS Scan Parameter) shows the Output Power (dB) for all eight channels.

Note: For each wavelength run, the program adds one point to the eight curves on the right-hand graphics. It might take several hours to complete the simulations.

- **TIP:** Once the simulations are performed, you can enlarge the graphic showing the output power in the channels, as shown below, since it contains the most important results. Click the right mouse button on this graph to bring up a menu, and select the axis option to adjust the scales for convenient viewing.

Figure 12 Output Power vs Scan Parameters



Summary of device performance

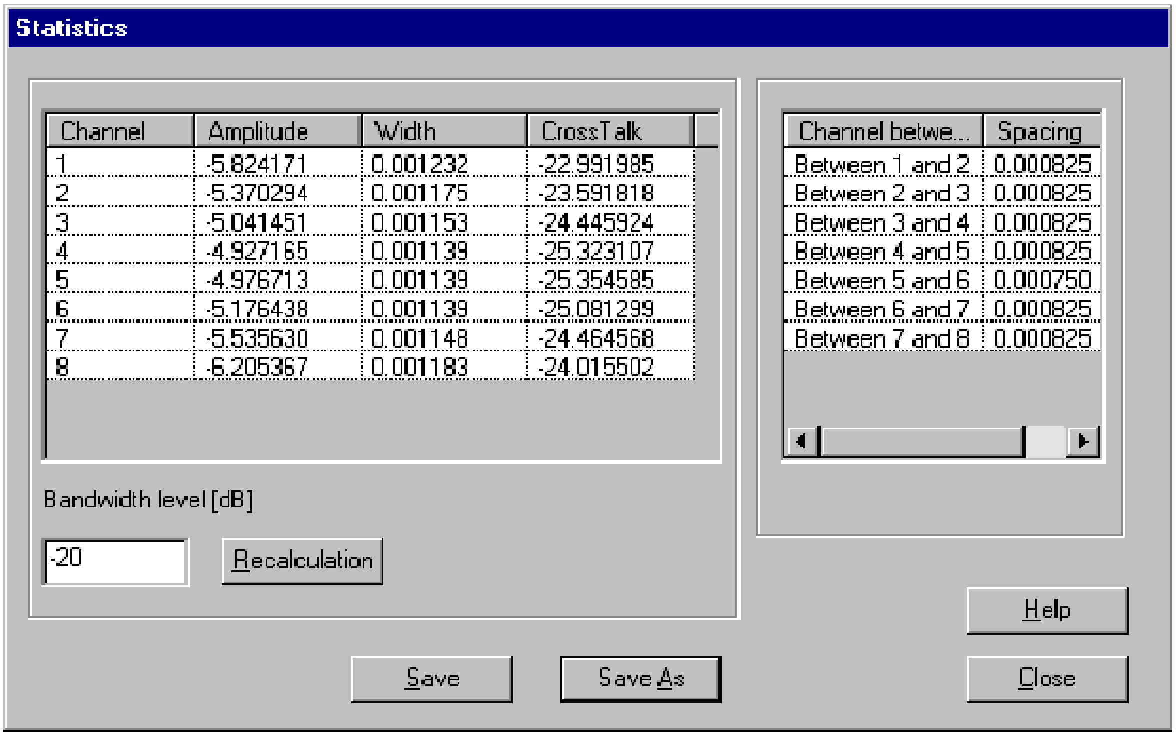
In this step, you will get a summary of the device performance: amplitude (in dB), width, spacing, and cross-talk level for all eight channels.

Obtaining a summary of the device performance

To obtain a summary of the device performance, perform the following procedure.

Step	Action
1	Right-click in the Output Power VS Scan Parameter dialog box and from the pop-up menu choose Statistics.
2	Carefully review the information in the Statistics dialog box.

Figure 13 Statistics dialog box



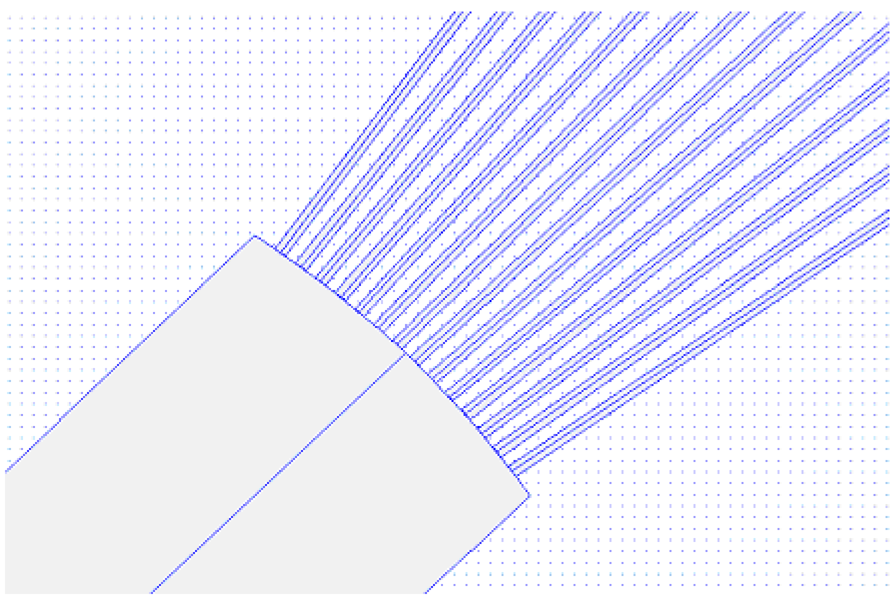
- **TIP:** To change the level of measuring of the bandwidth, type a value in the Bandwidth Level box and click the Recalculation button.

Example 1: Tapered waveguides in the phased array

Reference files: `TaperReference.wdm, Taper.wdm`

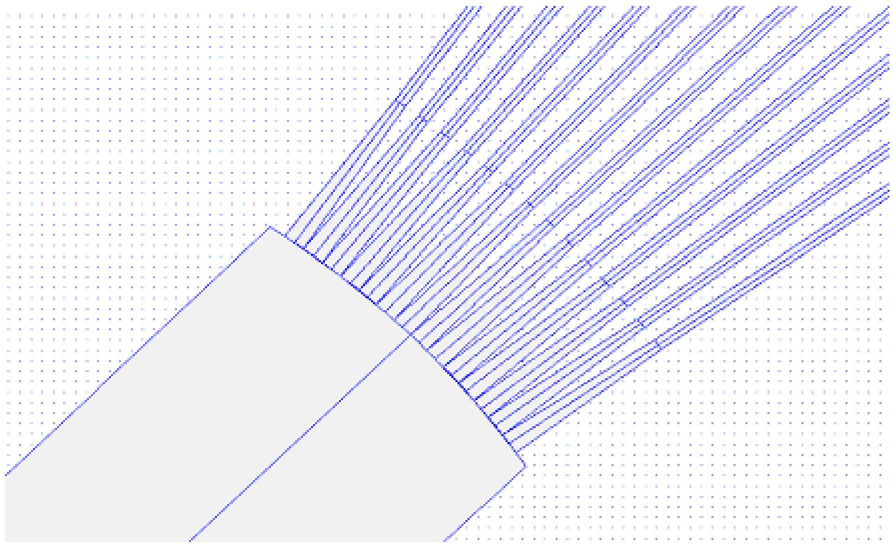
The insertion loss of phasar arrays can be reduced by tapering the waveguides at the ends of the phased array. Consider the end of the input coupler in the file TaperReference.wdm. When the light gets to the end of the input coupler, it is almost a plane wave that must be launched into waveguides. The optical fields of the waveguides overlap somewhat, but still there will be losses as some of the light will fail to enter the waveguide modes.

Figure 1 Phasar arrays



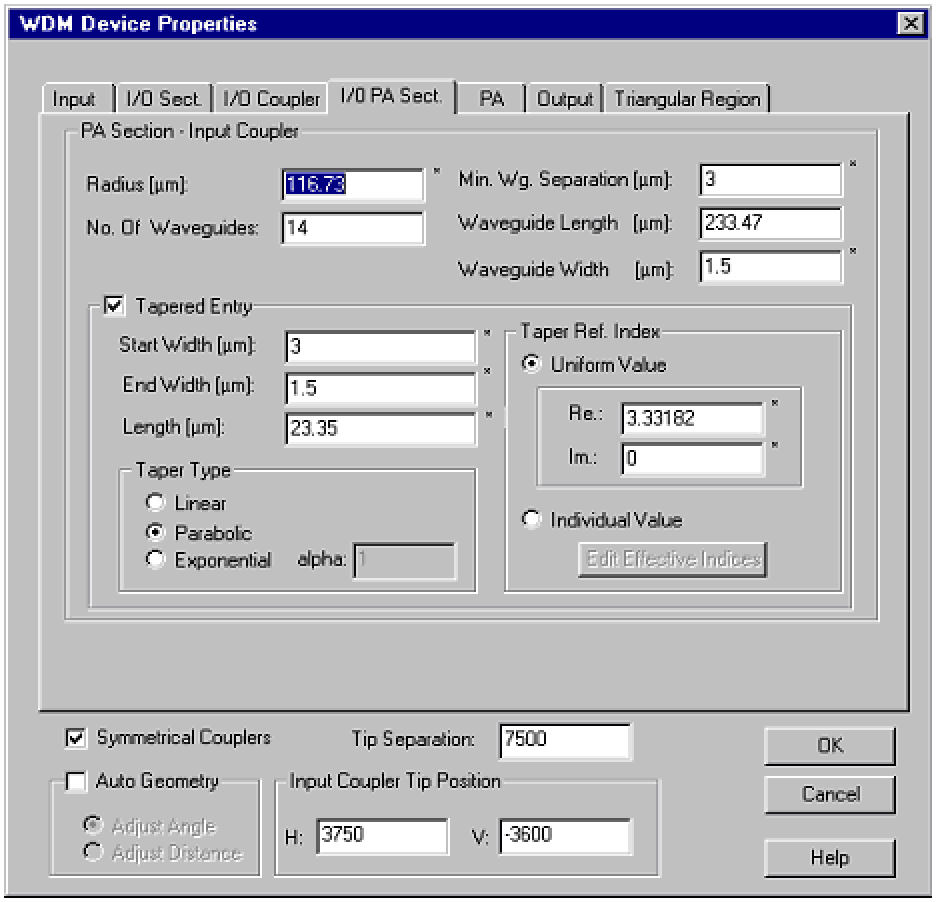
The losses can be reduced by tapering the ends of the waveguides. This makes a smoother transition, as seen in **`Taper.wdm`**:

Figure 2 Tapering the ends of the waveguides



The tapers are created by first selecting the device, and then opening the WDM Device Properties dialog box (Edit>>Properties…>>I/O PA Sect.). Enable the Tapered Entry checkbox, and enter the refractive index of the tapered waveguide, its length and starting and ending widths. The taper can be linear, parabolic, or exponential. The parabolic taper is specified from these data by setting the slope of the boundary tangent to the connecting waveguide. The exponential taper is not constrained this way, but needs the user to specify the constant (called "alpha") used in the exponential.

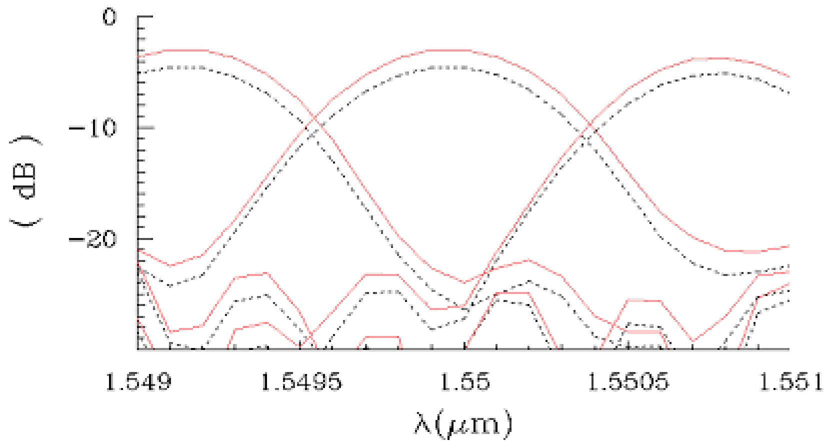
Figure 3 Creating the tapers



In **`TaperReference.wdm`**, the distance between the waveguides at the coupler was 3.0, so setting the start width to 3.0 completely fills the end of the coupler.

The simulator is run for both **`Taper.wdm`** and **`TaperReference.wdm`**, and the results compared. **`TaperReference.wdm`** is shown in black dotted lines and **`Taper.wdm`** in red solid lines. The taper doesn't change the device performance, except for the insertion loss, which is reduced equally for each channel and wavelength.

Figure 4 Comparing simulation results — TaperReference.wdm and Taper.wdm

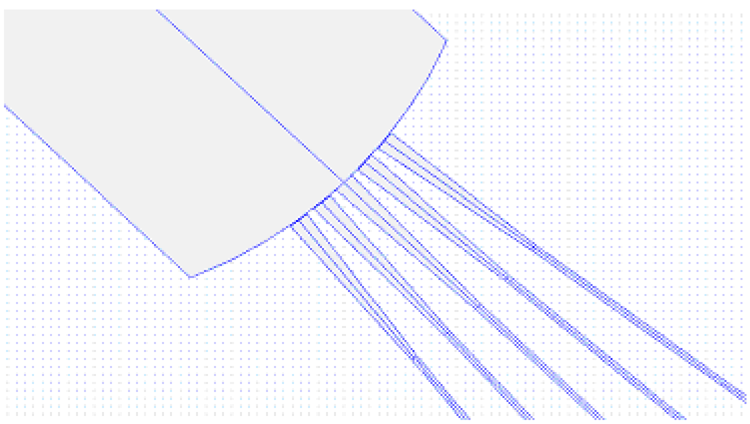


Example 2: Tapers in the output waveguides

Reference files: `TaperFlatRef.wdm, TaperFlat.wdm`

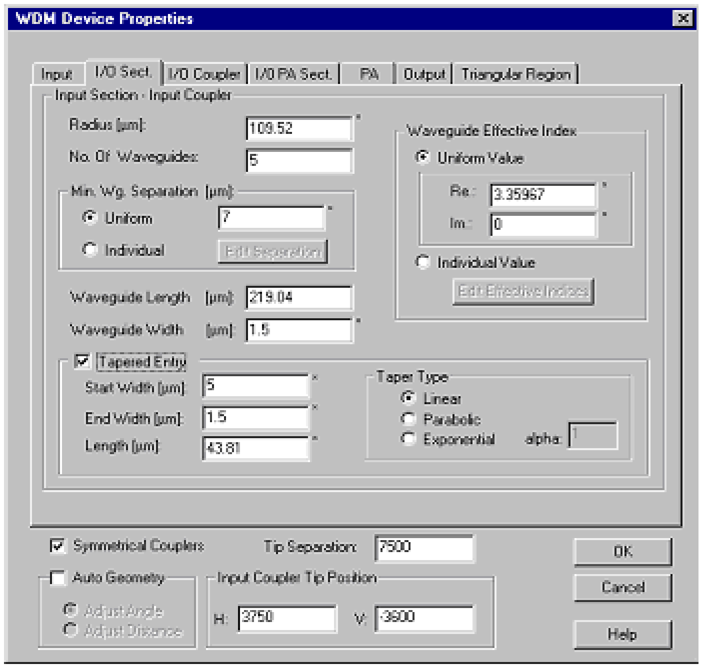
A taper in the output waveguide can also reduce the insertion loss. This taper will increase the effective width of the receiver, which will increase the range of wavelengths coming into the channel. This is an advantage in the case where a wider bandwidth of the signal channel, or a flatter passband, is desired. For example, the two phasar arrays above are identical except that the second one has tapered output waveguides:

Figure 1 Phasar array with tapered output waveguides



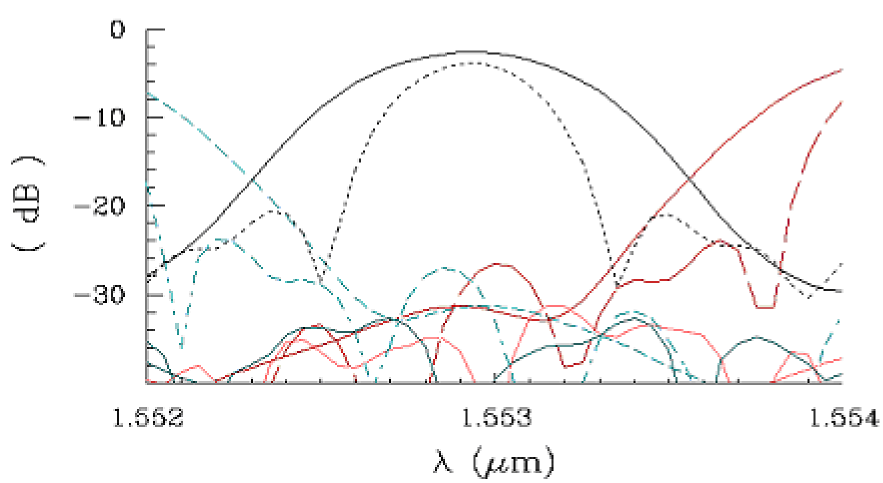
These tapers are made by using the WDM Device Properties box (Edit>>Properties…>>I/O Sect.). Enable the Tapered Entry checkbox, and enter the refractive index of the tapered waveguide, its length and starting and ending widths. The taper can be linear, parabolic, or exponential. The parabolic taper is specified from these data by setting the slope of the boundary tangent to the connecting waveguide. The exponential taper is not constrained this way, but needs the user to specify the constant (called "alpha") used in the exponential. Here the linear taper has been used.

Figure 2 Linear taper used as the constant



The result of the simulation is shown for the two phasar arrays. The curves centred at 1.553 show the power in the 3rd (centre) output waveguide. The dotted line is the phasar device with untapered waveguides. The solid line shows the effect of the taper. The overall insertion loss is reduced, but also the bandwidth of the channels is increased.

Figure 3 Simulation results for the two phasar arrays

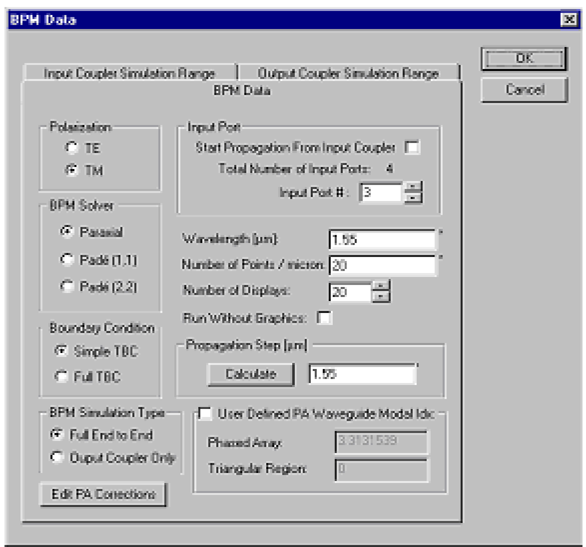


Example 3: Phased array corrections

Reference files: `PAcorRef.wdm`, `PAcorAdv.wdm`

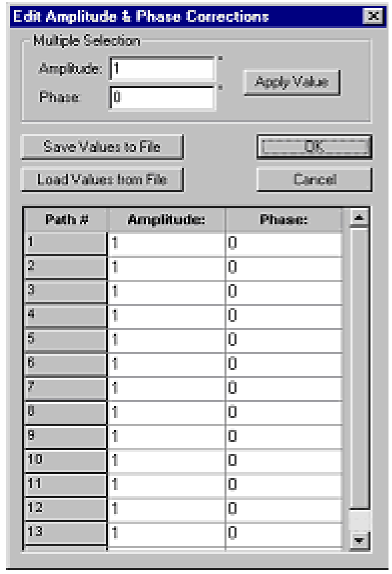
The BPM Data dialog box has a button called Edit PA Corrections which allows the phase and amplitude of the light at the end of the phasar array to be modified. The BPM Data dialog box is reached from the Simulation menu. This feature may be useful if there is some special circumstance that modifies the optical phasars in a known way, and the response of the device needs to be modelled. This feature can also be used to model the effects of fabrication errors in the array, as the effects of a given phase error can be investigated by adding random phases of a given distribution.

Figure 4 BPM Data dialog box — Edit PA Corrections



Clicking on Edit PA Corrections brings up the following box.

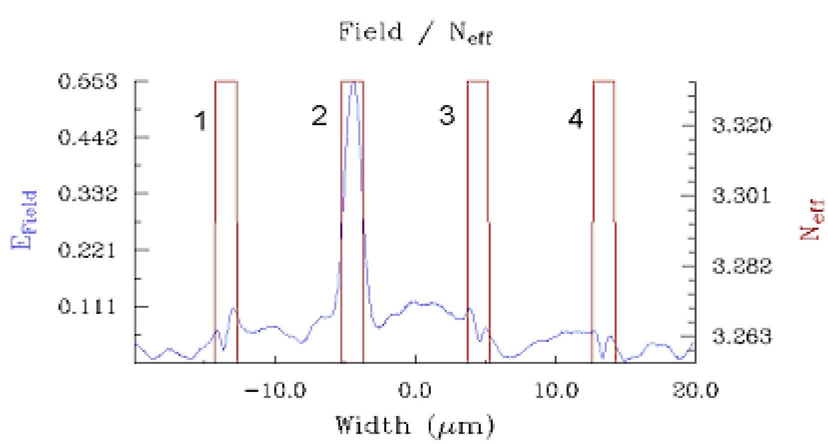
Figure 5 Edit Amplitude & Phase Corrections dialog box



At the end of each phasar waveguide, the optical phasar will be multiplied by the complex number shown in the box. The default value is 1+0j, so by default this box does nothing.

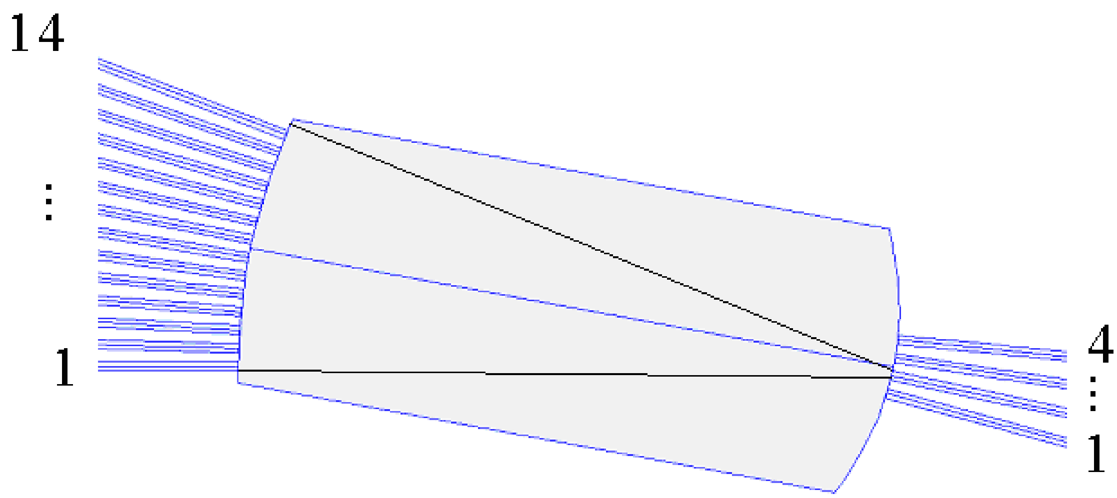
In the example **`PAcorRef.wdm`**, a phasar array is simulated with the following output.

Figure 6 Simulated phasar array — PAcorRef.wdm



Most of the optical power goes to the second output channel. The situation in the output coupler is shown below.

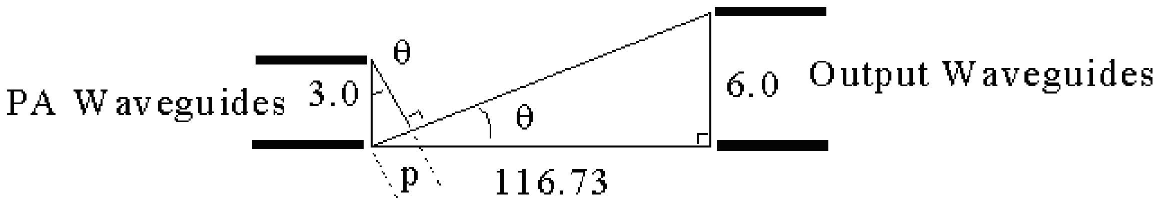
Figure 7 Situation in output coupler



This example will show how to modify the optical phase and amplitude in the phasar array directly. By adding the correct phase advance to each of the 14 waveguides in the phased array, the power can be redirected to output channel 4.

The length of the coupler is 116.73 mm, and the spacing between the waveguides is 3.0 mm. To move the power to channel 4, a deflection of 6 mm is needed. Since the length of the coupler is much longer than the deflection, the curvature of the input and output aperture planes can be neglected. The necessary phase advance can be found from a diagram of adjacent waveguides at the junction with the coupler.

Figure 8 Phase advance



The path length is longer for the lower PA waveguide by a length, p. Therefore the lower waveguide must have a phase advance over the upper one. The length is

$$p = 3\sin\theta \approx 30 \approx \frac{3(6)}{116.73} = 0.1542\mu m$$

The wavelength inside the coupler is

$$\lambda_g = \lambda / n_{FPR} = 1.55/3.332 = 0.465$$

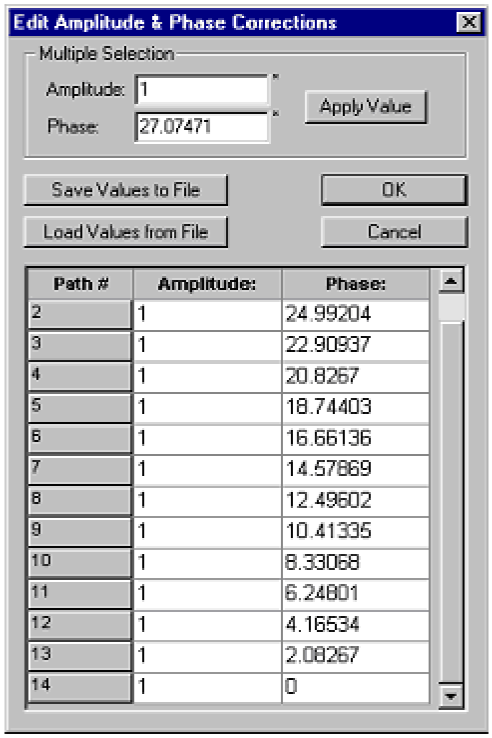
The phase advance is calculated by comparing this wavelength to the path difference

$$\phi = 2\pi\frac{p}{\lambda_g} = 2.08267$$

If waveguide 14 is kept the same, then the above phase should be added to waveguide 13. Waveguide 12 needs 2ϕ, and so on.

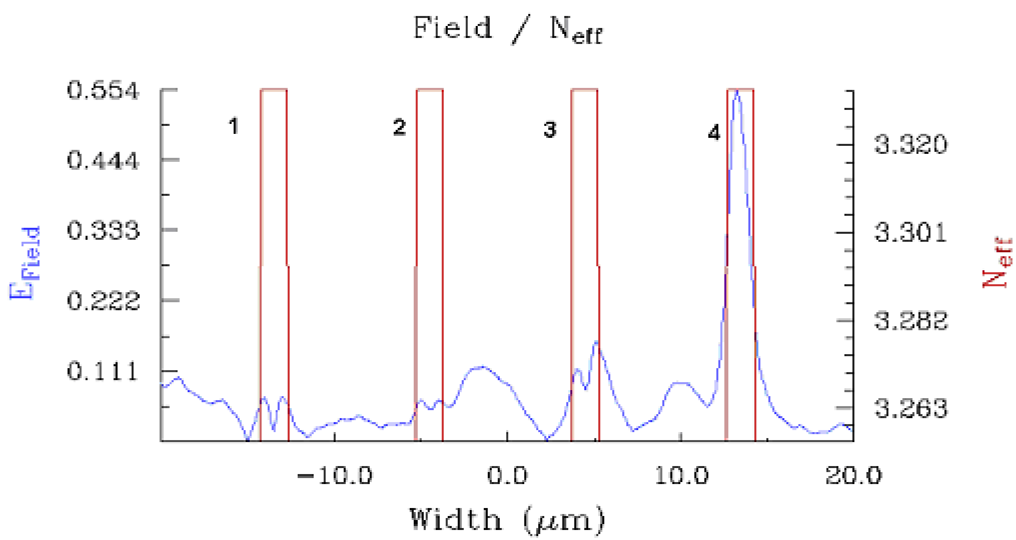
`PAcorAdv.wdm` is the same as **`PAcorRef.wdm`** except that the Edit Amplitude and Phase Corrections dialog box has the phase corrections as described above.

Figure 9 Phase corrections for PAcorAdv.wdm



When a simulation is run from PAcorAdv.wdm, the result of the calculation shows the power moves to the fourth channel, as expected.

Figure 10 Result of the simulation calculation



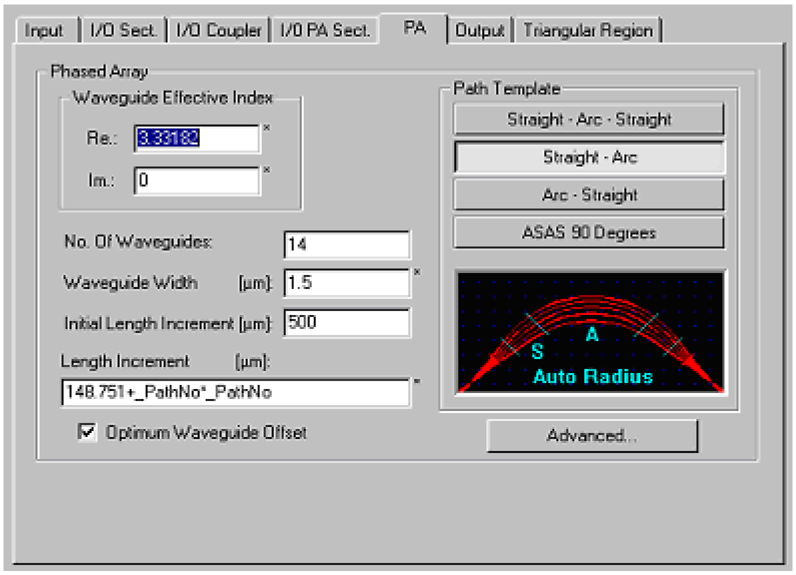
The amplitudes of the optical phasars in the phasar array may be modified as well, if desired.

Example 4: Phased array with variable increment in the path length

Reference file: `VarIncr.wdm`

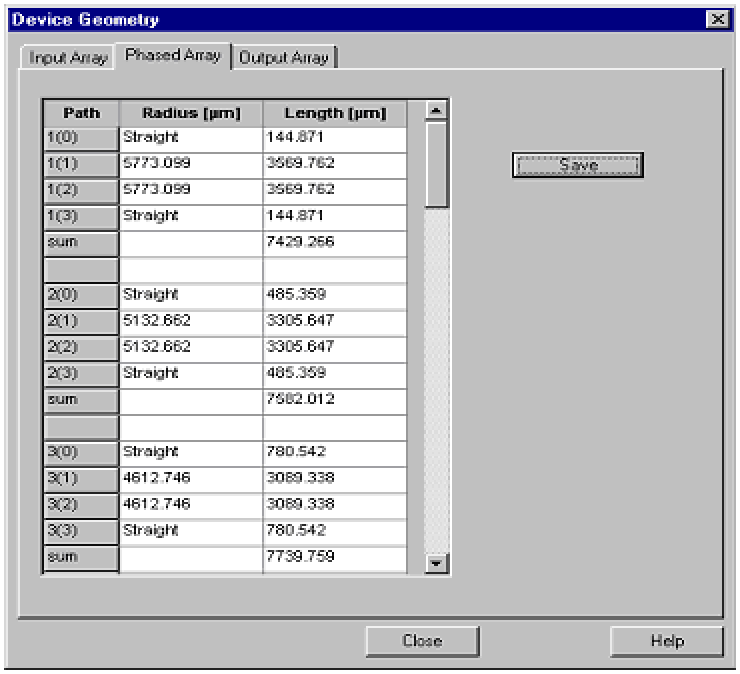
The phasar array in **`VarIncr.wdm`** has the path number index in the specification of the length increment. This allows the length increment to be specified by a user defined formula. A simple example is shown in the WDM Device Properties box (Edit>>Properties…) of the file **`VarIncr.wdm`**.

Figure 1 Example of VarIncr.wdm



The actual lengths of the waveguides in the phased array can be seen in the Device Geometry dialog box (Performance>>Device Statistics>>Device Geometry…>>Phased Array)

Figure 2 Device Geometry dialog box



To get the path increment for the second waveguide, the program calculates the length increment for path 2 as

$$148.751 + 2*2 = 152.751$$

Then this increment is added to the first path length, 7429.266, to get the length of waveguide 2, 7582.017. The difference between this value and the one shown in the box is due to the precision (tolerance) of the WDM_Phasar layout, which is about ±10nm.

The path increment for the later waveguides is calculated in a similar way.

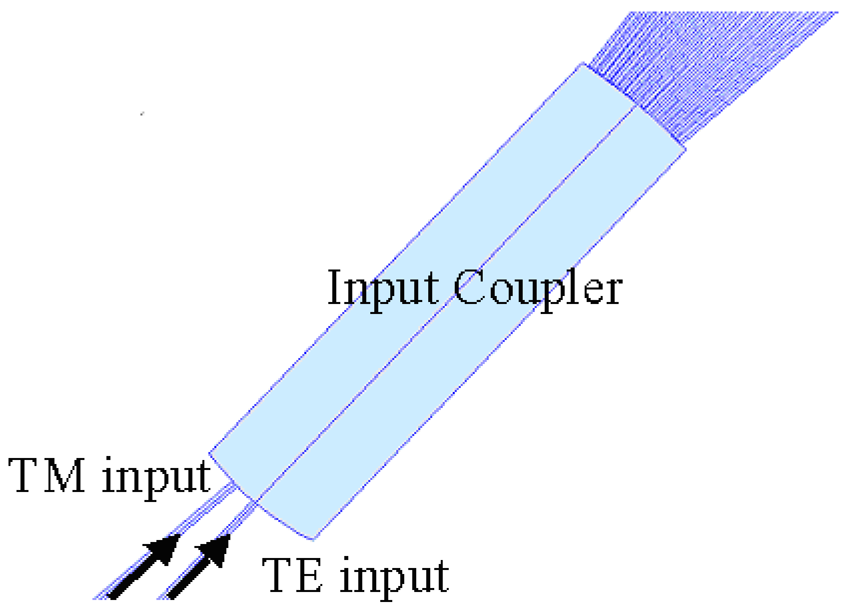
Notes

Example 5: Polarization independent device by splitting the input

Reference files: `PolSplitTE.wdm, PolSplitTM.wdm`

The response of a simple phasar array will depend on the polarization of the light. The dependence is a result of the dependence of the modal index of planar waveguides on polarization. One way to reduce the effect of the polarization of the input light is to split the input signal into horizontal and vertical components before it is sent to the device. The separated horizontal and vertical waves are sent to separate input ports on the device. When they enter the separate planar waveguides, the vertical waves become TM waves and the horizontal ones, TE. The TE and TM waves have different propagation constants on the waveguides, so they accumulate different phases on the phased array, and (in general) focus to different spots at the end of the output coupler. However, the position of the focus at the end of the output coupler also depends on the position of the input waveguide at the beginning of the input coupler. It is possible to arrange the position of the input waveguide of the TE waves and the position of the input waveguide of the TM waves in such a way that they will arrive at the same spot at the end of the output coupler.

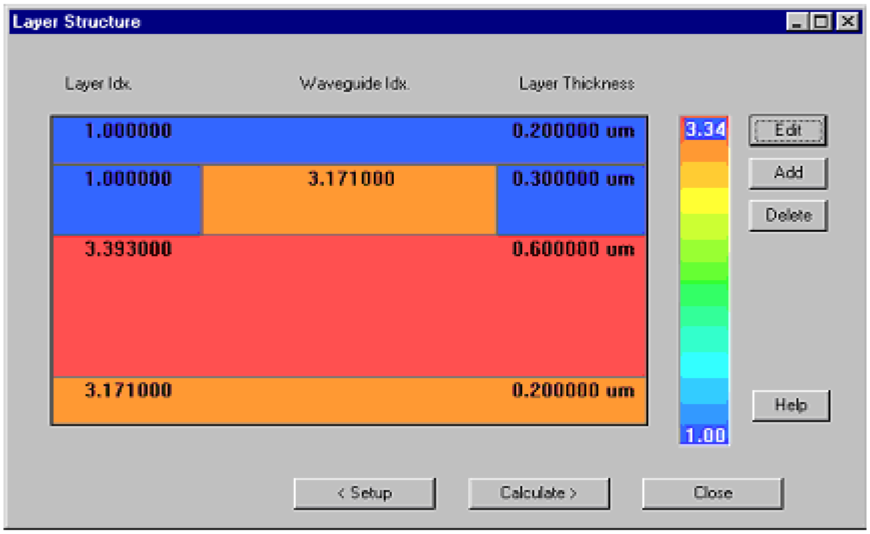
Figure 1 TE and TM waves



The difference in the optical phase accumulated by the TE and TM waves is compensated by the different angle of incidence of the TE and TM waves at the end of the Input Coupler (the beginning of the phased array). See Smit and VanDam, IEEE Journal of Selected Topics in Quantum Electronics, 2(2) p243 (1996) for a discussion of this strategy.

As an example, consider the rib waveguide of width $3\mu m$ at $\lambda = 1.55\mu m$ below.

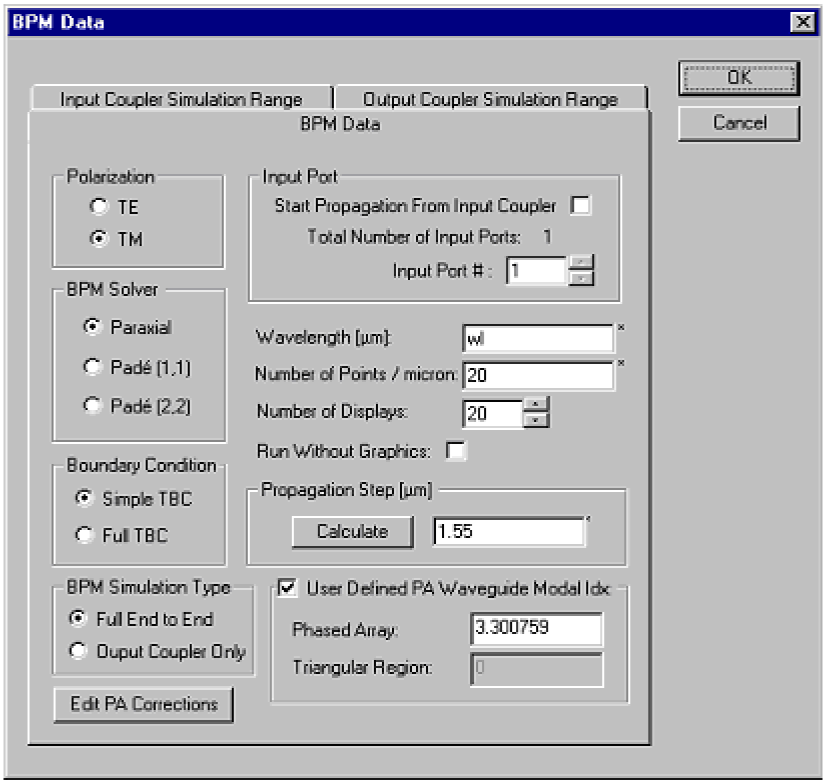
Figure 2 Rib waveguide



The calculation of the modal index of the fundamental mode by the Weighted Index Method is 3.300759 for TE polarization, and 3.292291 for TM.

In **`PolSplitTE.wdm`**, the TE modal index is entered directly through the User Defined PA Waveguide Modal Idx frame of the BPM Data dialog box.

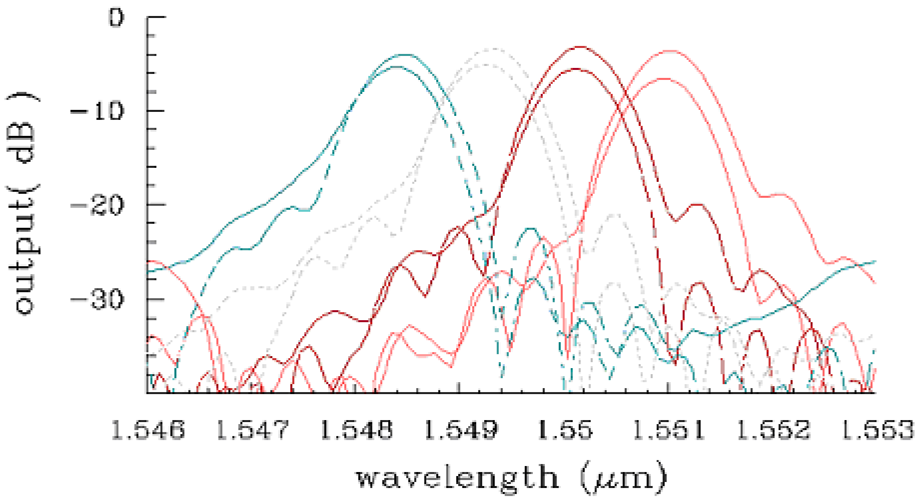
Figure 3 TE modal index



When this simulation is run, the focal point at the far side of the output coupler can be found. Running the same simulation with the TM modal index (and changing the polarization to TE in the Polarization frame) will show where a TM wave would focus, some distance from the TE focus. Since the device is symmetric, displacing the input by the same distance (11.5 mm) will give the same focal point for both TE and TM.

In **`PolSplitTM.wdm`**, the TM path is simulated. Both paths are simulated and scanned in wavelength from 1.546 to 1.553 mm. VIEW2D is used to load both **`.piw`** files, to compare the TE and TM response.

Figure 4 Comparison of TE and TM response



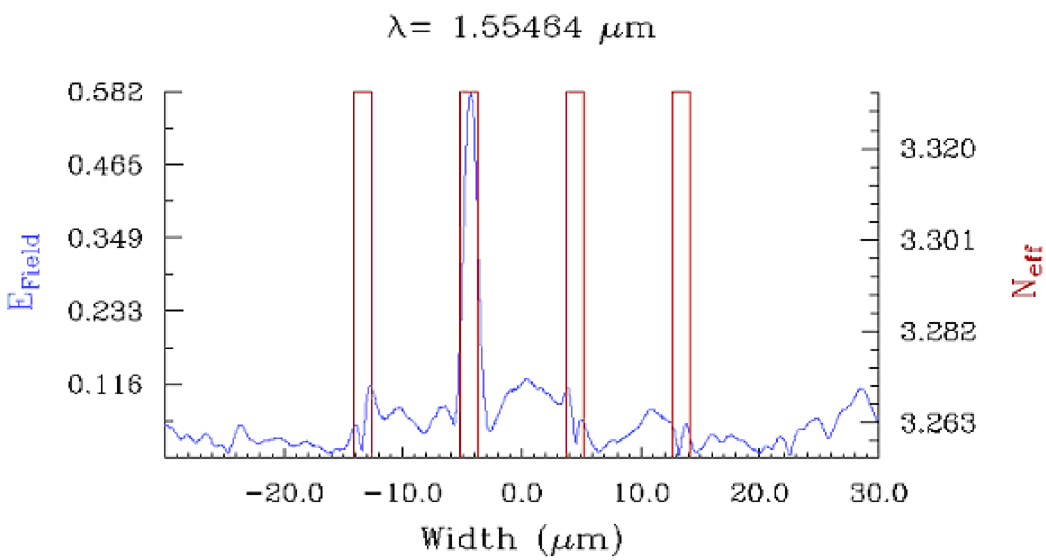
From the above graph we can see that, for example, input light of wavelength 1.550 mm, whether it is horizontally or vertically polarized, will go mostly to the second output channel, with only a small fraction (-20 dB) going to the adjacent channels.

Example 6: Triangular region in the phased array

Reference files: `Triangle.wdm, NoTriangle.wdm`

The phasar array in **`NoTriangle.wdm`** has four output channels spaced at 0.81 nm. As can be seen from running the simulator, light with $\lambda = 1.55464\mu m$ starts from input channel 3 and goes to output channel 2.

Figure 1 Light from input channel 3 to output channel 2



Decreasing the wavelength by 0.81 nm changes the deflection to send the light to output channel 3. The switching can also be induced by a physical change in the waveguide instead of a change in wavelength, as the output is a sensitive function of the propagation constant of the array waveguides.

The optical phase in the ith waveguide of length L_i is:

$$\varphi_i = knL_i \tag{1}$$

where n is the modal index of the waveguides.

The effect of a change in wavelength on the phase of these waveguides is:

$$\Delta\varphi_i = nL_i\Delta\frac{2\pi}{\lambda} \approx -knL_i\frac{\Delta\lambda}{\lambda} \tag{2}$$

Suppose the material index of refraction in the waveguide and substrate can be increased by Δn, (by an electro-optic effect, for example), and that this effect applies on part of the length of each waveguide. For small changes in index, the modal index will change by about the same amount as the material index. Let the fraction of distance on each waveguide where the index is changed be represented by the dimensionless parameter, x. The change on the optical phase due to the change in refractive index is:

$$\Delta\varphi_i = xkL_i\Delta n \tag{3}$$

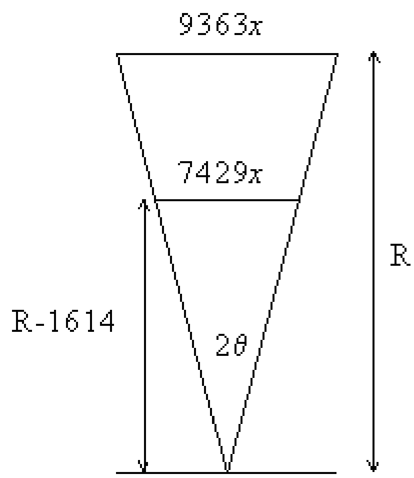
In order to simulate a change in wavelength by a change in refractive index, the change should be applied over a limited fraction of the total length of the waveguides, x. By equating Equation 2 and Equation 3,

$$x = -\frac{n\Delta\lambda}{\lambda\Delta n} \tag{4}$$

Suppose the change in index of the core and cladding of the equivalent waveguide is $\Delta n = 0.01$. In **`NoTriangle.wdm`**, the modal index is 3.313 (this number can be seen in grey in the BPM Data dialog box). Using the values of λ and $\Delta\lambda$ above gives the required fraction of length to apply the change in index, x = 0.173.

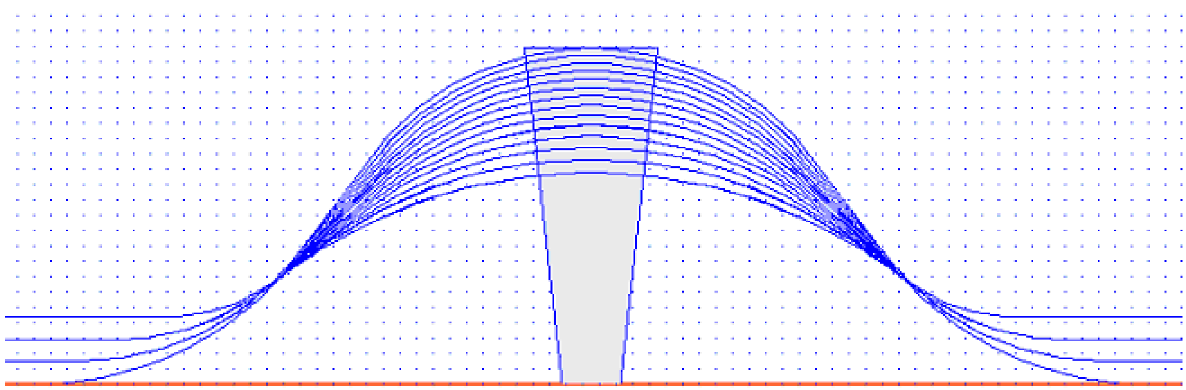
The Phased Array tab of the Device Geometry box (reached from Performance>>Device Statistics>>Device Geometry>>Phased Array) indicates the length of the first and last waveguides in the phased array. These are given as $L_1 = 7429\mu m$ and $L_{14} = 9363\mu m$ respectively. The change in index will have the same effect as the change in wavelength if the index change is applied for xL_i for each of the waveguides $1 \le i \le 14$. This can be achieved by defining a triangular shaped region, as shown in **`Triangle.wdm`**. At the top of the phasar array, the first and last waveguides are separated by a distance of $1614\mu m$, so if the apex of the triangle is placed the appropriate distance R from the last waveguide, the index change is equally graded over the waveguides.

Figure 2 Index change over waveguides



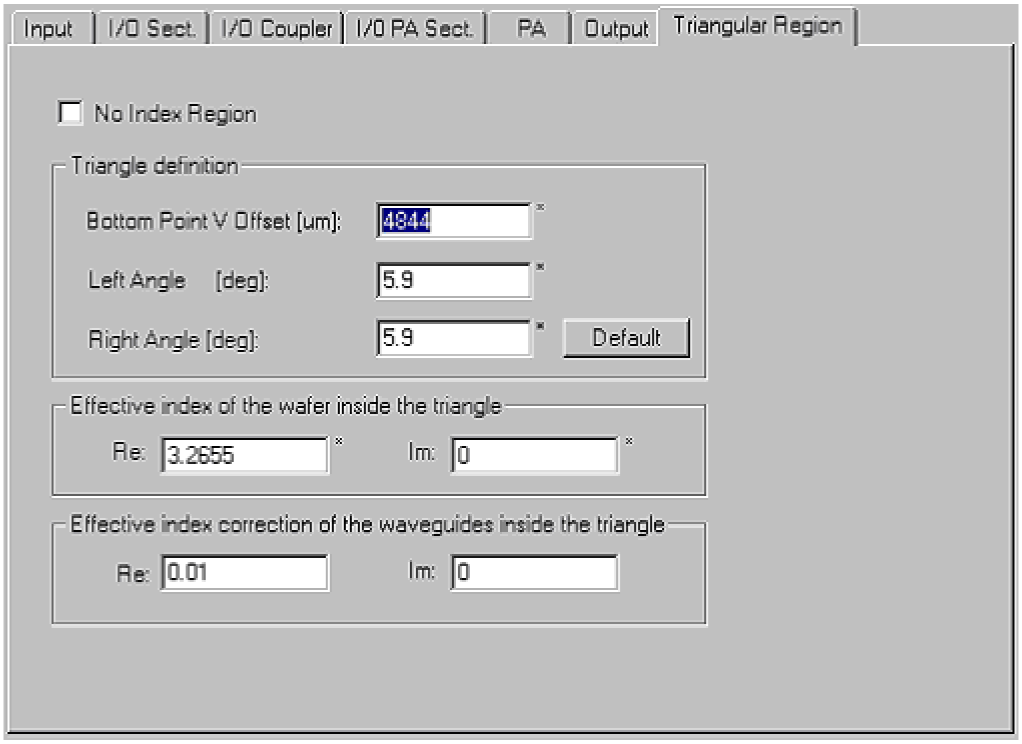
Solving for R gives $R = 7814$ and $\theta = 5.9°$.

Figure 3 Solution for R



The triangular region is set up in **`Triangle.wdm`**. The Triangular Region tab in the WDM Device Properties box (Edit>>Properties…) shows the parameters defining the size and location of the triangle: the two interior half angles and the offset needed to make the height equal to 7814 mm.

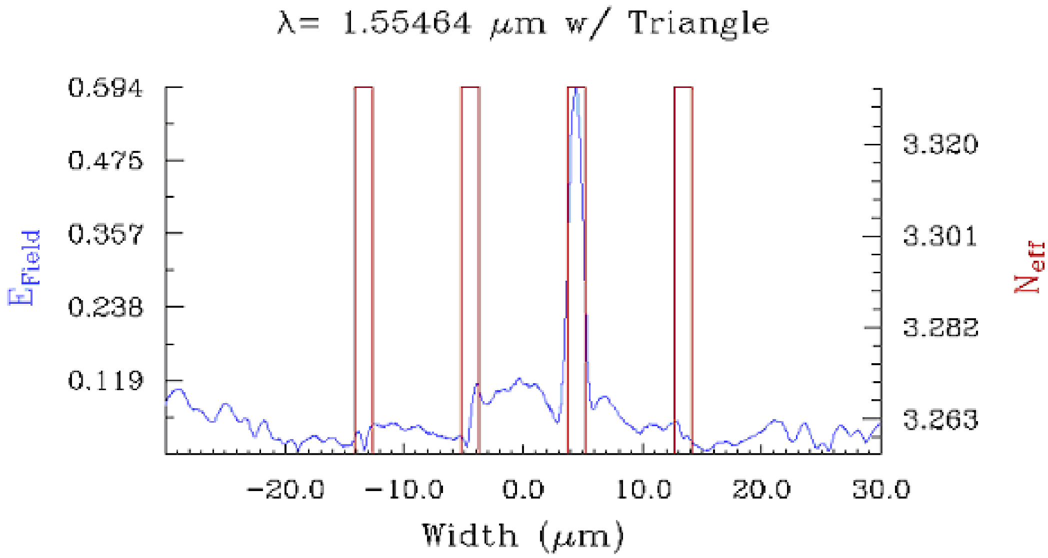
Figure 4 Parameters defining size and location of triangle



The modified physical parameters are also shown. The effective index of the wafer inside the triangle is increased by 0.01 over the default wafer value, and the correction 0.01 has been added to the index of the waveguide itself.

Running the simulation shows that, with the triangular region, the light is diverted from channel 2 to channel 3.

Figure 5 Light diverted from channel 2 to channel 3



Notes

Appendix 1: Parameter Atlas

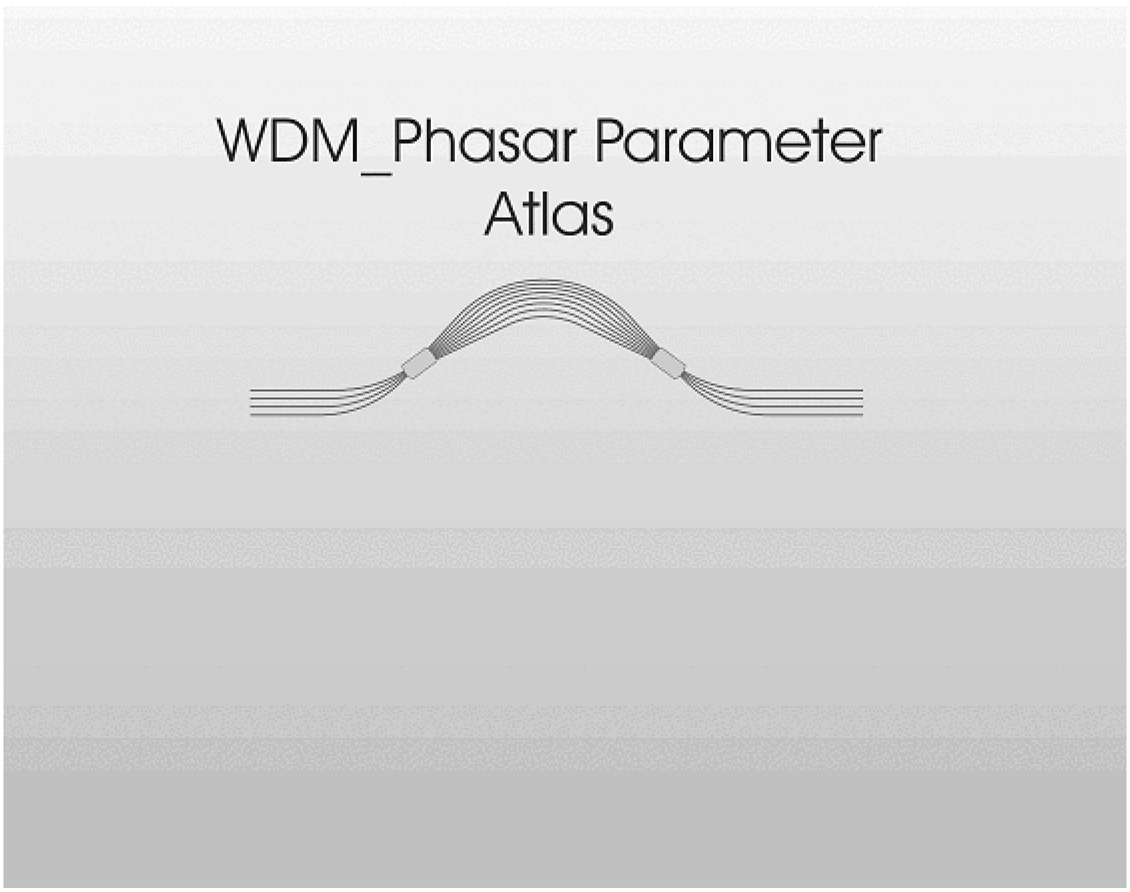


Figure 6 Overview

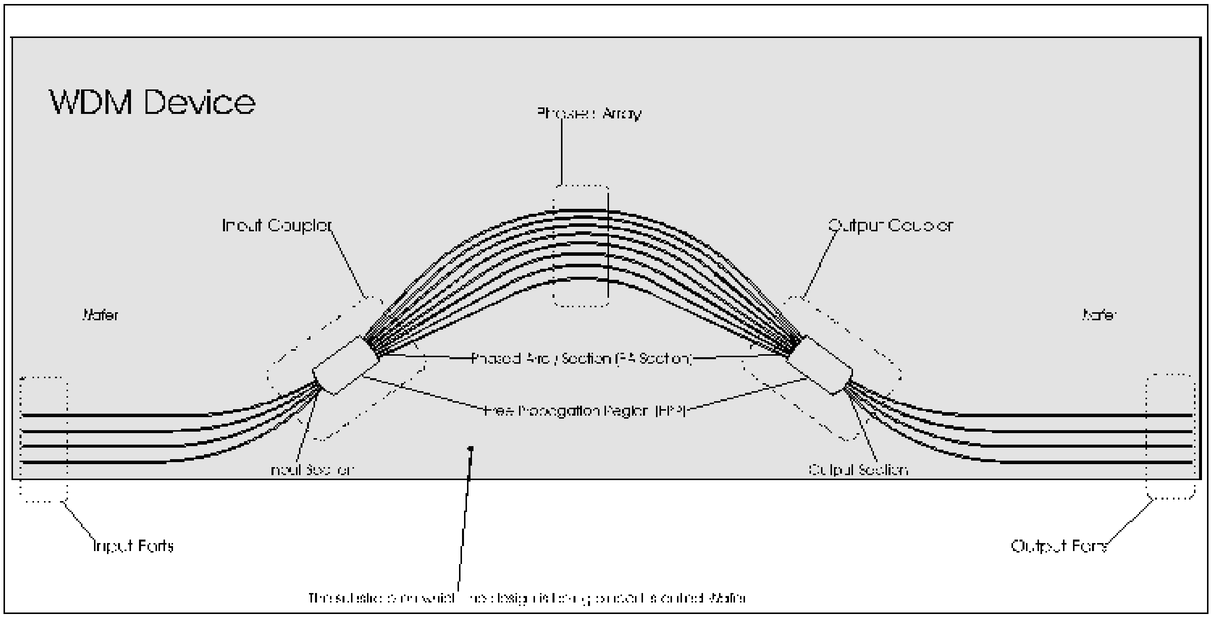


Figure 7 WDM Device- Input ports

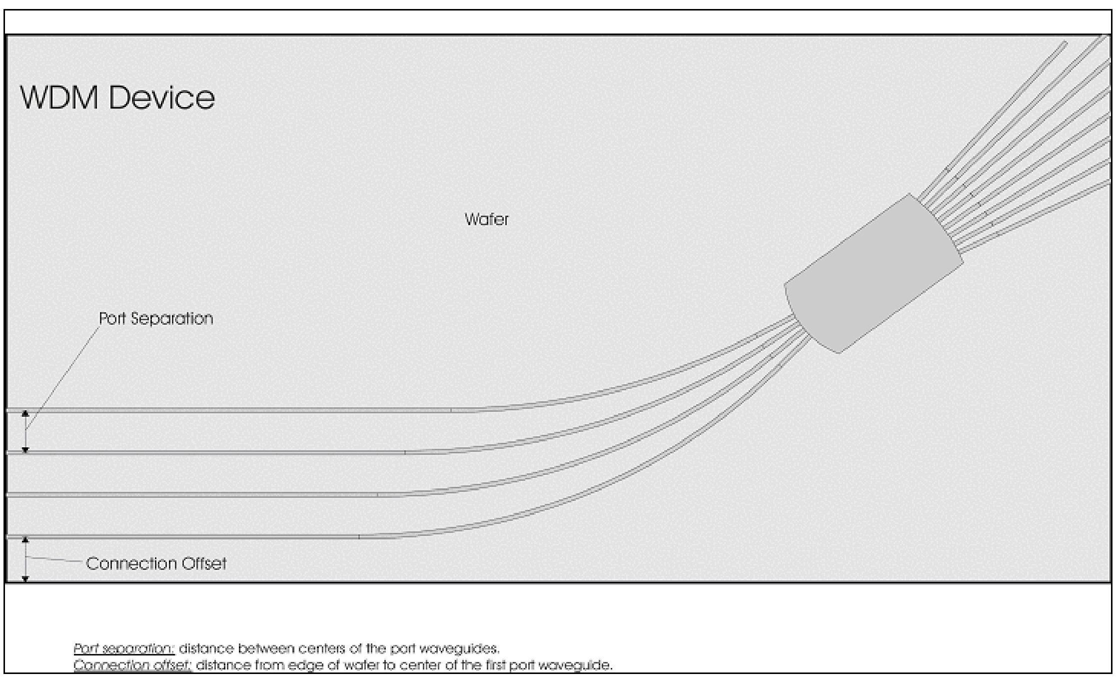


Figure 8 WDM Device - Input Coupler

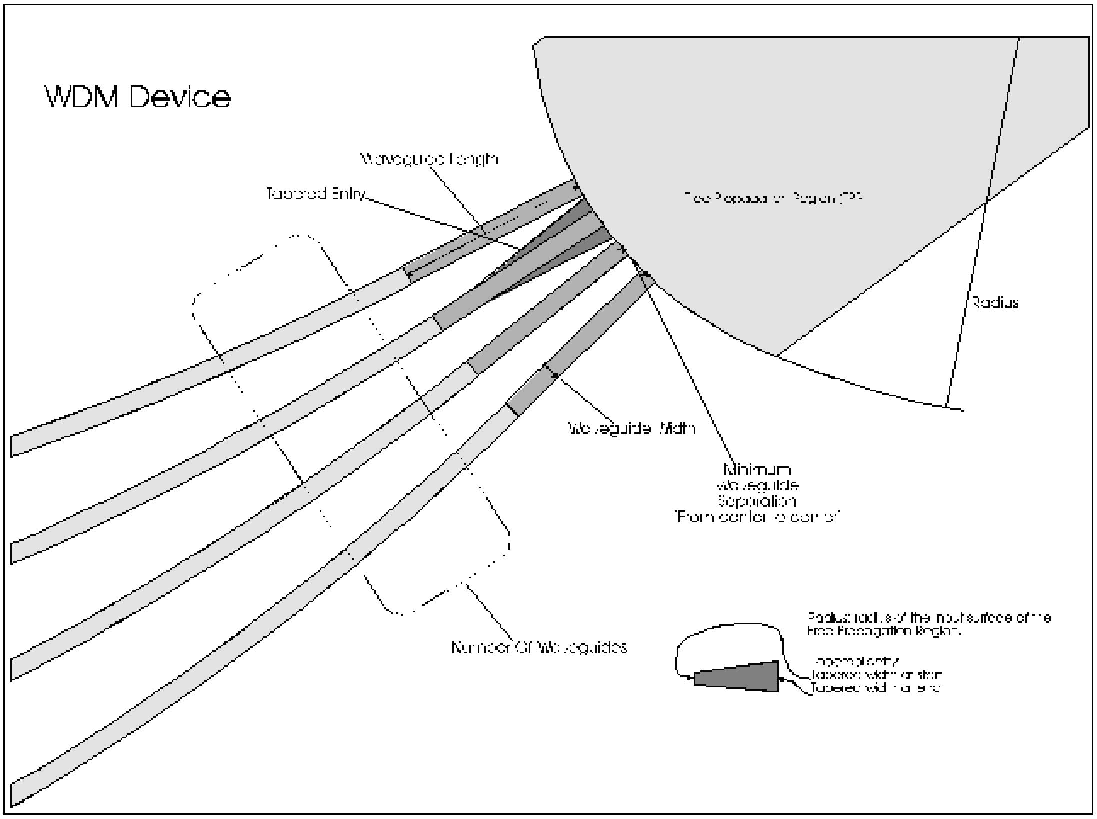


Figure 9 WDM Device - Output Coupler

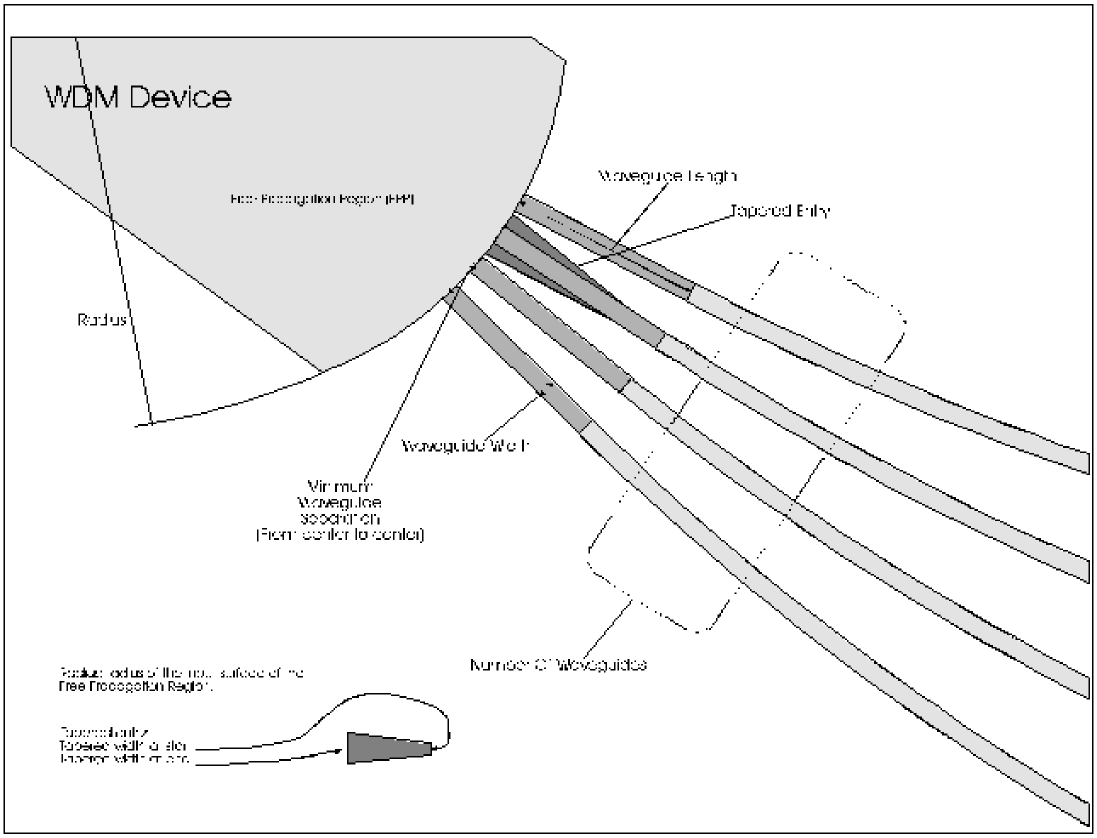


Figure 10 WDM Device - Input Coupler Free Propagation Region (FPR)

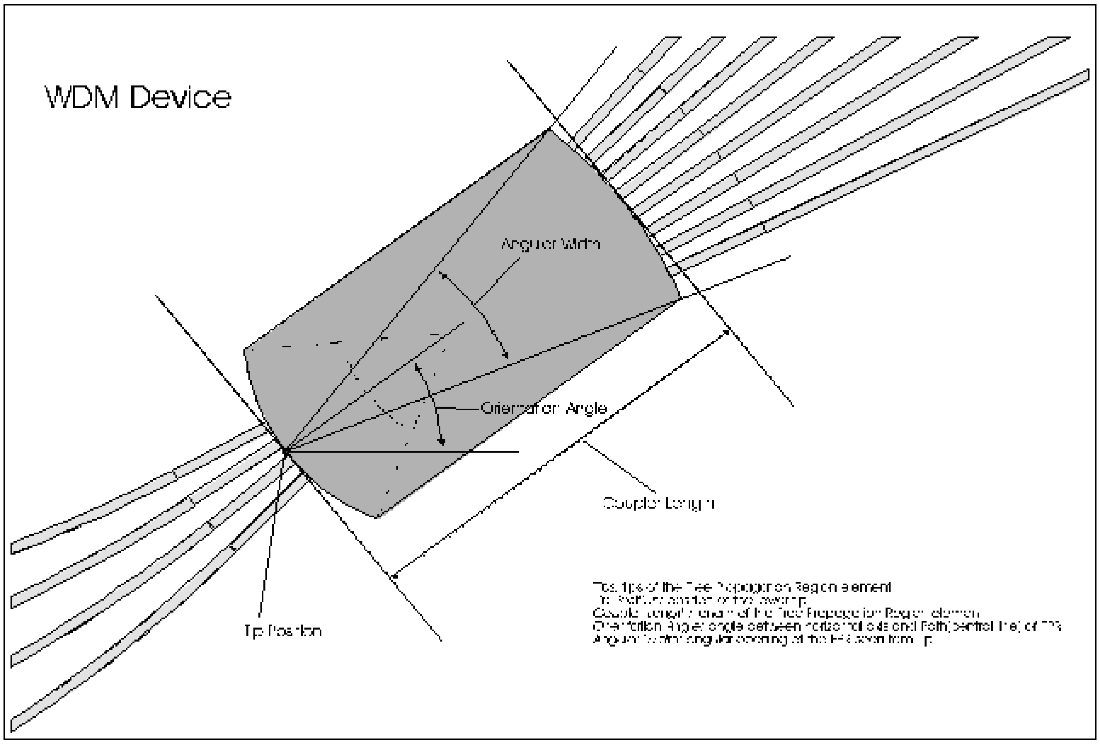


Figure 11 WDM Device - Output Coupler Free Propagation Region (FPR)

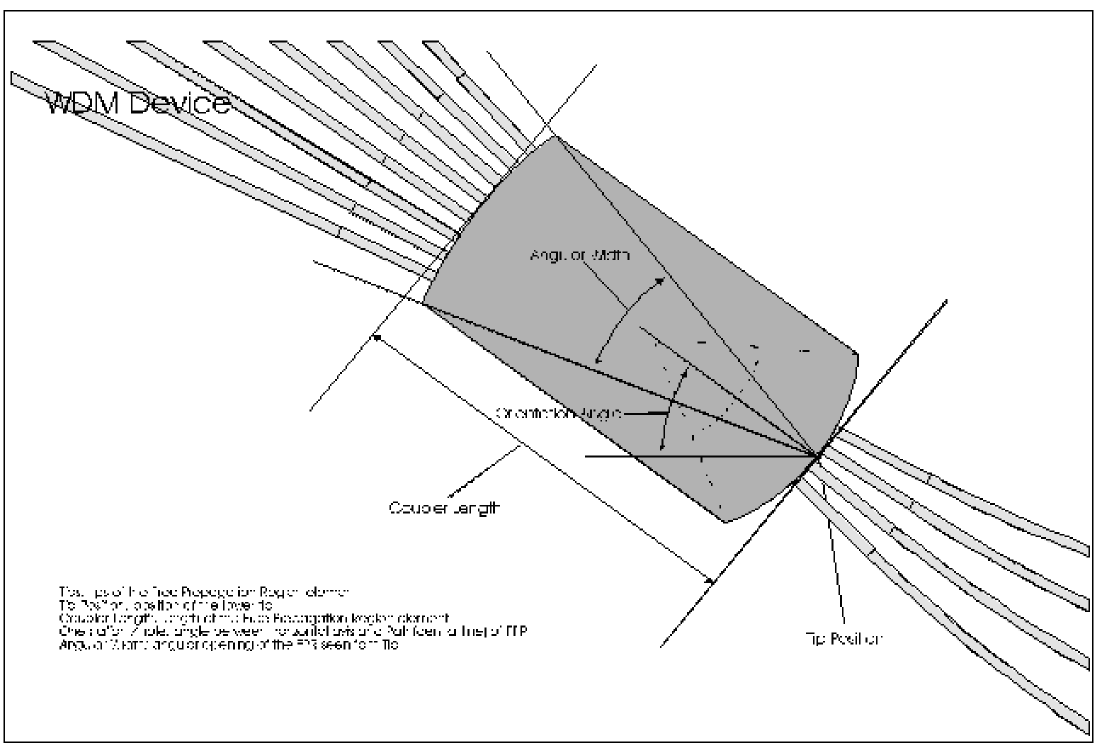


Figure 12 WDM Device - Phased Array Section Input Coupler

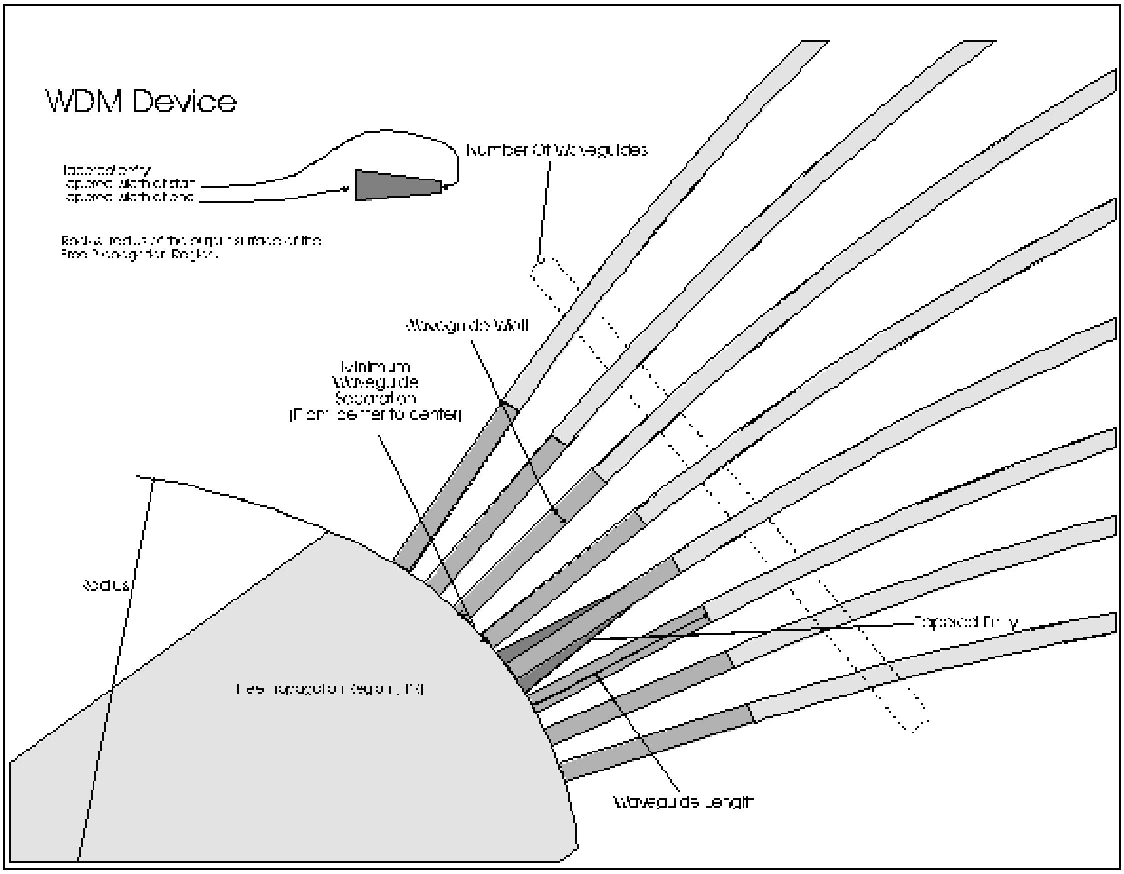


Figure 13 WDM Device - Phased Array Section Output Coupler

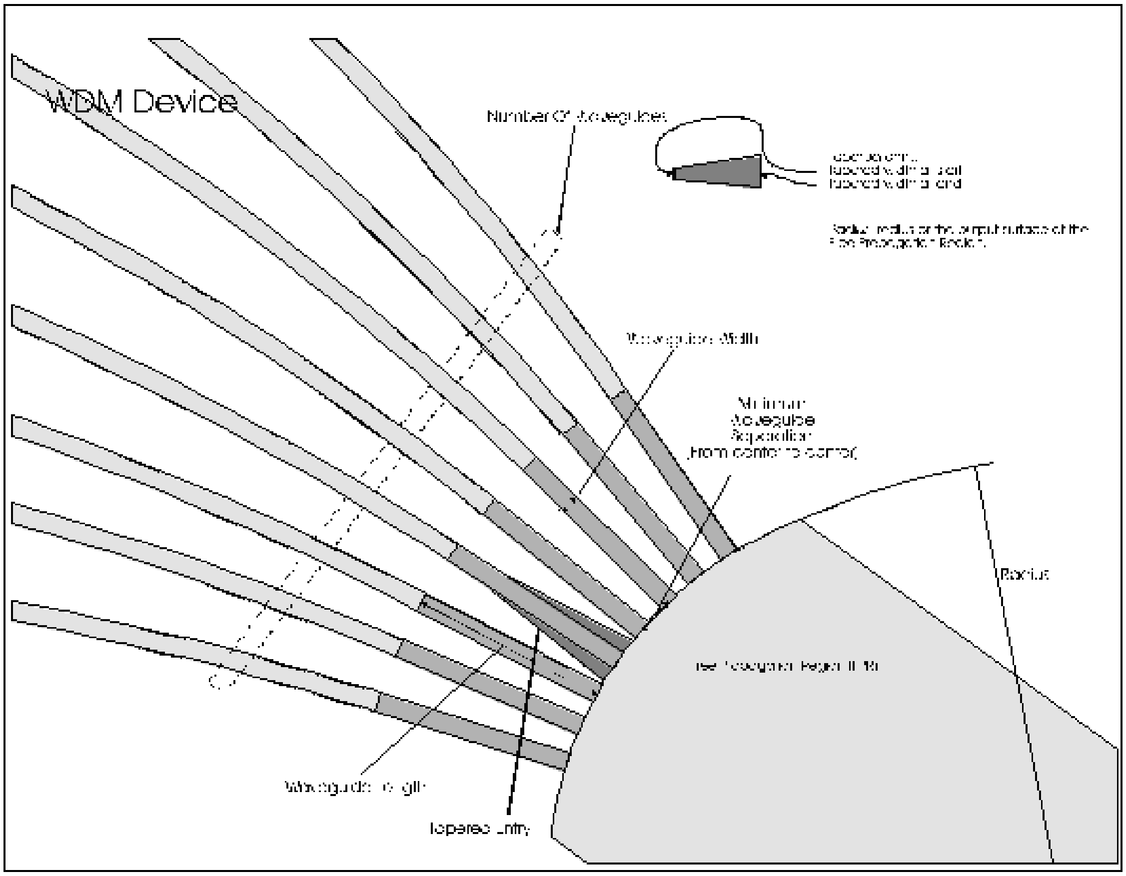


Figure 14 WDM Device - Output Ports

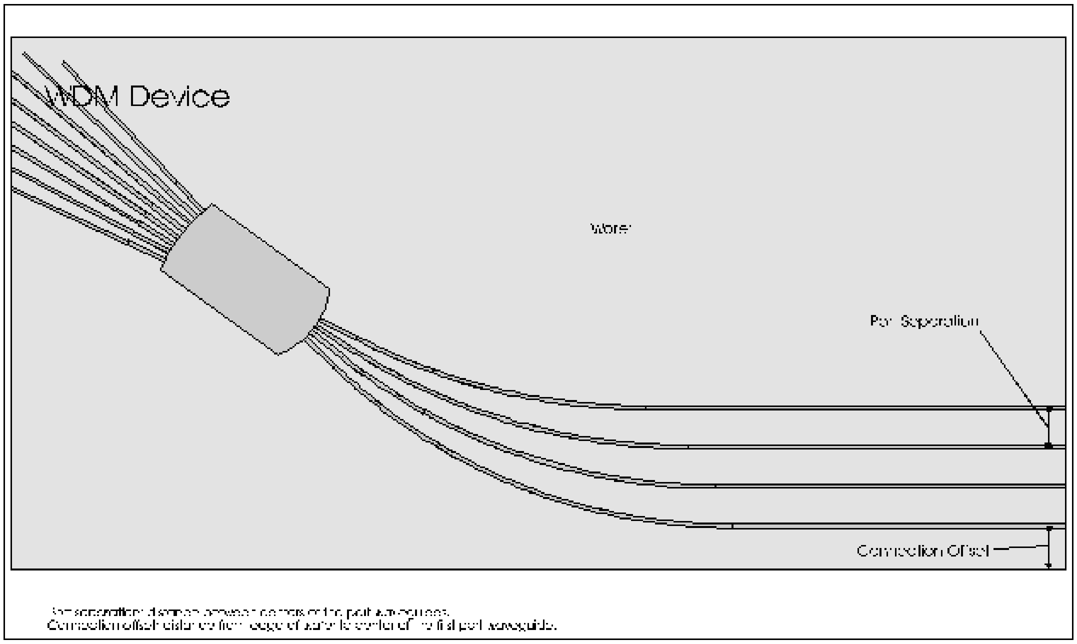
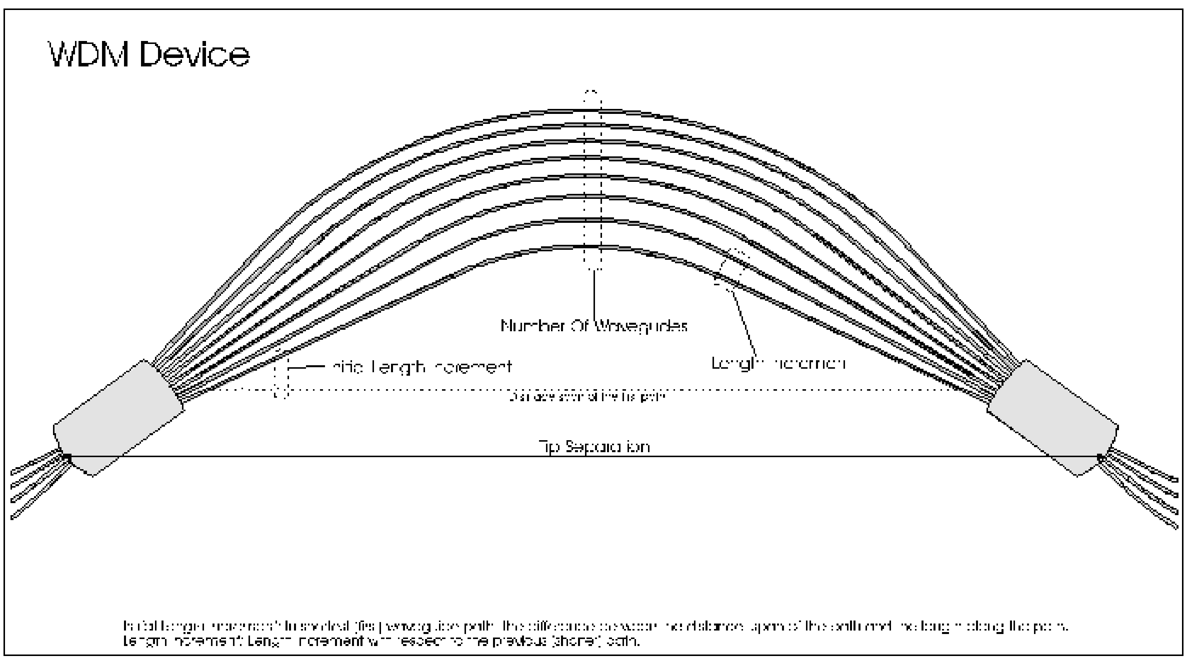


Figure 15 WDM Device - Phased Array



Appendix 2: Phased Array Templates

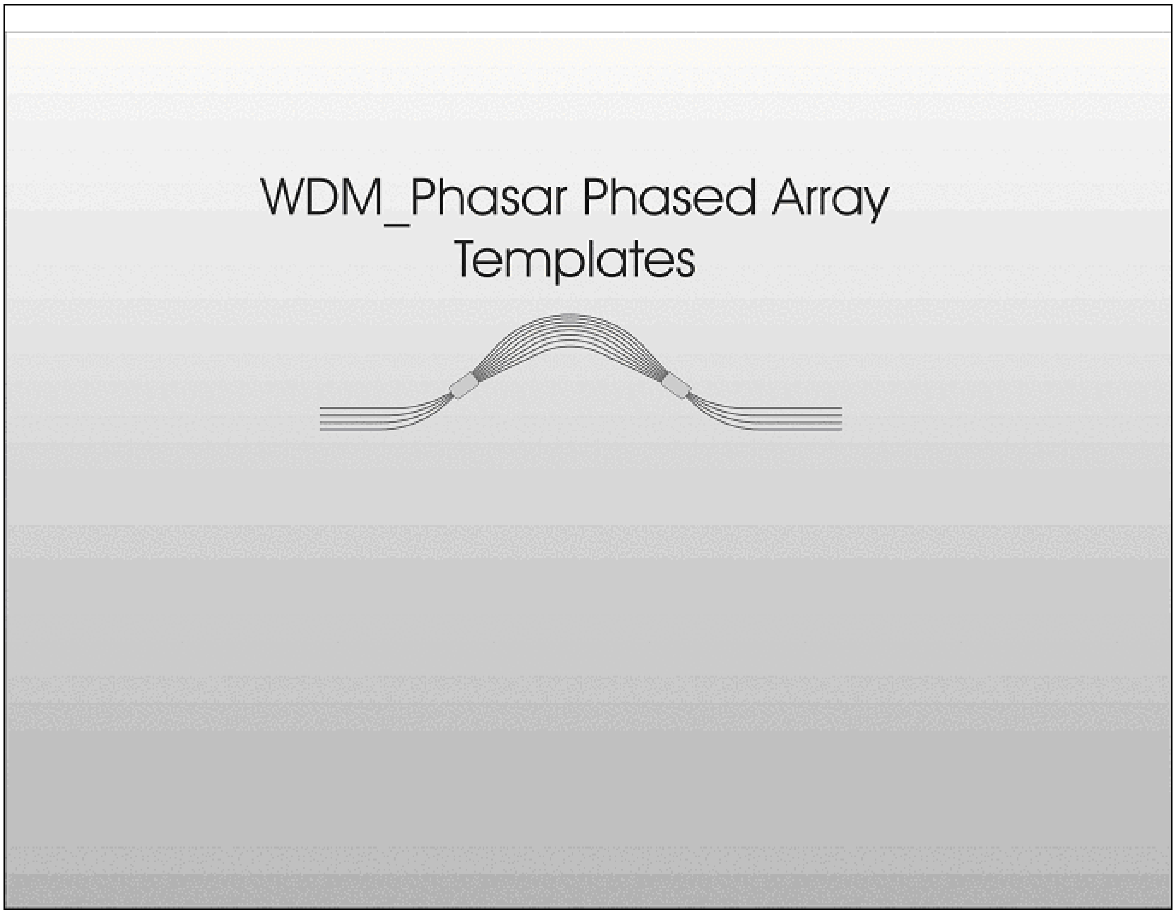


Figure 1 WDM Device - Straight Arc Straight template

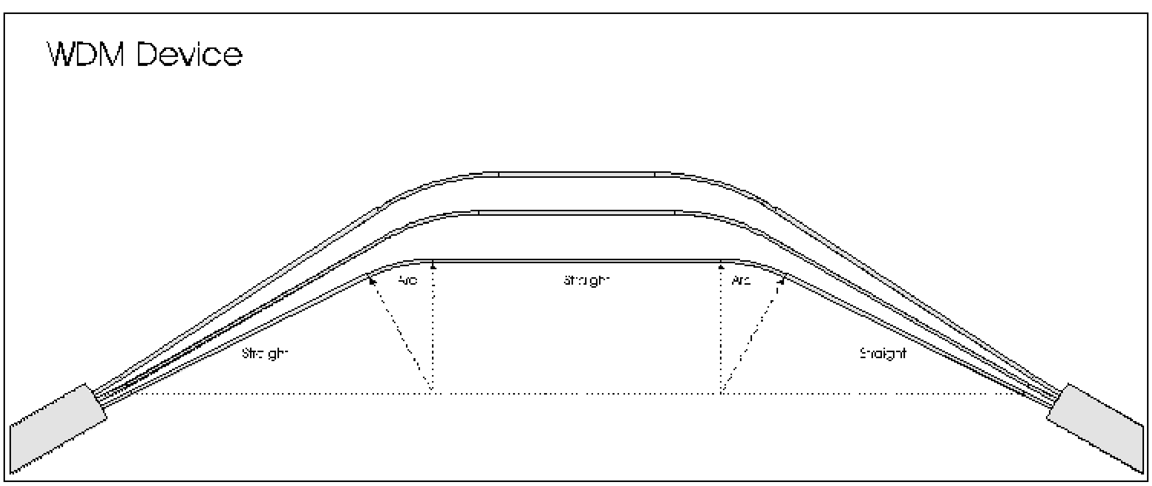


Figure 2 WDM Device - Straight Arc template

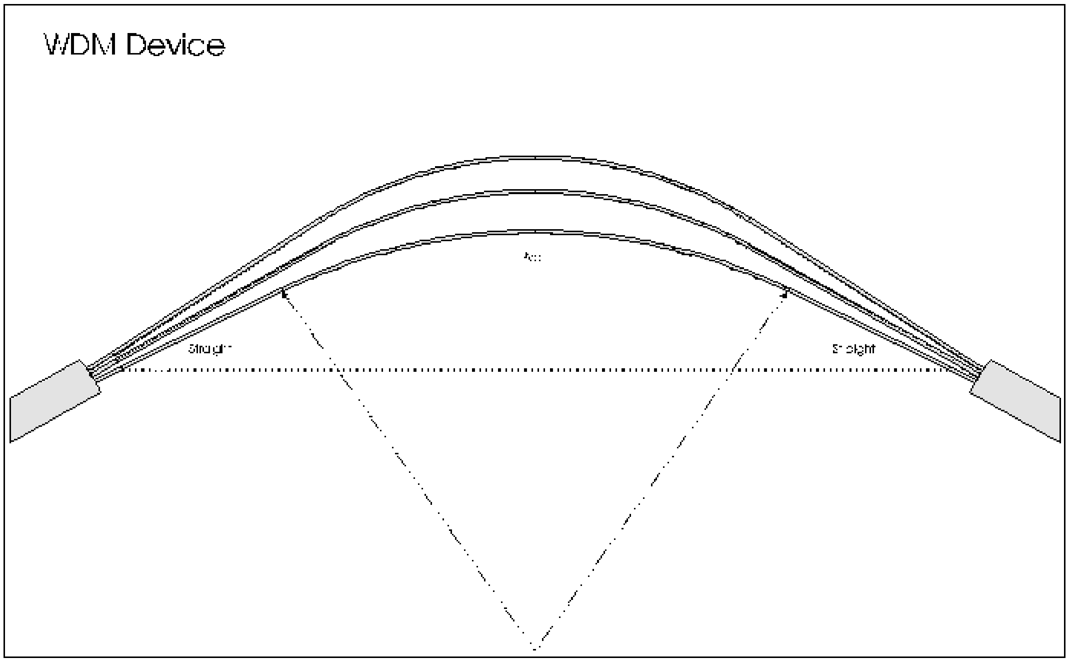


Figure 3 WDM Device - Arc Straight Arc template

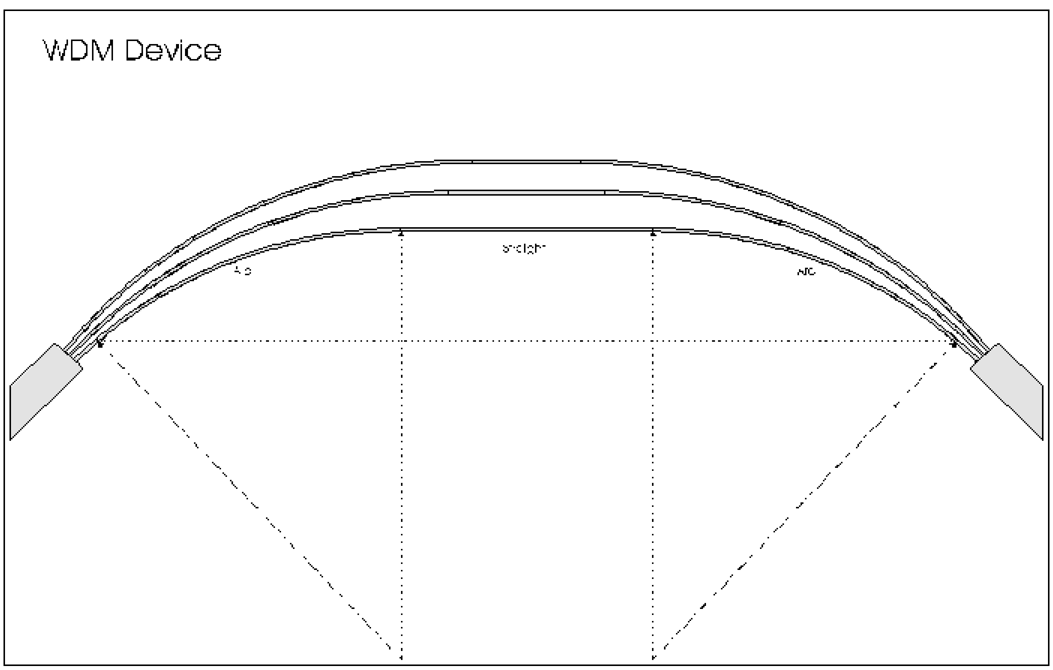
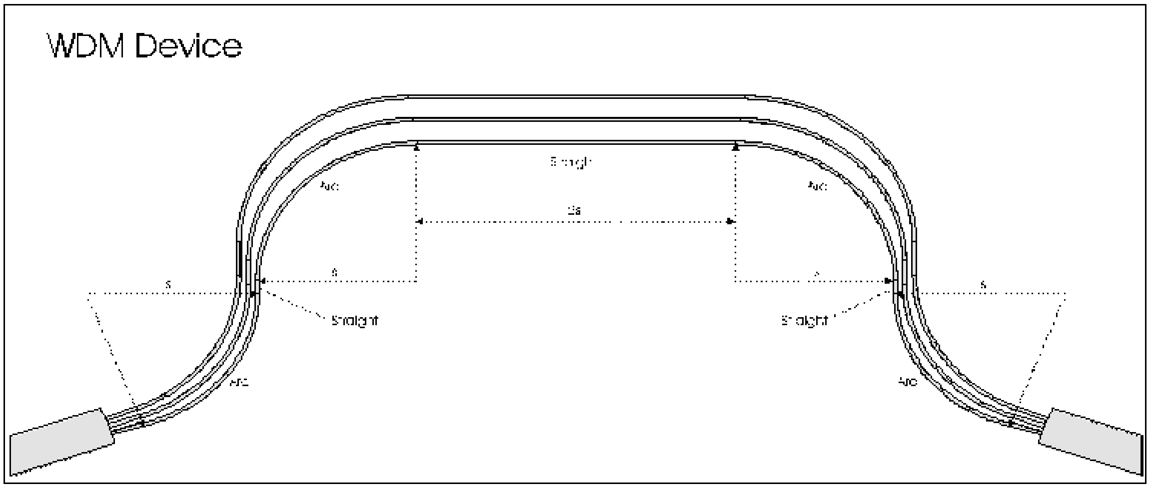


Figure 4 WDM Device - Arc Straight Arc Straight template



Notes

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