



EXPERIMENT - 1

OPTOELECTRONICS LAB

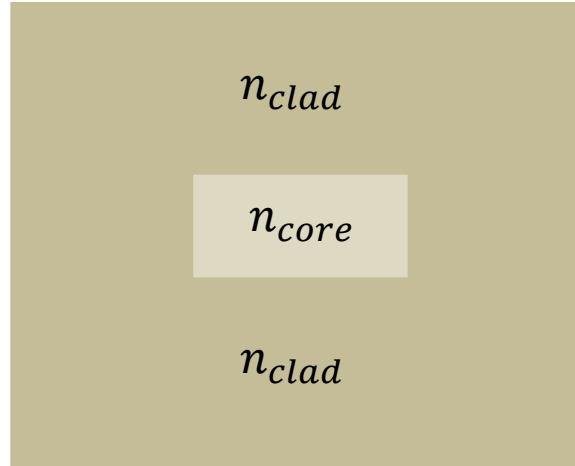
Design and modal analysis of different types of on chip waveguides.

Optical waveguides

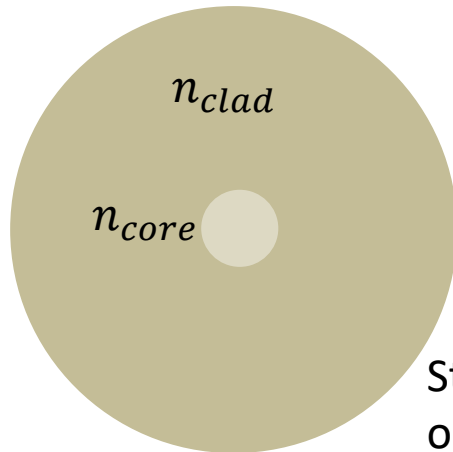
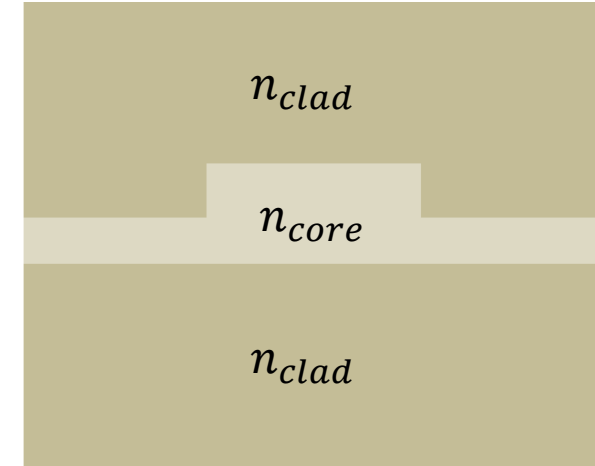
Slab waveguide



Ridge waveguide



Rib waveguide



Step-index
optical fiber

An optical waveguide has the general property that there is always a material with high refractive index (n_{core}) surrounded by a material with lower refractive index (n_{clad})

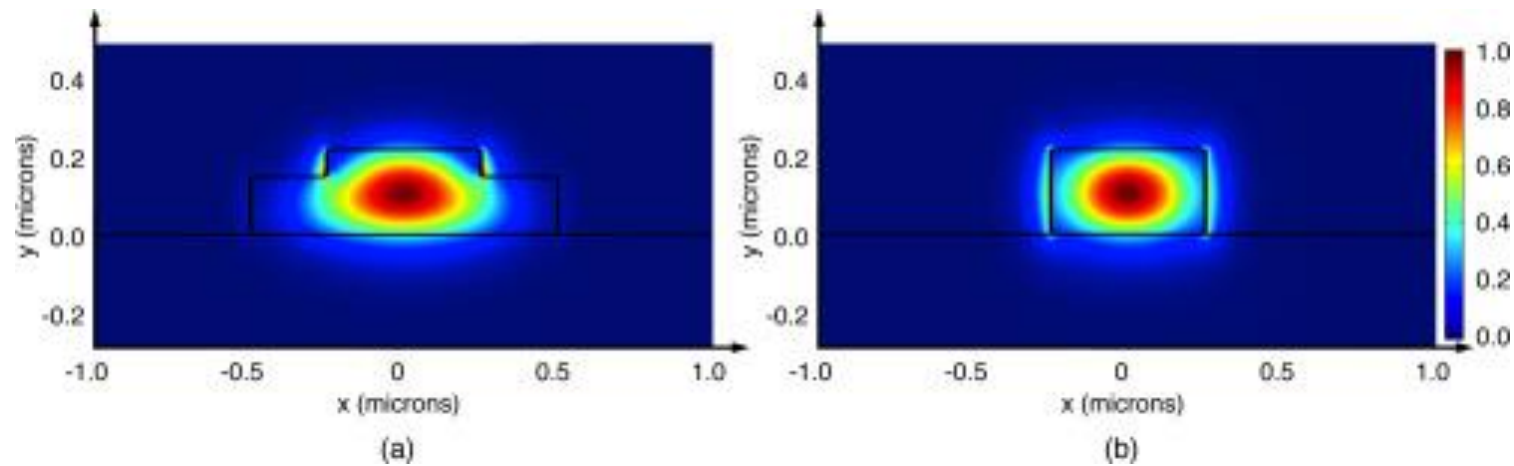
Light is confined by total internal reflection in ray optics picture

Need wave optics to solve for guided modes

Ref: Chuang, Ch. 7

What is a waveguide mode?

- A mode (in general) is a time-harmonic solution to Maxwell's equations ($\propto e^{i\omega t}$)
- A waveguide mode is a stable propagating mode with the special property that its spatial field distribution does not change with propagation (in the absence of loss)
- Waveguide modes are determined by the cross-sectional refractive index profile of the waveguide
- Waveguide modes are wavelength dependent



Wang et al. Opt. Express **20**, 15547-15558 (2012)

Waveguide mode properties / figures-of-merit

- **Effective index:** $n_{eff} \rightarrow k_z = n_{eff} \frac{2\pi}{\lambda}$
 - This number depends upon waveguide design and mode. Larger number means mode is more tightly confined to waveguide core.
- **Modal dispersion:** $n_{eff}(\omega)$
- **Modal group velocity:** $v_g = \frac{\partial \omega}{\partial k_z}$
 - Velocity at which energy flows
- **Group velocity dispersion:** $D = \frac{\partial(v_g^{-1})}{\partial \lambda}$
 - Different wavelengths travel at different speeds down waveguide! Units are time per unit wavelength per unit length. Particularly important for fiber optic cable.

Effective index

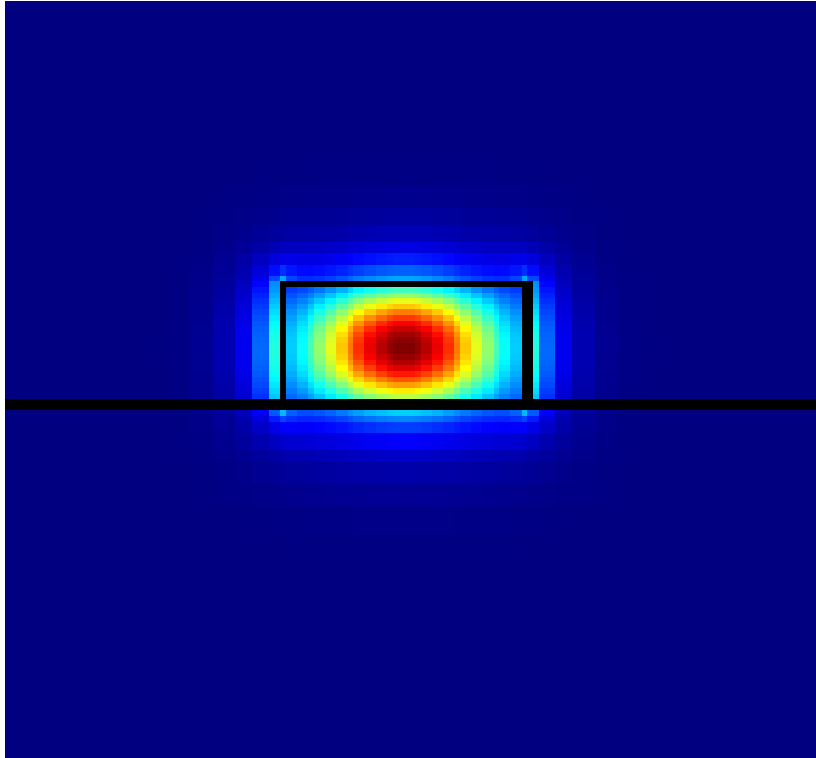
- Each mode has an effective index that can be defined by:

$$k_z = n_{eff} \frac{2\pi}{\lambda}$$

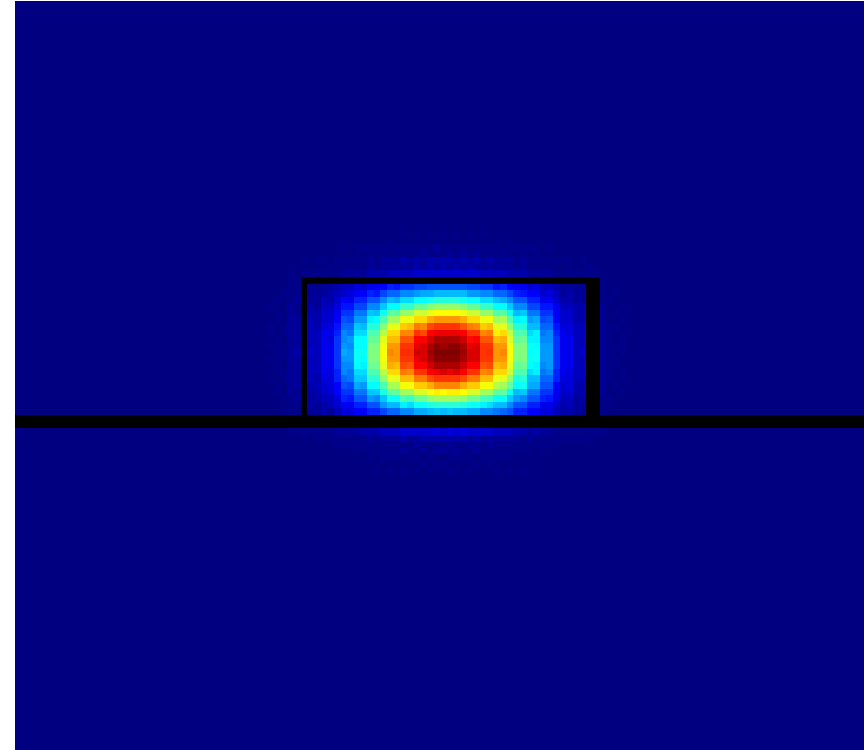
- The effective index tells you how tightly the mode is confined to the waveguide core
 - Guided mode $\rightarrow n_{clad} < n_{eff} < n_{core}$
 - Tightly confined to the core $\rightarrow n_{eff} \sim n_{core}$
 - Weakly confined to the core $\rightarrow n_{eff} \sim n_{clad}$
 - Unguided or radiating modes $\rightarrow n_{eff} < n_{clad}$

Effective index

Small effective index

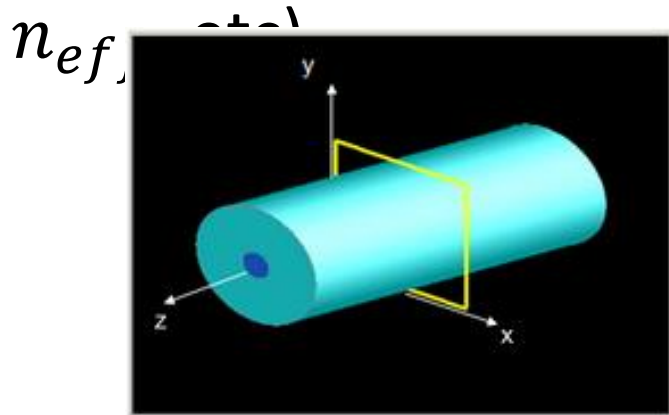


Large effective index

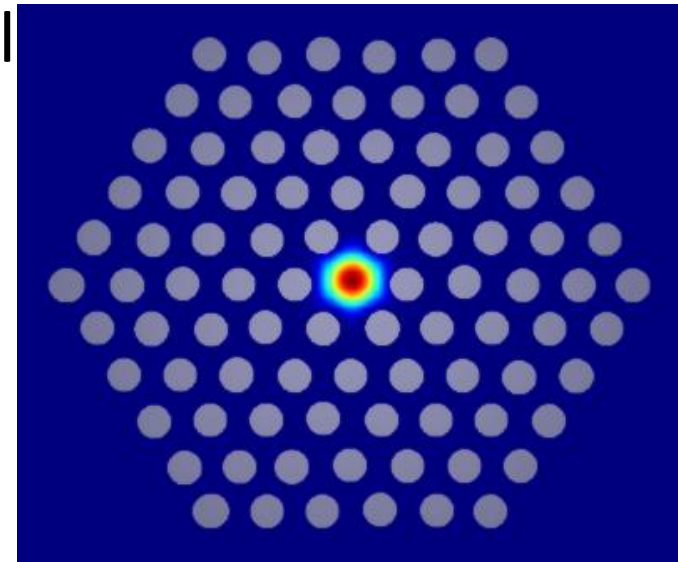
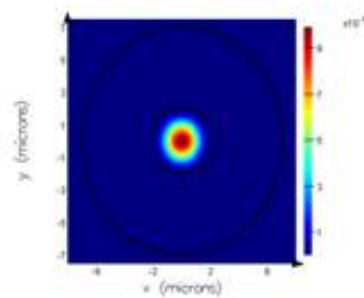


Lumerical MODE

- Lumerical MODE is a finite difference frequency-domain solver that can be used to find waveguide modes
- 1D or 2D cross-section of a waveguide is discretized and simulated. MODE will solve for each mode and display the effective index (n_{eff}) and electric field distribution (e.g.



Single-mode optical fiber



Photonic crystal fiber

Basic waveguide theory

- Time-harmonic electromagnetic fields in a source-free region must satisfy the vector Helmholtz equation

$$(\nabla^2 + \omega^2 \mu \epsilon) \mathbf{E} = 0 \quad (\nabla^2 + \omega^2 \mu \epsilon) \mathbf{H} = 0$$

- The electric-field and magnetic-field vectors in general will have components in the x, y, and z directions.
- Writing out the equation for E_x :

$$(\nabla^2 + \omega^2 \mu \epsilon) E_x = 0$$

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} + (\omega^2 \mu \epsilon) E_x = 0$$

Basic waveguide theory

- Solve by separation of variables

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} + (\omega^2 \mu \epsilon) E_x = 0$$

$$E_x = X(x)Y(y)Z(z)$$

- Plug back into scalar Helmholtz equation to find:

$$X = A_x e^{\pm jk_x x} \quad Y = A_y e^{\pm jk_y y} \quad Z = A_z e^{\pm jk_z z}$$

$$k_x^2 + k_y^2 + k_z^2 = k^2 = \omega^2 \mu \epsilon \quad \leftarrow \text{Important result!}$$

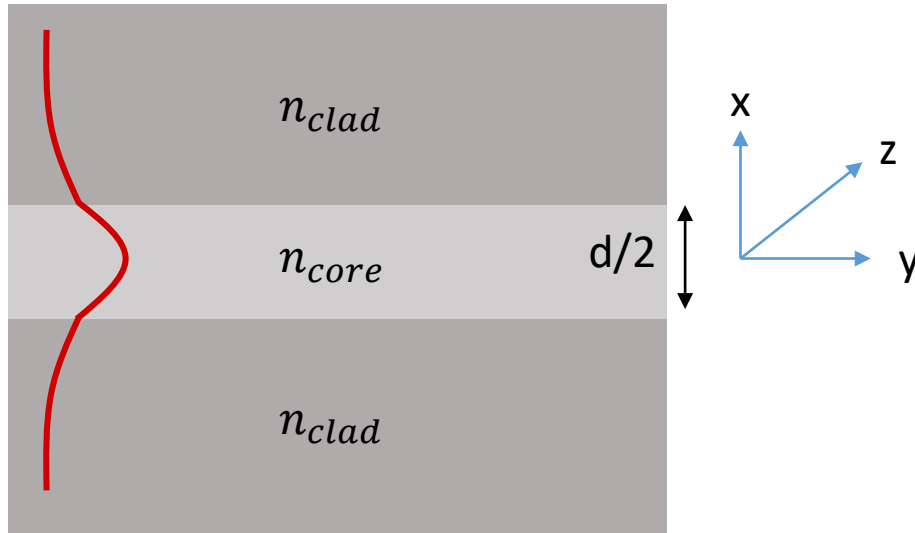
- The same can be done for the other electric and magnetic field components. Usually some field components are either exactly zero or very small and can be ignored.

Solving for waveguide modes:

General approach

- 1) Assume propagation in the z-direction: $\mathbf{E}, \mathbf{H} \propto e^{jk_z z}$
- 2) Make an educated guess for the form of the solution in each dielectric region
 - Traveling wave: $E_x = E_0 e^{jk_x x} e^{jk_z z}$
 - Standing wave: $E_x = E_0 \cos k_x x e^{jk_z z}$
 - Decaying wave: $E_x = E_0 e^{-\alpha x} e^{jk_z z}$
- 3) Plug educated guess back into the Helmholtz equation and apply boundary conditions at interfaces to find characteristic equations that will allow you to solve for k_z

Planar slab waveguide

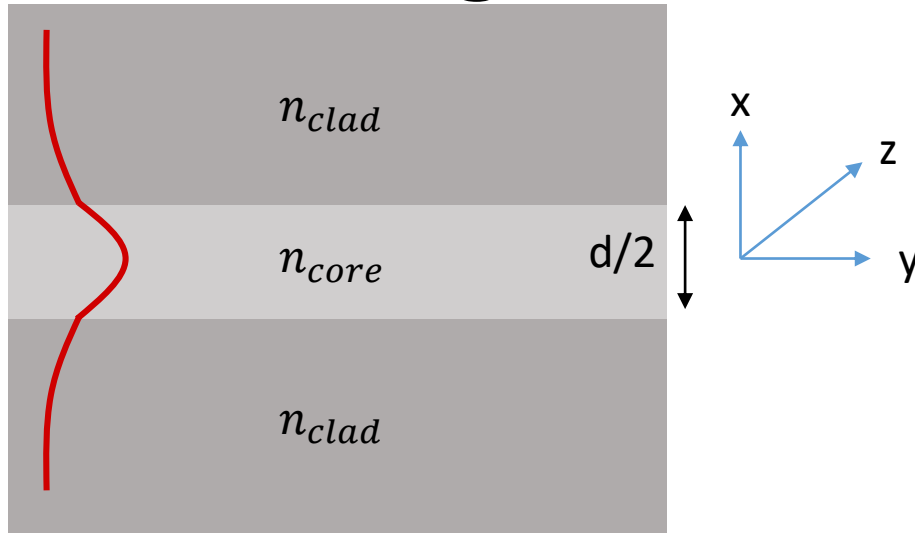


Slab waveguide has two types of modes
transverse electric (TE) and
transverse magnetic (TM)

For **TE mode** the E-field only has a component in the y-direction. Assuming we are trying to solve for a wave guided along the z-direction we also recognize that the structure is y-invariant therefore we can simplify the scalar Helmholtz equation as:

$$\frac{\partial^2 E_y}{\partial x^2} + \cancel{\frac{\partial^2 E_y}{\partial y^2}} + \frac{\partial^2 E_y}{\partial z^2} + (\omega^2 \mu \epsilon) E_y = 0$$
$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2} + (\omega^2 \mu \epsilon) E_y = 0$$

Planar slab waveguide



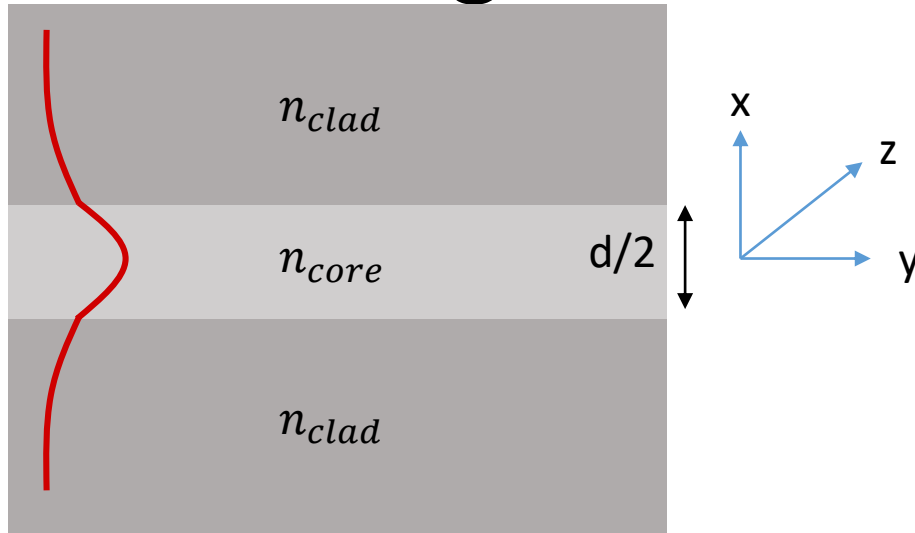
Slab waveguide has two types of modes
transverse electric (TE) and
transverse magnetic (TM)

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2} + (\omega^2 \mu \epsilon) E_y = 0$$

The general solution will take the form:

$$E_y = e^{jk_z z} \begin{cases} A_{y0} e^{\pm jk_{x1} x} & |x| \geq d/2 \\ A_{y1} e^{\pm jk_{x2} x} & |x| \leq d/2 \end{cases}$$

Planar slab waveguide



Slab waveguide has two types of modes
transverse electric (TE) and
transverse magnetic (TM)

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2} + (\omega^2 \mu \epsilon) E_y = 0$$

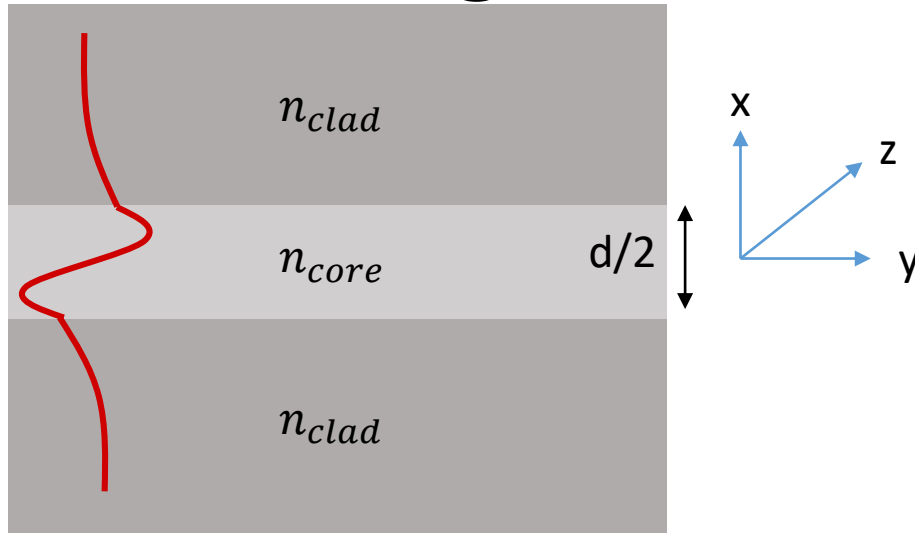
Further simplify as (even solutions):

$$E_y = e^{jk_z z} \begin{cases} A_{y0} e^{-\alpha(|x| - d/2)} & |x| \geq d/2 \\ A_{y1} \cos k_x x & |x| \leq d/2 \end{cases}$$

Field decays into cladding layers

Standing wave solution in core

Planar slab waveguide



Slab waveguide has two types of modes
transverse electric (TE) and
transverse magnetic (TM)

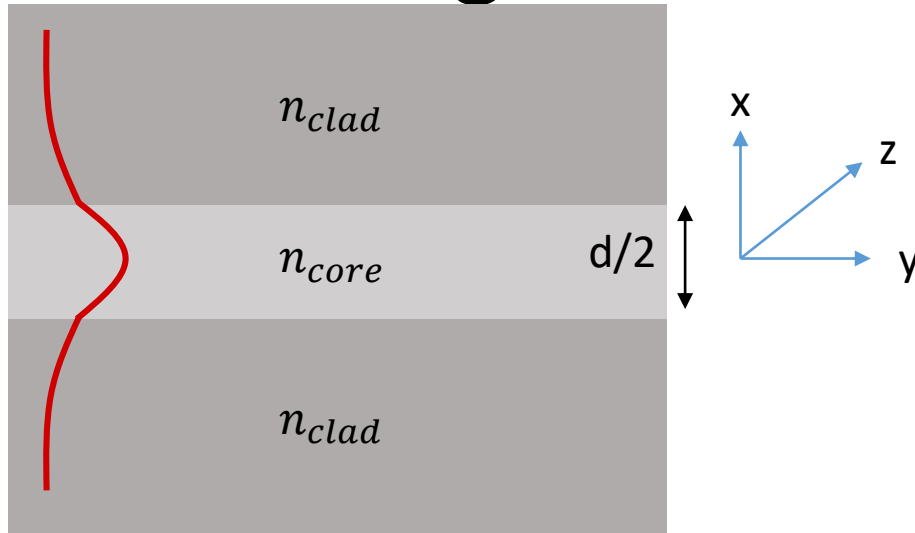
$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2} + (\omega^2 \mu \epsilon) E_y = 0$$

Further simplify as (odd solutions):

$$E_y = e^{jk_z z} \begin{cases} A_{y0} e^{-\alpha(x-d/2)} & x \geq d/2 \\ A_{y1} \sin k_x x & |x| \leq d/2 \\ -A_{y0} e^{\alpha(x+d/2)} & x \leq -d/2 \end{cases}$$

← Field decays into cladding layers
 ← Standing wave solution in core
 ← Field decays into cladding layers

Planar slab waveguide



Slab waveguide has two types of modes
transverse electric (TE) and
transverse magnetic (TM)

Plug back into the wave equation and apply boundary conditions to find:

Even solutions

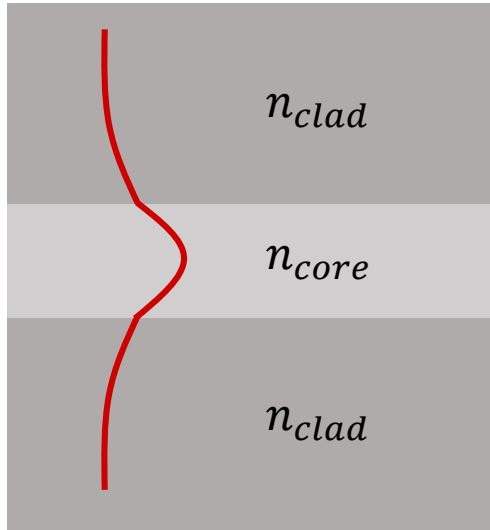
$$\begin{aligned}k_x^2 + k_z^2 &= \omega^2 \mu \epsilon_1 \\ -\alpha^2 + k_z^2 &= \omega^2 \mu \epsilon_2 \\ \alpha &= k_x \tan(k_x d/2)\end{aligned}$$

Odd solutions

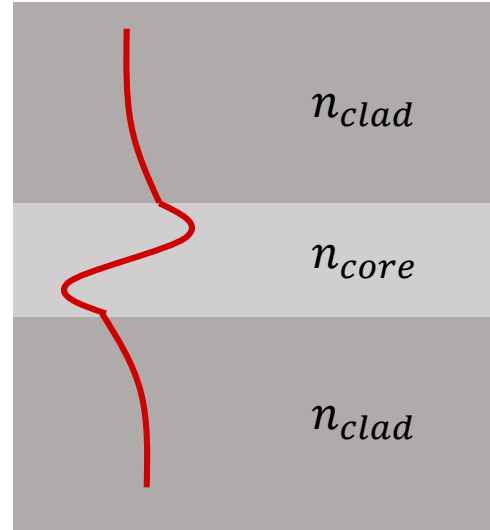
$$\begin{aligned}k_x^2 + k_z^2 &= \omega^2 \mu \epsilon_1 \\ \alpha^2 + k_z^2 &= \omega^2 \mu \epsilon_2 \\ \alpha &= -k_x \cot(k_x d/2)\end{aligned}$$

TE modes

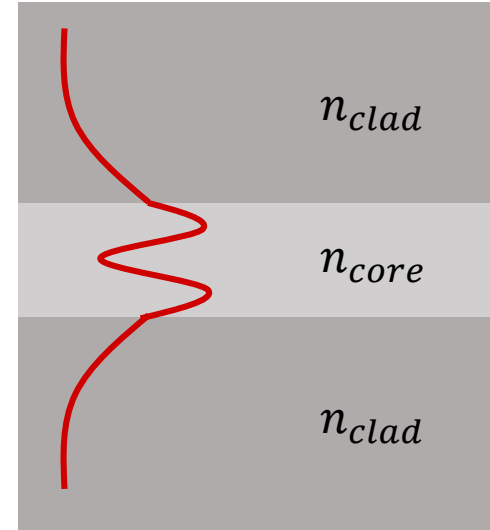
TE₀



TE₁

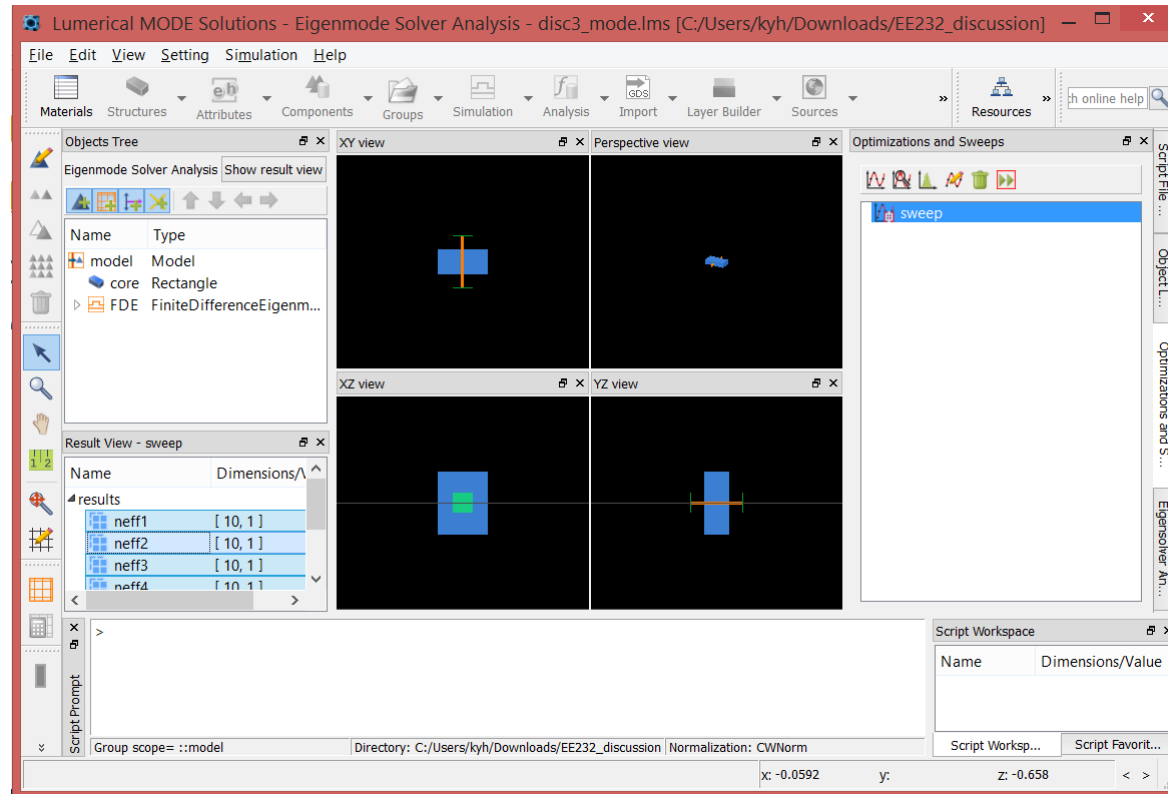


TE₂

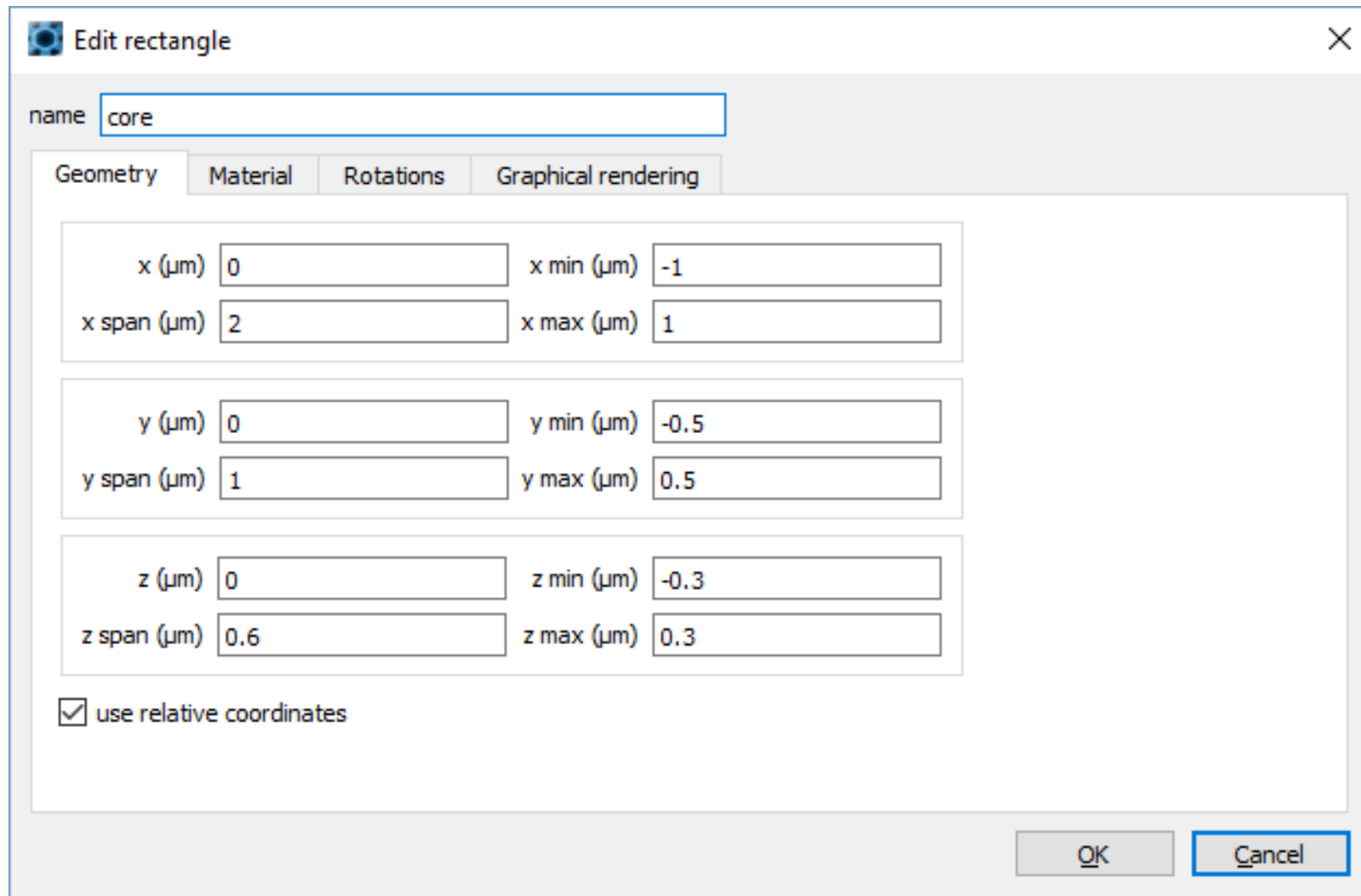


Simulating slab waveguide with Lumerical MODE

- Open MODE software
- Create new rectangle: **Structures > Rectangle**



Create waveguide core



The image shows a software dialog box titled "Edit rectangle" with a close button (X) in the top right corner. The dialog has a "name" field containing the text "core". Below this are four tabs: "Geometry", "Material", "Rotations", and "Graphical rendering", with "Geometry" being the active tab. The "Geometry" section contains three groups of input fields for x, y, and z coordinates. Each group has a central value, a minimum value, and a maximum value, along with a span value. The x-axis values are: x (0), x min (-1), x max (1), and x span (2). The y-axis values are: y (0), y min (-0.5), y max (0.5), and y span (1). The z-axis values are: z (0), z min (-0.3), z max (0.3), and z span (0.6). At the bottom left of the dialog, there is a checked checkbox labeled "use relative coordinates". At the bottom right, there are "OK" and "Cancel" buttons.

name

Geometry Material Rotations Graphical rendering

x (μm) x min (μm)
x span (μm) x max (μm)

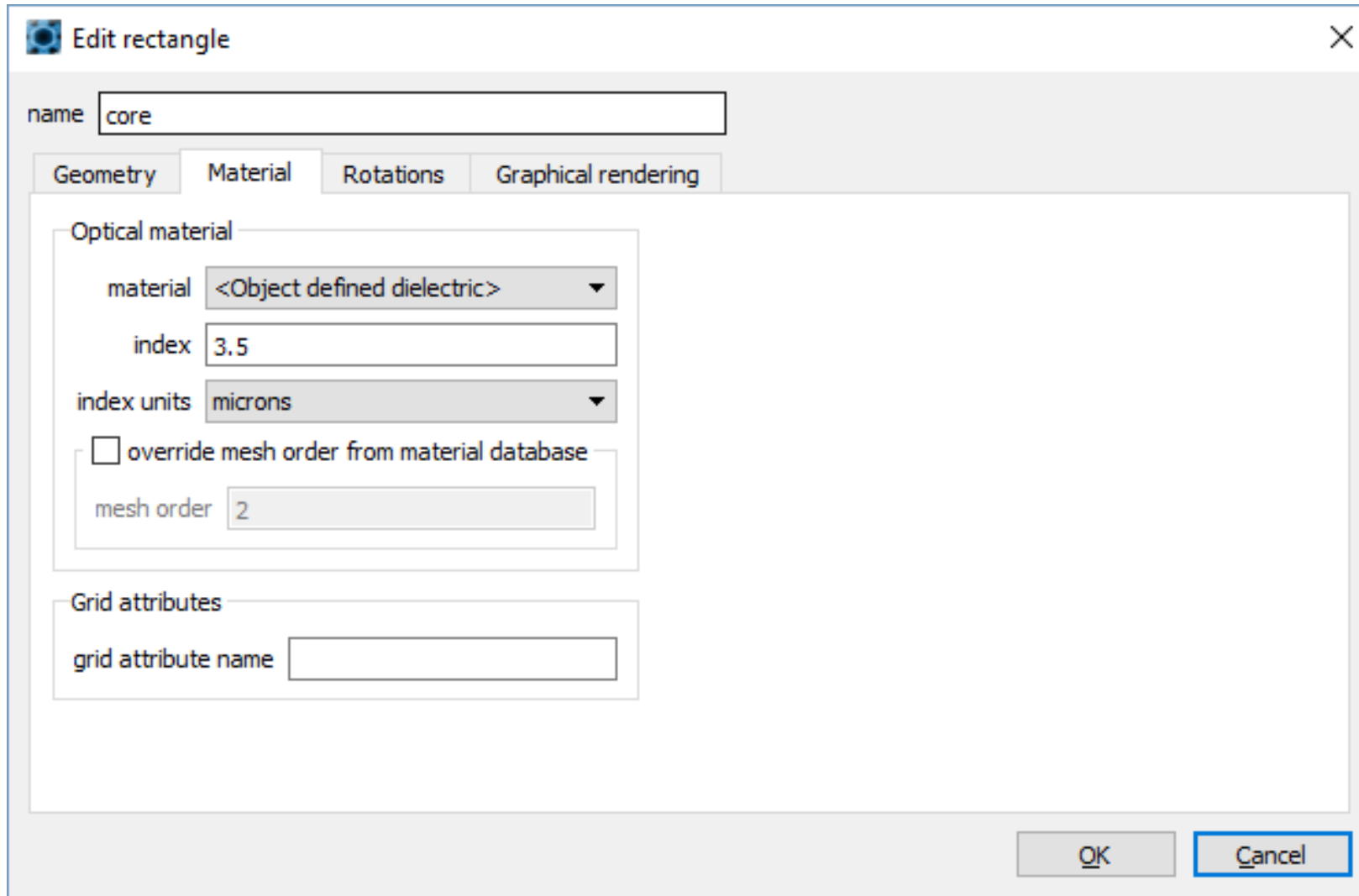
y (μm) y min (μm)
y span (μm) y max (μm)

z (μm) z min (μm)
z span (μm) z max (μm)

☒ use relative coordinates

OK Cancel

Create waveguide core



The image shows a software dialog box titled "Edit rectangle" with a close button (X) in the top right corner. The dialog has a tabbed interface with four tabs: "Geometry", "Material", "Rotations", and "Graphical rendering". The "Material" tab is currently selected. At the top, there is a text field labeled "name" containing the text "core". Below the tabs, there are two main sections. The first section, titled "Optical material", contains a dropdown menu for "material" set to "<Object defined dielectric>", a text field for "index" with the value "3.5", a dropdown menu for "index units" set to "microns", an unchecked checkbox for "override mesh order from material database", and a text field for "mesh order" with the value "2". The second section, titled "Grid attributes", contains a text field for "grid attribute name" which is currently empty. At the bottom right of the dialog are two buttons: "OK" and "Cancel".

name

Geometry Material Rotations Graphical rendering

Optical material

material

index

index units

☐ override mesh order from material database

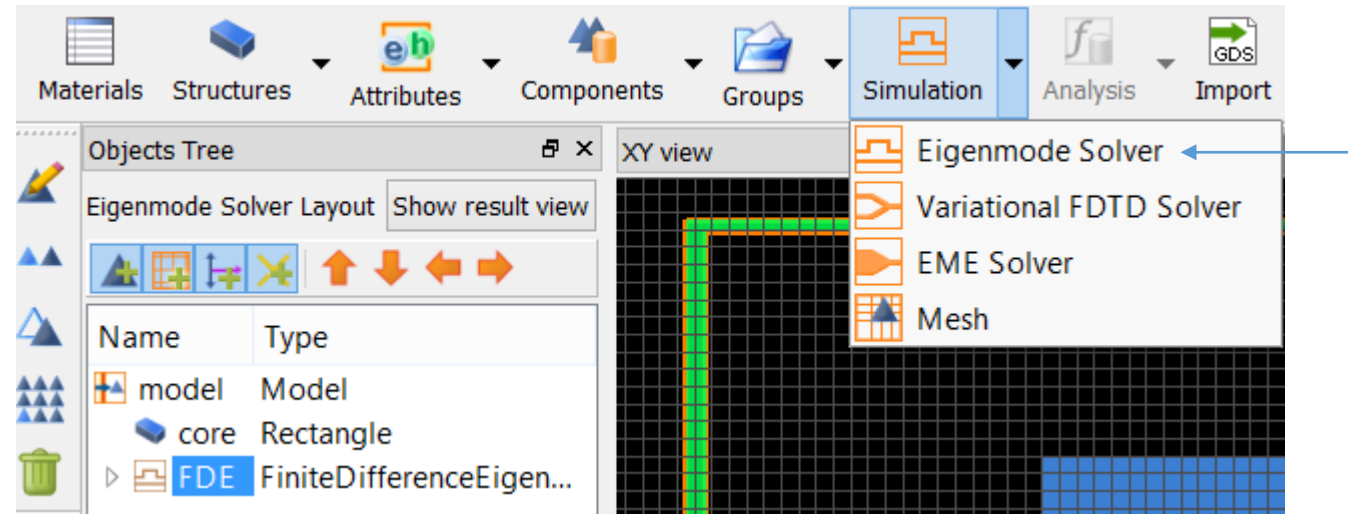
mesh order

Grid attributes

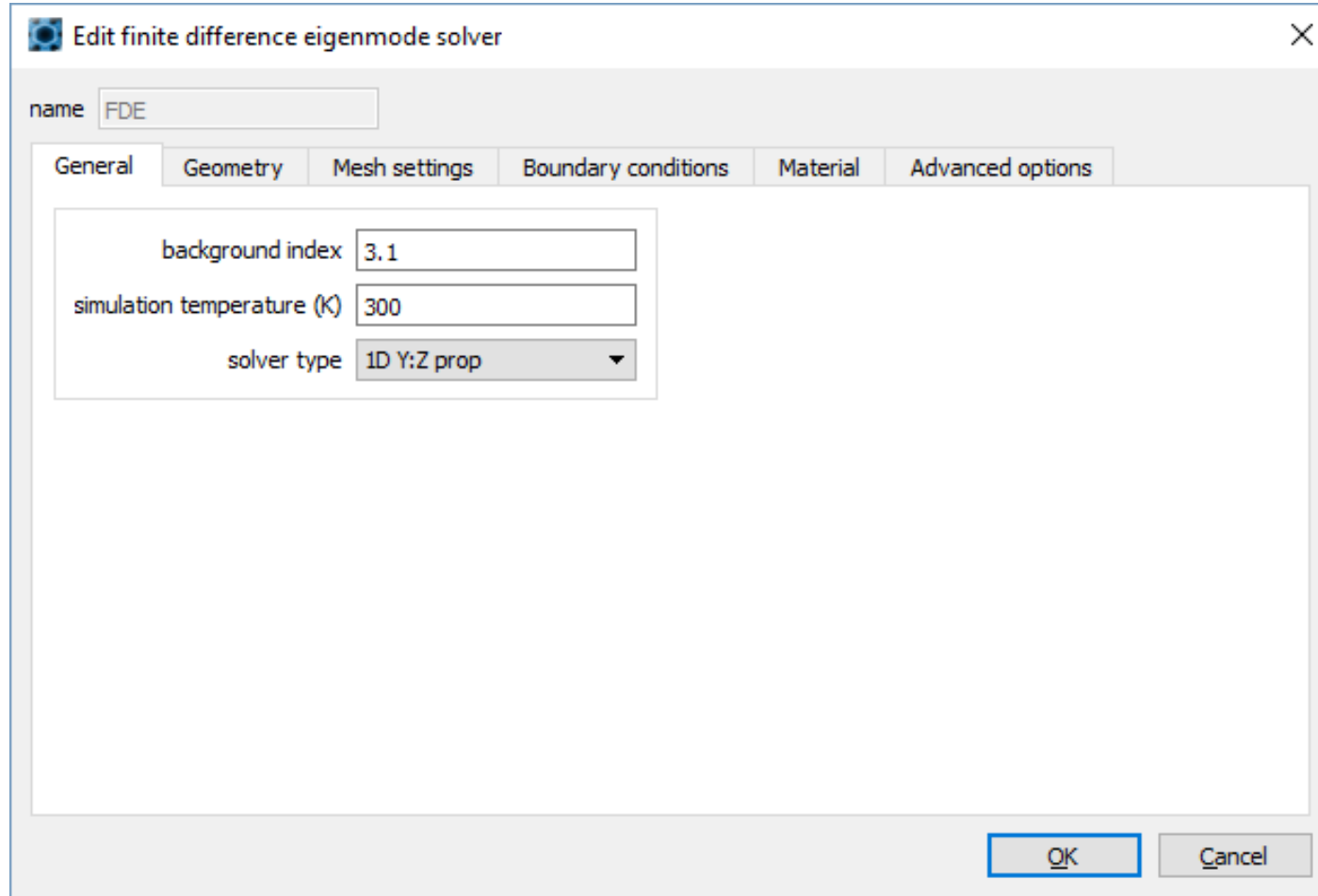
grid attribute name

OK Cancel

Create 1-D FDE simulation region



Create 1-D FDE simulation region



The image shows a software dialog box titled "Edit finite difference eigenmode solver". At the top, there is a "name" field containing the text "FDE". Below this is a tabbed interface with six tabs: "General", "Geometry", "Mesh settings", "Boundary conditions", "Material", and "Advanced options". The "General" tab is currently selected. Inside the "General" tab, there are three input fields: "background index" with the value "3.1", "simulation temperature (K)" with the value "300", and "solver type" which is a dropdown menu currently showing "1D Y:Z prop". At the bottom right of the dialog box are two buttons: "OK" and "Cancel".

name

General Geometry Mesh settings Boundary conditions Material Advanced options


background index

simulation temperature (K)

solver type

OK Cancel

Create 1-D FDE simulation region

 Edit finite difference eigenmode solver ✕

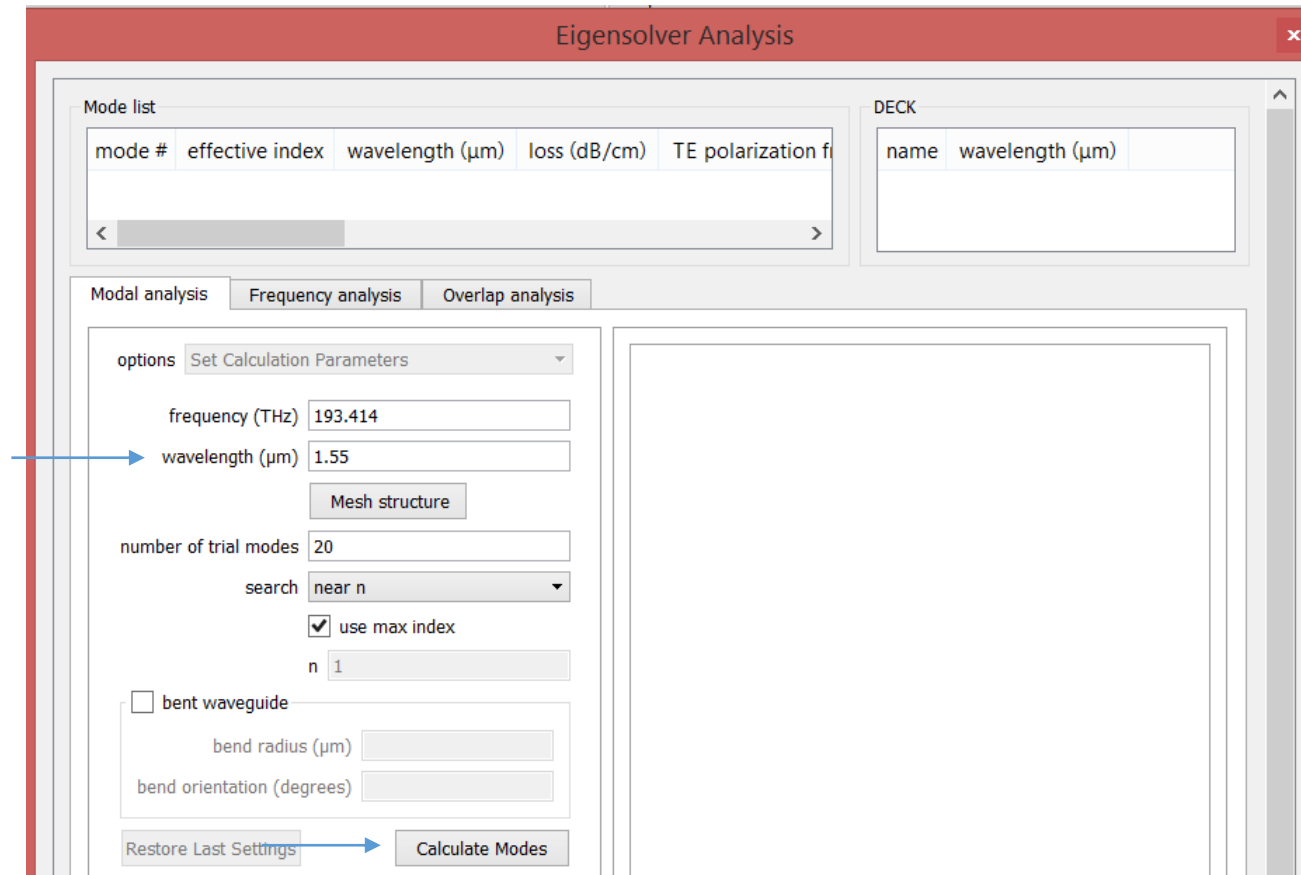
name

General Geometry Mesh settings Boundary conditions Material Advanced options

x (μm)	<input type="text" value="0"/>	x min (μm)	<input type="text" value="0"/>
x span (μm)	<input type="text" value="0"/>	x max (μm)	<input type="text" value="0"/>
y (μm)	<input type="text" value="0"/>	y min (μm)	<input type="text" value="-1"/>
y span (μm)	<input type="text" value="2"/>	y max (μm)	<input type="text" value="1"/>
z (μm)	<input type="text" value="0"/>	z min (μm)	<input type="text" value="0"/>
z span (μm)	<input type="text" value="0"/>	z max (μm)	<input type="text" value="0"/>

Calculate modes

- Click **Run**
- Set wavelength to 1.55 and click **Calculate Modes**



Mode list

mode #	effective index	wavelength (μm)	loss (dB/cm)	TE polarization fraction (Ex)	waveguide TE/TM fraction (%)
1	3.449820	1.55	0.00000	100	100 / 97.83
2	3.444592	1.55	0.00000	0	97.41 / 100

DECK

name	wavelength (μm)
------	------------------------------

Modal analysis

Frequency analysis

Overlap analysis

options Set Calculation Parameters

frequency (THz) 193.414

wavelength (μm) 1.55

Mesh structure

number of trial modes 20

search near n

☒ use max index

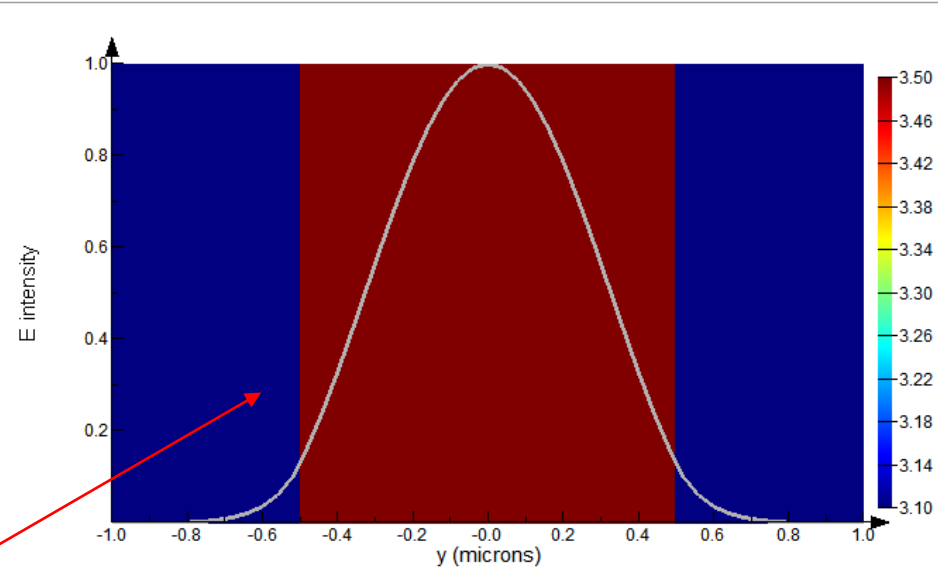
n 2

☐ bent waveguidebend radius (μm)

bend orientation (degrees)

Restore Last Settings

Calculate Modes



Mode plot options

plot Modal fields

component E intensity

☒ linear scale

amplitude

coordinates cartesian

☐ log scale☒ superimpose structure

Plot in New Window

Advanced options...

Redock

Hide

Mode list

Field profile

Mode analysis

- There are a lot of modes here! But remember, not all of these modes are guided. Only modes with $n_{eff} > n_{clad} = 3.1$ are guided modes

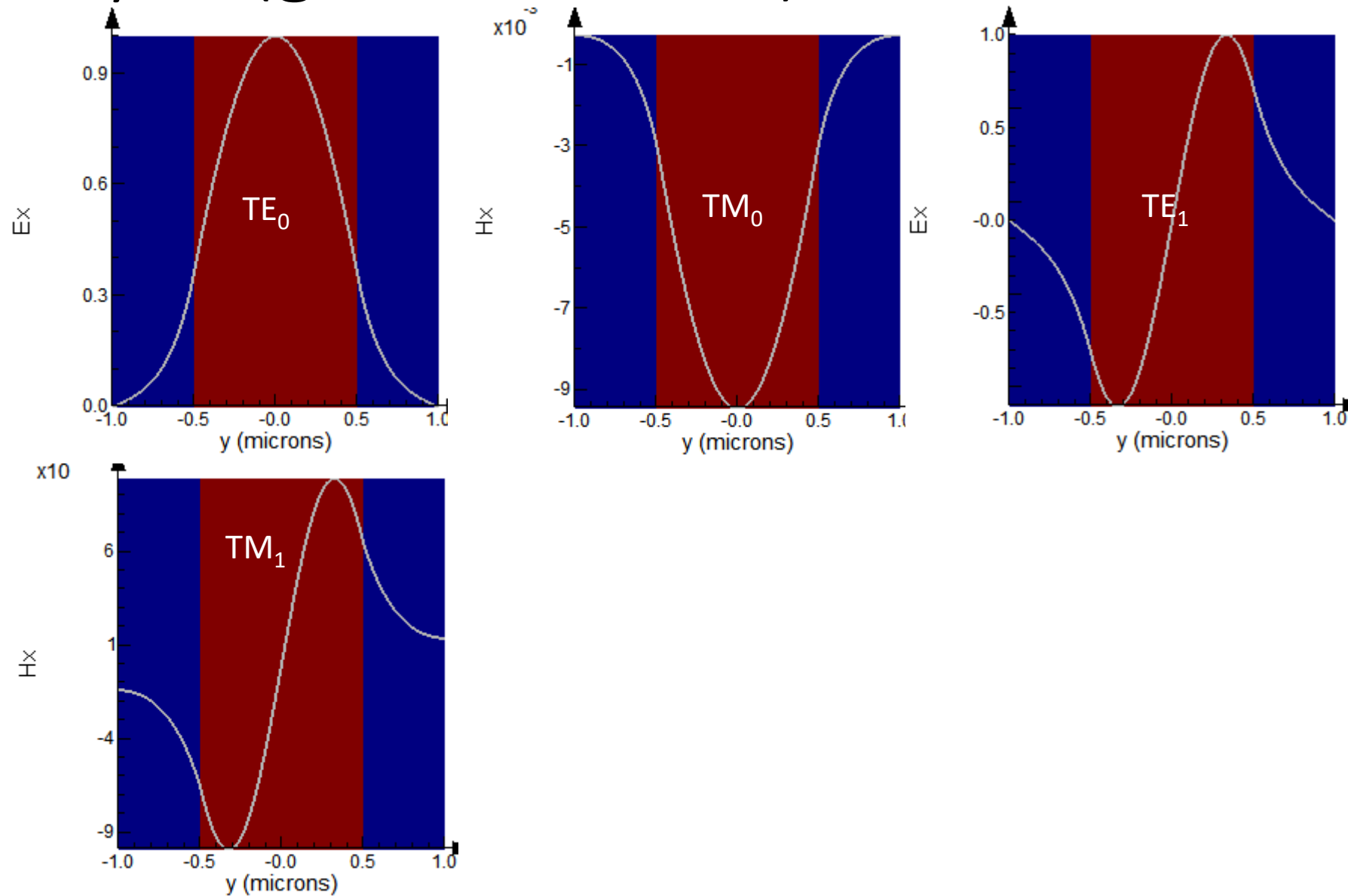
Eigensolver Analysis

Mode list					
mode #	effective index	wavelength (μm)	loss (dB/cm)	TE polarization fraction (Ex)	waveguide TE/TM fraction (%)
1	3.449820	1.55	0.00000	100	100 / 97.83
2	3.444592	1.55	0.00000	0	97.41 / 100
3	3.302481	1.55	0.00000	100	100 / 91.89
4	3.289505	1.55	0.00000	0	91.88 / 100
5	3.112555	1.55	0.00000	0	93.41 / 100
6	3.080020	1.55	0.00000	100	100 / 84.64
7	3.027600	1.55	0.00000	0	92.62 / 100
8	2.911655	1.55	0.00000	0	79.35 / 100
9	2.858940	1.55	0.00000	100	100 / 78.56
10	2.668221	1.55	0.00000	100	100 / 68.36
11	2.661953	1.55	0.00000	0	66.46 / 100
12	2.375614	1.55	0.00000	100	100 / 52.38
13	2.347635	1.55	0.00000	0	52.19 / 100
14	1.899889	1.55	0.00000	0	32.25 / 100
15	1.889043	1.55	0.00000	100	100 / 34
16	1.188893	1.55	0.00000	0	12.32 / 100
17	1.180108	1.55	0.00000	100	100 / 13.76

Guided modes

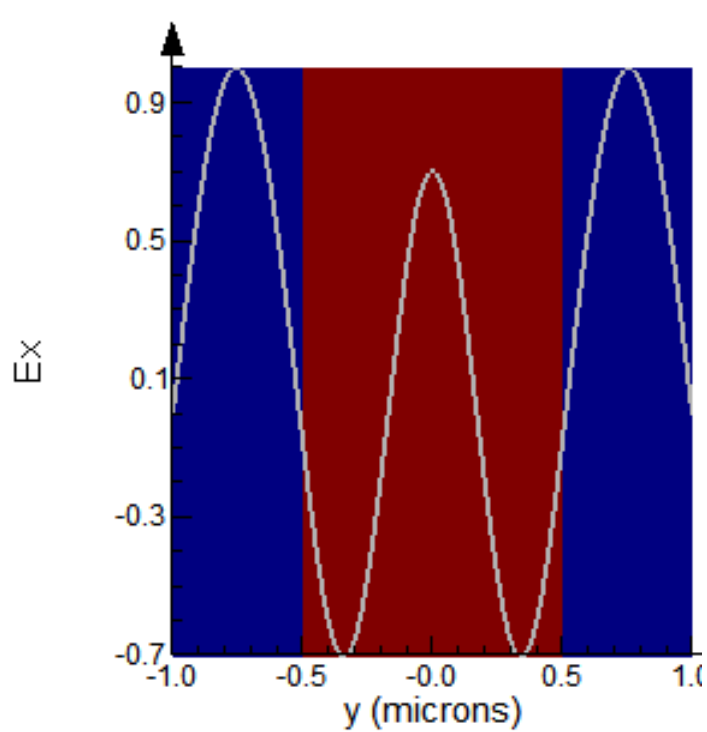
Unguided radiating modes

Mode analysis (guided modes)

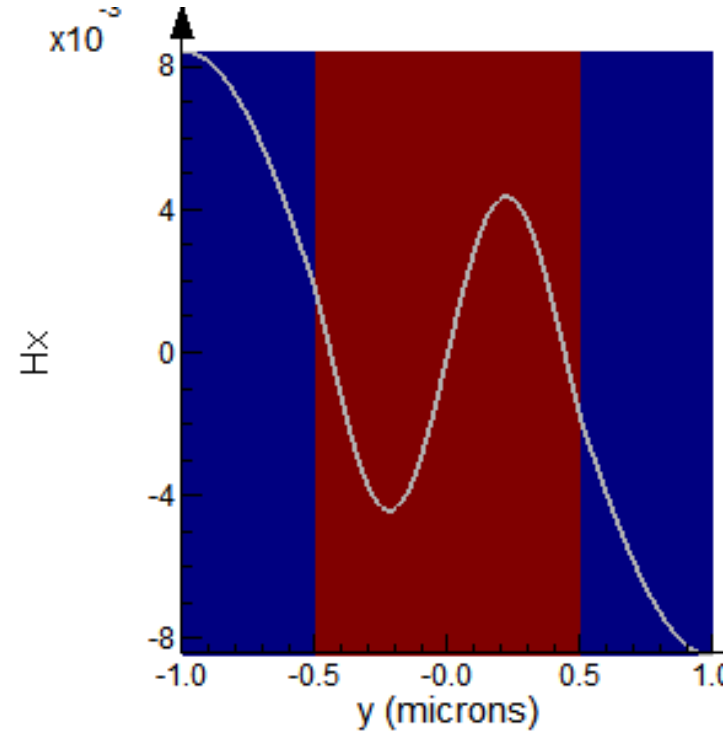


Mode analysis (unguided modes)

Notice: There is no exponential decay in the cladding! Power will be radiated into the cladding as these unguided “modes” propagate down waveguide



Example #1



Example #2

Waveguide cutoff

- Let's run a parameter sweep to plot effective index as a function of slab core thickness
- You should set your minimum mesh spacing to 10nm for this analysis

Waveguide cutoff

Edit Parameter Sweep

Name:

Parameters

Type: Ranges Number of points:

Name	Parameter	Type	Start	Stop	Units
core_thickness	::model::core::y span	Length	0.1	1	microns

Add
Remove

Results

Name	Result	Operation
neff1	::model::FDE::data::mode1::neff	
neff2	::model::FDE::data::mode2::neff	
neff3	::model::FDE::data::mode3::neff	
neff4	::model::FDE::data::mode4::neff	

Add
Remove

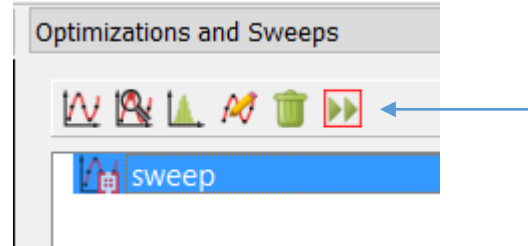
Advanced

☐ resave files after analysis

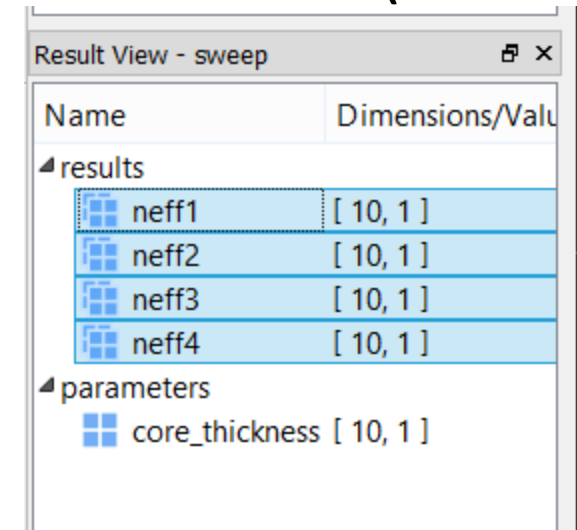
OK Cancel

Waveguide cutoff

- Click run button:



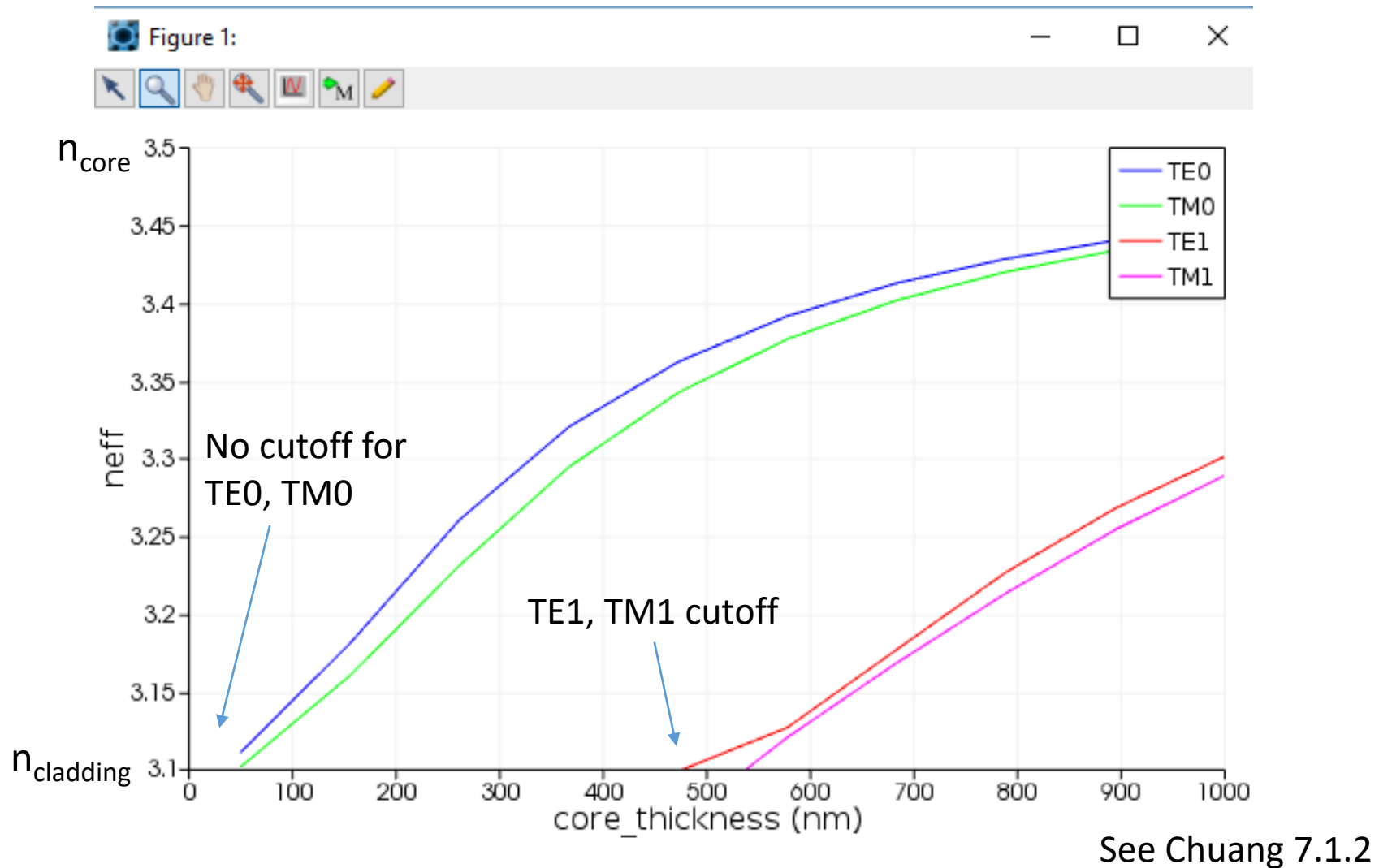
- When done, select sweep, select all results in Result View (bottom left), right click > Visualize > New Visualizer



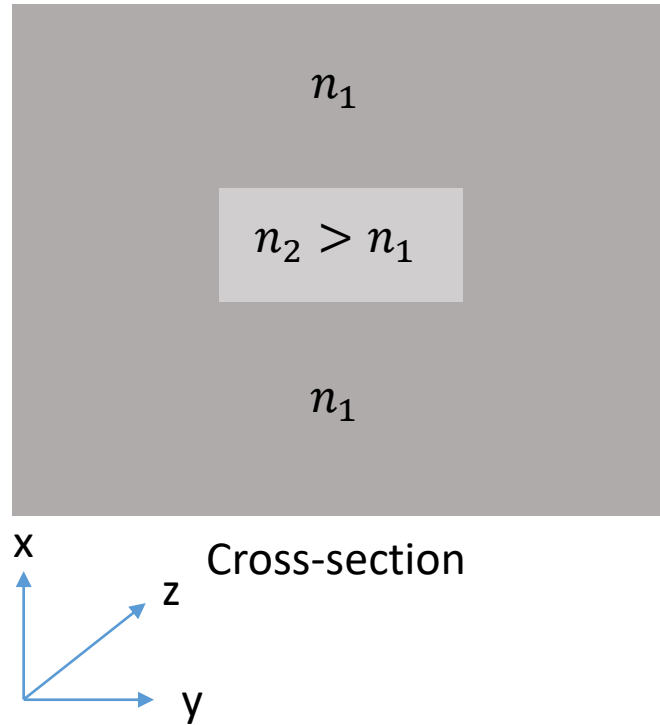
Result View - sweep

Name	Dimensions/Value
results	
neff1	[10, 1]
neff2	[10, 1]
neff3	[10, 1]
neff4	[10, 1]
parameters	
core_thickness	[10, 1]

Waveguide cutoff

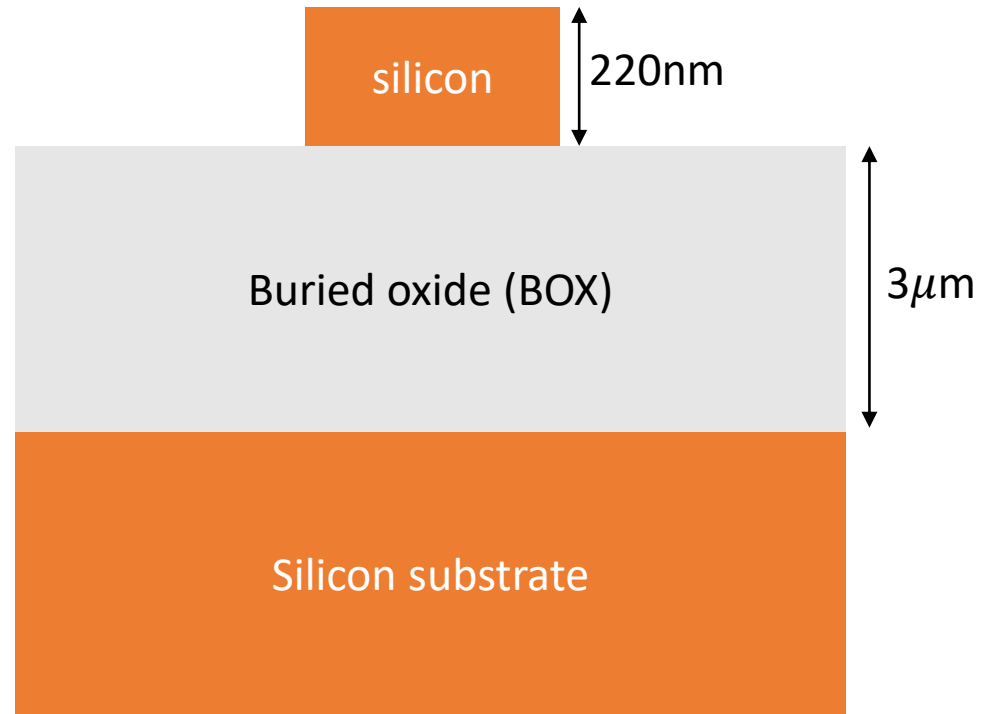


Rectangular waveguide



- Pure TE and TM modes do not exist instead we have hybrid modes (all field components exist for each mode).
- BUT, the transverse components of fields dominate and so they are often called quasi-TE and quasi-TM (often we even drop the term quasi)

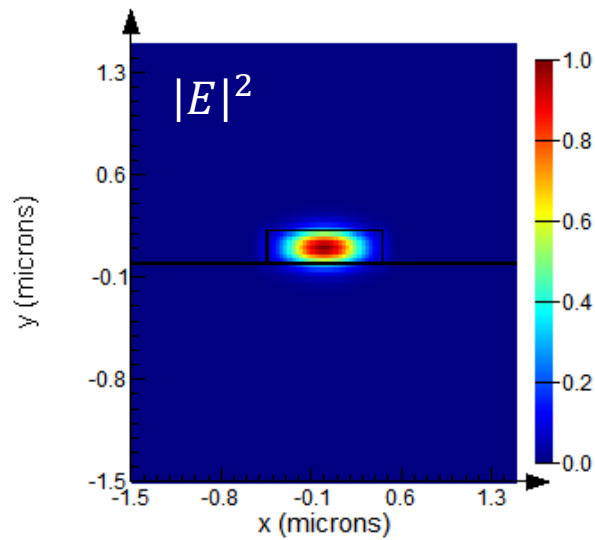
Silicon photonic ridge waveguide



Waveguide modes

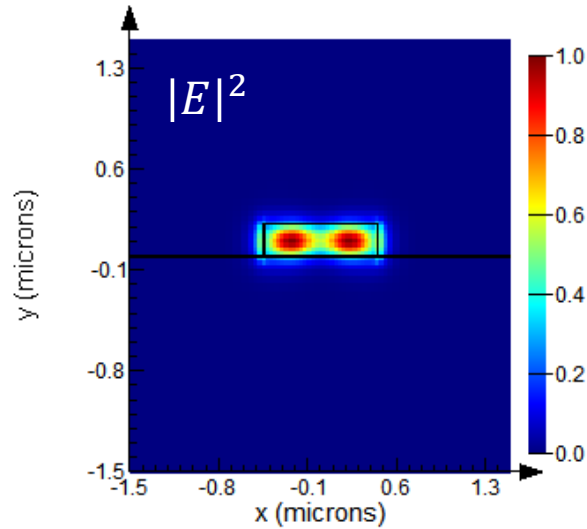
- Silicon thickness of 220nm for silicon-on-substrate (SOI) substrate is somewhat standardized
- We often desire waveguide to contain only a single mode
- Our goal is to determine the silicon ridge width such that that waveguide is single mode
- Open **Silicon_Photonic_Ridge_Waveguide.lms** from the bcourses website
- You will see a silicon photonic ridge waveguide with 220nm height and 900nm width.
- Use MODE to calculate the guided modes.

900nm width ridge waveguide



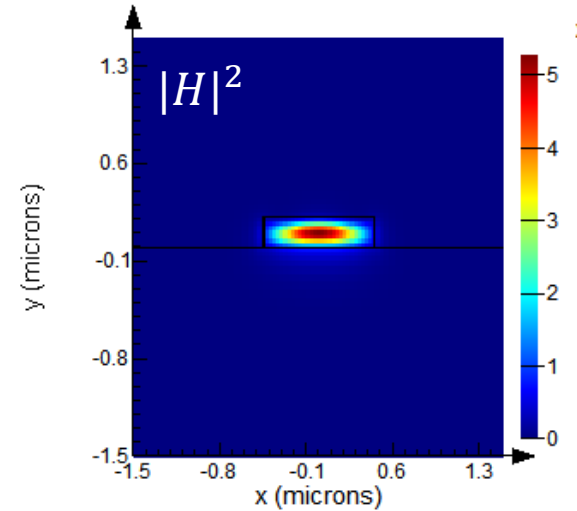
Quasi-TE₀₀

E_x dominates,
1 lobe in x,
1 lobe in y



Quasi-TE₁₀

E_x dominates,
2 lobes in x,
1 lobe in y



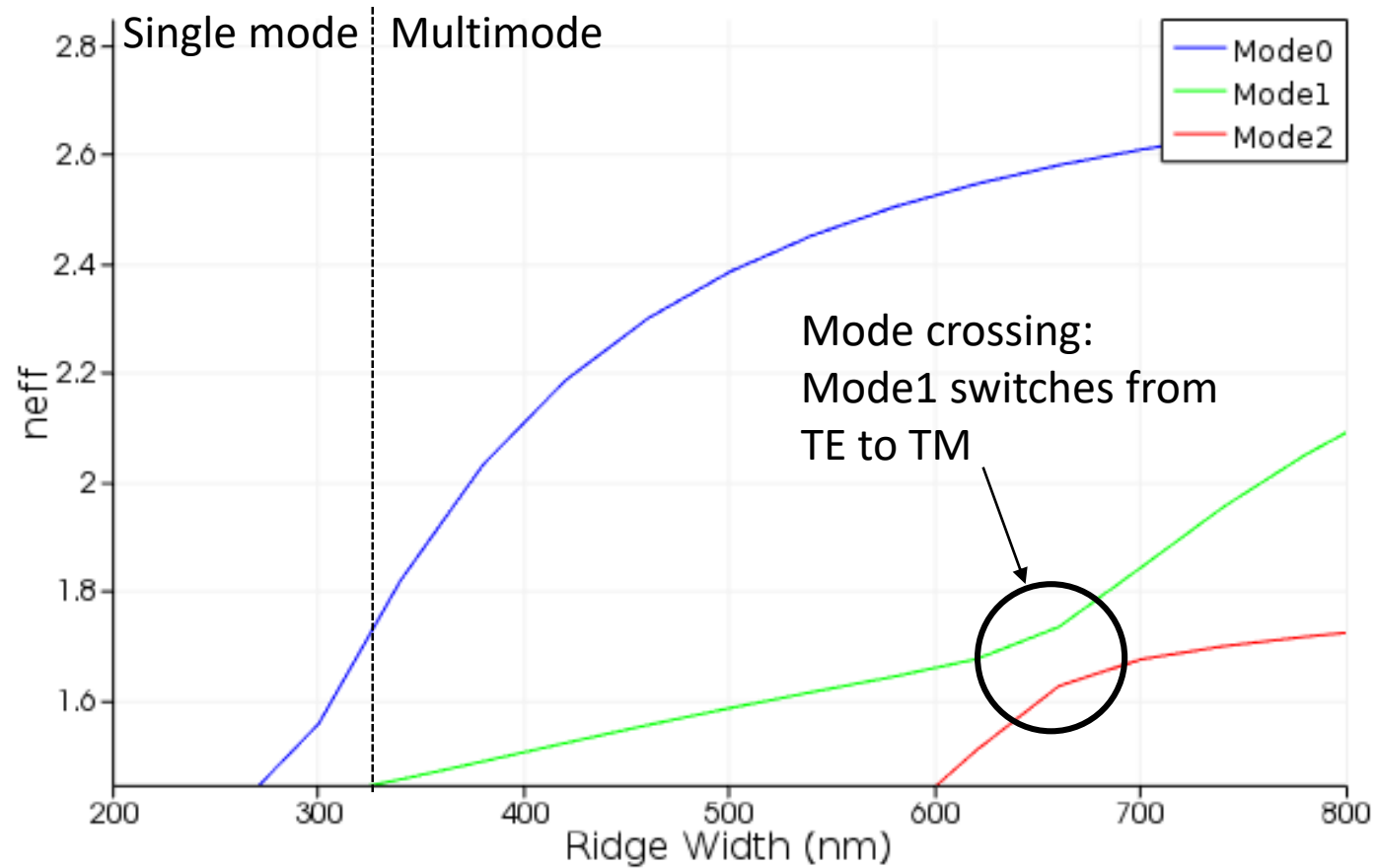
Quasi-TM₀₀

H_x dominates,
1 lobe in x,
1 lobe in y

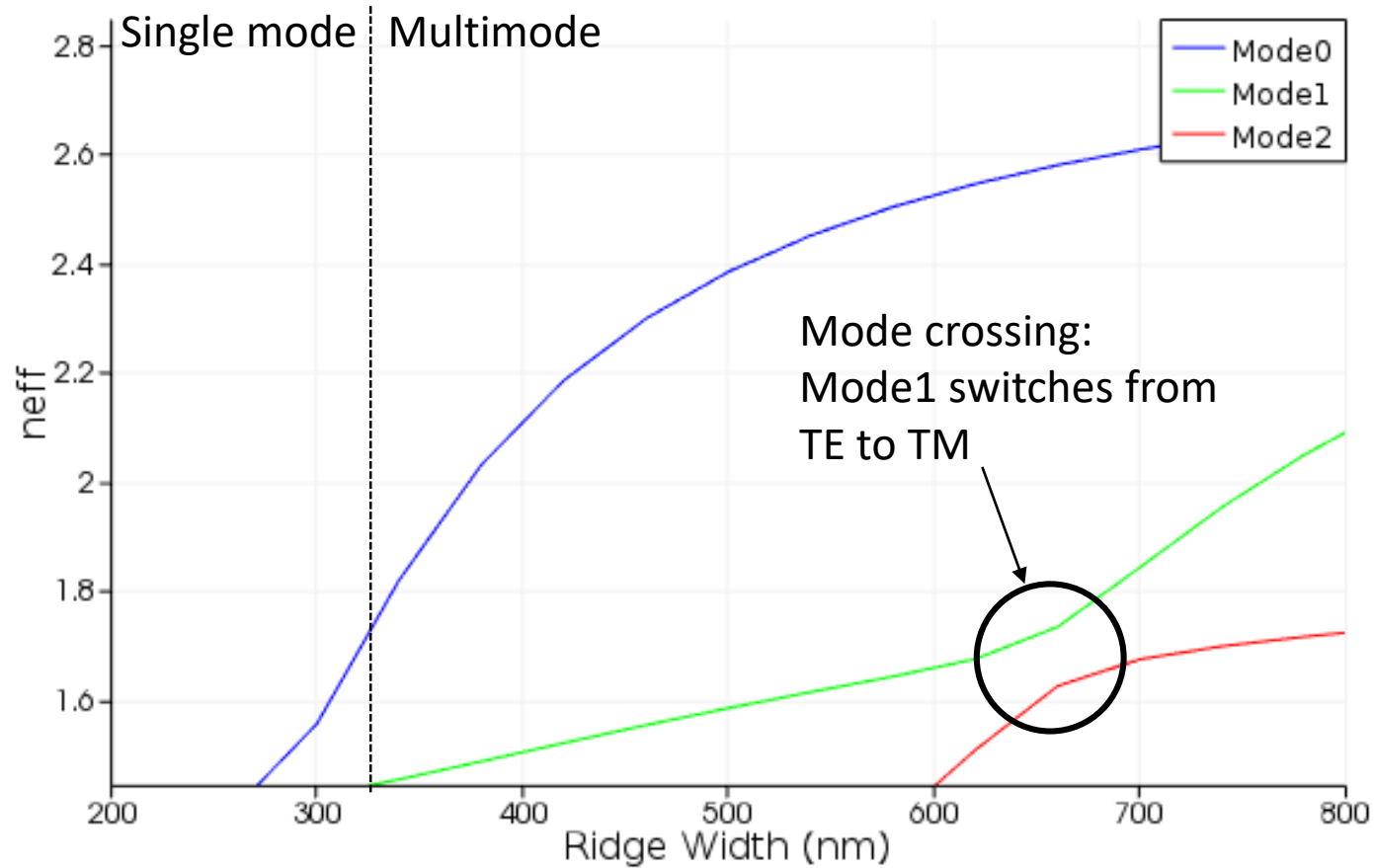
Single-mode waveguide

- Run the parametric sweep on the silicon ridge width and plot n_{eff} for each of the modes on the previous slide as a function of n_{eff}

Single-mode waveguide



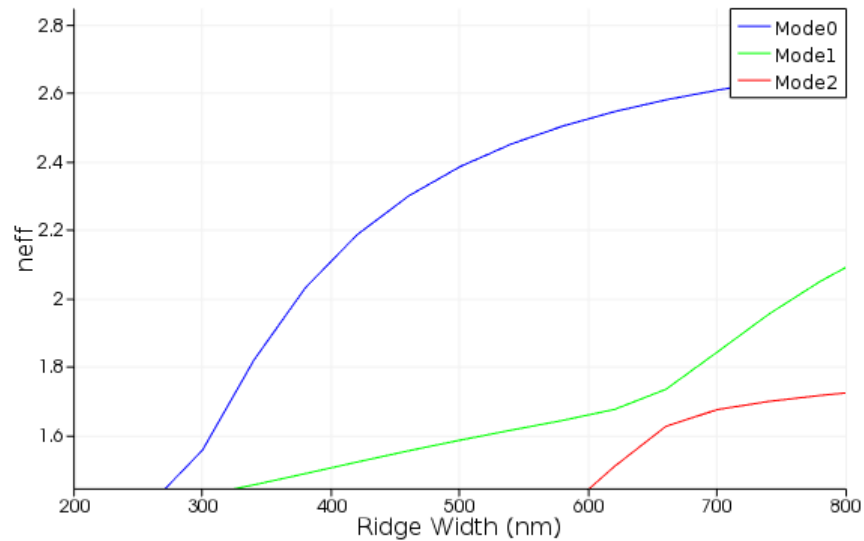
Single-mode waveguide



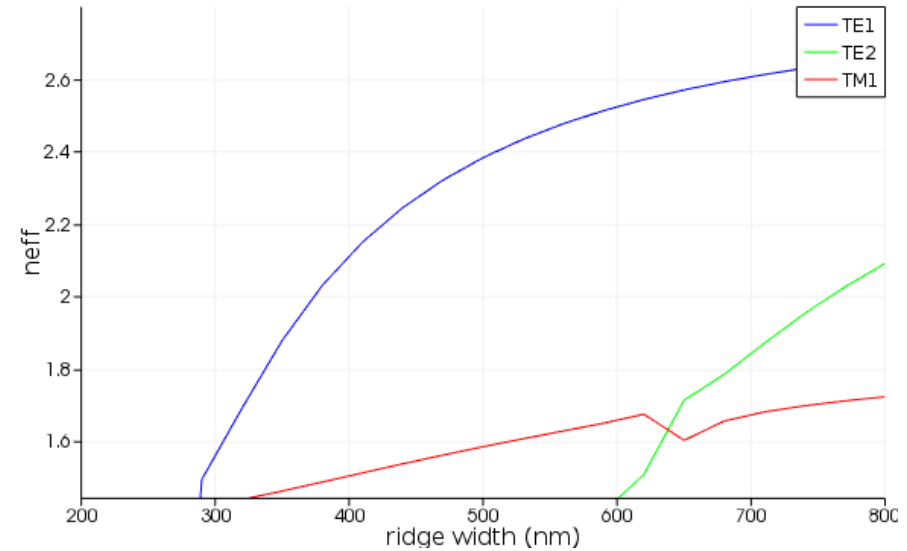
Note: Lumerical indexes modes by effective index, while we usually want to sort by spatial distribution

Single-mode waveguide

Index mode by eigenmode



Index mode by spatial distribution




Mode source in FDTD

- When running FDTD simulation we often want to excite a particular waveguide mode
- This can be done using a *mode source* in Lumerical FDTD.
- Open the file Silicon_Photonic_Waveguide_Port_Source.fsp from bcourses
- This Lumerical FDTD simulation file contains 3D silicon photonic ridge waveguide that we just simulated with ridge height of 220nm and ridge width of 500nm to ensure single mode operation

Mode source in FDTD

- Click **Sources** → **Mode**
- Select the geometry tab first

 Edit Mode Source (Mode has not been selected)

name

General Geometry Frequency/Wavelength

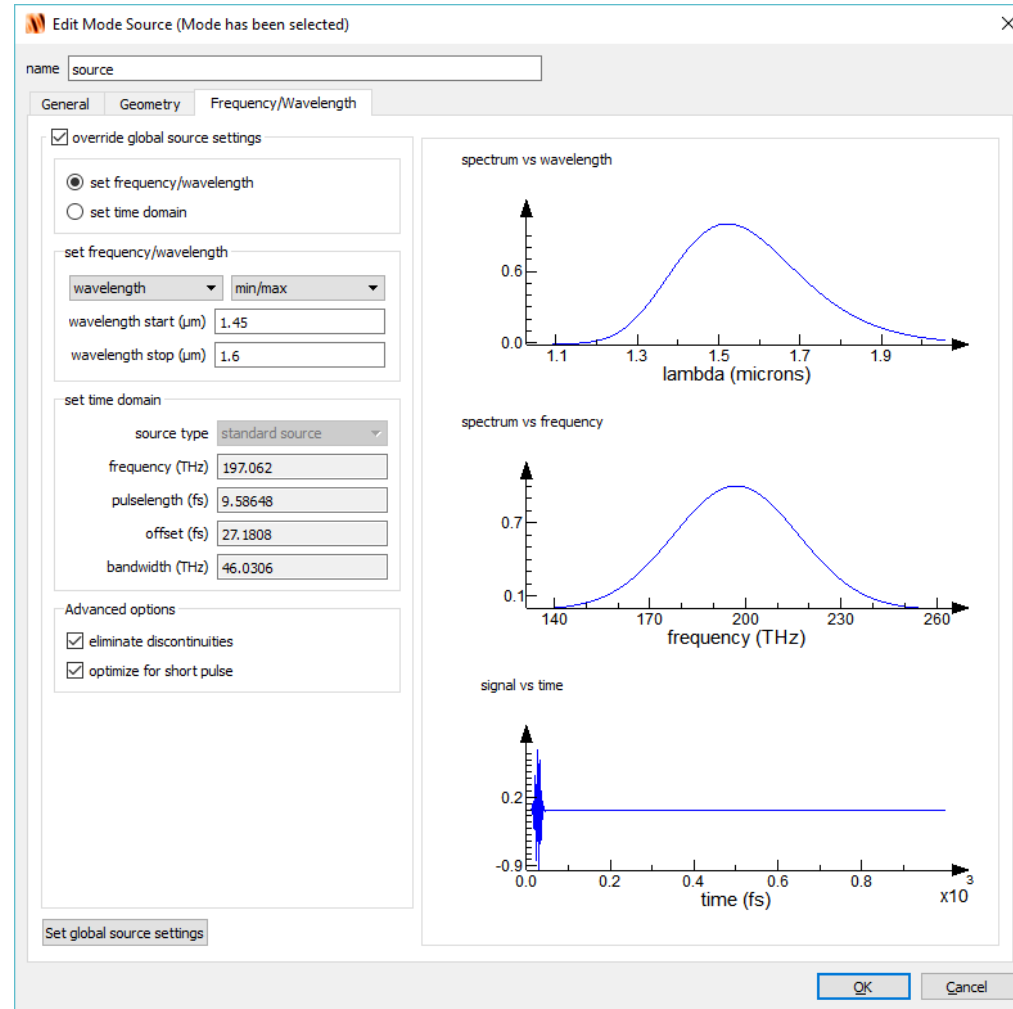
x (μm) x min (μm)
x span (μm) x max (μm)

y (μm) y min (μm)
y span (μm) y max (μm)

z (μm) z min (μm)
z span (μm) z max (μm)

☒ use relative coordinates

Mode source in FDTD



Mode source in FDTD

- Click ***Visualize Data***

Edit Mode Source (Mode has been selected)

name

General Geometry Frequency/Wavelength

injection axis

direction

amplitude

phase

mode selection

Select Mode

Visualize Data

Clear Data

☐ multifrequency mode calculation

frequency points

☐ bent waveguide

bend radius (μm)

bend orientation (degrees)

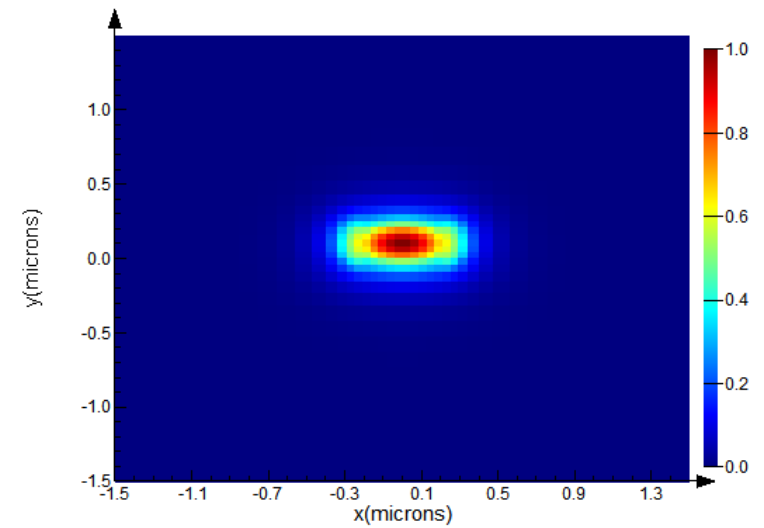
Rotations

theta (degrees)

phi (degrees)

offset (μm)

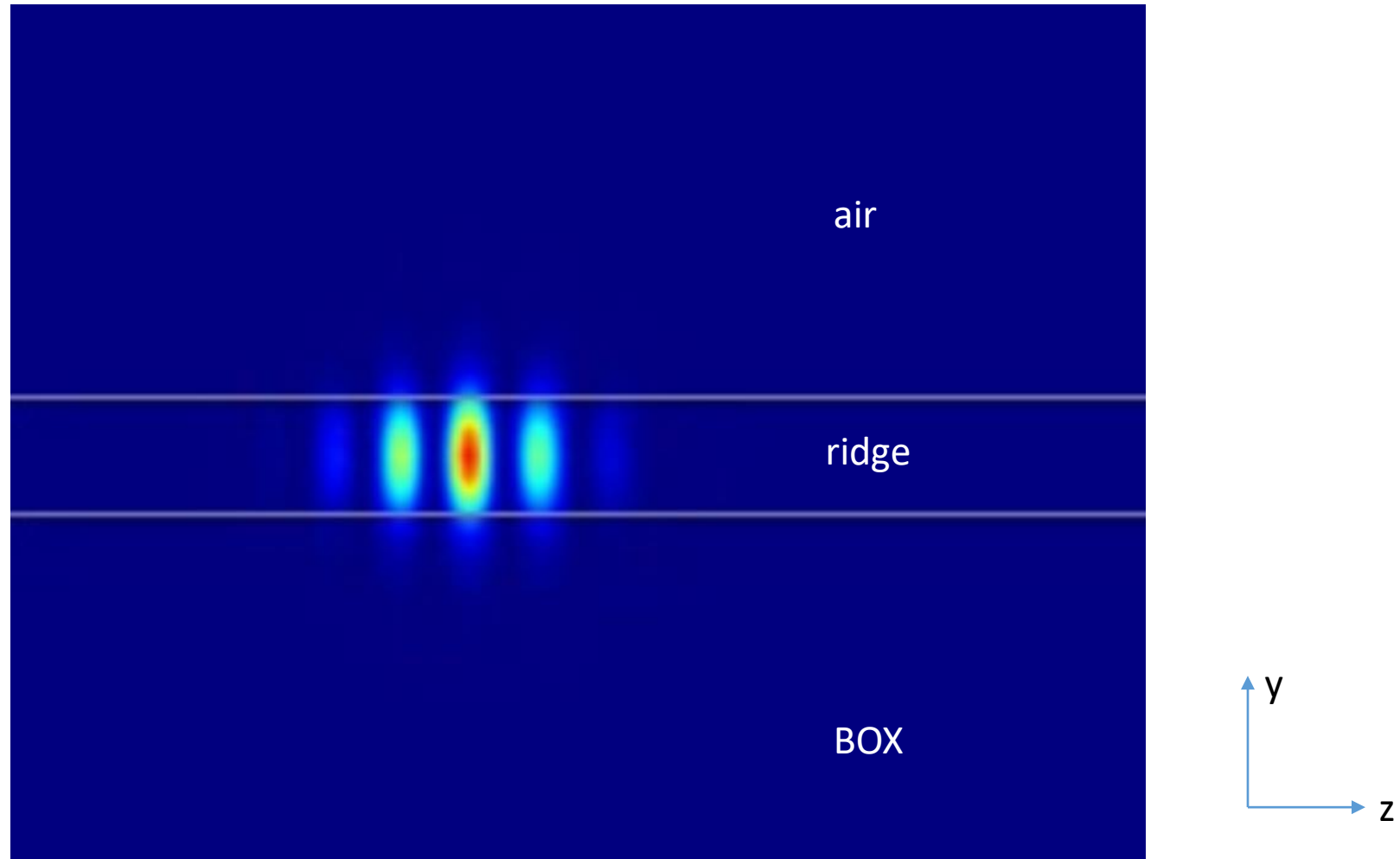
OK Cancel



Mode source in FDTD

- A movie monitor has already been added at the $x = 0$ plane so that we can see the wave propagate down the waveguide
- Click ***Run***

Movie monitor



Limitation to port source

- Caution should be used when applying port source
- Port source mode is only calculated at the center frequency therefore there will be some mode mismatch (i.e. reflections) at other frequencies.
- Keep this in mind if you are running a broadband simulation.