MODESolutions 11 h 35	MODESolutions
Getting Started	Cơ bản (Loạt bài hướng dẫn ban đầu)
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1   Getting Started | 1   Cơ bản

Welcome to the MODE Solutions Getting Started Guide. | Đây là phần hướng dẫn cơ bản về MODE Solution.

The ability of MODE Solutions to accurately model complex waveguide geometries provides the user with the flexibility needed to design and analyze a wide range of industrial interesting devices, including: | MODE Solutions với khả năng mô hình hóa chính xác các ống dẫn sóng có dạng hình học phức tạp cung cấp cho người dùng sự linh hoạt cần thiết để thiết kế và phân tích một loạt các thiết bị công nghiệp, bao gồm:

- micro-structured optical fibers | • Các sợi quang cấu trúc micro
- photonic crystal fibers | • sợi tinh thể photonic
- coaxial Bragg fibers | • sợi Bragg đồng trục
- planar integrated-optical waveguides and sensors | • ống dẫn sóng và các cảm biến quang học planar tích hợp

The Getting Started Guide provides | Sổ tay hướng dẫn cơ bản này bao gồm

several tutorials with step by step instructions on how to solve a number of realistic problems. An introduction to the basic functionality of MODE Solutions is given followed by application specific examples.

All simulation and script files used in the tutorials are available for download. Additionally, the files can be found in the Examples folder of the installation directory. Note that for all operating systems, you must save a copy of the file in another location before they can be modified or run. Files in the installation directory are read-only.

Eigenmode solver Tutorials

Photonic Crystal Fibres

The Large Mode Area PC fiberlTTl tutorial shows how to use MODE Solutions to study a photonic crystal fiber (PCF). Using the built-in analysis tools, we will

• calculate the effective index and dispersion of the PCF

• estimate how efficiently light can be coupled in to the PCF

• calculate how much loss can result from bending the fiber

ARROW waveguides

In the ARROW waveguide!^ example, we will use MODE Solutions to study a multilayer planar waveguide that takes advantage of the Anti-Resonant Reflecting Optical Waveguide (ARROW) structure. This tutorial shows how to

add materials to the material database

use the mesh order property to distinguish two overlapping materials

measure the propagation loss as a function of operating wavelength

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một số bài hướng dẫn chi tiết từng bước về cách giải một số bài toán thực tế. Tiếp theo sau một số ví dụ ứng dụng cụ thể, chúng tôi sẽ giới thiệu một số chức năng cơ bản của MODE Solutions.

Tất cả các mô phỏng và tập tin lệnh được dùng trong bài hướng dẫn đều có thể tải trên mạng. Ngoài ra, các tệp nằm trong thư mục Ví dụ của thư mục mục cài đặt. Lưu ý rằng đối với tất cả các hệ điều hành, bạn phải lưu một bản sao của tệp ở một vị trí khác trước khi điều chỉnh hoặc cho chúng chạy. Các tệp trong thư mục cài đặt thuộc loại tệp chỉ đọc.

Các bài hướng dẫn về trình giải mode riêng

Sợi tinh thể Photonic

Bài hướng dẫn sợi tinh thể photonic diện tích mode rộng 17 trình bày cách dùng MODE Solutions để nghiên cứu sợi tinh thể photonic (PCF). Dùng công cụ phân tích có sẵn, chúng ta sẽ

Tính toán chiết suất hiệu dụng và độ tán sắc của PCF

Ước lượng hiệu suất ghép ánh sáng vào PCF

Tính toán mức độ tổn hao do sự bẻ cong sợi

Ống dẫn sóng ARROW

Trong ví dụ về ống dẫn sóng ARROW 32, chúng ta sẽ dùng MODE Solutions để nghiên cứu ống dẫn sóng planar đa lớp tận dụng cấu trúc Ống Dẫn Sóng Quang Học Phản Xạ Khử Cộng Hưởng (ARROW). Bài hướng dẫn này trình bày cách

bổ sung vật liệu vào cơ sở dữ liệu vật liệu

dùng tính chất thứ tự đưa vào lưới để phân biệt hai vật liệu xen phủ nhau

Đo tổn hao lan truyền theo bước sóng hoạt động

Surface plasmons	Plasmon bề mặt
In this tutorial, the Plasmon waveguide^ will be studied by MODE Solutions by simulating surface plasmon modes. We will use a non-uniform mesh to more accurately resolve the fields near the metal interface. The user will learn to:	Trong bài hướng dẫn này, chúng ta nghiên cứu ống dẫn sóng Plasmon 45 bằng MODE Solutions thông qua mô phỏng các mode Plasmon bề mặt. Chúng ta sẽ dùng lưới không đồng đều để phân giải chính xác hơn các trường gần bề mặt phân cách kim loại. Người dùng sẽ học cách:
Create a new material	Tạo vật liệu mới
Use symmetric boundary conditions	Dùng các điều kiện biên đối xứng
Use mesh override regions to create a non-uniform mesh	Dùng các vùng ghi đè lưới để tạo lưới không đồng đều
• Use a built in parameter sweep to get the effective index and loss vs. thickness of the waveguide	Dùng chức năng quét tham số có sẵn để nhận được chiết suất và tổn hao theo độ dày của ống dẫn sóng.
Combined Eigenmode solver and 2.5D FDTD Propagator Tutorials	Các bài hướng dẫn về Bộ giải mode riêng kết hợp và 2.5D FDTD Propagator
	Propagator: hàm truyền
Ring resonator	Buồng cộng hưởng vòng
(design and initial simulation)	(thiết kế và mô phỏng ban đầu)
The example will show how to design and simulate a Ring Resonatorl~58|. We will use the software to achieve a desired free spectral range (FSR) and quality factor (Q factor) for a silicon on insulator (SOI) based waveguide design targeting on-chip communication applications. The user will learn to:	Ví dụ sẽ chỉ cách thiết kế và mô phỏng Buồng Cộng Hưởng Vòng 58. Chúng ta sẽ dùng phần mềm để đạt được dải phổ tự do (FSR) và hệ số phẩm chất (hệ số Q) mong muốn cho thiết kế ống dẫn sóng mạch silic trên điện môi (SOI) hướng tới các ứng dụng truyền thông trên vi mạch. Người dùng sẽ biết được cách
• Insert a ring resonator object from the components library	Chèn đối tượng buồng cộng hưởng vòng từ các thư viện thành phần
• Use the Eigenmode Solver to choose the waveguide spacing, coupling length and ring length for the desired FSR and Q factor	Dùng Bộ Giải Mode Riêng để chọn khoảng cách ống dẫn sóng, chiều dài ghép và chiều dài vòng để đạt được FSR và hệ số Q mong muốn
• Compare results with the theoretical design and 3D FDTD results	So sánh các kết quả với thiết kế lý thuyết và các kết quả FDTD ba chiều
Ring resonator	Buồng cộng hưởng vòng
(parameter extraction and yield analysis)	(trích xuất tham số và phân tích hiệu suất)

This example will use the initial design introduced in Ring Resonator (design and initial simulation) perform additional analysis with Propagator features.

The user will learn to:

• Use Mode Expansion Monitors to extract the parameters for interfacing with circuit level simulations in INTERCONNECT.

• Compare the S parameter results with 3D FDTD.

• Use the Yield Analysis feature to track the effect of fabrication errors on the free spectral range (FSR) of the ring resonator.

For additional information and examples, please visit Lumerical's online help at http://docs.lumerical.com/en/mode/ for up-to-date MODE Solutions resources. The online help contains a number of advanced application examples, complete with lms and script files. Finding an example similar to your problem is a quick way to get started.

2 Introduction

MODE Solutions is useful for designing and analyzing waveguide components of arbitrary geometry and construction. Given its flexibility in describing complicated device geometries, it is especially suited to address micro-structured optical fiber, such as photonic crystal fiber, and multilayer integrated optical waveguides.

MODE Solutions

The following sections provide a brief overview of navigating the program GUI, setting up a simulation and then analyzing the results.

Note:

Ví dụ này sử dụng thiết kế ban đầu được trình bày trong Buồng Cộng Hưởng Vòng 58 (Thiết kế và mô phỏng ban đầu) để thực hiện phân tích bổ sung với các đặc tính Propagator.

Người dùng sẽ học cách:

Dùng các Monitor khai triển mode để trích xuất các tham số nhằm giao tiếp với các mô phỏng mức mạch trong INTERCONNECT.

So sánh các kết quả tham số S với FDTD ba chiều

Dùng tính năng phân tích hiệu suất để theo dõi ảnh hưởng của sai số chế tạo đến dải phổ tự do (FSR) của buồng cộng hưởng vòng.

Để biết thêm thông tin và ví dụ, độc giả có thể truy cập trang web hỗ trợ của Lumerical theo địa chỉ http://docs.lumerical.com/en/mode/ để truy cập các nguồn tài liệu MODE Solutions cập nhật. Trên trang web hướng dẫn trực tuyến có một số ví dụ ứng dụng nâng cao, hoàn chỉnh với lms và các tập tin lệnh. Tìm một ví dụ giống với vấn đề của bạn là cách khởi đầu nhanh nhất.

The online help toolbar in the program can be used to quickly access the online help. Simply enter a query in the online help toolbar and press on the magnifying glass. This will bring up the search results in a new tab in current default browser if an instance of the browser exists, and opens a new browser window otherwise.

Search online help

2.1 What is MODE?

MODE Solutions is a combination eigenvalue mode solver and wave propagator that accurately simulates structures that support guided modes.

Highlights of MODE Solutions include:

- Free-Form Design of Truly-Arbitrary Waveguide Geometries
- Design Parameterization and Hierarchical Layout •
- Optimization Framework •
- Advanced Meshing Algorithms
- Graded/Non-Uniform and Conformal Mesh Capabilities
- Fully-Vectorial Calculation Methods

Eigenmode solver

The eigenmode solver is a fully-vectorial mode solver that determines the modes of waveguide structures of arbitrary geometry. The solver hosts a frequency-domain solver that discretizes the structure of interest. The finite difference engine of MODE Solutions allows users to mesh and to analyze devices of arbitrary geometries, including both planar and cylindrical devices, that are composed of dispersive materials such as dielectrics and metals.

The eigenmode solver provides

performance information of various wave guiding devices through:

- A Highly Optimized Mode Solving Engine
- Dispersion, Group Velocity, and Group Index Frequency Data Calculations
- Dispersive and Lossy Media models
- Bent Waveguides and Fibers, Bend Loss

Modal Overlap and Power Coupling Calculations

Propagator

The propagator describes the propagation of light in planar integrated optical systems, from ridge waveguide-based systems to more complex geometries such as photonic crystals. The propagator allows for planar propagation without any assumptions about an optical axis, which allows for structures like ring resonators and photonic crystal cavities to be efficiently modeled - devices that have been traditionally treated with 3D FDTD. The propagator can model devices on the scale of hundreds of microns quickly. For an overview of the 2.5D Propagator, see the Lumerical's 2.5D FDTD Propagation Method whitepaper on our website.

The propagator features:

- A fast 2.5D Calculation Method
- Omni-Directional Propagation
- Hme-Domain Calculation Providing Broadband Results in a Single Simulation
- Parallel Computation on Multicore and Multinode Systems
- An Optimized Computational Engine

• Movies of Simulation Dynamics

Graphical User Interface: Windows and Toolbars

The graphical user interface contains useful tools for editing simulations, including

• a toolbar for adding objects to the simulation

• a toolbar to edit objects

• a toolbar to run simulations

• an objects tree to show the objects which are currently included in the simulation

• a script file editor window

• a window to set up parameter sweeps and optimizations

In the default configuration some windows are hidden. To open hidden windows, click the right mouse button anywhere on the main title bar or the toolbar to get the pop up window shown in the screen shot below. The visible windows/toolbars have a check mark next to their name; the hidden ones do not have check marks. A second option is to use the VIEW->WINDOWS menu.

For more information about the toolbars and windows see the Layout editor section of the reference guide.

Add Objects to the simulation

The Graphical User interface is used to setup a simulation. Simulation objects include structures, simulation regions, sources and monitors. Click on the arrow next to the image to get a pull down menu which shows all the available options of that category. The screenshot below shows what happens when we click on the arrow next to the STRUCTURES button.

The ZOOM EXTENT button in the
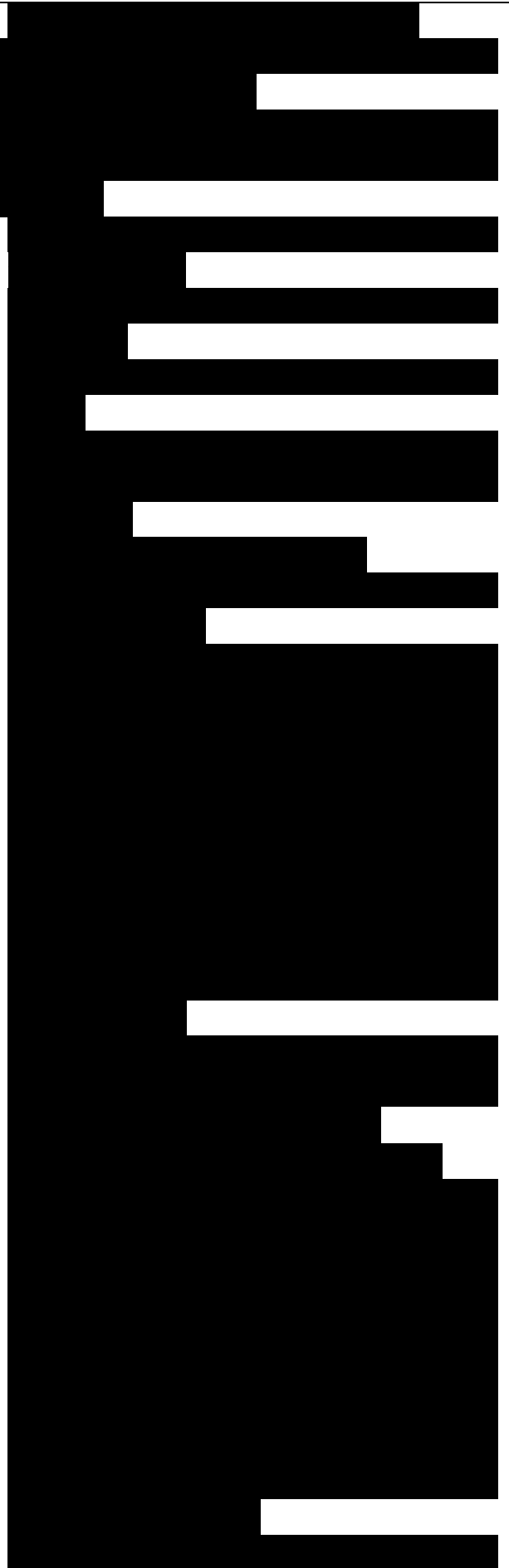
toolbar, or pressing X on the keyboard will resize the viewports to show the selected objects.

Edit objects

To edit an object, select the object and press E on the keyboard or press the EDIT button on the toolbar. The easiest way to select an object is to click on the object in the objects tree. Objects can also be selected by clicking on the graphical viewports of them when the mouse is in Select mode. Click the SELECT button to go into Select mode. For more information see the Layout editor section of the reference guide.

When the Edit button is clicked, the Edit window appears, allowing you to setup each object. To change the property units (i.e um for lengths), use the SETTINGS->LENGTH units in the main menu. Fields in the edit windows act like calculators, so that equations can be entered in the fields. See the y span field below for an example.

name |MOOE |

Edit Eigenmode solver

2.3   Running simulations

This section discusses important checks which should be made before running a simulation (memory requirements, material fits) and gives links to more information about running simulations and parameter sweeps or optimizations.

In this topic

Check memory requirements ITU

Check material fitslTTl

Setup parallel options IT2l

Run simulationlT?l

Run parameter sweeps and optimizations

|T?i

Check memory requirements

To check the memory requirements for propagator simulations, press the CHECK button

If this is not the current icon, you can find it by pressing the arrow next to the button. Note that the memory report indicates the amount of memory used by each object in the simulation project as well as the total memory requirements. This allows for judicious choice of monitor properties in large and extensive simulations.

Check material fits

Check

The CHECK button also contains a material explorer option allows you to see the material properties that will be used in your simulation. The paragraphs below give a brief introduction to the material explorer behavior for each solver. More details can be found in the materials section of the reference guide.

The Material explorer

Eigenmode solver

Many materials in MODE Solutions use the Sampled data material model, where the material is defined by a set of refractive index measurements. By default, MODE Solutions will use the refractive index data directly. Linear interpolation is used between data points. In some cases, such as when you are trying to calculate dispersion, you may want a smoother fit. In this case, you can choose to fit the materials with a multi-coefficient material model. The Material Explorer allows you to check the material properties, and adjust the fits, before the simulation is run.

Propagator

The Propagator will automatically calculate the effective index of your

structure at 5 different locations. The green cross drawn in the graphical user environment shows the location of the core mode which you would like to use in your simulation. You can change the location of the green cross with your mouse, or by changing the location in the effective index tab when you edit the propagator region.

There are also 4 blue crosses, so you can see the effective index at other spatial points in the simulation volume. The number of extra test points can be modified by editing the propagator region.

Before running a propagator simulation, MODE Solutions automatically generates a either an (n,k) material fit (for narrowband simulations) or a multi-coefficient model fit (for broadband simulations) to the effective index data in the source wavelength range. Before running a propagator simulation, it is a good idea to check and optimize the effective index material fit.

Setup the resource configuration

The resource configuration options can be accessed by pressing the Resources button

J^L

TL This button allows users to configure how many computers to run simulations on, and how many cores to use. Configuration details can be found in the links in the run simulation section below.
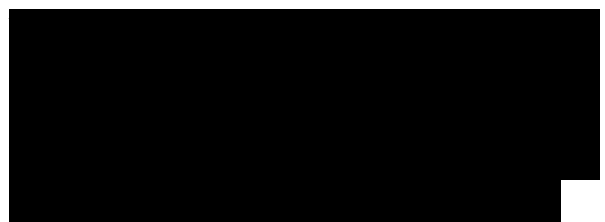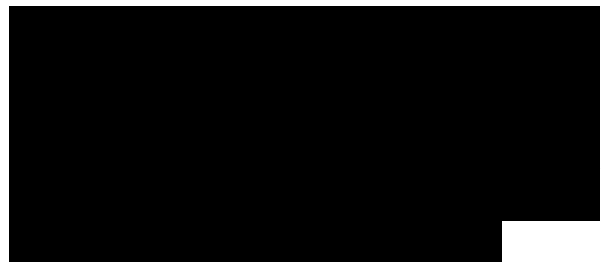
Run simulation

Eigenmode solver

►►

Run

When the eigenmode solver is active, the RUN button the eigenmode solver

analysis window. The eigenmode solver analysis window is discussed in the next section (Analyzing Simulation data).

on the mail toolbar will open

Propagator

When the propagator is the active solver, you can run simulations by pressing the RUN button on the main toolbar. For more details, such as how to run multiple simulations in distributed mode, please see the Run Simulations section in the online User Guide, or the Running simulations and analysis section of the Reference Guide.

Run Parameter Sweeps/Optimizations/Yield Analysis projects MODE Solutions also has a built in"Optimizations and Sweeps" window. This window can be seen at the top of the page, and can be opened using the instructions in the Graphical User Interface discussion just prior to this topic. The "Optimizations and Sweeps" window includes buttons to add a parameter sweep/optimization/yield analysis project. Parameter sweeps and optimizations can include multiple parameters, or be nested.

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2.4 Analyzing simulation data 11 h 6

This section discusses the tools used to analyze simulation data: the Results Manager and Visualizer, the script environment and data export to third party software such as MATLAB. For more details please see the Analysis tools and the Scripting language chapters in the Reference Guide.

The Eigenmode solver has a separate analysis window which appears when the RUN button Run is pressed. This analysis window includes options for modal, frequency, farfield and overlap analysis.

In this topic
VisualizerH?!
Scripting R4|
Eigenmode solver analysis windowR5|
Result analysis

The Results Manager is a tool for analyzing simulation data. The Results View window shows all the results for the simulation object that is currently selected in the Object Tree. The Script Workspace and Script Favorites windows work in conjunction with the scripting environment to provide additional GUI-based functionalities.

When used in conjunction with the Visualizer, the Results Manager provides a very useful and intuitive way of analyzing and visualizing variables and results through the GUI.

More complex analysis can also be carried out in MODE Solutions' powerful scripting environment.

Scripting

MODE Solutions contains a built in scripting language which can be used to obtain simulation data, and do plotting or post-processing of data. The script prompt can be used to execute a few commands, or the built in script file editor can be used to create more complex scripts.

A thorough introduction to the Lumerical scripting language can be found in the Scripting section of the MODE Solutions online user guide. Definitions for all of the script commands are given in the Scripting

language chapter in the Reference Guide.

Data Export

MODE simulation data can be exported into text file format using the Visualizer, into a Lumerical data file format (*.ldf) which can be loaded into another simulation, or into a Matlab data (*.mat) file. Instructions for exporting to these file formats can be found in the links under the Scripting section.

Eigenmode solver analysis window

The screenshot below shows the eigenmode solver analysis window. It contains the following 3 tabs.

• Modal Analysis: includes options to change the parameters used to find modes, such as the center frequency. It also has options for bent waveguide analysis, power and field integration, and far field projections

• Frequency analysis: provides an easy and intuitive interface for running frequency sweeps

• Overlap analysis: includes options to create a Gaussian or Fully Vectorial NA beam and place that profile on the DECK or calculate overlaps between modes in the mode list and modes in the DECK. Modes can be placed on the deck from the mode list at any point, or imported from another file format.

For more details, see the Eigenmode analysis Chapter of the Reference Guide.

3 Large Mode Area Photonic Crystal Fiber

Problem definition

In this example, we show how to use MODE Solutions to study a photonic crystal fiber (PCF). Using the built-in
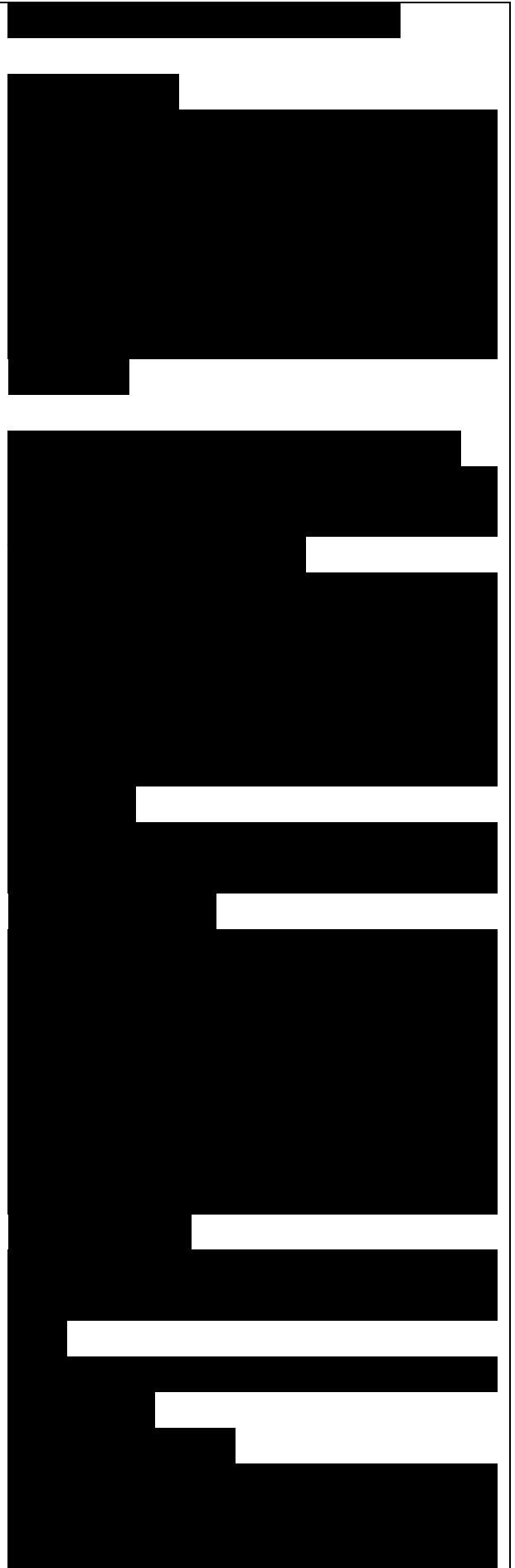
analysis tools, we will calculate the effective index and dispersion of the PCF, as well as estimate how efficiently light can be coupled in to the PCF, and how much loss can result from bending the fiber.

Associated files

Example files can be found in the Examples subdirectory of the installation directory, or downloaded from the online MODE Solutions Knowledge base. LMA-35.lms

In this topic

Modeling instructions [23^

Discussion and results H^l

Problem definition: More details

Consider a micro-structured silica fiber that uses a PCF of air holes with pitch = 23.2 microns and hole radius = 5.8 microns, with the central air hole missing. Here, the user will learn to:

• Create a PCF using the Object Library

• Find the effective index of the fundamental mode at 1550 nm using Modal Analysis

• Measure both the waveguide and the total (including material) dispersion of the PCF using Frequency Analysis

Analyze the total loss, including both the propagation loss and the macro-bending loss, in 90 degree bend using Bend Analysis

3.1   Discussion and results

Simulation set up

The PCF is constructed by perforating a circular fiber of radius 300 um with air holes forming a hexagonal lattice. The lattice constant is 23.2 um, and the air hole radius within the photonic crystal lattice is 5.8 um. The cavity itself is formed by removing a central hole. Since the material of the air hole

is specified as "etch" (with mesh order 1), whereas the mesh order of the fiber is 2, MODE Solutions will use the refractive index data from the air holes in regions where the two objects overlap. For more details about mesh order, refer to the mesh order page in the Reference Guide.

It is always a good idea to start with a relatively coarse mesh (a good rule of thumb is 50 grid points in each of the x and y direction). This way the simulation will run quickly and still provide reasonable results. When high accuracy is required, increase the number of grid points. Note that the more grid points you use, the more memory required.

It is important to make sure that periodic structures are properly discretized in order to get accurate results. In general, it is always good to ensure that you can fit an integer number of mesh cells within each period of the device, and within the span of the simulation region. In this example, the x and y span are both 12 times the period of the structure along the respective axis, and there are 60/12=5 mesh cells per period.

In the screen shot below (or if you view the mesh in MODE Solutions by clicking on VIEW), it is possible to see that there is a mesh cell at the same point at each period of the hole array. If the mesh lines fall at different locations, each hole will have a slightly different size and shape, reducing the accuracy of the simulation.

Note that by setting the y min boundary condition to symmetric the lowest order mode with electric field polarized along the x axis has been chosen.

Modal Analysis Results

Before beginning Modal Analysis, one should always mesh the structure to see that the material properties that will be used in the calculation are correct. Next, we provide an estimate of the mode effective index to the solver. In this case, we use the SEARCH IN RANGE option because we do not yet know the effective index of the fundamental mode. With this setting, MODE Solutions will iteratively move through the effective index range (n1 to n2) specified, and locate any modes where the majority of the optical energy is located in the interior (and not along the boundaries) of the computation region. Once you see a number (say, more than 5) modes appear in the index table, press the STOP button on the progress window.

You should now have in front of you the following results:

By selecting various modes within the table, the spatial intensity profile of the mode will be plotted in the window. Note that mode #1, with the highest effective refractive index, consists of a central intensity lobe - this is the fundamental mode that we are looking for (with effective index of approximately 1.4436). We can now use this value to speed up the calculation process when using a finer mesh with the SEARCH NEAR N option. Note that the fundamental mode is found in the first attempt, but now with a higher spatial resolution. The effective index may shift slightly due to the higher resolution meshing.

The modes of interest are typically those that have energy near the center of the photonic crystal fiber (and away from the PML boundary layers).

Modes found near the PML boundary conditions tend to be artificial, and are automatically hidden. The ADVANCED OPTIONS tab can be set so that MODE Solutions returns all of the modes found should you be interested in doing so.

For each mode listed in the mode table, the effective index, propagation loss and polarization properties (see Mode List and Deck for a more precise definition) are shown.

Frequency Analysis Results

The frequency dependence of the effective index and propagation loss of a particular mode can be calculated with the frequency analysis tool. From this the associated modal group velocity, group effective index, modal delay and dispersion can also be determined. This type of analysis is done in the Frequency Analysis Tab. Here we determine the waveguide dispersion of the lowest order mode over a broad range in frequency (or wavelength).

We can get the dispersion plot below by following the instructions in the "Modeling instructions" section. Note that this is the plot of the total dispersion (i.e. material dispersion + waveguide dispersion), which at 1.55 microns is equal to 25.8 ps/(nm*km). To calculate the dispersion to greater precision, the number of grid points could be increased.

It is good practice to double the number of grid points and see if the results change significantly.

A

Wavelength (microns)

Now, to determine the fraction of the

total measured dispersion results from the waveguide itself, we need to remove the material dispersion from the Corning material. To do this, we need to determine the refractive index of the Corning material at the wavelength of interest (1550nm) using the MATERIAL EXPLORER (press the MATERIAL EXPLORER button in the Material Database):

Note that the material is set to "Corning 7980 Silica". To determine the refractive index, set the min and max wavelengths to 1.55 microns and press "Fit and plot", and read off the real part of the effective index (1.4440) from the Re(index) plot. Once we set the index of the fiber to be a non-dispersive material of index 1.4440 and re-perform the sweep, the frequency sweep plot will show that the (waveguide only) dispersion is equal to about 1.3 ps/(nm*km). Thus, the material dispersion is the dominant component of the total dispersion for this micro-structured fiber design.

Bend Analysis Results

The plot below shows that the total loss decreases as the radius of curvature decreases from 2 meters. However, at around .3 meters the loss arising from the bend begins to increase dramatically. For smaller radius of curvature bends, the fundamental mode of interest begins to couple significantly to cladding modes within the photonic crystal fiber, leading to a complicated loss versus bend radius relationship.

3.2   Modeling instructions

This page is divided into 4 sections. The first section describes how to set up the model (PCF structure +
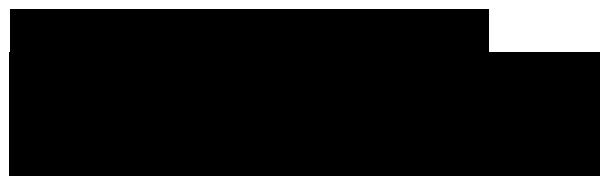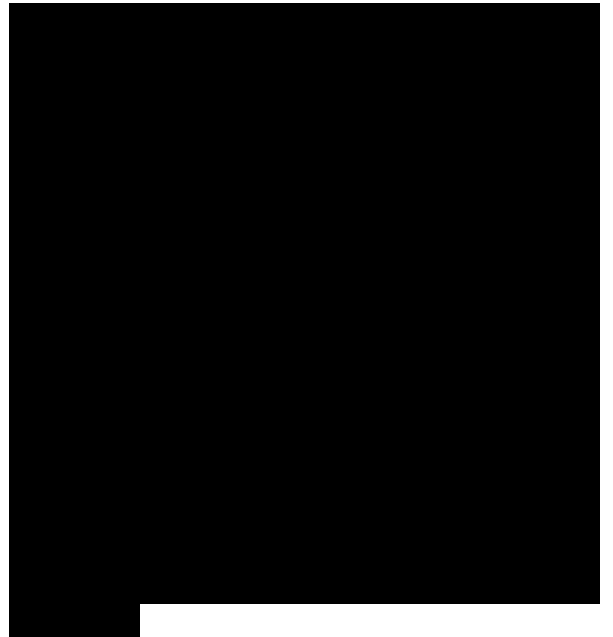
simulation parameters). Sections 2 and 3 describe how to perform Modal analysis and Frequency analysis, and section 4 demonstrates how to use the built-in parameter sweeping tool to study the loss as function of bending.

In this topic

Set up model fi?!

Modal analysis^

Frequency analysisfi?!

Bend analysis fi?!

Set up model

The physical structures to be modeled are created using the STRUCTURES tab in the Layout Editor. The first step is to create the fiber with the air holes.

• Begin by starting MODE Solutions. You can save the MODE Simulation Project file (extension *.lms) at any point in this process. To do so, choose SAVE in the FILE menu.

Press the MATERIAL DATABASE button Materials and add a new sellmeier material with the following properties:

• Press on arrow on the STRUCTURES button and select a CIRCLE from the pull-down menu. Set the properties of the circle according to the following table.

Press on arrow on the COMPONENTS button and select PHOTONIC CRYSTALS from the pull-down menu. This will open the object library window.

Select HEXAGONAL LATTICE PC H-CAVITY from the list and press the INSERT button. Set the properties of the PC Cavity according to the following table.

• Press on the SIMULATION button
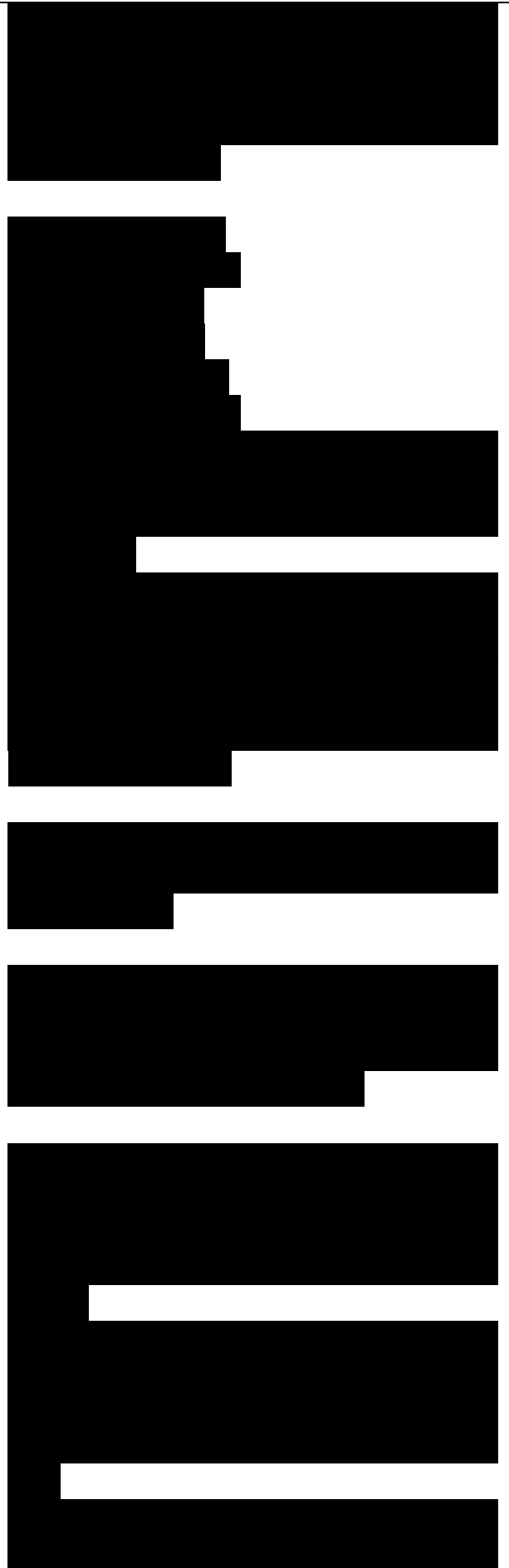
simulation region. Note that if your button does not look like the button to the left, you will need to press on the arrow to get the simulation region. Set the properties according

Press the Zoom EXTENT button to resize the view in the Layout Editor.

• Select the ANALYSIS tab with the RUN ACTIVE SIMULATION button Run

Click the MESH STRUCTURE button to see the meshed PCF.

Press the CALCULATE MODES button. Once you see a few modes appear in the index table, press the STOP button on the progress window.

Once we determine the effective index of the fundamental mode to be near 1.4436, return to the layout editor by LAYOUT button

number of mesh cells in x and y to be 120. This will make the simulations slower, but more accurate.

Back to the MODAL ANALYSIS tab, now select the SEARCH NEAR N option, uncheck use max index, and enter the effective index of 1.4436. Then press the CALCULATE MODES button.

In addition to the Modal Analysis tab, one can also view the calculated modes using the Visualizer. In the Object tree as shown below, under the Eigensolver simulation region there is a EigensolverDataGroup called "data", which contains a material monitor as well as all the modes in the current mode list. One can then right click on the object and choose to Visualize the different datasets corresponding to each object.

For example, one can visualize the Electromagnetic fields of model:

5 h 24 27 11

Frequency Analysis

• Under the Frequency analysis tab, select the mode that you want to track (by clicking on it in the mode table), and enter the following parameters:

Frequency analysis

stop wavelength (um)   1.4

number of points   10

number of test modes   3

track selected mode   on

detailed dispersion calculation

Click on the FREQUENCY SWEEP button to begin the scan. The scan will take about a minute.

To plot the calculated dispersion as a function of wavelength, select the FREQUENCY PLOT tab in the bottom righthand corner of the frequency analysis window. Then select "Dispersion" in the plot pull down menu. The plot can be seen above the frequency plot tab. If you press the PLOT IN NEW WINDOW you will get a new window.

To determine the fraction of the total measured dispersion results from the waveguide geometry, as opposed to bulk material dispersion, we need to return to the layout editor and change the material properties of the fiber. Return to the layout editor by clicking the LAYOUT button Switch , MODE Solutions will automatically close the Analysis Tab. Select the fiber structure, set the material from "Corning 7980 Silica" to "<Object defined dielectric>" and set the INDEX to 1.444, rerun the frequency sweep.

Bend Analysis

In the following step of analyzing the photonic crystal fiber, we examine how the total loss in a 90 degree bend varies as a function of the radius of curvature. Before running the sweep, switch back to LAYOUT and set the material for the fiber back to "Corning 7980 Silica" and recalculate the modes. To perform a series of simulations to investigate the effect of systematic changes on cavity performance, it is convenient to take advantage of the built-in parameter sweep tool in MODE Solutions. There are 3 steps to setting up the bend analysis parameter sweep:

Step 1: Make data available to parameter sweep
We are interested in obtaining the loss from the fundamental mode, but the mode solver generally finds multiple modes. In order to keep track of the desired mode, we need to store a reference copy of the fundamental mode as a D-CARD (the D-CARD is a convenient data storage system which allows you to define, analyze, and transport data between analysis routines and applications). Within the MODE LIST, highlight the fundamental mode, right click and "Add selected modes to global deck", a D-CARD with the default name "global_mode1" will be created. Double click on this D-CARD and change the name to "FUND" (note that the name should be entered in capitals).
Switch back to LAYOUT and edit the MODE data group by right clicking on the object with your mouse. Select the Edit object option from the list as shown in the figure above. In the
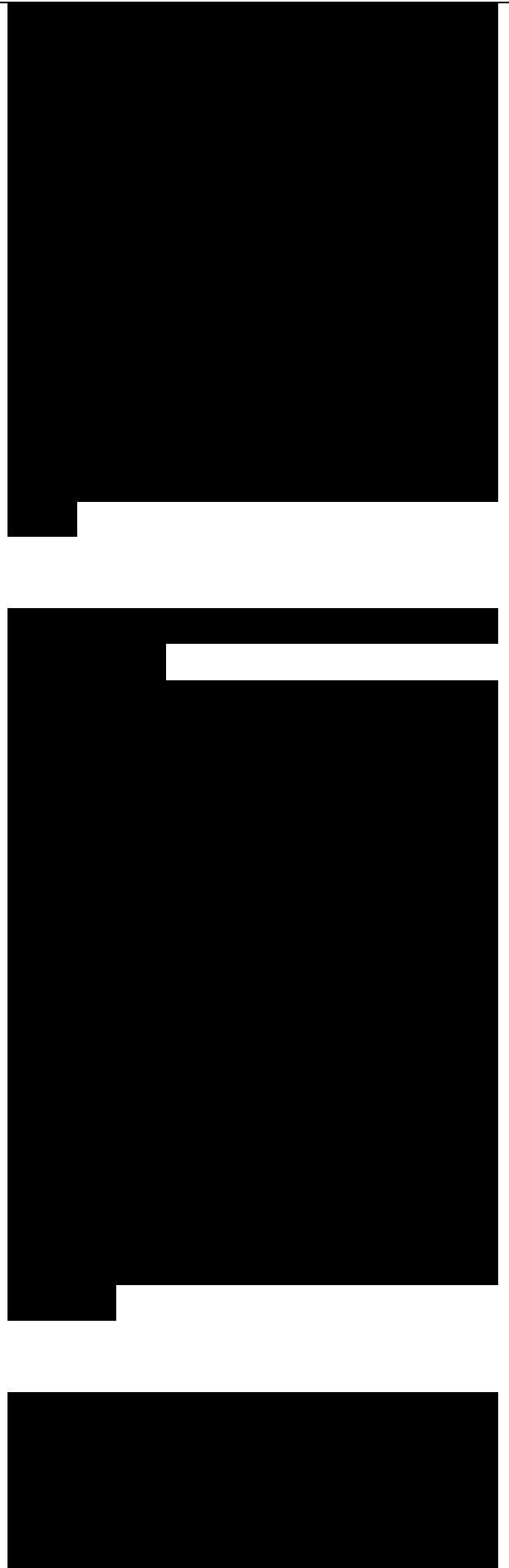
Analysis->Variables tab click the bottom ADD button. This will add a result which the data group can give to the parameter sweep. Rename the result to "loss" as shown in the bottom left window.

Switch to the Analysis_>Script tab shown in the right part of the image below. Then add the following lines of script commands which will add data to the "loss" result once a simulation has run. Press OK to save your changes.

fund = bestoverlap("FUND"); # find the mode that best overlaps with "FUND"

loss = getdata(fund,"loss"); # save the loss result for this mode

Step 2: Create a sweep

• Open the Optimization and Sweeps window using the VIEW menu at the top of the graphical user interface, or by right clicking on the top title barl~81 of the MODE Solutions GUI.

Press on the CREATE NEW PARAMETER SWEEP button the simulation. Right click on the parameter sweep and choose to edit the parameter sweep. Set the properties according to the following screenshot. Notice that the only results you can chose are the results which are seen in the screenshot of the Analysis->Variables tab above.

Here, the values specified for "roc" (radius of curvature) follow the equation roc = 2/ linspace(1,5.5,10)A2, so we select "Values" as shown below and enter each value one by one. If we wish to sweep the parameter in evenly spaced intervals, it would be easier to select "Range" and enter the Start/Stop
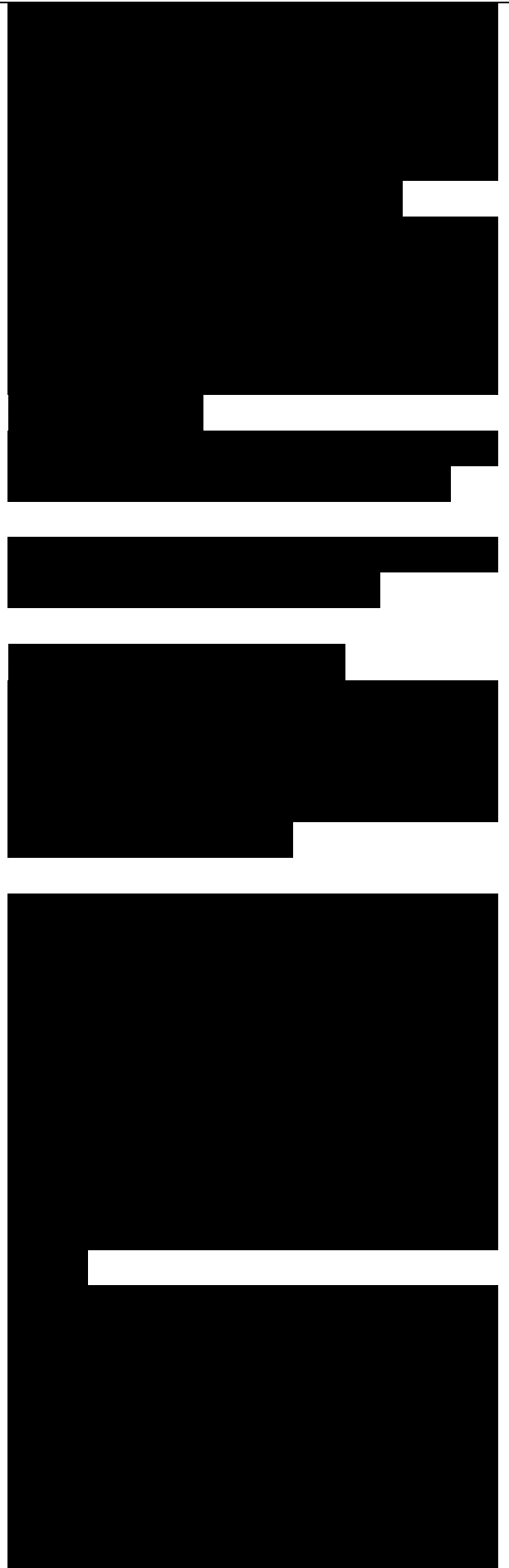
values instead.

Step 3: Run the sweep and plot the data
•   In the Modal analysis window, select the "bent waveguide" option under modal analysis, and click "Calculate Modes". This will enable the sweep to change the value for the bend radius.

Press the RUN SWEEP button in the Optimizations and Sweeps Window to run the
Just like in Modal Analysis[261. we can use the Visualizer to plot the results.

However, here it is more useful to plot   (instead of just loss), since we want to determine the loss in a 90 degree bend. Note that this is the actual bend angle, not the bend orientation.

To do this, open the script prompt window using the VIEW menu at the top of the graphical user interface, or by right clicking on the top title barf^l of the MODE Solutions GUI. Copy and paste the following commands into the script prompt and press ENTER on the keyboard to execute them.

4   ARROW waveguide
Problem definition
We are interested in determining how the propagation loss of the ARROW waveguide described in F. Prieto et. al. The goal is to plot the propagation loss from 0.5 to 1 microns.

Associated files
Example files can be found in the Examples subdirectory of the installation directory, or downloaded

from the online MODE Solutions Knowledge base. arrow_rib.lms
In this topic
Set up Arrow A Structure |~33|
Find TM mode at 632.8nm[~3?|
Loss as a function of Wavelengthf36||
Reference

F. Prieto, L. M. Lechuga, A. Calle, A. Llobera, and C. Dominguez. "Optimized silicon antiresonant reflecting optical waveguides for sensing applications," IEEE J. Lightwave Tech., 19, 75-83 (2001)

Learning objectives
In this example, we will use MODE Solutions to study a multilayer planar waveguide that takes advantage of the Anti-Resonant Reflecting Optical Waveguide (ARROW) structure. In this example, you will learn how to:

•   Add materials to the material database
•   Use the mesh order property to choose which material properties are used when two materials overlap
•   Measure the propagation loss as a function of operating wavelength.
4.1   Discussion and results Set up ARROW A Structure
The structure in this example is based on the optimized ARROW A Structure for sensing applications from the Prieto reference on the previous page.
We construct the core of the waveguide with a rectangle. To make the coating 1 layer, we take the same rectangle, change the material and make it a bit larger. Then we set the mesh order property. This acts like a Boolean operation so that when the core and the coating rectangle overlap, the eigensolver uses only the material

properties from the core.

The coating 2 layer is created similarly. We use an even larger rectangle, and place it on top of the core and first coating layer. Then we set the mesh order so that where the three materials overlap, the eigenmode solver uses only the material data from the core. When the two coating layers overlap, the eigenmode solver uses only the material data from the first coating layer.

The medium to which this structure is exposed, in this case water, is modeled by setting the background index of the eigenmode solver to 1.3325.

Find TM Mode at 632.8nm

First, we will find the fundamental TM mode for this structure at the wavelength for the He- Ne source used in the paper, ie at a wavelength of 632.8nm.

Because we are looking for the fundamental TM mode, we know that we can use Symmetric boundary conditions. This filters out the modes which do not have the correct symmetry, for example the fundamental TE mode. You can get a complete list of the modes the structure supports by setting all the boundary conditions to PML. You can find more information about symmetric/anti-symmetric boundary conditions in the Simulation Chapter of the Online user guide.

Note that the simulation x span is 3 times the width of the core. Also the y span is large enough to include both the silicon substrate and a bit of the solution above the top coating layer.
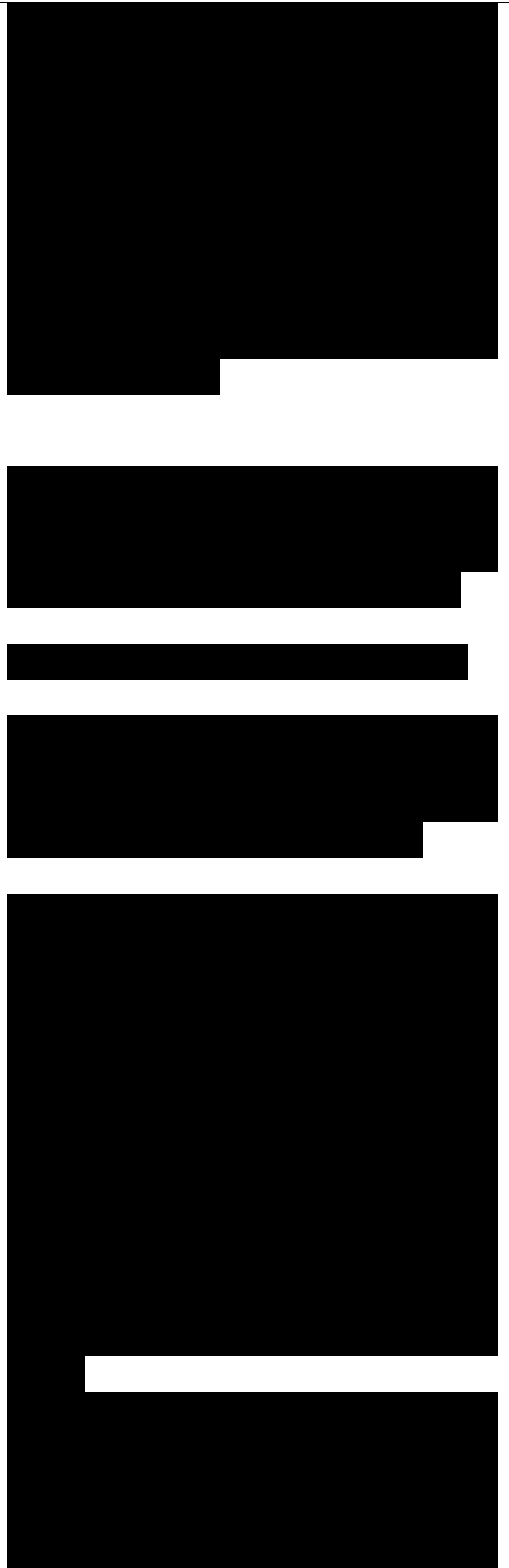
This is done to ensure that the location of the PML does not affect the mode profile, and hence the loss and effective index. Some convergence testing should be done to find the optimal size of the simulation span.

Three mesh override regions were added in this example to resolve the thin coating layer deposited on top of the core. The image shows a close up of the xy view when the view mesh button has been selected. You can see that there are four mesh cells in the coating layers.

The reason that the boundary conditions have been set to PML is because this waveguide is expected to have attenuation loss. The loss returned by the eigenmode solver is equal to the loss to dispersive materials plus the loss through the PML.

The loss returned for this mode is 2.07 dB/cm. Figure 12a of the reference contains a plot of loss versus structure size for a slightly different structure. Nevertheless, the loss from the eigenmode solver lies close to what would be expected from the plot in the paper.
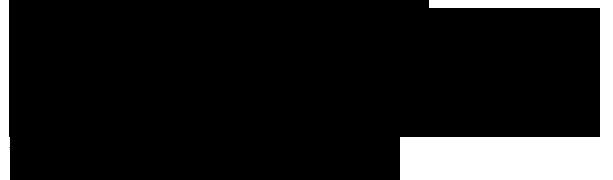
Loss as a function of Wavelength

The following plot shows the loss for this mode as a function of wavelength. You can see that the loss increases quickly as the wavelength increases.

4.2   Modeling Instructions

This page contains 4 independent sections. The first section describes how to add materials to the simulation, and the second step describes how to set up the structure.

You can skip these steps by opening the associated arrow_rib. lms file and proceed on to the third and fourth
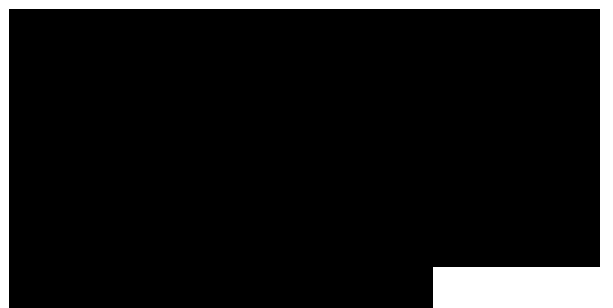
sections to find the modes and plot loss as a function of wavelength.

In this topic

Add materials to the material database^

Create structured

Mesh the structure and find TM mode at 632.8nmf41|

Loss as a function of Wavelength^

Add materials to the material database

o core layer o high-index cladding o low-index cladding o silicon

• Press the ADD button and select DIELECTRIC to add a new dielectric material to the database. You will see an entry named "New Material 1" appear in the material list.

• In the material list, change the name of the material to "core" and select a light blue color for the material.

• In the material properties, set the refractive index to be 1.485.

• Create 3 more materials with the properties from the following table

• Press the OK button. All four of these materials have now been added to the material database, and will be used in the construction of the ARROW waveguide.

Create structure

• Open the simulation up in 2D drawing mode by selecting the menu options below. This hides the z dimension since we are not using it.

Create waveguide core and coating layers

Press on the expand arrow on the STRUCTURES button and select a RECTANGLE from the pull-down menu. Set the properties according to the the following table.
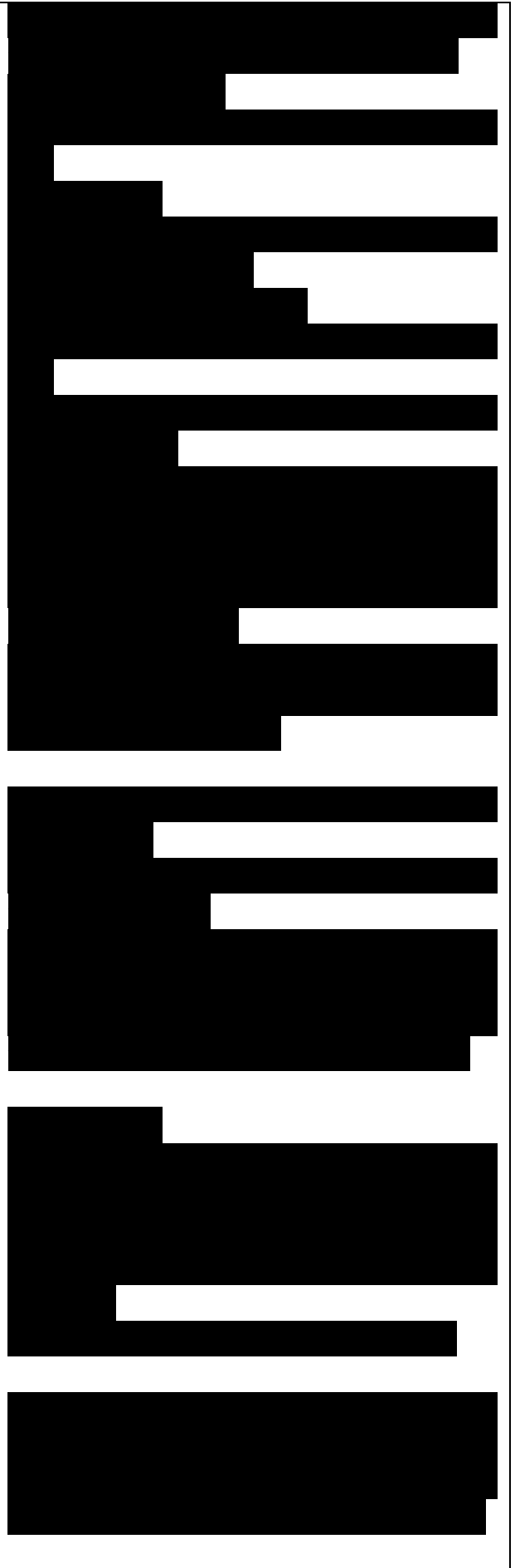
Select the core_top rectangle in the object tree and press the DUPLICATE button twice to create two copies of the the rectangle. Edit the properties of the new rectangles according to the following table.

• Press on the expand arrow on the STRUCTURES button and select a RECTANGLE from the pull-down menu. Set the properties according to the following table.

Select the core_bottom rectangle in the object tree and press the DUPLICATE button twice to create two copies of the the rectangle. Edit the properties of the new rectangles according to the following table.

Create substrate and cladding layers

• Duplicate one of the rectangles with the 40^m x span three times and set the properties of the newly created rectangles as described in the following table.

Mesh the structure and find TM mode at 632.8nm

• Press on the arrow on the SIMULATION button 5 "ulation and select an EIGENMODE

• Press on the arrow on the SIMULATION button and select a MESH OVERRIDE region

m . Set the properties according to the following table. Note that the value for dx is written as 0.034/4 because we want 4 mesh cells for the high-index cladding layer that is 0.034um thick.
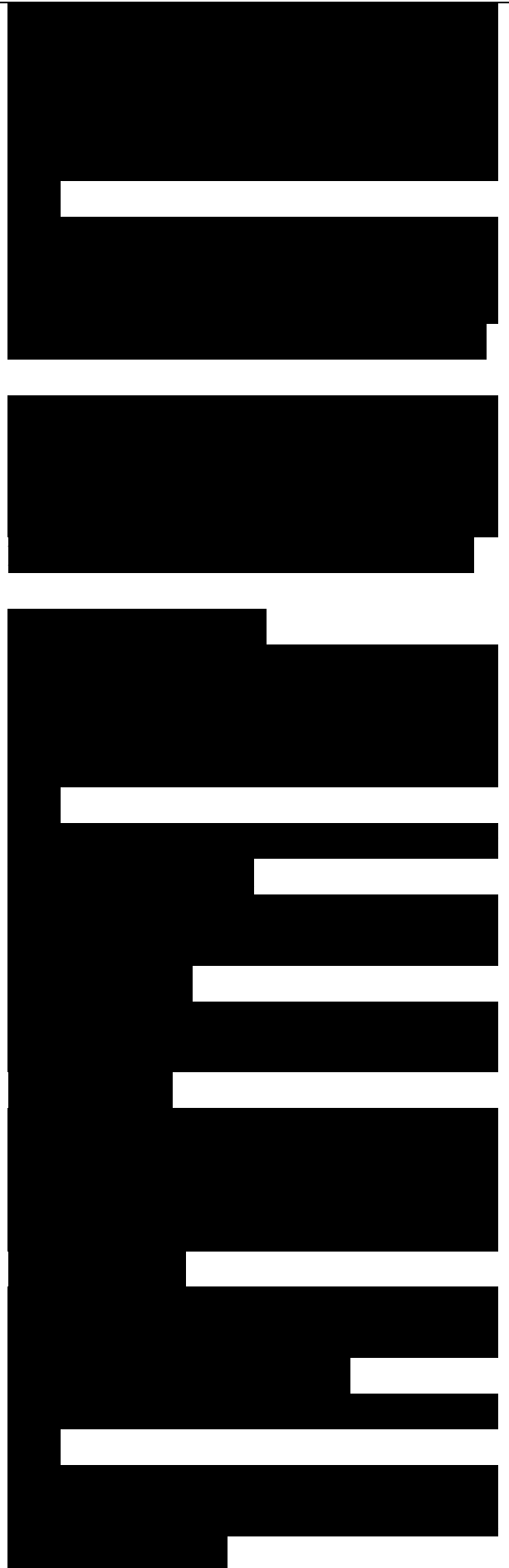
• Press on the arrow on the SIMULATION button and select a MESH OVERRIDE region

m . Set the properties according to the following table.

Select the 2nd mesh that we just created (if it is not already selected) and press the DUPLICATE button

Open the analysis window by pressing on the RUN button Run First press the MESH STRUCTURE button to mesh the structure, and obtain a spatial plot of the refractive index

In the MODAL ANALYSIS section set the wavelength to 632.8nm.

Uncheck "use max index". We are looking for the fundamental guided mode in the core, so we expect that the effective index will be close to the refractive index of the core. Set n to 1.485, the refractive index of the core.

Set the number of trial modes to 10. The default is 20, but the calculation is quicker if we find only 10 modes.

Go to the Advanced Options at the bottom left and change threshold for pml mode removal to 0.1

Finally press CALCULATE MODES. As you can see from the previous page, the fundamental mode is the second mode which appears on the mode list.

Loss as a function of Wavelength

• In the Frequency analysis tab, select the mode that you want to track on the mode list

• Set the calculation parameters as shown in the screenshot below

• Press the Frequency Sweep button. You will see a progress bar appear. Note that the progress bar does not give a good indication of the actual progress in the sweep. It will reach 99% after about the second mode and will stay there until the sweep is complete.

• To plot the results of the frequency sweep, set the plot drop-down on the Frequency plot tab to "loss", or visualize the result from the object tree (see below).

Eigensolver Analysis

Mode list

Modal analysis Frequency analysis Overlap analysis

options

Set Calculation Parameters

[Vi track selected mode

start frequency (THz) stop frequency (THz) 440.871 start wavelength (pm) stop wavelength (pm) 0.68 number of points 20 number of test modes 10 effective index

5   Plasmon waveguide

Problem definition

Consider a rectangular silver surface plasmon waveguide with dimensions 1000nm x 100nm described in Berini, "Plasmon-polariton waves guided by thin lossy metal films of finite width: Bound modes of symmetric structures", Phys. Rev. B, 61, 10484-10503 (2000).

We want to measure the effective index of the ssb0 mode at 633nm. We will also calculate the effective index of this mode as a function of waveguide thickness, from 50nm to 200nm.

Associated files

Example files can be found in the Examples subdirectory of the installation directory, or downloaded from the online MODE Solutions Knowledge base.   plasmon.lms plasmon_plot. lsf

In this topic

Simulation SetupR?!

Find and plot MODE SSb0[47^

Effective Index as a function of waveguide thickness

Learning objectives

In this example, we show how MODE Solutions can be used to study surface plasmon modes. We will use a non-

uniform mesh to more accurately resolve the fields near the metal interface. The user will learn to:

• Create a new material
• Use symmetric boundary conditions
• Use mesh override regions to create a non-uniform mesh
• Use a built in parameter sweep to get the effective index and loss vs. thickness of the waveguide

5.1 Discussion and results

Simulation Setup

We are trying to recreate the results in the Berini paper, so it is important to use the same material properties. We will create a new silver material, rather than using the standard silver definitions included with MODE Solutions. the permittivity of Ag given in the Berini paper is -19+0.53j).

The screenshot below shows the plasmon waveguide and the mode solver region.

Notice the shaded green and blue regions. The blue shaded section is a result of the fact that the x min boundary condition of the simulation region has been set to symmetric. In other words, we have put a magnetic wall (perfect magnetic conductor) at x = 0. Similarly, the green shaded region indicates that the y min boundary condition is anti-symmetric.

This indicates that we have put an electric wall (perfect electric conductor) at y = 0.

Table 1 of the reference shows that the fields from the ssb0 posses this symmetry. The boundary conditions will need to be changed if you are

interested in finding modes which have fields with different symmetry. You can find all of the modes that the waveguide supports if you set all of the boundary conditions to metal. Note that the time to find modes and memory required to find modes will increase if all the boundary conditions are metal. This is because the mode solver can use shortcuts to find the fields in the shaded region if your simulation posseses symmetry/anti-symmetry about one axis.

The orange lines in the screenshot above show the mesh used in the mode calculation. Notice that the mesh is finer at the edges of the structure. This is because we expect the fields to be concentrated near the edges of the waveguide. Increasing the mesh here, will increase the rate of convergence of the effective index, loss and field profiles as you reduce the size of the mesh.

Finally, notice that we use metal boundary conditions instead of PML boundary conditions. The reasons for this are described in the Starting with metal boundary conditions page in the Simulation chapter of the online user guide.

Find and plot MODE SSb0

To find the SSb0 mode, we overrode the default "search near n" settings in the analysis window. This is because plasmon modes often exhibit a higher effective index than would be predicted by the maximum effective index estimate. In this case, we set the mode solver to search near an effective index of 2.5, which is slightly above the guess for the maximum effective index. We knew the effective index from the reference. If you set this
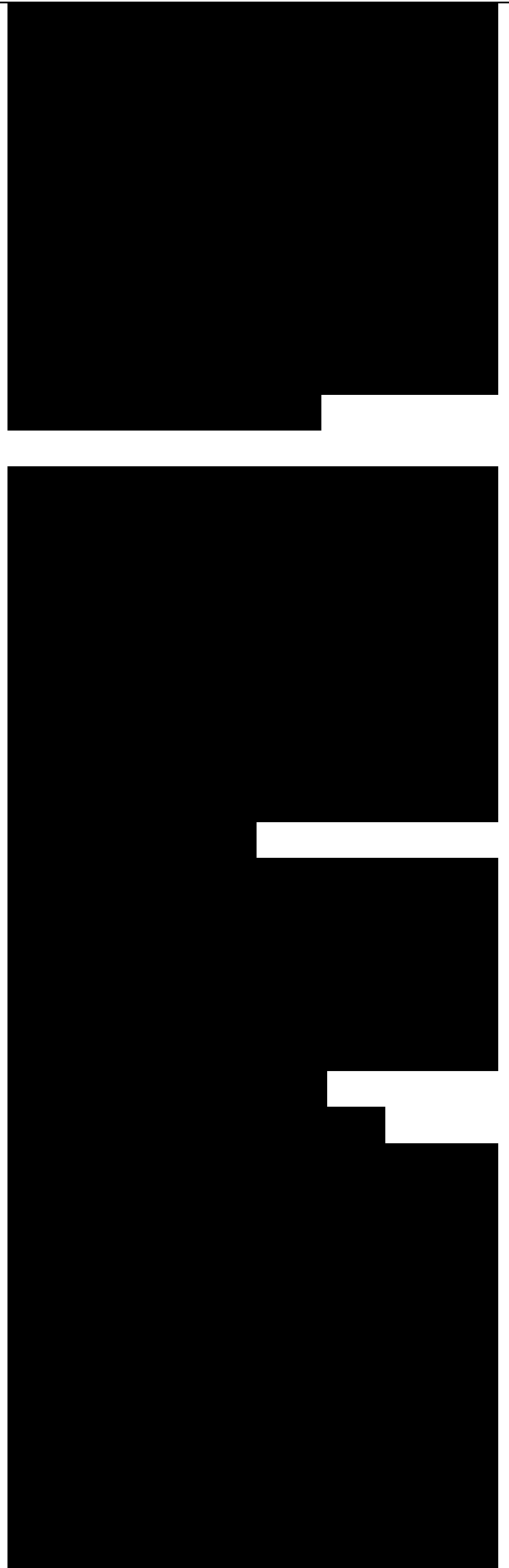
number to 5 then you will find the same modes, but it will take the mode solver a bit longer to find the modes.

The following figures show the field components of the SSb0 mode. The phase of the mode automatically determined from MODE Solutions differs from the Berini figures by 180 degrees. This phase difference can be correct in the plasmon_plot. lsf script.

It is important to notice that most of the field energy is confined to the corners of the waveguide. The following figures show the electric field intensity over the entire waveguide area (left figure), then zoomed in near the waveguide corner (right figure).

Effective Index as a function of waveguide thickness

The plots below show the results of a sweep calculating the ssb0 mode effective index as a function of waveguide thickness, from 50nm-200nm. The effective index increased from about 2.18 to 2.63. These results are in very good agreement with Figure 2A and 2B from Berini.

5.2   Modeling Instructions

This page contains 3 independent sections. The first section describes how to setup the structure and the MODE mesh. You can skip this step, open the associated plasmon. lms file and proceed to the following steps. Section 2 describes how to find the SSb0 mode and plot the field profiles. Section 3 describes how to set up a sweep to obtain the effective index as a function of waveguide thickness.

In this topic

Simulation Setup^

Find and plot mode SSbQ^

Effective Index as a function of
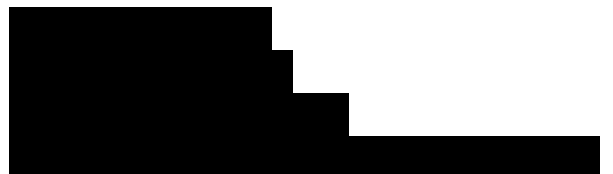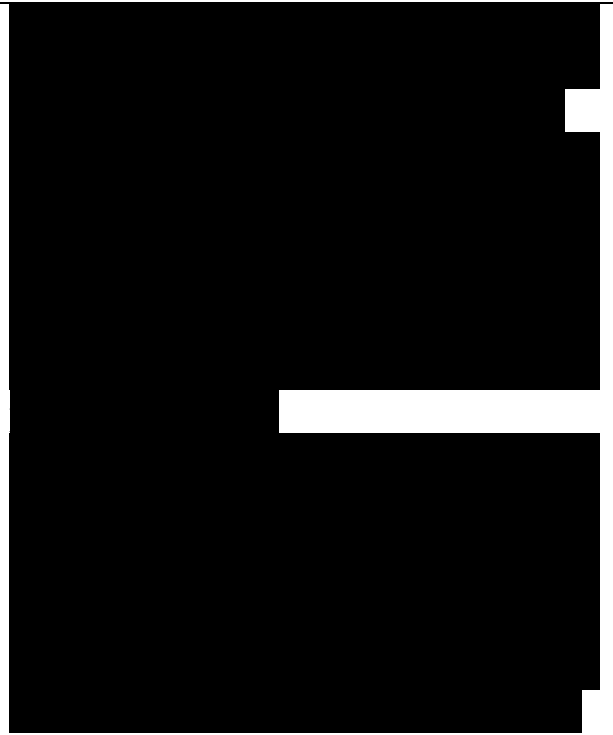
waveguide thickness l~5?|

Simulation Setup

Start a new simulation. Since we are using a 2D Z-normal Eigenmode solver you can open the simulation up in 2D drawing mode by selecting the menu options below. This hides the z dimension since we are not using it.

Add new material to material database
• Press on the MATERIAL database button Materials
• Click on the Add button and select (n,k) material. This adds a new material named "New Material 1" to the database. Edit this material according to the following table.

Set up structure and MODE Solver region

Press on the arrow on the STRUCTURES button and select a RECTANGLE from the pull-down menu. Set the properties according to the following table.

Press on the arrow on the SIMULATION button and select a MESH region

Find and plot MODE SSb0

Run

Open the analysis window by pressing on the RUN button First press the MESH STRUCTURE button to mesh the structure, and obtain a spatial plot of the refractive index

In the MODAL ANALYSIS section set the properties according to the following table. Then press CALCULATE MODES. The effective index of plasmon modes is often higher than the maximum real part of the effective index. For this reason we want to search for a n which is higher

than the default "use effective index" setting.

There are 3 different methods which can be used to create the plots of the ssb0 mode

You can plot the components of the profile using the mode plot options of the analysis window. See the mode plot options page in the reference guide for more details.

Open the script file editor, as shown on the MODE Solutions GUIfi^ page of the Introduction section. Next, press on the OPEN button ' ^ and browse to the plasmon_plot.lsf script file included in the installation directory for MODE Solutions or on the first page of this example. Then press on the RUN SCRIPT button on the previous page.

In the analysis window, the mode data appears in a list with mode numbers. Find the mode of interest and select it in the Object tree as shown below. Choose to Visualize the electromagnetic fields.

You can then select which components of the E field data you want to plot in the Visualizer. The screenshot below shows how to plot the real part of the z component of the Electric fields.

Effective Index as a function of waveguide thickness

Step 1: Make model data available to parameter sweep

We are interested in obtaining the effective index and loss data from the ssb0 mode. Note that when we found modes in the previous step, the ssb0 was always the first mode in the mode list. In analysis mode we can see the mode1 data in the MODE data group (left image below). If you switch to layout (right image below), the mode1

data is no longer available. The first step is to make sure the mode1 data is available for the sweep.

• Edit the MODE data group by right clicking on the object with your mouse. Select the Edit object option from the list.

• In the Analysis->Variables tab click the bottom ADD button twice. This will add two results which the data group can give to the parameter sweep. Rename these two results "neff and "loss" as shown in the bottom left window.

• Switch to the Analysis->Script tab shown in the right part of the image below. Then add the following two lines of script commands which will add data to the "neff' and "loss" results once a simulation has run. Press OK to save your changes.
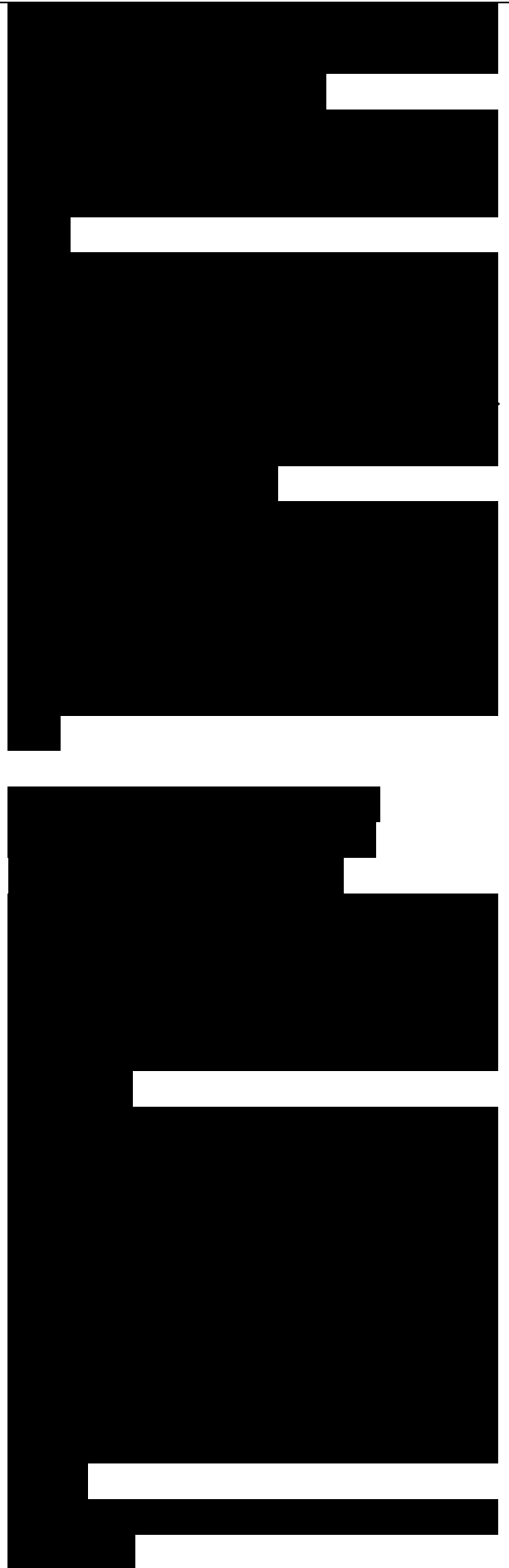
```
neff=getdata("model","neff");
loss=getdata("model","loss");
```

Step 2: Create a sweep

• Open the Optimization and Sweeps window using the VIEW menu at the top of the graphical user interface, or by right clicking on the top title barm of the MODE Solutions GUI.

• Press on the CREATE NEW PARAMETER SWEEP button the simulation. Right click on the parameter sweep and choose to Edit the parameter sweep. Set the properties according to the following screenshot. Notice that the only results you can chose are the results which are seen in the screenshot of the Analysis->Variables tab above.

Step 3: Run the sweep and plot the data

Press on the RUN SWEEP button in the Optimizations and Sweeps Window to run

• Plot the sweep data using one of the methods below. The first method was used to create the plots on the previous page.

Open the Script Prompt Window using the VIEW menu at the top of the graphical user interface, or by right clicking on the top title barlT'l of the MODE Solutions GUI.

Copy and paste the following commands into the Script Prompt and press ENTER on the keyboard to execute them.

thickness = getsweepdata("thickness","waveguide_span") neff = getsweepdata("thickness","neff") loss = getsweepdata("thickness","loss")
# plot results
plot(thickness*1e6,neff,"Waveguide thickness (um) ","effective index");
plot(thickness*1e6,loss*633e-9/(2*pi*20*log10(exp 1))),"Waveguide thickness (um) ", "loss (k)

Right click on the parameter sweep and choosing what data to visualize, as shown in the image below. Note that the loss will be in dB/cm, and that the script commands above converted the units of the loss to k.

6 Ring resonator (design and initial simulation)

Problem definition

This is Part 1 of the ring resonator getting started tutorial. Here, we will consider how MODE Solutions can be used to design and simulate a ring resonator. We will use the software to achieved a desired free spectral range (FSR) and quality factor (Q factor) for
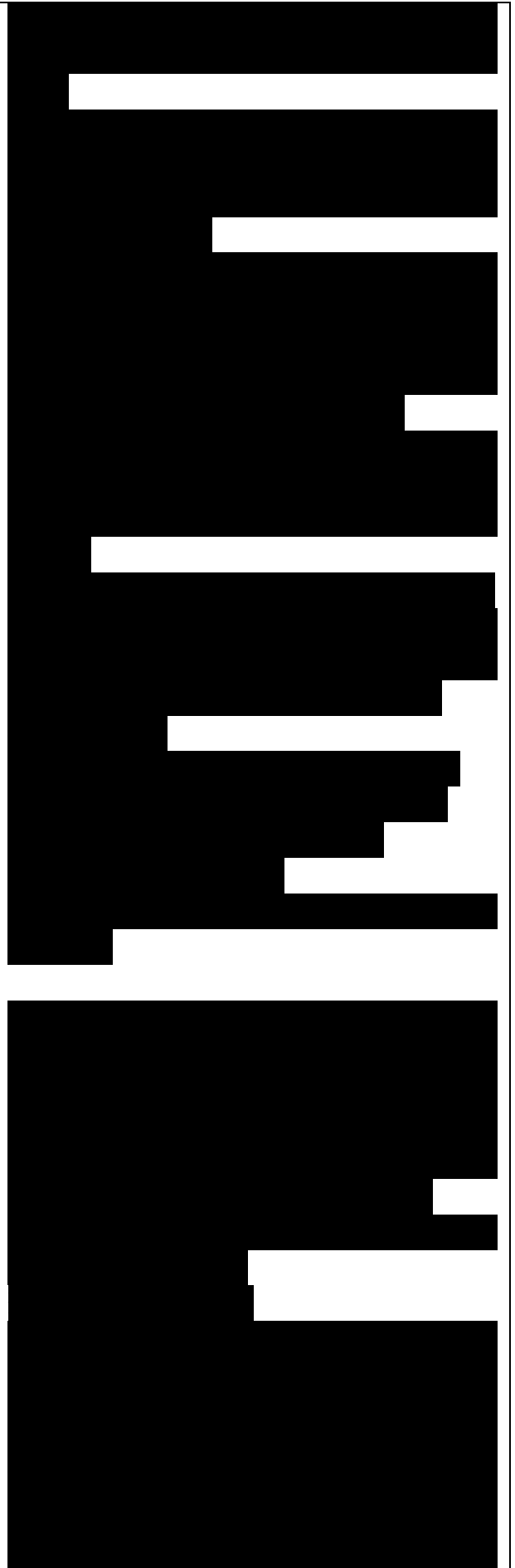
a silicon on insulator (SOI) based waveguide design targeting on-chip communication applications. In Part 2, Ring resonator (parameter extraction and yield analysis)^, we will consider how to carry out the parameter extraction and yield analysis process for this design.

Associated files
Example files can be found in the Examples subdirectory of the installation directory, or downloaded from the online MODE Solutions Knowledge base. ring_resonator.lms ring_resonator.fsp fdtd_results.ldf ring_resonator.lsf ring_resonator_fdtd.lsf
In this topic
Brief reviewf^
Ring resonator designfiPl
Simulation^
Results [64^
References
Hammer, M. and Hiremath, K.R. and Stoffer, R. (2004) Analytical approaches to the description of optical microresonator devices. (Invited) In: Microresonators as Building Blocks for VLSI Photonics, 18-25 October 2003, Erice, Italy. pp. 48-71. AIP Conference Proceedings 709. Springer. ISSN 0094-243X ISBN 978-0-7354-0184-6
Learning objectives
In this example, we show how MODE Solutions can be used to design a ring resonator. The user will learn to:

• Insert a ring resonator object from the components library
• Use the Eigenmode Solver to choose the waveguide spacing, coupling length and ring length for the

desired FSR and Q factor

• Compare results with the theoretical design and 3D FDTD results

6.1 Discussion and results

Basic concepts of Ring Resonators from a designer's point of view

The most basic configuration of the microring resonator is shown in the image below. It consists of a ring-shaped waveguide coupled to two optical waveguides. The cavity mode is excited by evanescent coupling between closely spaced optical waveguides.

The major defining quantities are the average (effective) ring length L, the complex propagation constant p of the circulating mode, the field transmission coefficients of the waveguide coupler ^ and t12, and the bend loss.

The real part of the propagation constant p is the phase constant. The total ring loss is due of the imaginary part of beta, the bend loss, and other scattering losses at the coupling region. For the high index contrast waveguides we are considering, at wavelengths around 1550nm, the propagation loss and bend loss are small. For this analysis we will neglect all losses, but the different loss contributions could easily be considered in a more detailed analysis.

For the case of the ring-shaped waveguide coupled to two optical waveguides, the dropped optical power can be expressed as

On resonance, the phase acquired by the wave after a complete round-trip is an integer multiple of 2n, i.e., pL =

2nN, with N as the mode number. If the effective refractive index is independent of wavelength, then ring length (also called the perimeter) is an integer multiple of the effective wavelength on resonance, or L = NA0/neff, where the effective refractive index is defined as neff = cp/w and A0 = c/f0 is the free-space wavelength at the resonance frequency f0.

In reality, the effective index does depend on wavelength and the resonances are separated by the free spectral range (FSR) which, in wavelength units, is given by

where n = c(dp/dw) is the group index. Since the bending loss is low for high index waveguides, and we are ignoring other sources of loss, the Q factor is approximately given by

We will now use the above formulas to design a ring resonator for a WDM system with a channel spacing of 200GHz (1.6nm at 1550nm). We want to design the system to drop every 16th channel. The FSR should therefore be 3200GHz (25.6nm at 1550nm). We would like the FWHM of the drop to be 100GHz, corresponding to a Q of approximately 1550nm/0.8nm ~ 2000.

We will use a system made of an SOI waveguide. The waveguide is 400nm wide and 180nm high.

Ring resonator design

Step 1: Find total length of the ring needed to obtain desired FSR

We use the Eigenmode Solver on the 3D waveguide cross section to

calculate the group index from 1500nm to 1600nm. We see that the group index is approximately 4.63 at 1550nm. This is significantly larger than the effective index at this wavelength.

Now that we know the group index, we can easily calculate the total desired ring length.

Step 2: Find the length and gap of the coupler segment

We want to design a resonator with a Q factor of 1.55mm/0.8nm the amplitude of t for a given Q with

Using our known group index, ring length and center wavelength, we find ^ ~ 0.95 and therefore t ~ 0.31

If we use the Eigenmode Solver to calculate the index of the coupled waveguide system, we know that the coupling length can be determined from the difference in effective index of the symmetric and anti-symmetric coupled modes by the formula

Using a 100nm gap between the waveguides, we find delta-n = 0.109 at 1550nm. This gives a coupling length of approximately 1427nm. In reality, we will use a coupling length of 0 and will obtain enough coupling from the bent section of the ring near the straight waveguide.

The radius of the ring can be chosen such that we have the desired coupling length and the desired total ring length. For the remainder of the example, we will use a radius of 3.1 microns, and we will use this design for the Propagator simulation in the next step.

Propagator Simulation

In this Propagator simulation, the MODE source will calculate the fundamental TE mode of the waveguide,and use this to inject a guided mode into the upper waveguide. For an overview of the 2.5D Propagator, see the Lumerical's 2.5D FDTD Propagation Method whitepaper on our website.

The ring resonator is a high Q device which traps the light for many round trips in the ring. These high Q devices require longer simulation times in the time domain than non-resonant devices. We will start with a simulation time of 5000fs, although more time may be necessary. Note that this is longer than our default simulation time (1000fs). It is important to increase the simulation time because the frequency domain monitor results are incorrect if the simulation time is not set long enough for the fields to decay. Further discussion based on this example can be found in the our Online User Guide -> Monitors and Analysis Groups -> Simulation time and Frequency domain monitors.

After running the simulation, we can consider the E field intensity near a drop resonance.

We can compare the result with the theoretical curve based on our target FSR and Q. Note that we have adjusted the phase of the coupling coefficient to align the peaks near 1550nm, since only the amplitude of the coupling coefficient is given by Q.

The results are in reasonable

agreement for the theoretical FSR but the Q factor is incorrect. This is due to
• neglecting all sources of loss in the theoretical curve calculation
• not achieving exactly the desired value of t12

The 3D FDTD simulation shows lower total transmission because it accounts for more sources of loss.

Note that we have adjusted the theoretical peaks to give a maximum at 1550nm. The precise position of this peak is very sensitive to the exact optical length of the ring.

Next Steps

Please see Part 2 of the ring resonator tutorial: Ring resonator (parameter extraction and yield analysis)[7?l. where we will consider how to carry out the parameter extraction and yield analysis process for this design.

6.2 Modeling instructions

This page contains 6 independent sections. The first section describes how to setup the model. You can skip this step, open the associated . lms file and proceed to the following steps if you want to know the results first. Section 2 and section 3 use the eigenmode solver and the analytical results from the discussion and results section to design the ring resonator. The fourth and sixth sections discuss how to set up the propagator simulation. The fifth section shows how to compare the propagator results with analytical and 3D FDTD results.

In this topic

Create Ring Resonatorfi?!

Add Eigenmode Solver and Find group index [i?!

Determine Coupling LengthfiTl

Update Ring Resonator properties and

Run Propagator Simulation [681

Compare dropped optical power with 3D FDTD and theory [72 1

Add other monitors to the propagator simulation [73^

Create Ring Resonator

• Begin by starting MODE Solutions. You can save the MODE Simulation Project file (. lms) at any point in this process. To do so, choose SAVE in the FILE menu.

Press on arrow on the STRUCTURES button and select a RECTANGLE from the pull-down menu. Set the properties of the insulator substrate rectangle according to the following table.

Press on arrow on the COMPONENTS button OPTICS from the pull-down menu. This will open the object library window.

Select RING RESONATOR from the list and press the INSERT button.

Set the properties of the ring resonator according to the following table. The coupling length and radius used for the first part of the simulation are just an initial guess and will be modified to the correct values later.

Add Eigenmode Solver and Find group index

Press on the arrow on the on the SIMULATION button and select the EIGENSOLVER from the pull-down menu. Set the properties according to the following table. This will place the eigensolver region at the input bus for the ring resonator.

to open the eigenmode solver analysis window. Press on

the MESH STRUCTURE button to plot the meshed structure. Set the wavelength to 1.5 microns.

• Click the "Calculate Modes" button and then, select the mode of interest (mode #1) in the Mode list

• Click on the FREQUENCY SWEEP button to begin the scan. The scan will take about a minute.

• To plot the calculated dispersion as a function of wavelength, select the FREQUENCY PLOT tab in the bottom righthand corner of the frequency analysis window. Then select "group index" in the plot pull down menu. The plot can be seen above the frequency plot tab. If you press the PLOT IN NEW WINDOW you will get a new window. If you zoom into the plot, you can see that at 1.55 microns, the group index is about 4.63.

Determine Coupling Length
Press the SWITCH TO LAYOUT button. This deletes all the mode data and allows us to edit the eigenmode solver.
Move the center of mode solver to x = 0 so that the mode solver is located in a region where two waveguides cross the mode solver.
10 h 18 1 12
Press on the RUN button to open the eigenmode solver analysis window. Press on the MESH STRUCTURE button to plot the meshed structure. Set the wavelength to 1.55 microns, and press FIND MODES.
The neff values for the first and second modes are given in the mode list. We can plug in these neff values into an analytical formula (see the discussion and results page) in order to determine

the coupling length.

Update Ring Resonator properties and Run Propagator Simulation

Press the SWITCH TO LAYOUT button so that it is possible to edit the simulation.

Set the properties of the ring resonator using the values of the coupling length and the radius determined from the previous steps, ie

• Press the arrow on the on the SIMULATION button SimLllation and select the PROPAGATOR from the pull-down menu.

Set the properties _ according to the following table

There is a green cross in the graphical user interface which sets the location of the core slab mode for the propagator. Click on PROP object to select the cross and then drag it so that it overlaps with the Silicon portion of the ring resonator.

Since the effective index is a broadband material, the propagator finds a material fit to the effective index data before running the simulation. Press on the arrow next to the CHECK button and select the MATERIAL EXPLORER. This will open the material explorer, where you can check the fit to the slab mode at the location you just selected. You can also see the material fit for the test materials (which are shown by blue crosses in the graphical user interface).

Next, re-edit the propagator region and select the EFFECTIVE INDEX tab. The plot of the slab mode should look like the image below.
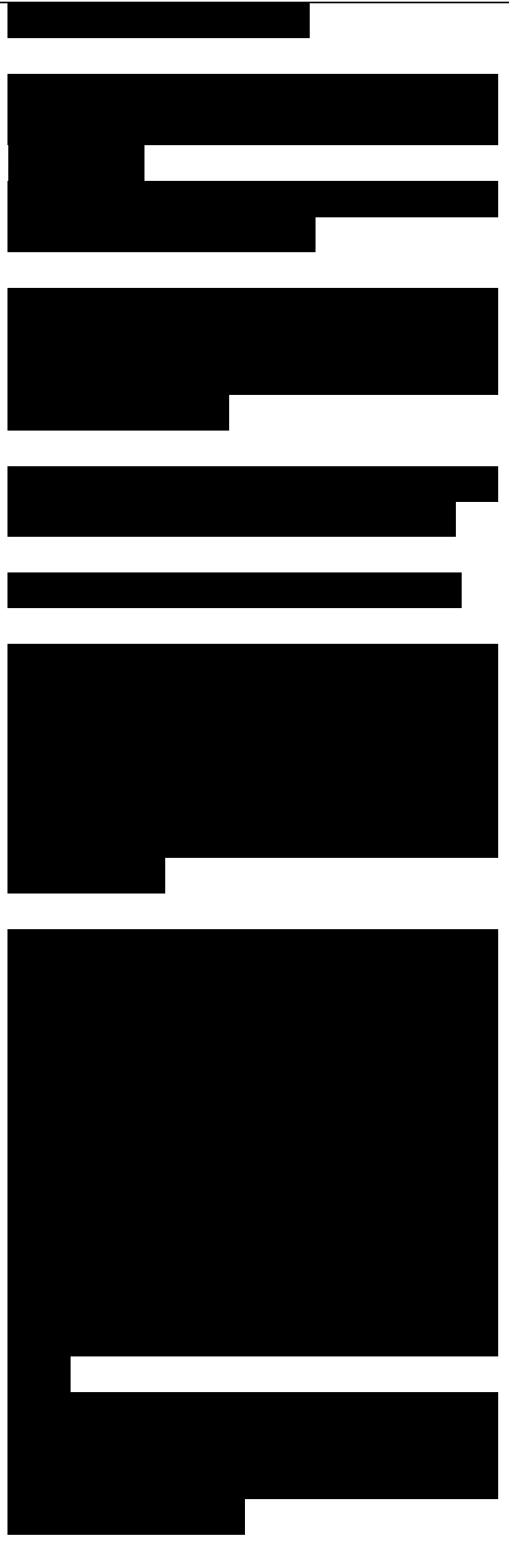
• Press the arrow on the on the SOURCES button SoLllces and select the MODE source from the pull-down menu. Set the properties according to the following table.

• In the previous step we calculated the coupling length from the effective index difference from the mode solver. You can see the effective index difference which the propagator sees by setting $x = 0$ so that the mode source is in between two waveguides. Then choose to user select the modes. This technique is shown in a bit more detail in the waveguide couplers application example in the MODE Solutions online help.

Add monitors for the propagator simulation

Press on the arrow on the on the Monitors button and select the frequency domain field and power monitor from the pull-down menu. Set the properties according to the following table

Press the DUPLICATE button to create a copy of the monitor. Set the properties according to the following table.

Press on the arrow on the on the Monitors button and select the field time monitor from the pull-down menu. Set the properties according to the following table

Press the DUPLICATE button to create a copy of the monitor. Set the properties according to the following table

Run simulation and plot results

Press on the RUN button to run the propagator simulation. The job manager will appear and show the
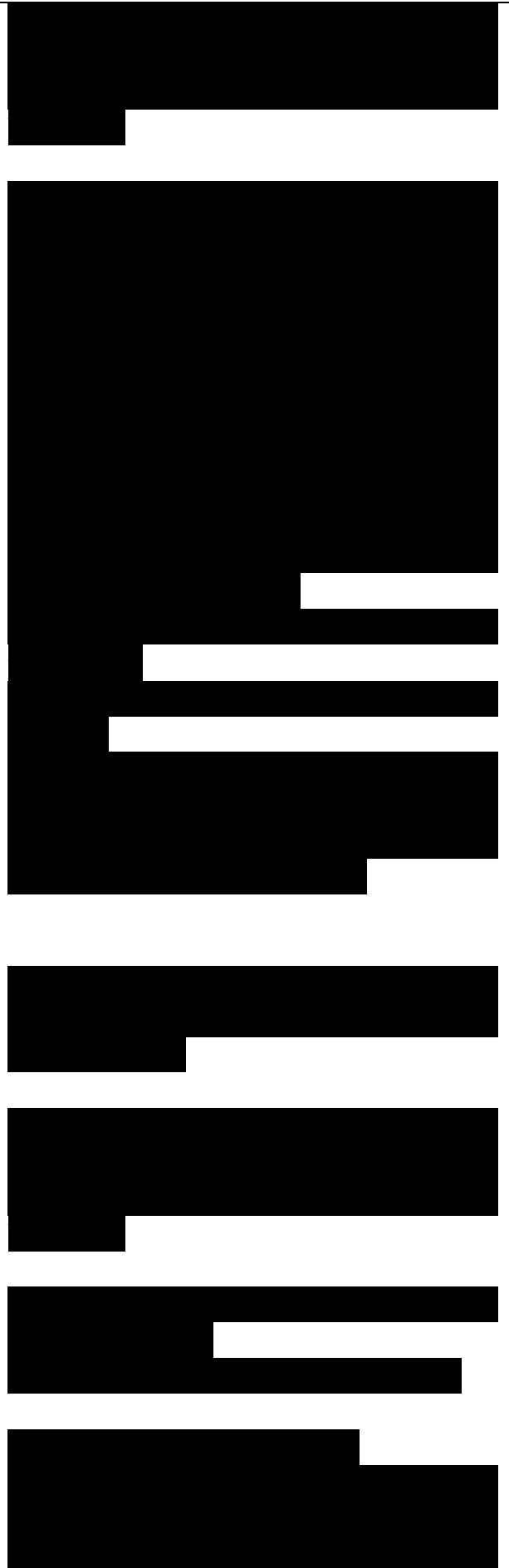
progress for the simulation.

Once the simulation finishes running, all the monitors and analysis groups in the object tree will be populated with data. The Results View window (which can be opened by clicking on the "Show result view" button) will display all the results and their corresponding dimensions/values for the selected object. Plot the time signal and spectrum Ey by right-clicking on the "time_drop" time monitor and selecting Visualize -> E or spectrum. (The field profiles can also be visualized in the same way.)

Compare dropped optical power with 3D FDTD and theory

The files which are mentioned in this section can be found in the Examples subdirectory of the installation directory, or downloaded from the online MODE Solutions Knowledge base.

• Open the script file editor as shown on the MODE Solutions GUlfs'l page of the Introduction section.

Press on the OPEN button < ^ and browse to the ring_resonator. lsf script file. Save the fdtd_results. ldf file in the same folder. This lumerical data file (. ldf) contains the results from the 3D FDTD simulation. This data file can also be created by running the ring_resonator. fsp 3D FDTD simuluation followed by the ring_resonator_fdtd. lsf script file. The aforementioned script file will automatically generate the data file.

Add other monitors to the Propagator simulation

The ring_resonator. lms simulation which is included in the Examples

subdirectory of the installation directory, or can be downloaded from the online MODE Solutions Knowledge base contains three additional monitors which have not been included in the above instructions.

The three additional monitors are
•   a field profile monitor
•   a movie monitor
•   an effective index monitor

Field profile monitor

The field profile can be created similar to the add and drop monitors which were created earlier. The field profile monitor in this example was set up after the simulation ran to completion once. That way, we can only set the monitor to record data exactly at a frequency which corresponds to the maximum power dropped through the drop monitor.
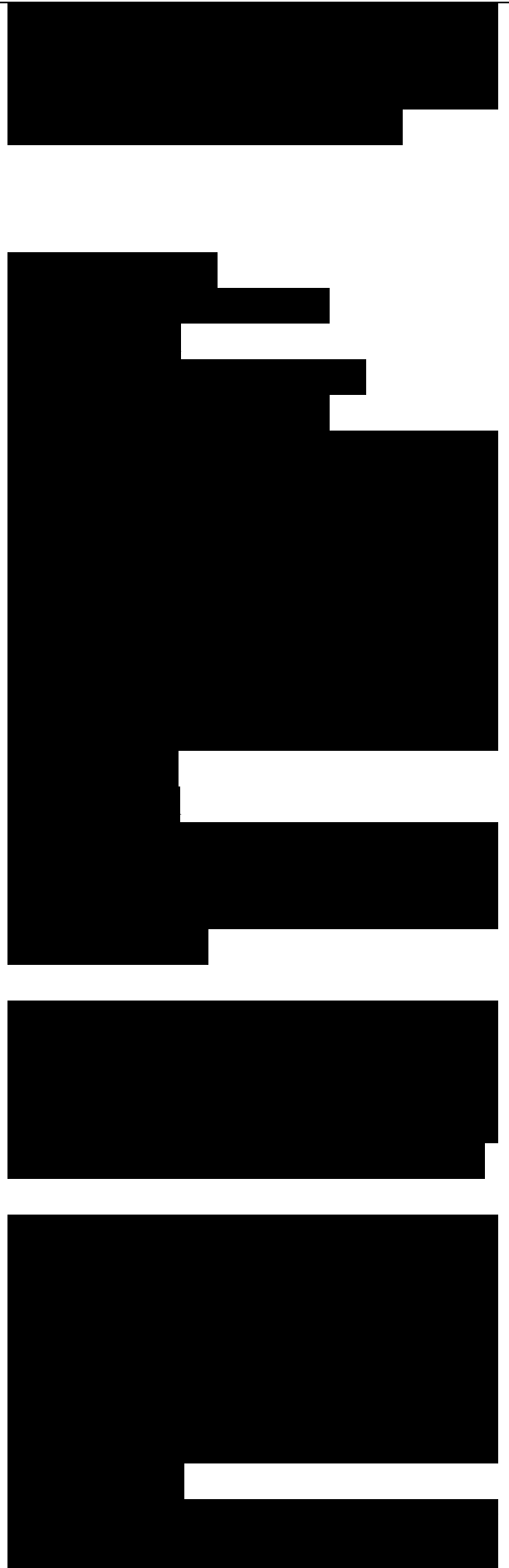
Movie monitor

To add a movie monitor to the simulation, press on the arrow on the on the Monitors button |V|UI IILiJI a and select the movie monitor from the pull-down menu.

Movie monitors are always 2 dimensional and show the progress of the 2D portion of the propagator simulation, which is run after the propagator compresses the z-dimension of the propagator region.

In the ring_resonator. lms simulation, note that the general tab is set up to plot the Ey component of the field (since the TE slab mode is chosen for the propagator). Also, notice that the scale is reduced from a default of 1 to a setting of 0.1 so the fields are more visible in the movie

By default the movie monitor is set as inactive. It is possible to

activate/deactivate the movie monitor by right clicking on the object with the mouse as shown in the screenshot to the right. When the movie monitor is active, a movie with the same name as the movie monitor is saved in the current working directory. The movie monitors are disabled in the simulation because the simulation takes longer to run when movie monitors are enabled.

Effective index monitor
The effective index monitor is also created similar to the other monitors in the simulation. It shows how the simulation volume is compressed in the z dimension. In contrast, an index monitor will only plot the refractive index of the structure. Further details can be found in the Simulation Objects chapter of the reference guide.

7   Ring   resonator   (parameter extraction and yield analysis)
Problem definition
This is Part 2 of the ring resonator getting started tutorial. Here, we will consider how to carry out the parameter extraction and yield analysis process for the design that we introduced in Ring resonator (design and initial simulation)^.
Please go through this example before proceeding.
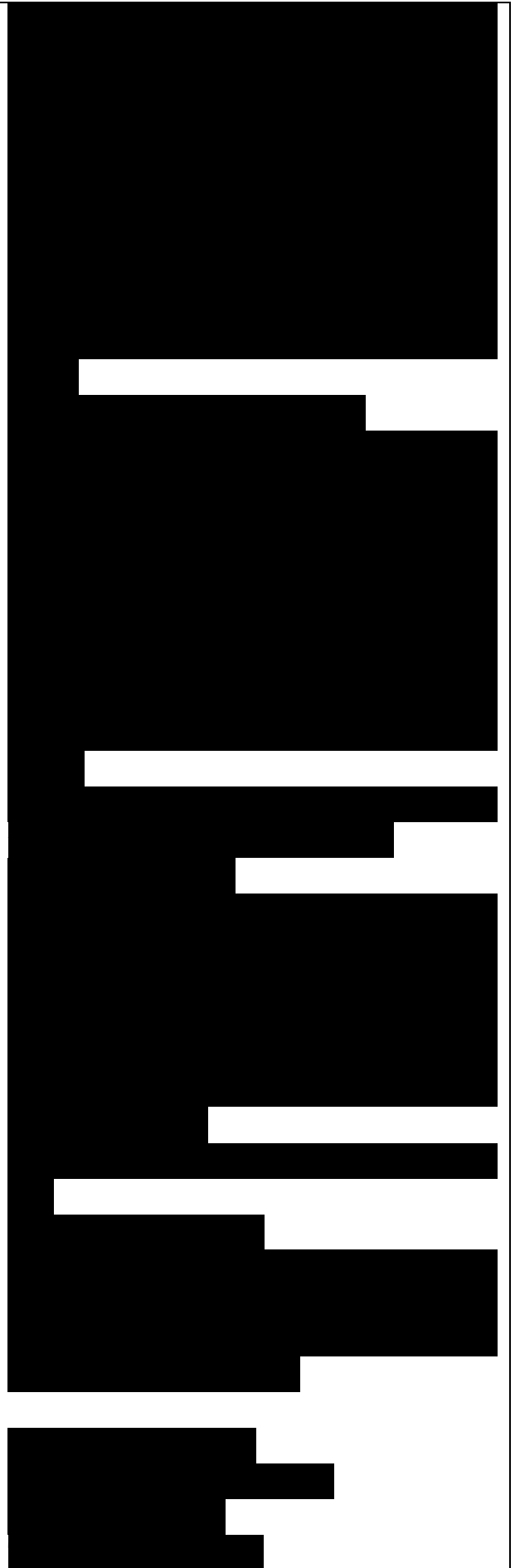Associated files
Example files can be found in the Examples subdirectory of the installation directory, or downloaded from the online MODE Solutions Knowledge base.
ring_resonator2.lms
ring_resonator2_yield.lms
In this topic
Brief reviewf59l

Ring resonator designfiPl

Simulation^

Results [64^

References

Hammer, M. and Hiremath, K.R. and Stoffer, R. (2004) Analytical approaches to the description of optical microresonator devices. (Invited) In: Microresonators as Building Blocks for VLSI Photonics, 18-25 October 2003, Erice, Italy. pp. 48-71. AIP Conference Proceedings 709. Springer. ISSN 0094- 243X ISBN 978-0-7354-0184-6

Learning objectives

In this example, the user will learn to:

• Use Mode Expansion Monitors to extract the parameters for interfacing with circuit level simulations in INTERCONNECT.

• Compare the S parameter results with 3D FDTD.

• Use the Yield Analysis feature to track the effect of fabrication errors on the free spectral range (FSR) of the ring resonator.

7.1 Discussion and results Problem definition Parameter extraction results

The ring resonator is a 4 port device, which we we can label 1 through 4, as shown below. We can use a mode expansion monitor to calculate the complex mode expansion coefficient for both forward and propagating modes in each waveguide. This allows us to easily construct the 16 parameter S matrix which can be exported for use in INTERCONNECT. In reality, this device is so symmetric, that only 4 coefficients of the S matrix need to be calculated - for example, $S11=S22=S33=S44$.

The mode expansion monitor is setup to calculate the amount of forward and backward propagating power in the fundamental TE mode for the 4 monitors at the input and output ports. First, we can look at this in the Visualizer. Note that this analysis takes several seconds because each waveguide mode is recorded over 500 frequency points. To speed up the calculation, we have used a single mode at the center frequency for the expansion, however we could calculate more mode profiles over the device bandwidth to obtain a more accurate expansion. Once calculated, the expansion is stored in memory and will be saved to the .lms file for quick future reference. The figure below shows the amount of power reflected in port 1 and transmitted through ports 2, 3 and 4 (T forward/T backward).

It is interesting to note the resonant reflection and transmission that is occurring at port 1 and port 4 (blue and green). The power reflected and leaking out port 4 is equivalent. These are due to weak coupling between forward and backward propagating modes in the ring, which can have a substantial effect due to the high Q of the device.

As mentioned in the Modeling instructions f87l section, the model itself is an analysis group that is setup to calculate the S parameters. Select the model and use the Results Manager to calculate the S matrix. During the calculation, S11, S21, S31 and S41 are saved to the text file FDTDtoINTERCONNECT.txt which can be used to create a ring resonator element in INTERCONNECT. The different S parameters can be easily
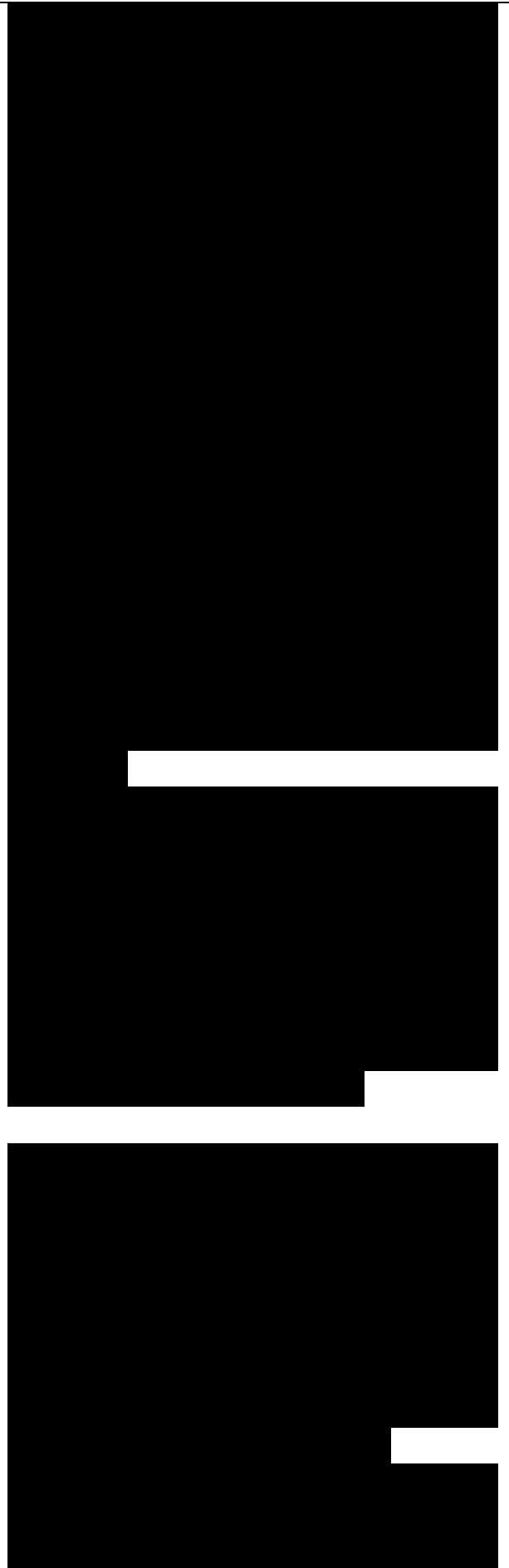
visualized. For example, below we see the phase of S21 and S31. We can see the effect of the resonances which lead to sudden changes in the slope of the phase which indicates the sudden change in group delay at resonance.

Comparing with 3D FDTD
The same ring resonator is modeled using 3D FDTD in the FDTD Solutions Ring Resonator Tutorial, and the results are shown below:

These are in reasonable agreement with the Propagator results shown in the previous section (especially in the FSR). There are some differences in the Q factors, which is not too surprising as FDTD accounts for more sources of loss. That being said, one can go a long way towards optimizing the design with only Propagator simulations. Below is a summary of the simulation requirements for the two types of solvers:

Note that this is a relatively small simulation (10x10um span in the x/y directions). Typical simulations with ring resonators or other silicon photonic devices require much larger simulation regions and much longer simulation times. In that case, it is even more important to consider using MODE Solutions' Propagator, which may lead to a significant amount of time savings.

Yield analysis
To make sure that the actual device will work as expected, it is often necessary to consider imperfections that can result from the fabrication
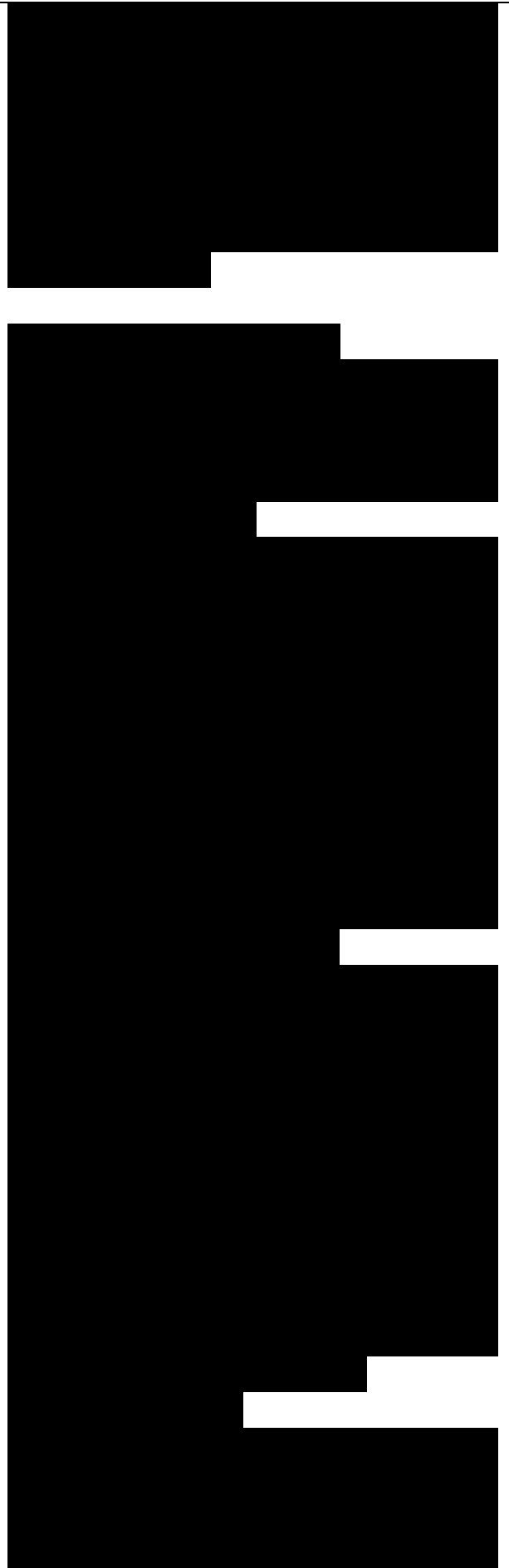
process. To do this, we first set up a nested parameter sweep to track change in FSR as a function of the waveguide height and width (assuming fabrication error of ±10nm). The following figure shows the map of the FSR vs waveguide height and width:

Then, in the yield analysis, we can define the target range for the FSR. Once the simulations finishes running, the log at the bottom of the "Yield analysis status" window will show the calculated yield percentage which corresponds to the percentage of trials that falll within the specified yield estimate range. One can also plot the FSR histogram as shown below. (Note that even though we are only considering the FSR in this example, it is very straightforward to extend this analysis to take into account other properties such as the shift in the resonance peaks, the Q factors ... etc using the same methodology.)

The parameter sweep and yield analysis shown in this example required more than 100 simulations. More simulations will be necessary if we want to change more parameters. This is another reason to consider using the Propagator instead of running 3D FDTD simulations.

7.2   Modeling instructions

This page contains 3 independent sections. The first section (Parameter extraction) describes how to setup the mode expansion monitors for parameter extraction. If you prefer to skip this section,the completed simulation files are provided on the first page of the tutorial. The second section describes how to use the S parameter results from the first section
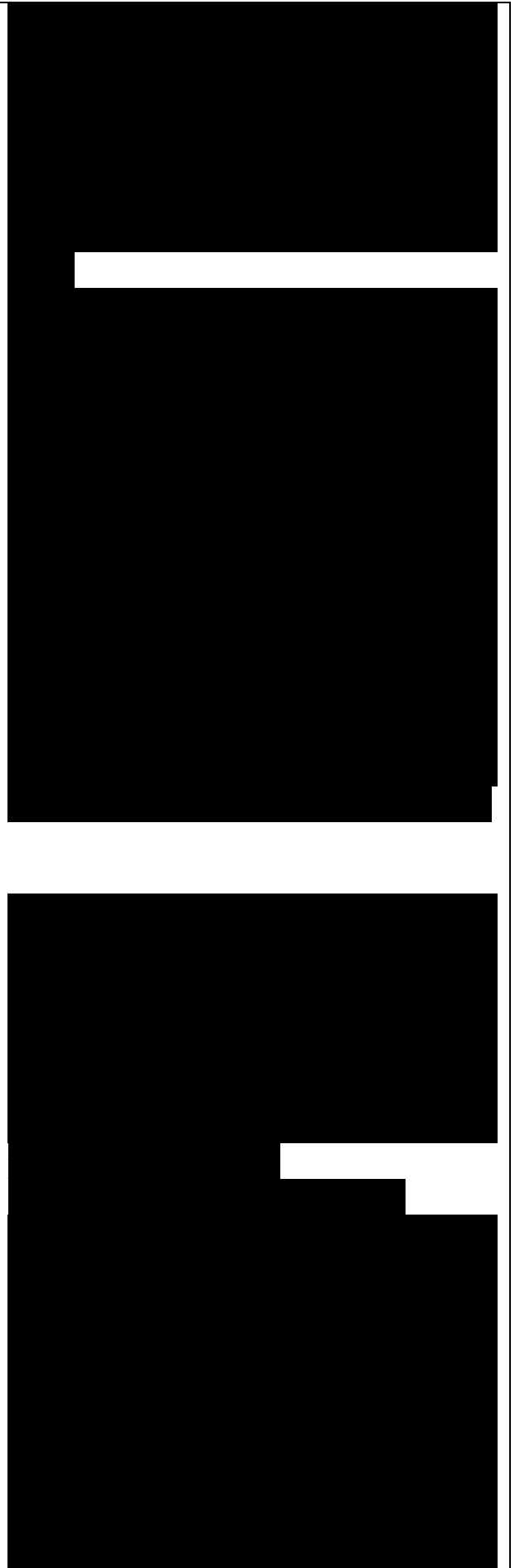
in a circuit level simulation in INTERCONNECT. The final section shows how to track the effect of fabrication errors on the free spectral range (FSR) of the ring resonator by performing yield analysis.

In this topic

Parameter extraction^ Yield analysisf8?1

Parameter extraction

Mode expansion monitors

We will start with the file ring resonator.lms from Ring resonator (design and initial simulation)!^.

Open the ring resonator.lms file and run the simulation.

Before adding the mode expansion monitor, please read the following page on the calculations behind mode expansion monitors: User Guide -> Using Mode Expansion Monitors.

Add a mode expansion monitor by pressing on the arrow on the Monitors button

■ ■ 1 and select the Mode expansion monitor from the pull-down menu. Set the properties according to the following table. (Note that you can add mode expansion monitors in layout or analysis mode, so it is not necessary to switchtolayout if the simulation has already been ran.)

We have positioned this monitor directly in front of the MODE source, and we will use the fundamental mode of the top waveguide to expand the field at the 4 ports of the ring resonator.

• In the Mode expansion tab, select the fundamental mode for "Mode calculation". You can use the Visualize Mode Data button to study

the field profile for this mode.

• In the "Monitors for expansion table", select the 4 power monitors we have set up at the 4ports of the Ring Resonator as follows:

Plot results

Once the mode expansion monitor has been defined, you will see the list of results in the Result VIew panel. Multi-select the modal expansion results and select "Calculate". Once the calculations are complete, one can plot the results in the Visualizer.

Note that when the Visualizer first opens up, you will see a list of all the attributes of all the results. One can use the "Remove" button on the right side of the attribute panel to remove any unwanted attributes, keeping only the relevant ones. For a complete description of all the results from the mode expansion monitors, please refer to User Guide -> Using Mode Expansion Monitors.

S parameter calculations

In ring resonator2.lms, the model analysis group in the provided pre-made simulation file has been set up to calculate the S parameters. Since the expansion monitor automatically returns the expansion coefficients for the forward and backward propagating light (a and b), we can calculate the S parameters very straightforwardly. The calculations can be found in the script under the Analysis tab of the "model" group, this script will also export the S parameter results into a .txt file, which can be imported directly by INTERCONNECT.

Edit analysis group

• As shown in the figures above, the Results View will automatically show the S parameters result returned

by the model analysis group. One can then visualize this result by right-clicking on "S" and selecting Visualize.

Yield analysis

To test how our design is affected by fabrication errors, we can use either a parameter sweep or an yield analysis project.

In ring resonator2 yield.lms, a "FSR" analysis group has been added, which will return the FSR by finding the peaks in the transmission spectrum of the "through" monitor. We will track the change in the FSR as a function of the waveguide width and height, assuming a fabrication error of ±10nm.

Parameter sweep

A nested parameter sweep project has been set up to track the change in FSR as a function of the width of the waveguide (from 0.39 to 0.41 microns) and the height of the waveguide (from 0.17 to 0.19 microns). Once the sweep is complete, one can plot the map of the FSR as a function of the waveguide height and width to see how the result deviates from the original design as a result of this ±10nm fabrication error.

Yield analysis

An yield analysis project has also been set up to vary the width of the waveguide based on a Gaussian distribution centered at 0.4 microns, with a standard deviation of 0.01 microns. Once this is run, we will be able to see whether the FSR falls within our target specification range of 27nm to 27.5nm.