Handbook
for
Generic Photonic IC Design

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Appendix D

FIMMWAVE-FIMMPROP Detailed Descriptions

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The approach followed in Chapter 5 is not systematic, but built around a number of practical examples. The descriptions assume that the reader has some basic experience with how to run the programs. In this Appendix more detailed information is given for readers that are not yet familiar with the sofware. The first example is described in great detail, for users without prior experience with the software. Following examples assume that the reader is familiar with the information provided in the previous examples. Reading linearly through the Appendix should make the reader familiar with the calculations for the graphs that are shown in the different chapters of the Handbook and discussed in Chapter 5.

D.1 Planar Waveguide Taper.

Figure 21.5shows the insertion loss of a taper with a taper ratio 1:2 in a (reduced) standard shallow and deep-etched waveguide, as a function of the taper length and the taper angle. With the FIMMWAVE/ FIMMPROP tool the curves can be calculated as follows:

- In the upper bar with icons click the icon **Add Fimmwave Project** (red circled) and name it InP Waveguide Taper. The full icon bar appears when the InP Waveguide Taper project is selected.
- In the **Projects** panel click the project **InP Waveguide Taper** and in the upper icon bar click the icon **Add SWG waveguide** to define the structure of the slab waveguide stack. Name it Waveguide Stack. A node **Waveguide Stack** appears in the Project panel.
- Double click the node **Waveguide Stack**. A window for editing the stack opens. Click the icon **edit structure**. The SWG editor window opens. Click the button

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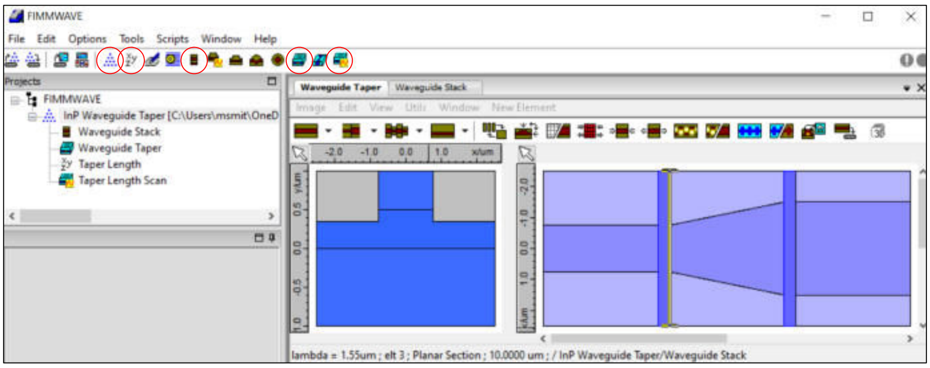

Figure D.1: FIMMWAVE Projects panel

New 4 times to define (from top) the upper medium (air), the upper cladding, the waveguide and the substrate. The four layers appear in the Editor window.

- Enter the thickness and the refractive index for the top layer (t=0, n=1). Double click the other layers and enter (t=0.5, n=3.17) for the top cladding, (t=0.5, n=3.36) for the waveguide layer and (t=1, n=3.17) for the substrate. This is representaive for the standard waveguide in the Smart Photonics platform, but slightly reduced to avoid unnecessary computations in the region without field.

- Click **OK** to close the window. The waveguide structure becomes visible. The top medium (air) is not visible but will become visible when we etch the structure.

- Click the project **InP Waveguide Taper** in the Projects panel and click the icon **Add FIMMPROP Device** to add a taper section. Name it Waveguide Taper. It will appear in the Projects panel.

- Double click the **Waveguide Taper** node in the Project panel. A window **Waveguide Taper** will open. In the icon bar on top of that window open the pop-up menu of the icon **Straight Guide Planar Section** and select the taper icon. A window for selecting the slab waveguide structure pops up. Select **Waveguide Stack** and click OK. The cross-section of the taper (with default etch depth) and the top view become visible.

- Click on the left side of the top view, open the pop-up menu of the icon **Straight Guide Planar Section** again and select the straight section icon. Click OK to close the **MOLAB Options** window and the **Planar Section Editor**. A straight section will be added left of the taper. Click the right side of the taper section and do the same to add a straight section at the right side. Now click on the junctions, open the pop-up menu of the icon **simple joint** and select the simple joint. Click OK to close the Editor window. Do this for both junctions.

- Right click the left section and select **Edit Properties ...**. In the **Path List** click the upper line, set the width to 2 μm, close the **Path Parameters** window and click OK to close the **Planar Section Editor**. Do the same for the right section and set the width to 4 μm. Do the same for the taper section and in the **Path Parameter** window set widthLhs to 2 μm and widthRhs to 4 μm. The lengths of the all the sections is 50 μm by default.

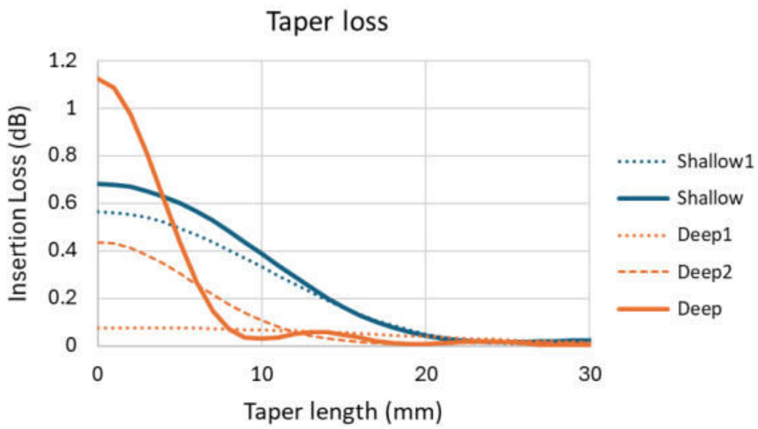

Figure D.2: Taper Loss of shallow and deep tapers, calculated with different settings. **Shallow1** and **Deep1** are calculated with the default settings. **Shallow**, **Deep2** and **Deep** are calculated with improved setting as described in the text. **Shallow** and **Deep** are final results.

- Now we will define the computation window and the etch depth for all sections. Double click the **Waveguide Taper** node in the Projects panel, open the **Edit** menu and select **Device Options**. The default-value for the wavelength (1.55 μm) is OK. Set the width of the computation window for all sections (psWidth) to 7 μm and the etch depth (psEtchDepth) to 0.65 μm, i.e. 150 nm into the waveguide layer.

- Now we are going to sweep the taper length. Click the **InP Waveguide Taper** project in the Projects Panel and click the **Add Variables** icon in the icon bar. Call the new node Taper Length. It will appear in the Projects panel. Double click it and click the **New variable** icon in the icon bar on top of the window. Call it Taper_Length. Double click the **Waveguide Taper** node in the Projects panel, right-click on the taper section, **select Edit Properties ...** and enter the Variable name Taper_Length in the box **length**.

- Click again the **InP Waveguide Taper** project in the Projects Panel and click the **Add FIMMPROP Scanner** icon and call the node Taper Length Scan, it will appear in the Projects Panel. Double click it, click the **Set...** button and select Waveguide Taper, set paramName to Taper_Length, paramStart and paramEnd to 0 and 30, and nstep to 31. Set Parameter Scan Mode Linear.

- Start the scan by clicking the **run the scanner** icon in the icon bar on top of the window. In the **FP3 Mode Coefficients** window remove the second mode (select it and click the button **Remove**) and click OK. The computation will start and a graph of the transmitted power in the fundamental mode is shown as a function of the taper length. The **FP3 Mode Coefficients** window will pop up again (with **profile type** we can select the metric to be displayed) and if we click OK the graph will appear in the lower left window. If we right-click it, select export > Data to clipboard, and chose Tab as delimiter we can directly copy the data into Excel with ctrl-V. If we convert the transmission values to dB we get the curve **Shallow1** in Fig. D.2.

- Looking to the modal field we see that it gets close to the surface of the top cladding. Therefore, we increase the thickness of the top-cladding to 1 μm (double click the **Waveguide Stack** node, right click **properties** and adapt the second layer). We have then to increase the etch depth to 1.15 μm (double click the **Waveguide Taper** node, open the edit menu, select **Device Option**s and adapt psEtchDepth). If we run the scan again we see that the difference with the previous scan is very small, so obviously a top layer of 0.5 μm is sufficient.

- For analyzing a deep-etched taper we first have to adapt the waveguide width in the three sections. Double click the **Waveguide Taper** node, right click in each section, select **Edit properties ...**, double click the line in the **Path List** and adapt the width of the input waveguide to 1.5 μm, the left and right taper widths to 1.5 μm and 3 μm and the output waveguide width to 3 μm. Next open the **edit** menu select **Device Option**s and adapt the etch depth to 1.1 μm (0.1 μm into the substrate) and run the taper length scan again. This brings us the curve labeled Deep1 in Fig. D.2.

- The curve **Deep1** looks suspect. From a simple 1D overlap calculation we expect a loss in the order of 0.8 dB for an abrupt junction. We will, therefore, do some convergence tests. But first we increase the computation efficiency by using the symmetry of the structure to reduce the number of required computations.

- Double click the node **Waveguide Taper**, open the **edit** menu, select **Device MOLAB options**, click **Edit solver params**, open the **Hsymmetry** list and select **Exsymm**. Note that FIMMWAVE uses the coordinate x for the lateral coordinate, and y for the vertical one, whereas in this Handbook x is used for the vertical dimension and y for the lateral one. So with Exsymm we tell FIMMWAVE that the field E_y is symmetric. See section 3.2.5 of the FIMMPROP manual for more detailed information on manipulating device symmetries to your advantage

- Under the **Mesh parameters** change the **meshType** from **Uniform** to **Non-uniform**, to enable the solver to use an adaptive mesh during mode solving. This adaptive mesh is generally more efficient for cross-sections with high index contrast (the air boundary counts for this) or very thin layers. The non-uniform option in the FDM solver is discussed in more detail in section 3.2.6 of the FIMMWAVE manual. Note that the primary resolution parameter of the non-uniform FDM solver is different from the uniform solver (**min Nx/Ny** for non-uniform, **nx/ny** for uniform).

- Enable the **isStraight** flag for the first and last sections of the device to save a small amount of computation time. This option can be found in the bottom left of the planar section properties (found by right clicking on the section and selecting **Edit Properties...**). This option will tell the taper algorithm that these sections are straight and do not need to use the taper algorithm to solve. A more detailed explanation of this option is available in section 3.2.8 of the FIMMPROP manual.

- Switch the **integrationOrder** parameter in the **Device Options** (found by clicking on the **Waveguide Taper** node in the **Projects** panel and opening the **Edit** window) to **Zero**. An explanation of integration orders is provided in section 4.3.1.5 of the FIMMPROP manual (subsection "Taper Integration: order 0 and order 1"). In summary, integration order 1 is the better option when you are certain you have included enough modes in your simulation to account for nearly all of the intermodal coupling. If there is likely some coupling to higher order modes which haven't been solved (for example due to maxNmodes being too low) then

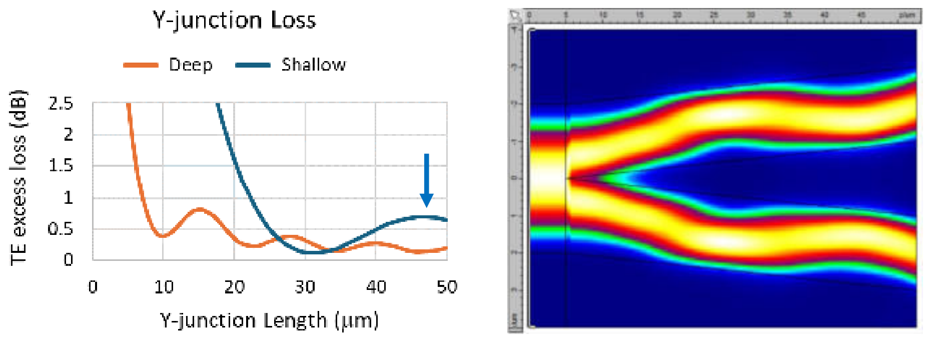

Figure D.3: (left) Excess loss of a Y-junction as a function of the length L where the gap ($2L\theta_Y$) is 2 μm wide.

integration order 0 is the more robust option. Broadly speaking integration order 0 is better for short tapers while integration order 1 is better for long tapers.

Changing the **Hsymmetry** to **Exsymm** has a significant effect on the curves: we find the curves labeled **Shallow** and **Deep2**. Changing the meshType to non-uniform and the integration order to 0 causes only minor changes. Next we test the convergence of the computations.

For convergence testing, there are 3 major parameters in FIMMPROP devices:

- **maxNmodes**, which controls the number of modes solved for each cross-section in a simulation. It can be set in the **Device MOLAB Options** window, which can be opened from the **Edit** menu of the **Waveguide Taper** node. Advice for determining the correct option for this parameter is given in section 3.2.9 of the FIMMPROP manual.

- Solver resolution (**min Nx/Ny** for the non-uniform FDM solver) which will control the precision of the grid used to compute each mode list in the simulation. Section 3.4 of the FIMMWAVE manual discusses how to confirm the accuracy of the solved modes in more detail but a more general convergence test approach is also effective in FIMMPROP.

- **minStepsizeFrac** which controls how finely the taper algorithm can sub-divide a taper section during simulations. Reducing this value will give a more accurate simulation. Section 4.3.1.5 of the FIMMPROP manual also discusses this parameter in more detail.

Changing **maxNmodes** from 10 to 20 gives a major change for the curve of the deep etched taper. For the shallow waveguide the effect is small, so for the shallow taper 10 modes is sufficient and the curve **Shallow** represents the final result. For the deep etched taper a further increase to 30 modes and an increase of **min Nx/Ny** from 50 to 100 gives only a small further improvement. So for the deep etched taper 20 modes look sufficient and the curve **Deep** can, therefore, be considered as a final result.

D.2 Y-junction

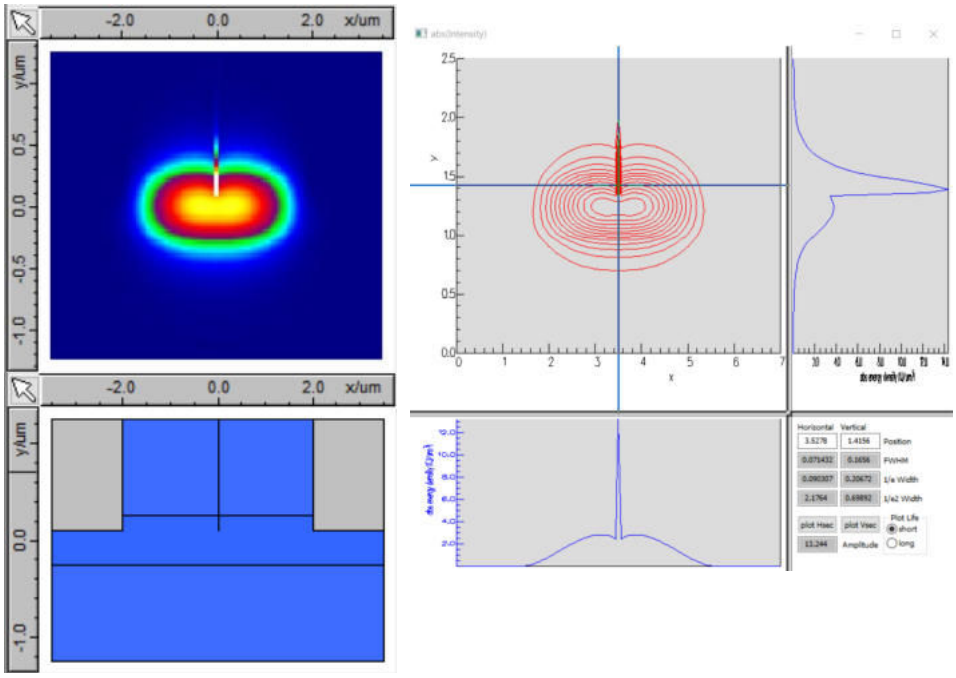

Figure D.4: The profile of the fundamental mode at the beginning of the Y-junction, where the gap is 1 nm wide.

In Figure 22.3(b) from Chapter 22 we see an unexpected fringe pattern at angles, where the Y-junction should behave adiabatic. Figure D.3 shows the excess loss as a function of the length where the gap ($2L\theta_Y$) is 2 μm wide, from which the graph of Figure 22.3(b) has been derived. The taper with a length of 47 μm (see the blue arrow), corresponds to a taper angle of 1.2°. At the right we see the intensity pattern along the Y-junction, which can be obtained by clicking the button **view field profile** in the icon bar of the FIMPROP Device. We see that in the beginning of the Y-junction the field shows a discontinuity, which leads to mode conversion. The wobbling of the field in the Y-branches indicates the presence of a first-order mode.

Figure D.4 shows the mode profile at the beginning of the Y-junction, at the position where the gap is 1 nm wide. It can be obtained by putting the pointer at the z-position where you want to see the field, right clicking to open the **Planar Section** pop-up menu and selecting **View XY field at ....** In the **Inspect Data** subwindow of the Inspect Optical Profile window we then select **Intensity** and click the **Plot Section** button. By moving the cross through the window we can see the x- and y-intensity profile at various positions.

In the gap we see a high field intensity, which is to be expected because of the high index contrast ($n_{InP}^2 \simeq 10$). What is not expected is that at the tip of the narrow gap the field in the waveguide becomes discontinuous, as can be seen from Fig. D.3(right). This discontinuity causes the exitation of higher order modes. The wobbling of the field in the two Y-junction branches indicates that a first-order mode has been excited. Obviously FIMMWAVE has problems with calculating the propagation of eigenmodes in narrow gaps with high index contrast. This problem can also have affected the results of Fig. 22.3(a), although there are no obvious problems visible in this graph.