Exercises

Waveguide and Coupler Design with Ansys Lumerical

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Ansys Software Used

This resource uses Ansys Lumerical MODE™ optical waveguide design tool and Ansys Lumerical FDTD™ advanced 3D electromagnetic FDTD simulation software.

Summary

This exercise explores waveguide design using Ansys Lumerical MODE tool. It was originally developed by Dr. Prabhav Gaur, Dr. Andrew Grieco, Karl Johnson, Dr. Peter Ilinykh, Prof. Saharnaz Baghdadchhi, Prof. Yeshaiahu Fainman for the *ECE 184: Optical Information Processing and Holography* course at the University of California San Diego.

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1. Objective

Design a simple waveguide and a coupler using Ansys Lumerical software; analyze propagating modes and other parameters.

2. Background

2.1 Waveguide modes

Consider the simplest planar optical waveguide, which consists of a layer of dielectric material sandwiched between materials of slightly lower refractive indices (see Figure 1).

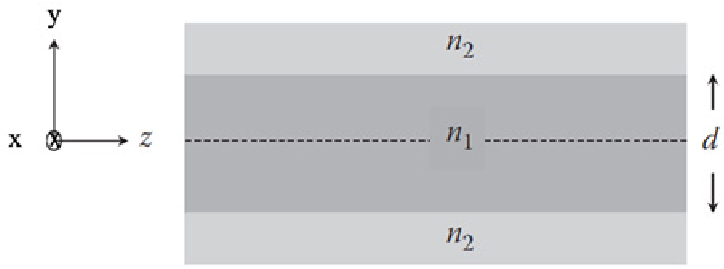


Figure 1.

If the light wave propagating in this layer arrives at the boundary at an angle that is greater than the critical angle of total internal reflection, the light wave is confined inside the waveguide. The wave components reflected from the top and the bottom boundaries interfere with each other. The interference is constructive if the phase change during traveling across the waveguide plus those due to the reflectance from both boundaries of a waveguide is an integer multiple of 2π. In this case, a stationary guided light mode travels along the length of the waveguide with an effective propagation constant, and the amplitude of the electromagnetic field varies across the waveguide.

To determine the waveguide modes, a formal approach may be pursued to find a solution of Maxwell's equations in the inner and outer media. Instead, we write the solution in terms of a plane wave bouncing at an angle θ_m between the boundaries of the slab. The wave travels with a phase velocity $c_1 = c_0/n_1$, has a wavenumber n_1k_0, and has wavevector components $k_x = 0$, $k_y = n_1k_0\sin\theta_m$, and $k_z = n_1k_0\cos\theta_m$. To determine modes, we impose the self-consistency condition that the wave reproduces itself after each round-trip.

If $A_m\exp(-jk_{ym}y - j\beta_mz)$ is the upward wave, then $e^{j(m-1)\pi}A_m\exp(jk_{ym}y - j\beta_mz)$ is the downward wave. There are, therefore, symmetric modes, for which the two plane-wave components are added, and antisymmetric modes, for which they are subtracted. The total field is $E_x(y, z) = 2A_m\cos(k_{ym}y)\exp(-j\beta_mz)$ for odd modes and $2jA_m\sin(k_{ym}y)\exp(-j\beta_mz)$ for even modes. Corresponding TE mode field distributions are shown in Figure 2. Thus, waveguide modes represent transverse field distributions that propagate unchanged and undergo only a phase change as they propagate through the waveguide along z. Note that although the field is harmonic, it does not vanish at the slab boundary.

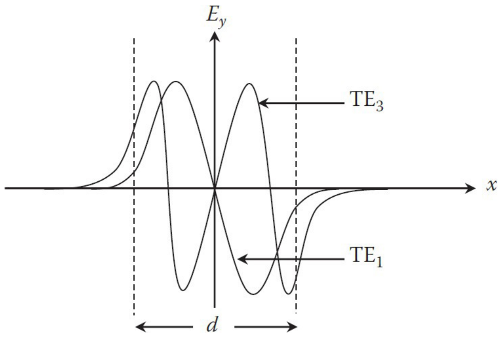


Figure 2.

2.2 MODE method

MODE is a powerful photonic simulation software designed for modeling and analyzing waveguides, photonic integrated circuits (PICs), and other optical structures. Utilizing a fully vectorial finite difference eigenmode (FDE) solver and beam propagation method (BPM), it enables accurate computation of optical modes, propagation characteristics, and dispersion effects. With support for custom materials, anisotropic structures, and seamless integration with other Lumerical tools like FDTD and INTERCONNECT, it is widely used in photonics research and industry. Its automation capabilities, including Python and MATLAB scripting, allow for efficient optimization and large-scale simulations, making it an essential tool for designing advanced photonic devices in fields like silicon photonics, quantum optics, and optical communications.

2.3 FDTD

The FDTD (Finite Difference Time Domain) technique is a numerical method for solving the three-dimensional Maxwell's equations. The technique is discrete in both space and time. The electromagnetic fields and structural materials of interest are described on a discrete mesh made up of so-called Yee cells (Figure 3). Maxwell's equations are solved discretely in time, where the time step used is related to the mesh size through the speed of light. This technique is an exact representation of Maxwell's equations in the limit that the mesh cell size goes to zero.

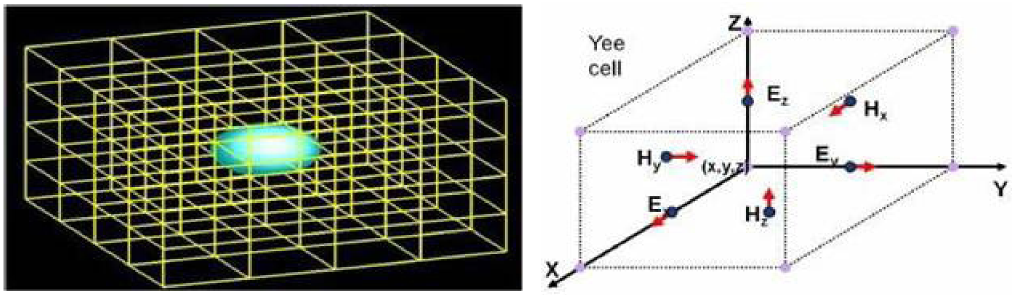


Figure 3.

As the name suggests, FDTD operates in the time domain. FDTD simulates the propagation of a pulse of light, which contains a broad spectrum of wavelength components. The system's response to this short pulse is related to the transmission spectrum via the Fourier transform.

Thus, a single simulation provides the response of the optical system for a wide range of wavelengths at once.

2.4 Ansys Lumerical Software

This lab uses Ansys Lumerical simulation software, which enables the design of photonics components, circuits, and systems. This software includes several sets of tools to be used depending on the task. Ansys Lumerical MODE is an FDTD solver that calculates the spatial profile and frequency dependence of modes by solving Maxwell's equations on a cross-sectional mesh of the waveguide. The solver calculates the mode field profiles, effective index, and loss. Integrated frequency sweep makes it easy to calculate group delay, dispersion, etc. An example of a calculated mode is shown in Figure 4.

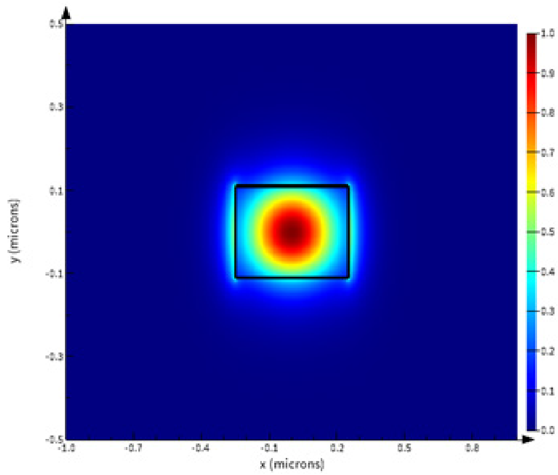


Figure 4.

The Ansys Lumerical package has different file formats corresponding to different functions. The MODE simulation file has a GUI that contains objects pertaining to the simulation and has .lms extension. Similarly, the FDTD simulation file has .fsp extension with a GUI. Both simulation files have a section where you can edit and run Ansys Lumerical scripts. The Ansys Lumerical script file has a .lsf extension. You can look up various scripting commands on the official website: https://optics.ansys.com/hc/en-us/articles/360037228834-Lumerical-scripting-language-By-category

3. Experimental Part

3.1 Waveguide Simulation and Design in MODE

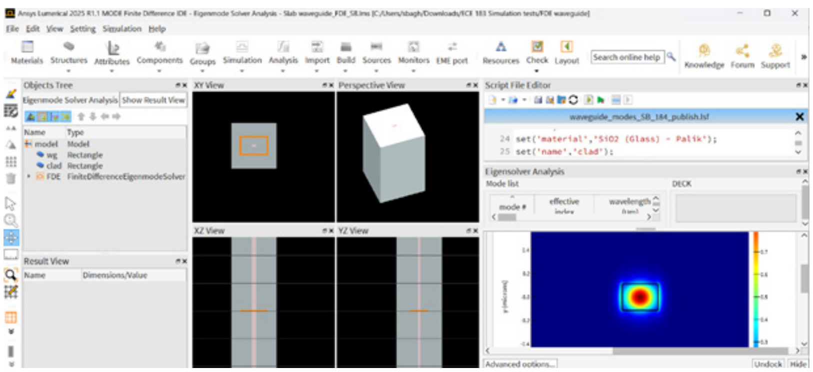
In this section, you will design a 3D waveguide in Ansys Lumerical MODE software and analyze the effective refractive index and other waveguide parameters.

1. Read and understand the waveguide_modes.lsf file that creates a Silicon waveguide buried in SiO2. You should open the script in an empty .lms file. The waveguide has the following dimensions:
   - » x span = 0.5µm, y span = 0.22µm and z span =10µm.
   - » Note that all units in the script are in meters and require a conversion factor of 1e-6 to convert to micrometers.

The file also creates an Eigensolver simulation region with a 2D Z normal solver type.

2. Run the script to set up the simulation. The number of Mesh cells used is 200 by 200 (higher for better resolution and accuracy)

3. Run the simulation and calculate modes using the Modal Analysis tab in the Eigensolver window.



   - » How many quasi-TE and quasi-TM modes does the WG support at 1.55 µm? at 0.8µm? at 3µm?

4. Effective index dependence on wavelength.
   - » Go to Frequency analysis.
   - » Select “track selected mode”
   - » Sweep down to 1.3µm
   - » Plot neff vs wavelength.
   - » Plot in a new window and save as a JPG file for the report. How does neff behave vs. wavelength?

5. Effective index dependence on width.
   - » Vary x span from 0.5 to 1, 2, 4, 8µm and record values of effective index for mode#1.
   - » Plot n_{eff} vs WG width. Comment on neff behavior.

6. Effective index dependence on height.
   - » Change x span back to 0.5µm.
   - » Vary y span from 0.22 to 1, 2, 4, 8µm and record values of effective index for mode#1.
   - » Plot n_{eff} vs WG height. Comment on n_{eff} behavior.
   - » Make x span = y span = 8µm. Record the value of the effective index for mode#1. Comment on n_{eff}.

3.2 Waveguide Simulation Design in FDTD

1. Open the file waveguide_fdtd.lsf (in an empty .fsp file) which has been partially written. Fill in the blank spaces to design a silicon waveguide buried in SiO2. You have to only modify the commented line (starting with #) in the given file. Use waveguide_modes.lsf as a reference to create the simulation objects. Some of the lines will use the same commands as waveguide_mode.lsf, but for other lines the students have to look up the codes on the official website. To figure out how to set a particular field on a given simulation object, you can create the object (e.g. 'addmode' in the console), then do "?set", which gives a big list of all the parameters you can set. Once you find the parameter you want to set, you can
type "?set("[PARAMETER NAME]")" (e.g, ?set("injection axis")), which tells you the options for that parameter. You can then even try to run the "set("[PARAMETER NAME]", [VALUE])" command in the console and check that it doesn't result in an error before inserting it into the script. Note that the first lines of the script delete all simulation objects, so you don't need to worry about any objects created in the simulation during such experimentation before running your script.

2. Fill in the details for the 2D Y-normal movie monitor that occupies the entire simulation in YZ plane and is situated at z=0.

3. Run the file to plot the mode profile captured on XY monitor. The movie monitor creates a video in your current directory. Report the mode profile and the movie.

4. Disable the movie monitor and set the z dimension of the simulation region between z=-0.6 um and 0.1 um. Also, reduce the mesh accuracy from 4 to 3. In the same .fsp file open the sweep.lsf script, which you will use to perform a parameter sweep on wavelength and calculate the effective index. Study the code and fill in the blanks to perform a wavelength sweep between 1.3 um and 1.6 um at 10 different points. Report the n_{eff} vs wavelength plot.

5. Create a new sweep file to sweep the waveguide width between 0.3 and 1.0 um with 0.1 um resolution and report the n_{eff} vs width plot.

6. Create a new sweep file to sweep the waveguide height between 0.2 um and 1.2 um with 0.1 um resolution and report the n_{eff} vs height plot. (Keep the width at 0.5 um).

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