PEC

EXPLORE INNOVATE EXCEL

EXPERIMENT - 1

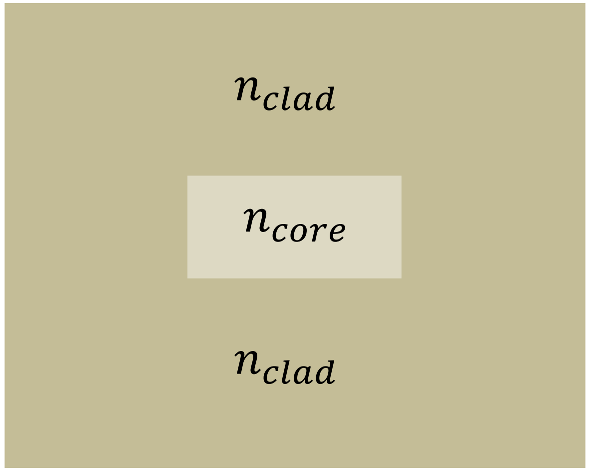
OPTOELECTRONICS LAB

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

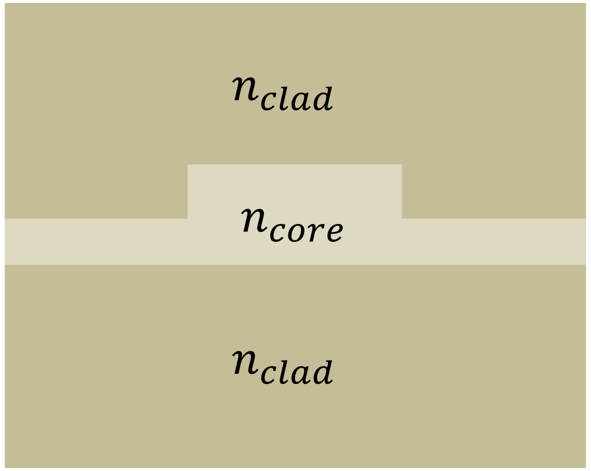
Optical waveguides

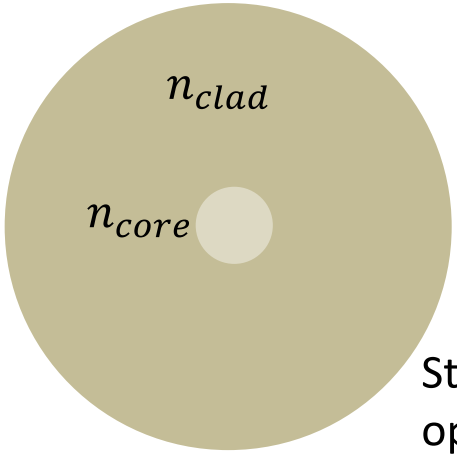
Slab waveguide

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})

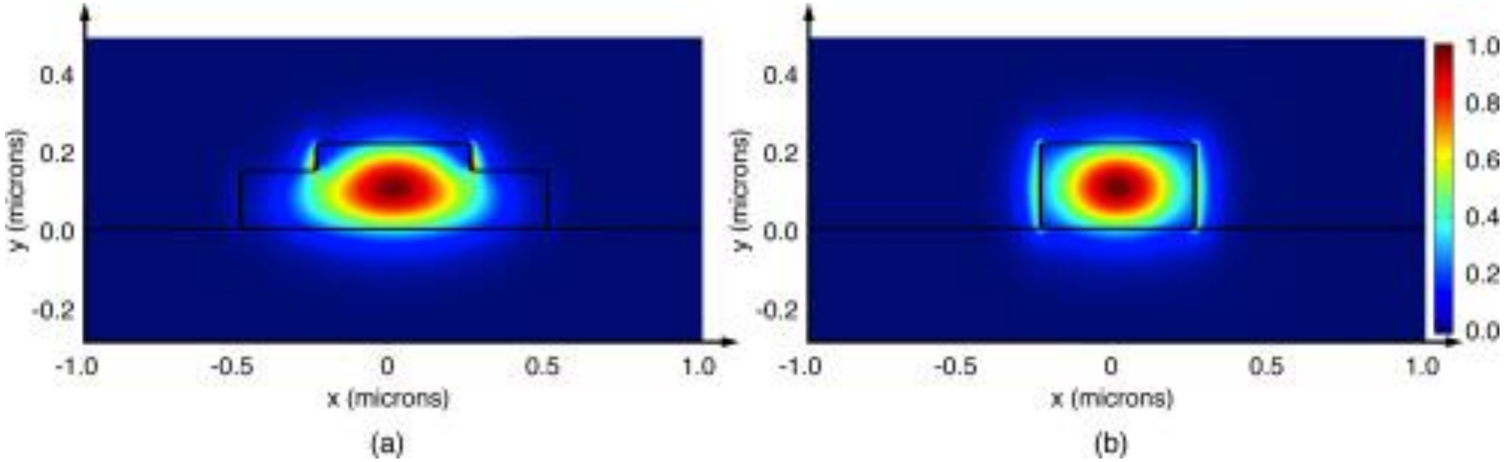
Light is confined by total internal reflection in ray optics picture

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

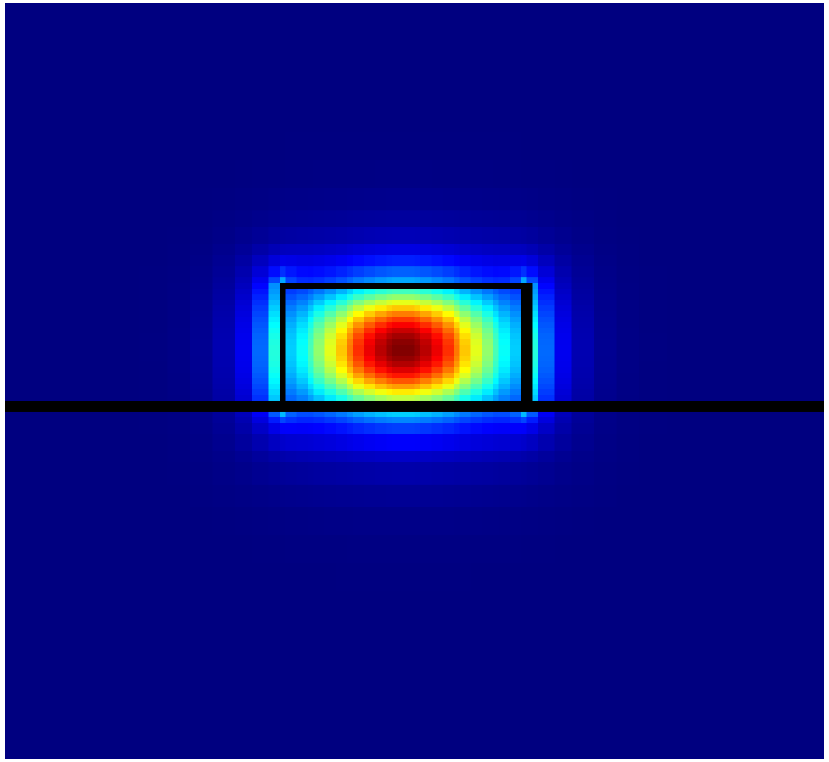
- Each mode has an effective index that can be defined by:

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

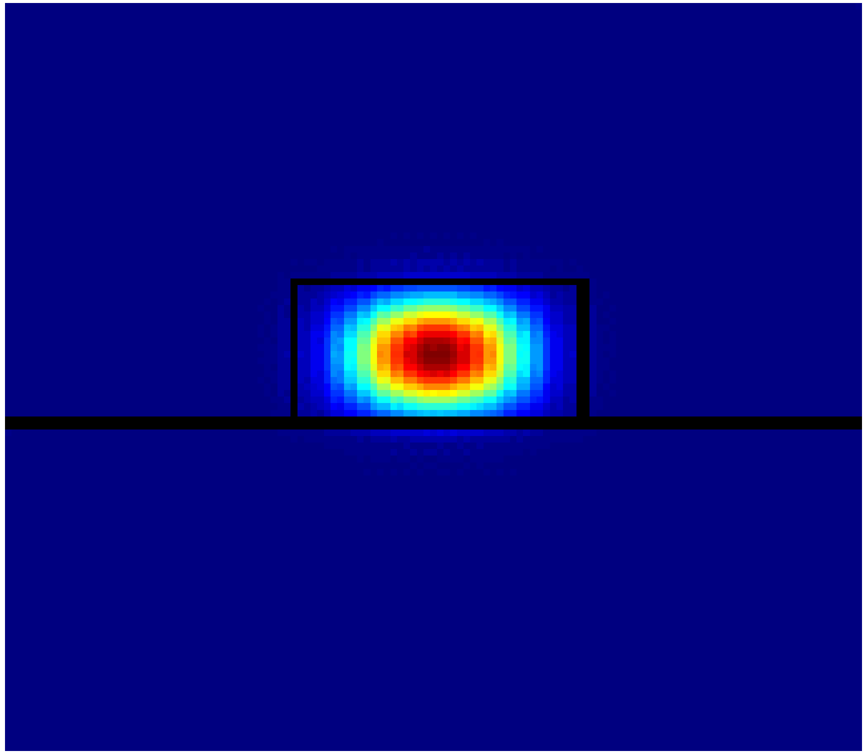
- The effective index tells you how tightly the mode is confined to the waveguide core
  - Guided mode → $n_{clad} < n_{eff} < n_{core}$
  - Tightly confined to the core → $n_{eff} \sim n_{core}$
  - Weakly confined to the core → $n_{eff} \sim n_{clad}$
  - Unguided or radiating modes → $n_{eff} < n_{clad}$

Effective index

Small effective index

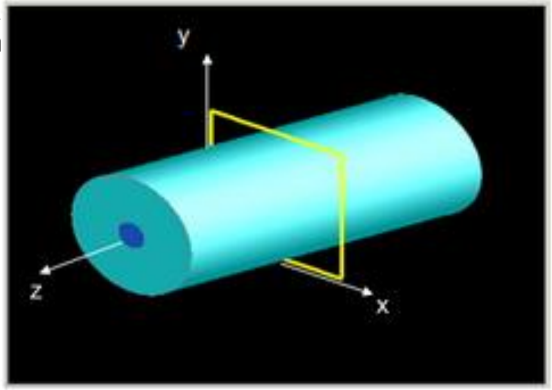


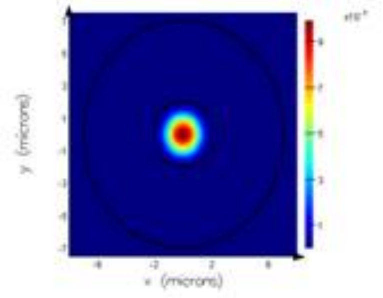
Large effective index



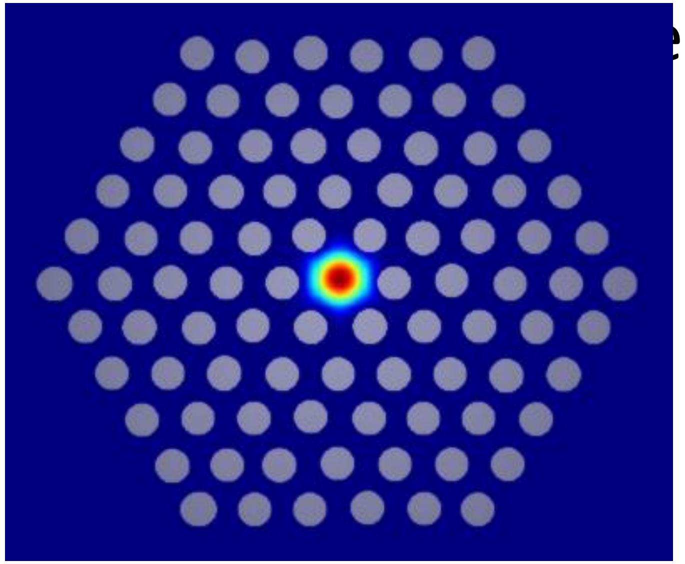
Lumerical MODE

- 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 displ es (e.g. n_{eff}, etc).





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

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

- 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:

$$X = A_x e^{\pm j k_x x} \quad Y = A_y e^{\pm j k_y y} \quad Z = A_z e^{\pm j k_z z}$$

$$k_x^2 + k_y^2 + k_z^2 = k^2 = \omega^2 \mu \epsilon$$ ← 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.

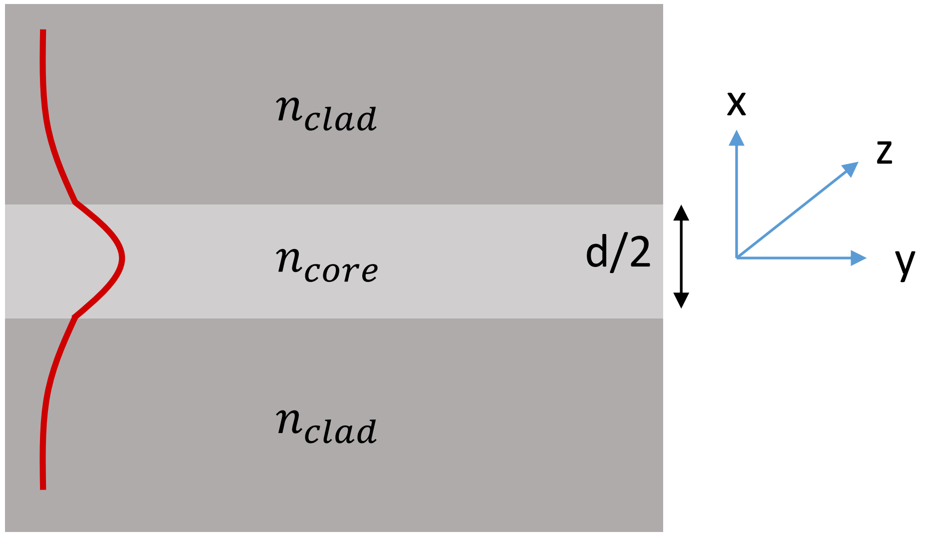
Solving for waveguide modes: General approach

1) Assume propagation in the z-direction: ***E, H*** $\propto \mathrm{e}^{jk_z z}$

2) Make an educated guess for the form of the solution in each dielectric region
   Traveling wave: $E_x = E_0 e^{jk_x x} \mathrm{e}^{jk_z z}$
   Standing wave: $E_x = E_0 \cos k_x x \, \mathrm{e}^{jk_z z}$
   Decaying wave: $E_x = E_0 e^{-\alpha x} \mathrm{e}^{jk_z z}$

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



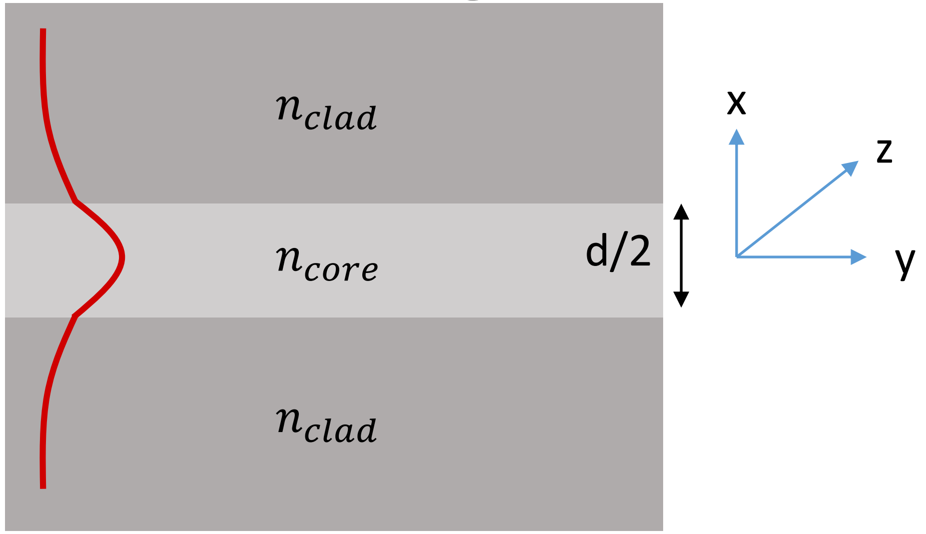
Slab waveguide has two types of modes **transverse electric (TE)** and **transverse magnetic (TM)**

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



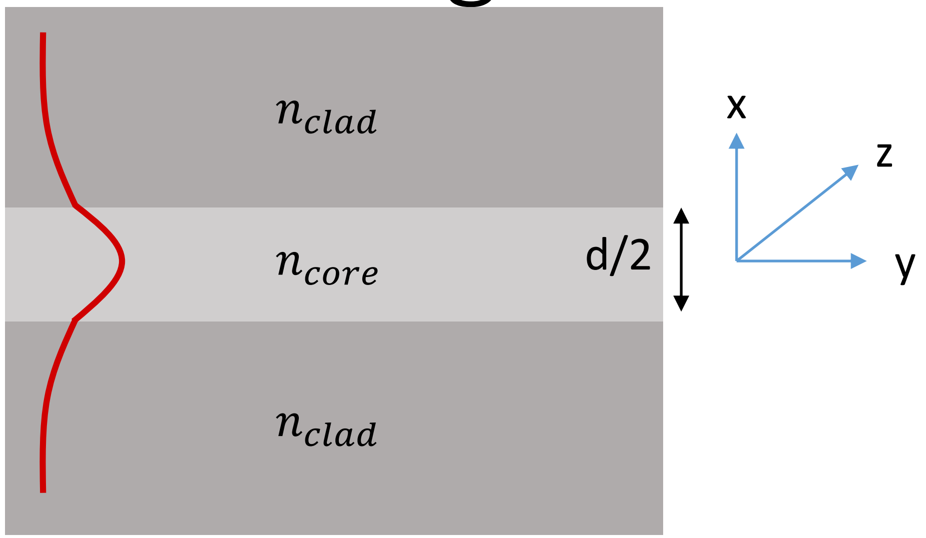
Slab waveguide has two types of modes
transverse electric (TE) and
transverse magnetic (TM)

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

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)**

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

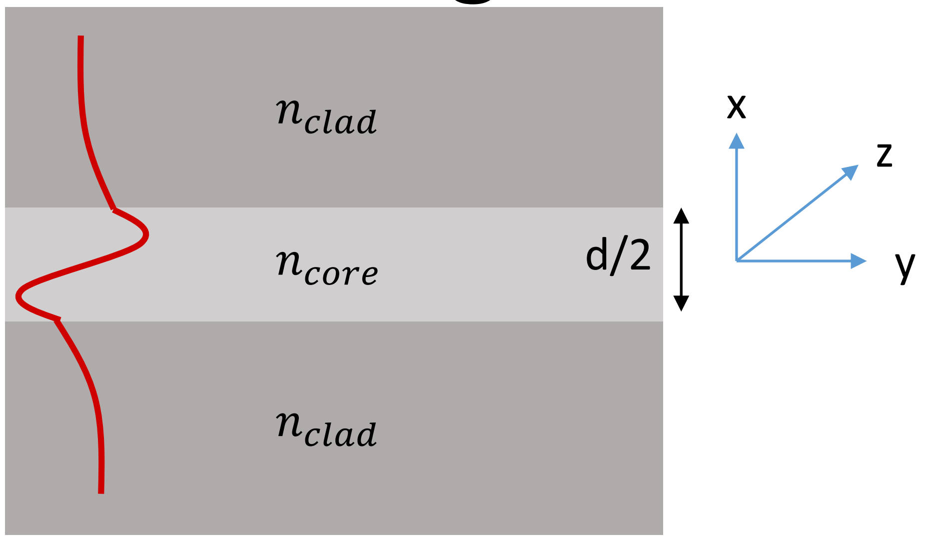
Further simplify as (even solutions):

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

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):

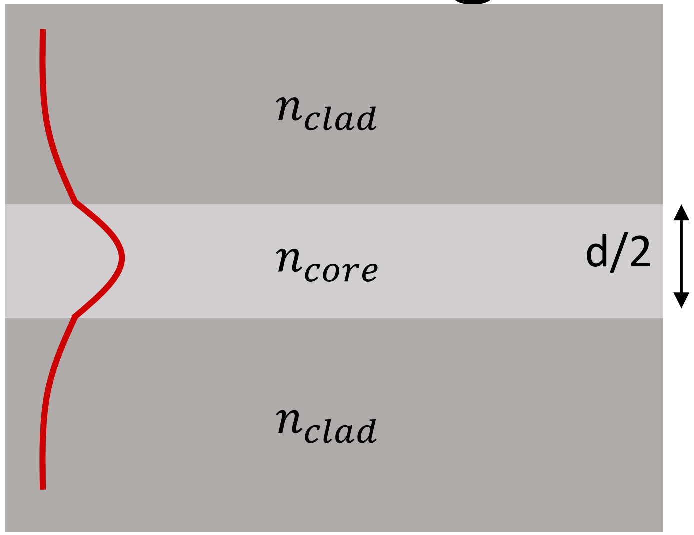
$$E_y = e^{jk_z z} \begin{cases} A_{y0} e^{-\alpha(x-d/2)} & x \geq d/2 \\ A_{y1} \sin k_x x & |x| \leq d/2 \\ -A_{y0} e^{\alpha(x+d/2)} & x \leq d/2 \end{cases}$$

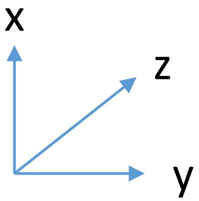
Field decays into cladding layers

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:

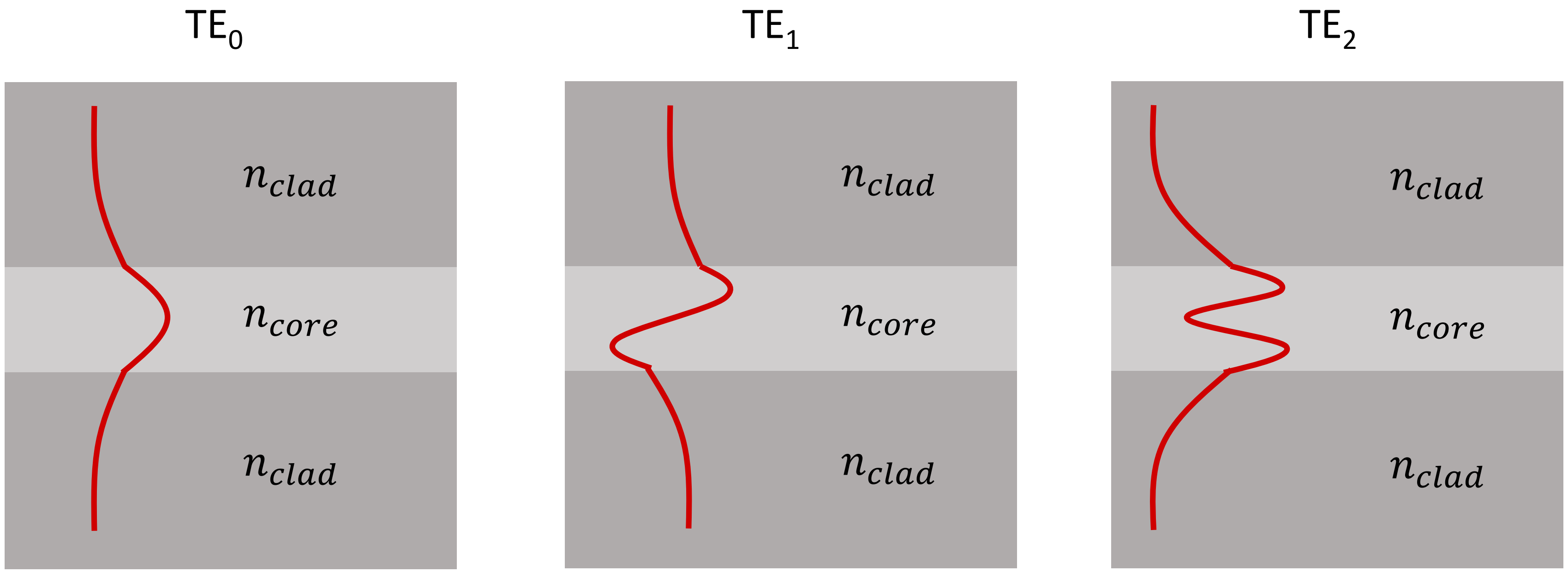
Even solutions

$$k_x^2 + k_z^2 = \omega^2 \mu \epsilon_1$$
$$-\alpha^2 + k_z^2 = \omega^2 \mu \epsilon_2$$
$$\alpha = k_x \tan(k_x d/2)$$

Odd solutions

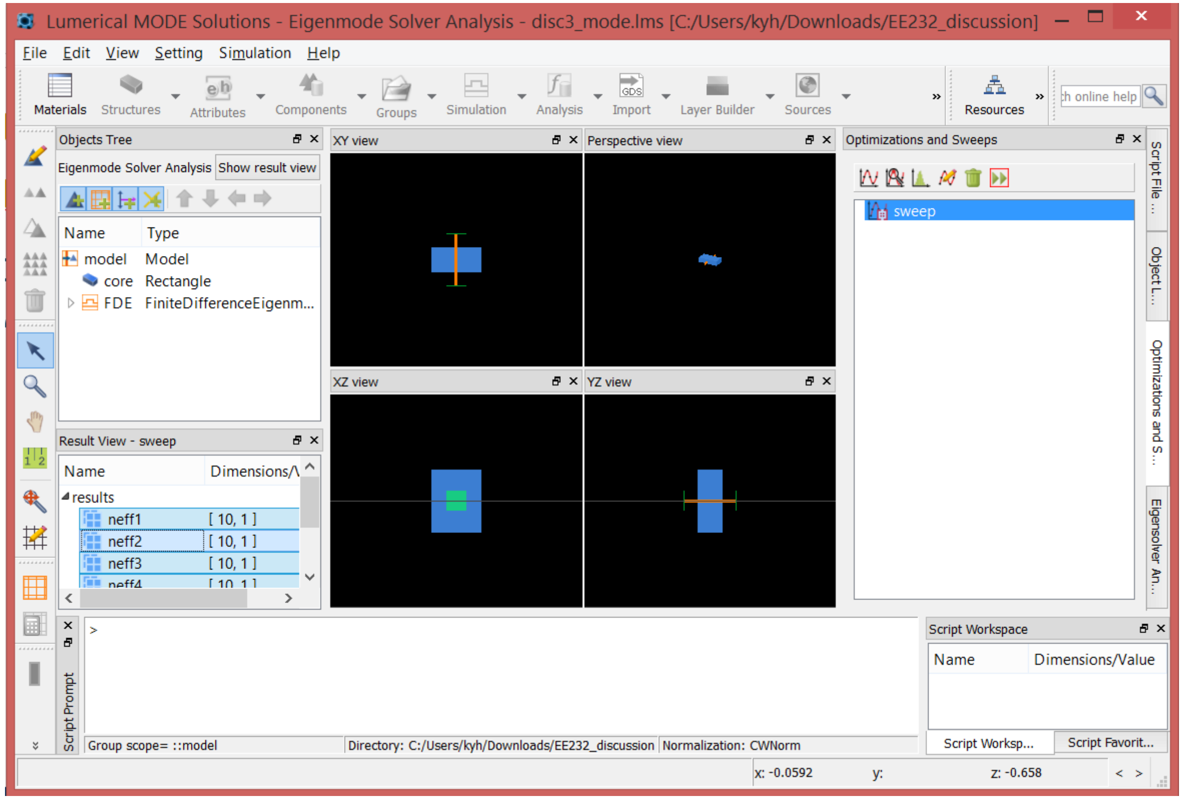
$$k_x^2 + k_z^2 = \omega^2 \mu \epsilon_1$$
$$\alpha^2 + k_z^2 = \omega^2 \mu \epsilon_2$$
$$\alpha = -k_x \cot(k_x d/2)$$

TE modes

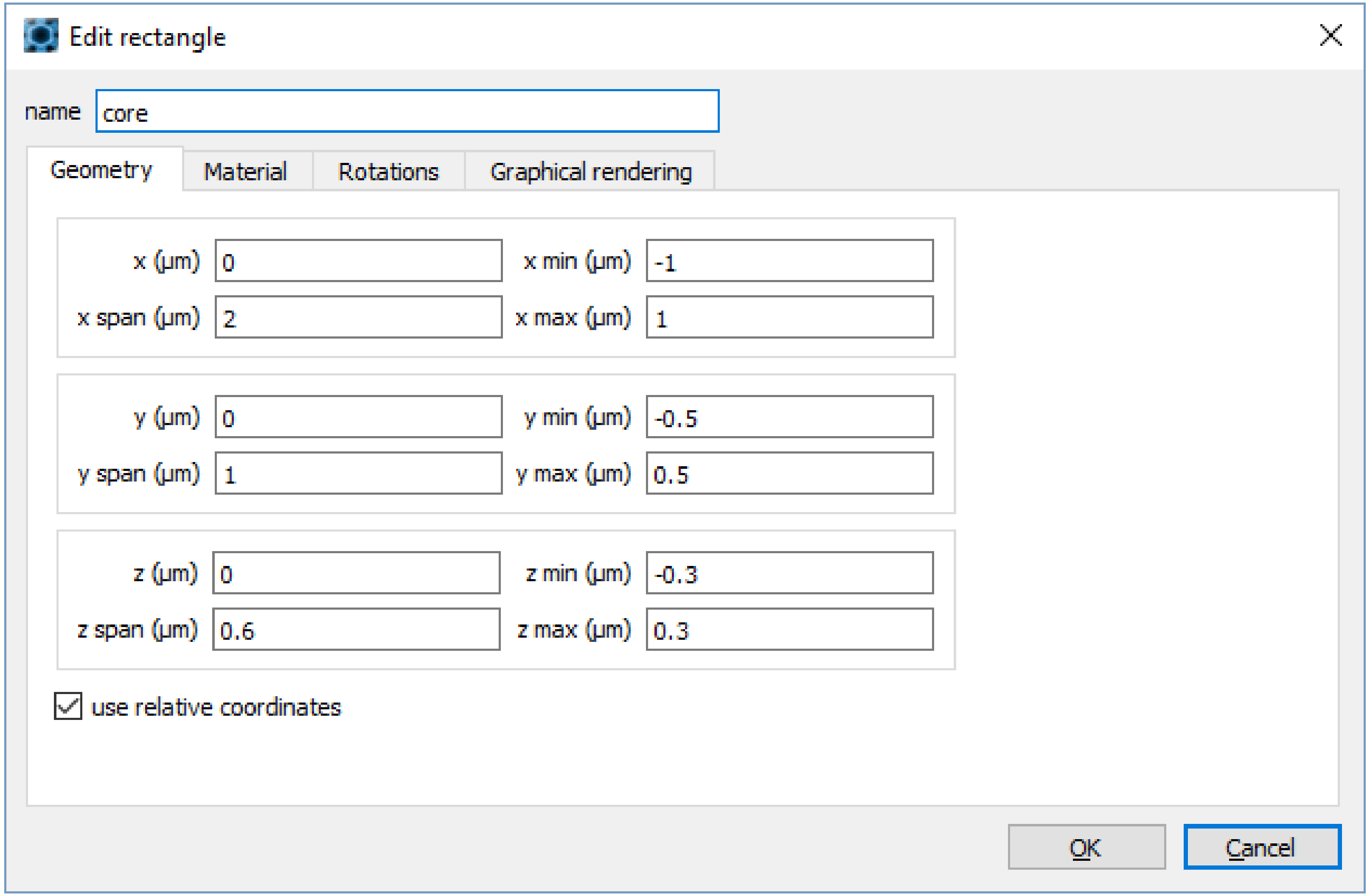


Simulating slab waveguide with Lumerical MODE

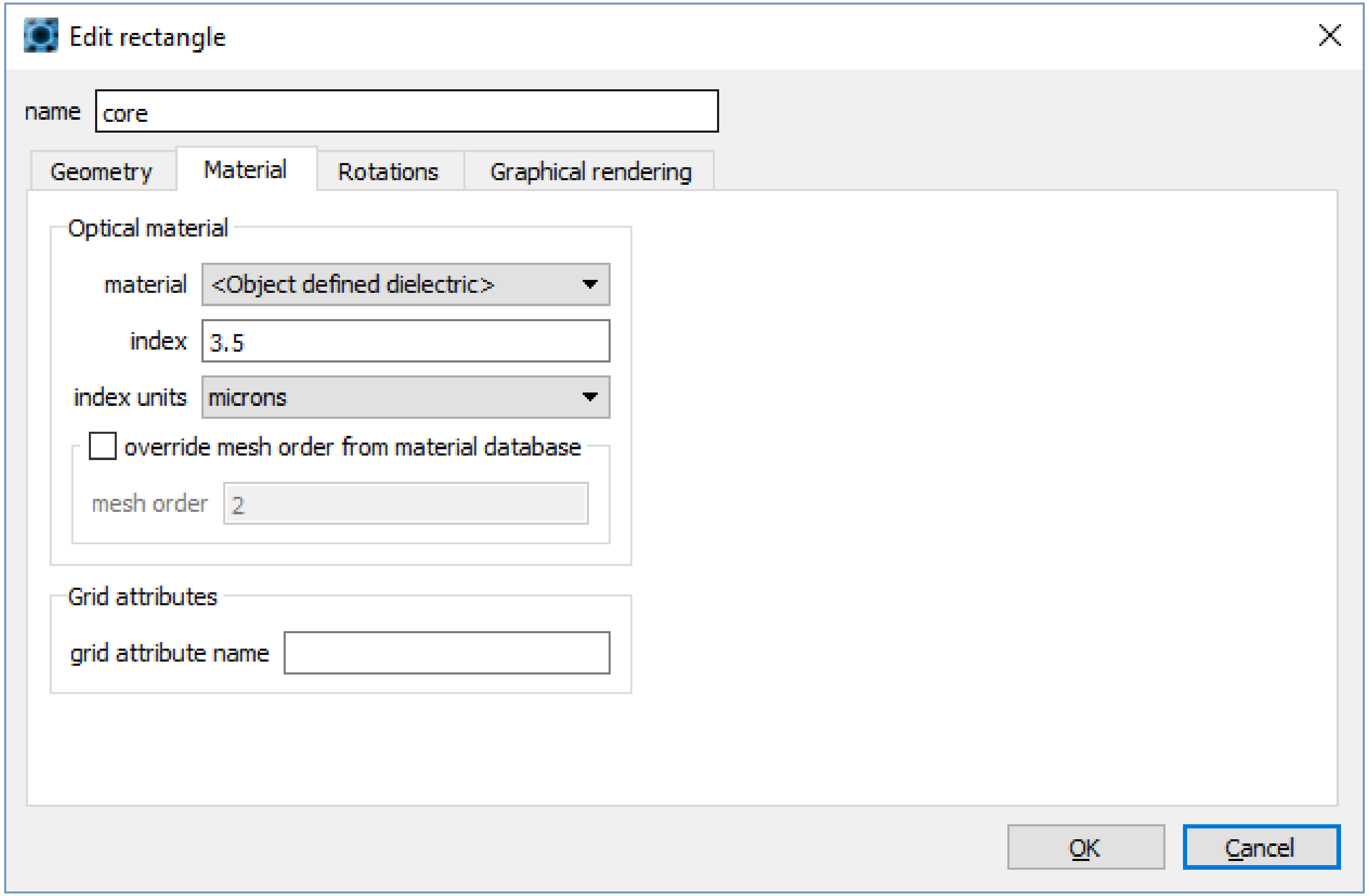
- Open MODE software
- Create new rectangle: ***Structures > Rectangle***



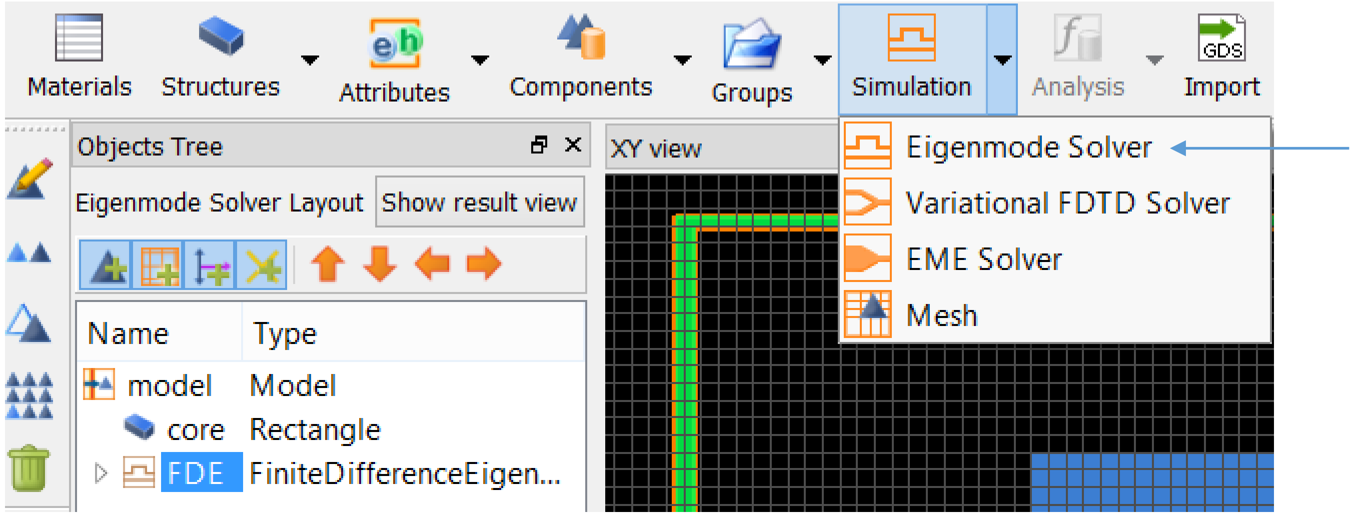
Create waveguide core



Create waveguide core



Create 1-D FDE simulation region



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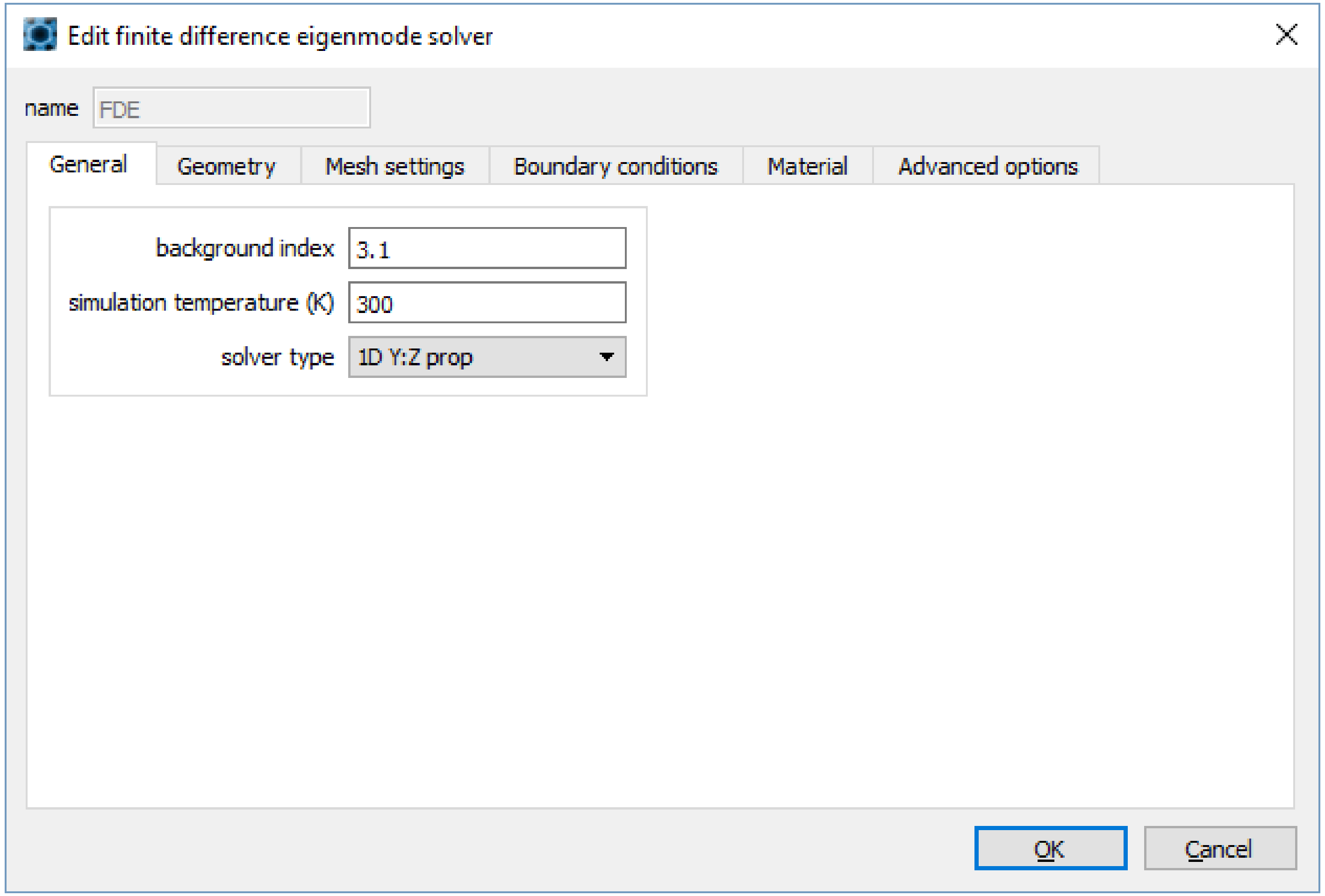
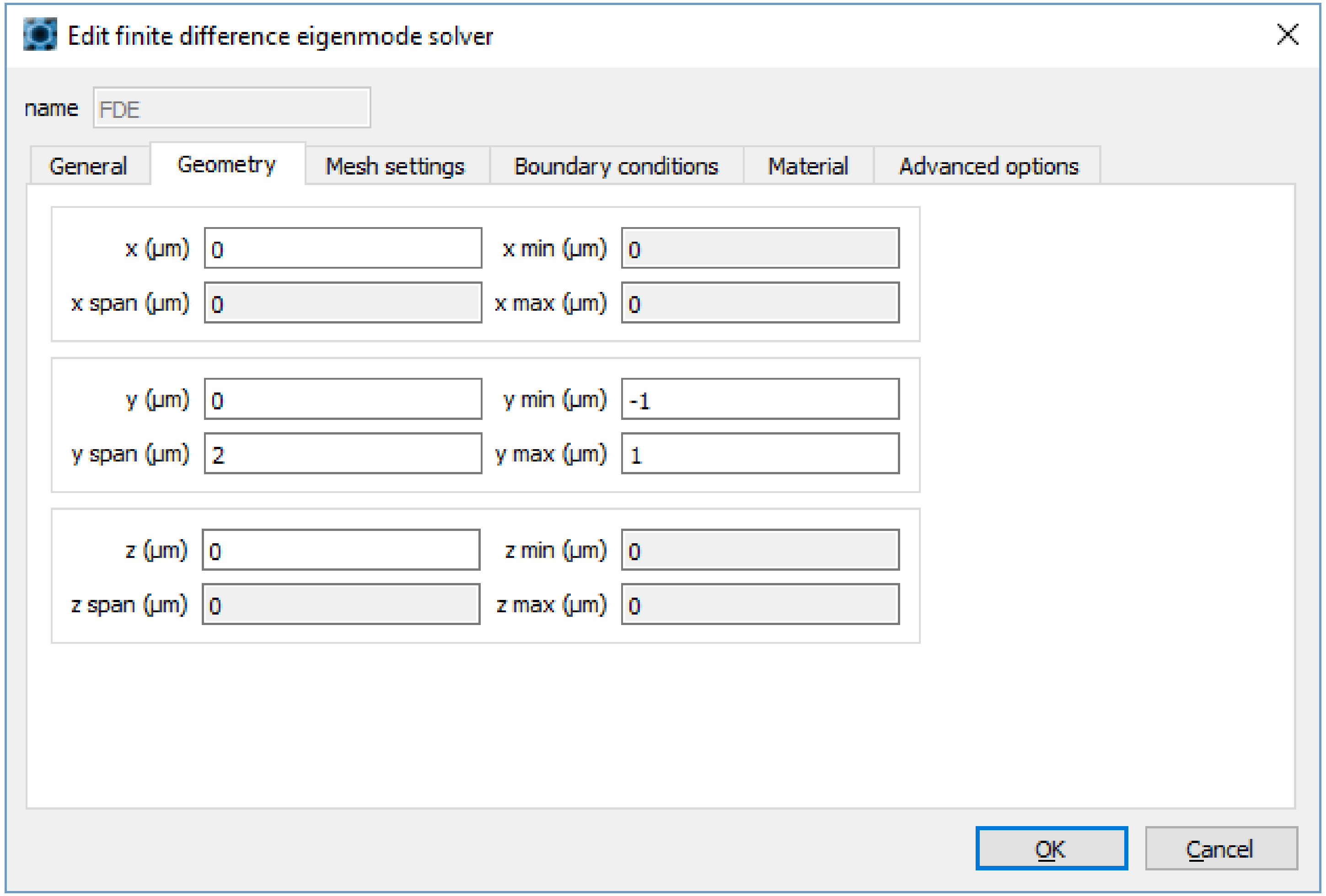
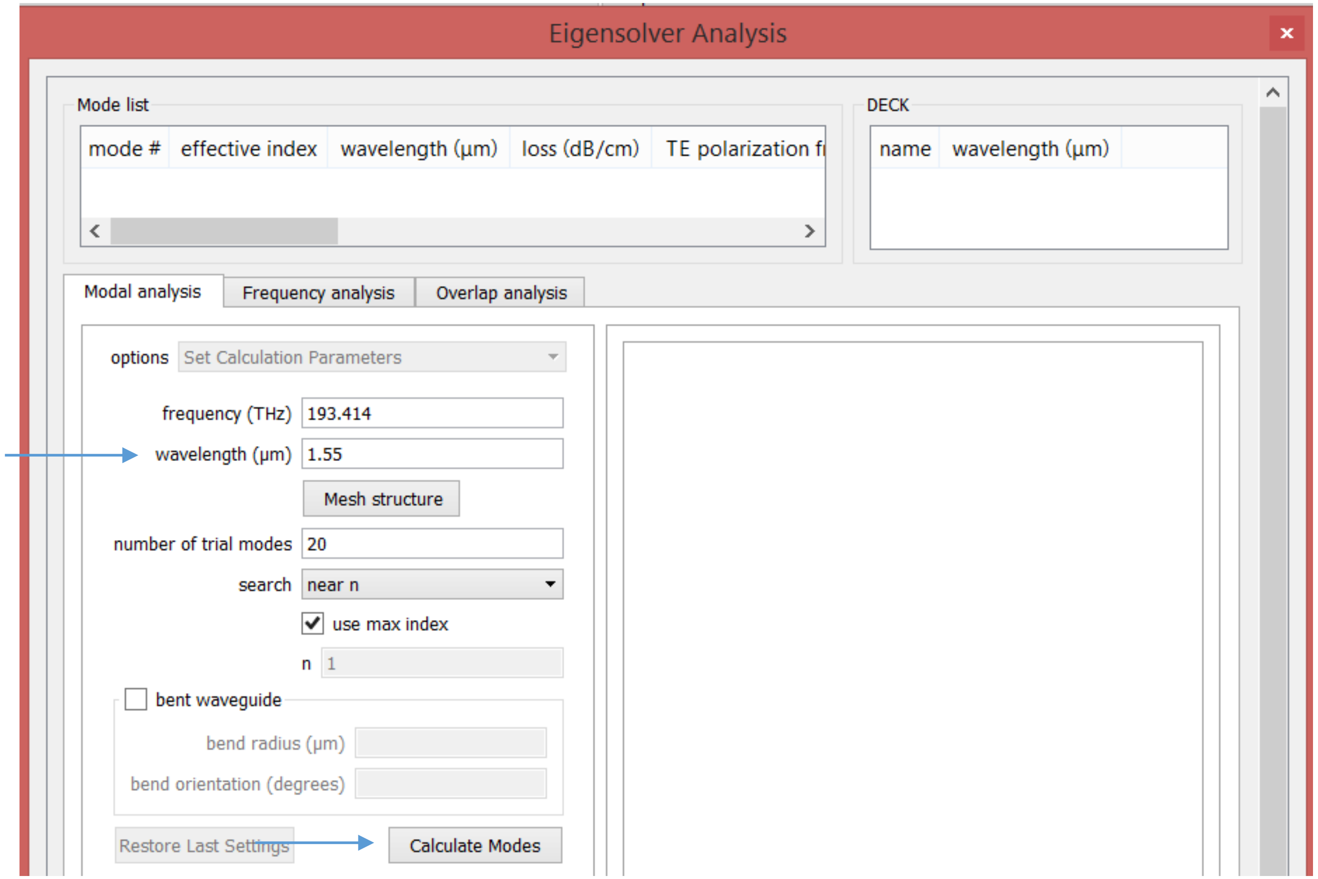


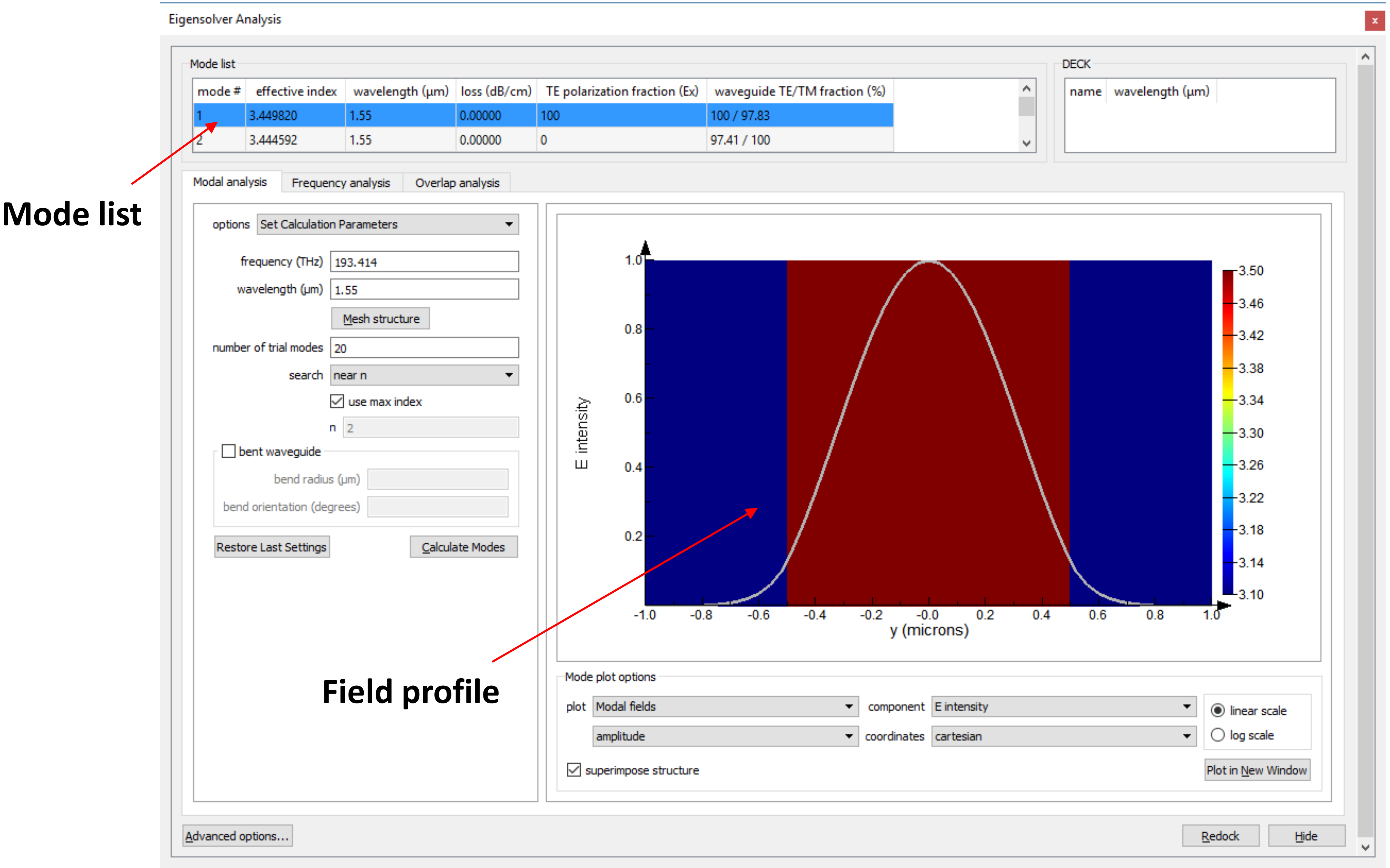
Create 1-D FDE simulation region



Calculate modes

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




Mode list
Field profile
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
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 waveguide
bend radius (μm)
bend orientation (degrees)
Restore Last Settings
Calculate Modes
E intensity
y (microns)
Mode plot options
plot
Modal fields
amplitude
component
E intensity
coordinates
cartesian
linear scale
log scale
superimpose structure
Plot in New Window
Advanced options...
Redock
Hide

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

Guided modes

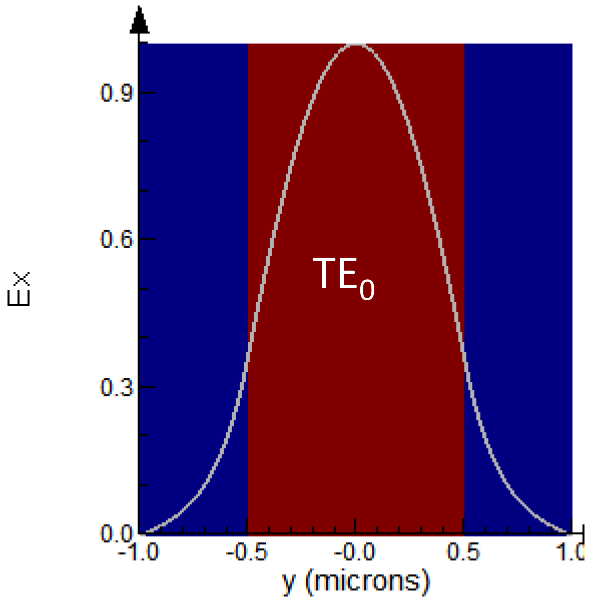
Unguided radiating modes

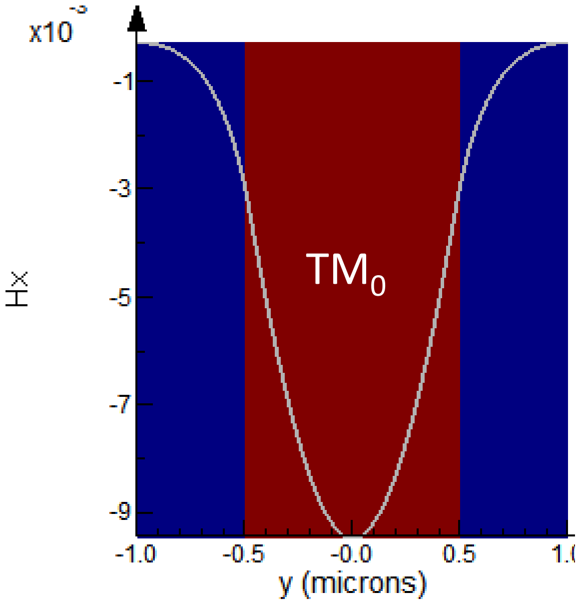
Eigensolver Analysis

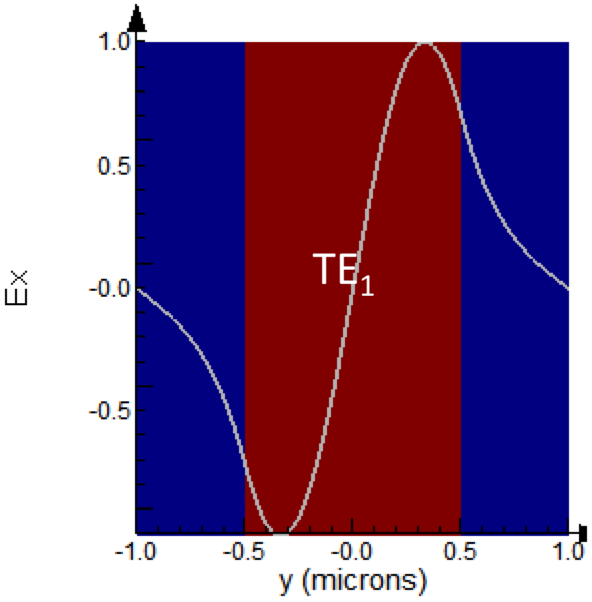
Mode list

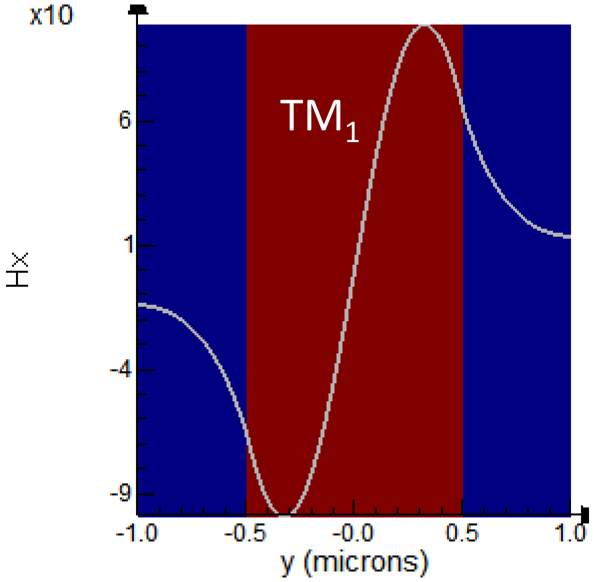
mode #	effective index	wavelength (µm)	loss (dB/cm)	TE polarization fraction (Ex)	waveguide TE/TM fraction (%)
1	3.449820	1.55	0.00000	100	100 / 97.83
2	3.444592	1.55	0.00000	0	97.41 / 100
3	3.302481	1.55	0.00000	100	100 / 91.89
4	3.289505	1.55	0.00000	0	91.88 / 100
5	3.112555	1.55	0.00000	0	93.41 / 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

Mode analysis (guided modes)



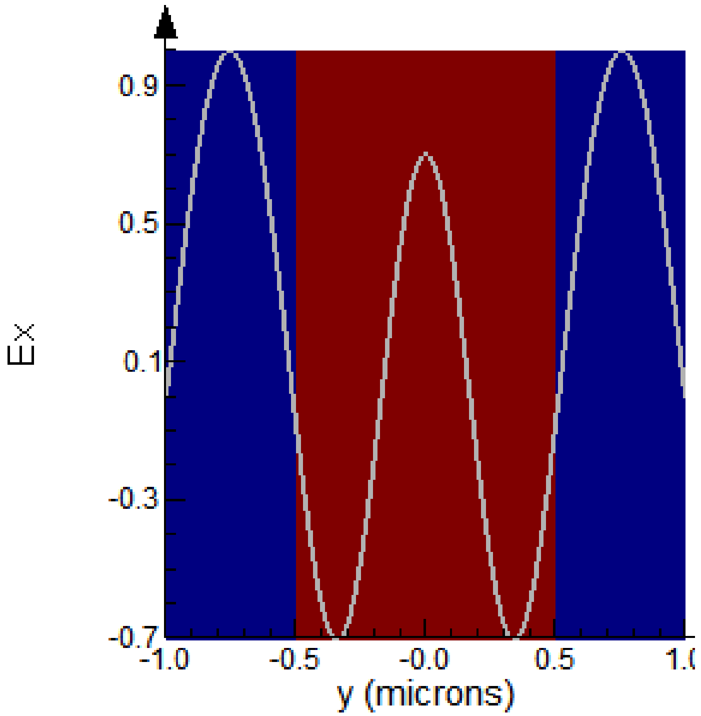




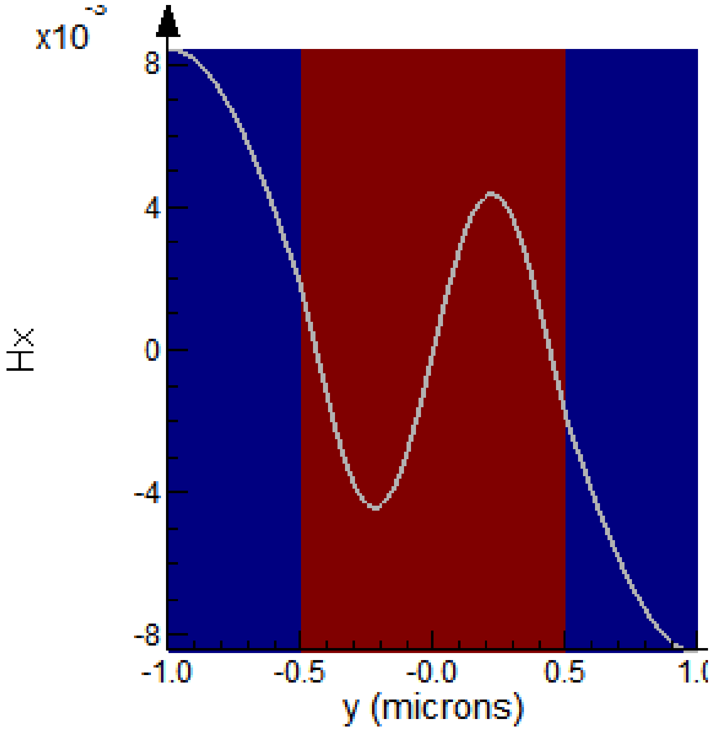


Mode analysis (unguided modes)

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

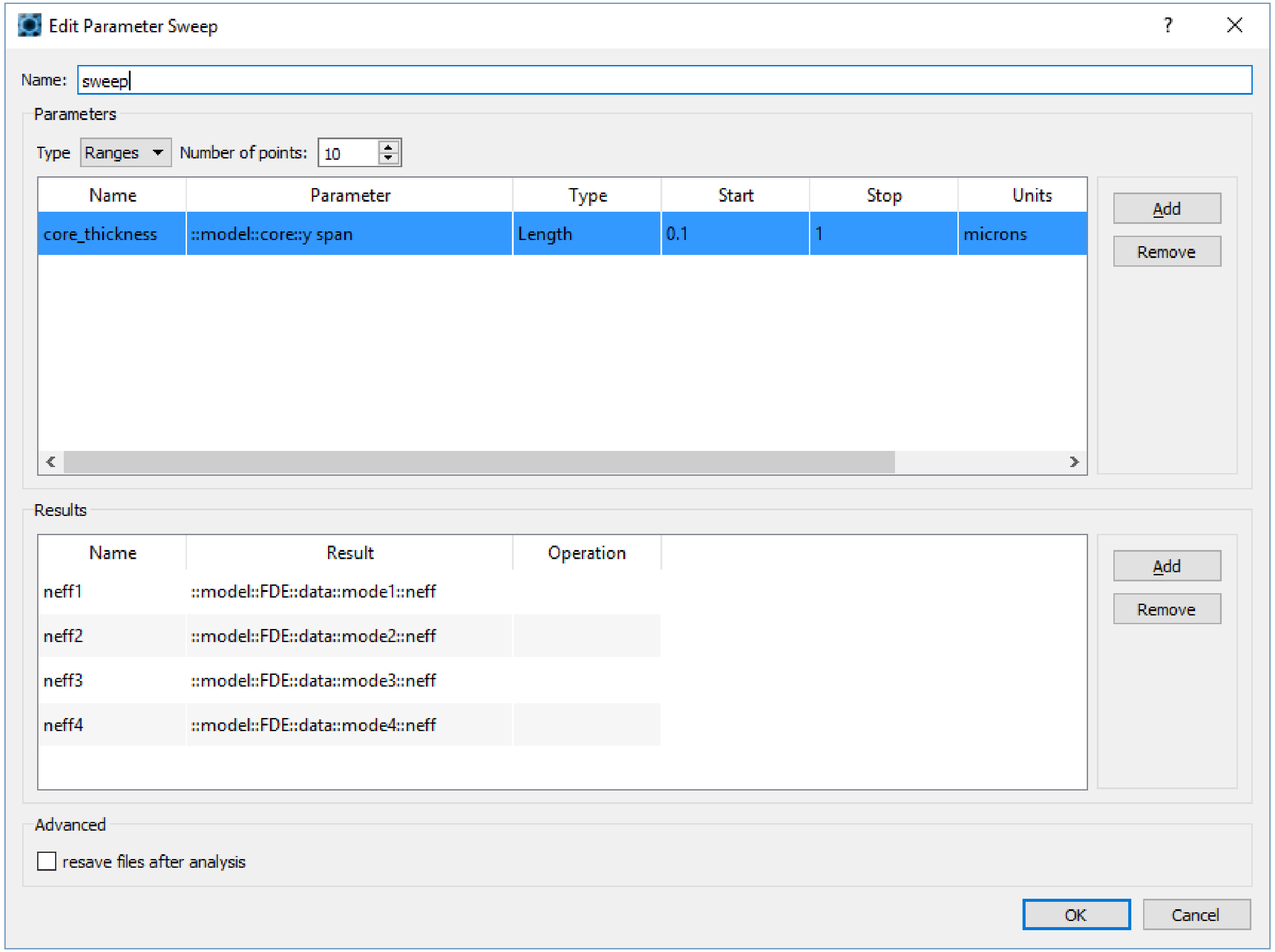


Example #2

Waveguide cutoff

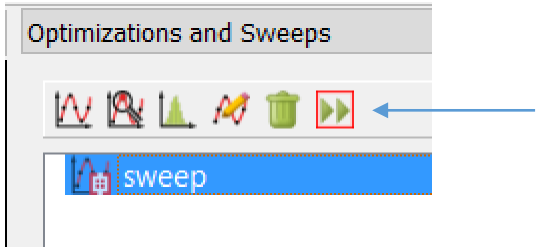
- Let's run a parameter sweep to plot effective index as a function of slab core thickness
- You should set your minimum mesh spacing to 10nm for this analysis

Waveguide cutoff

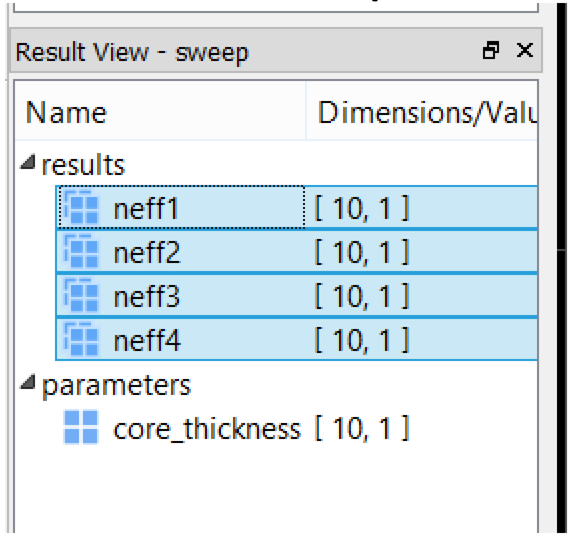


Waveguide cutoff

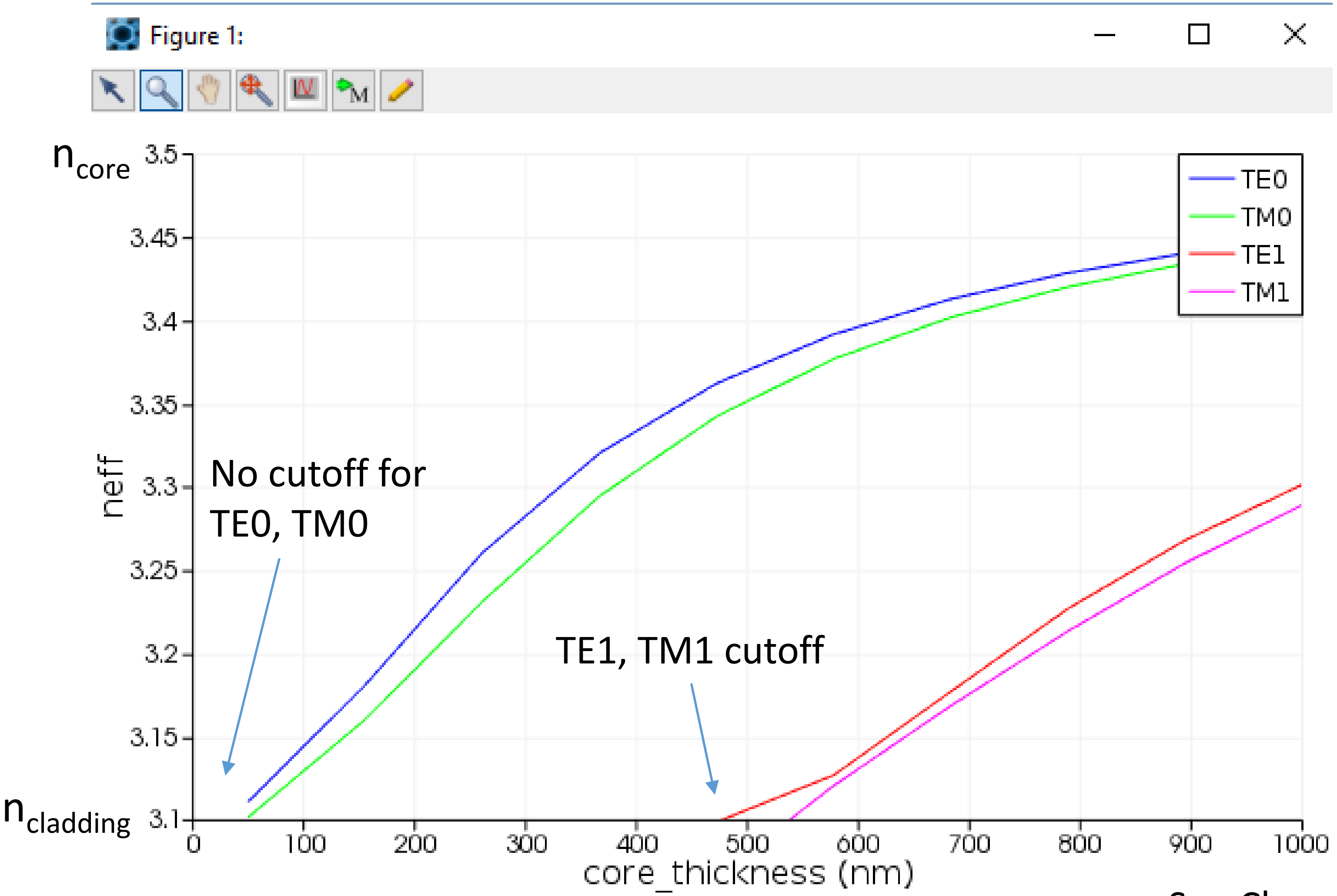
- Click run button:



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

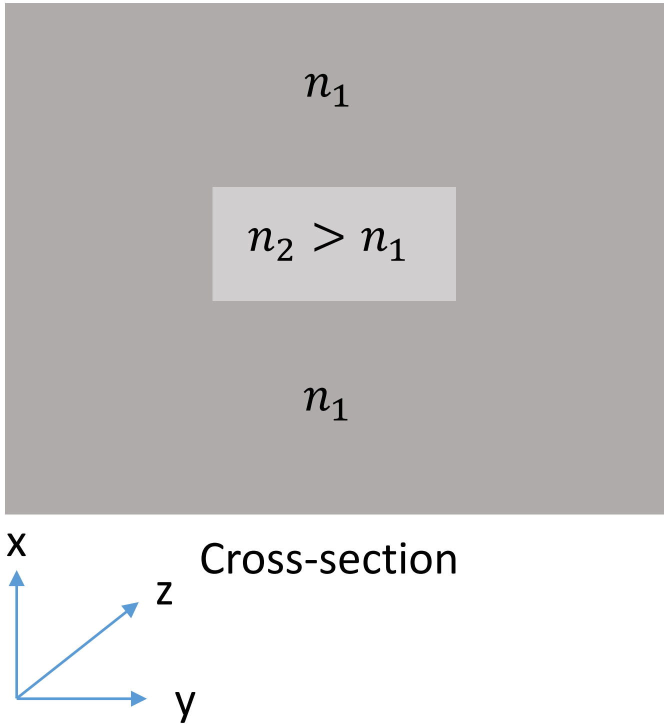


Waveguide cutoff



See Chuang 7.1.2

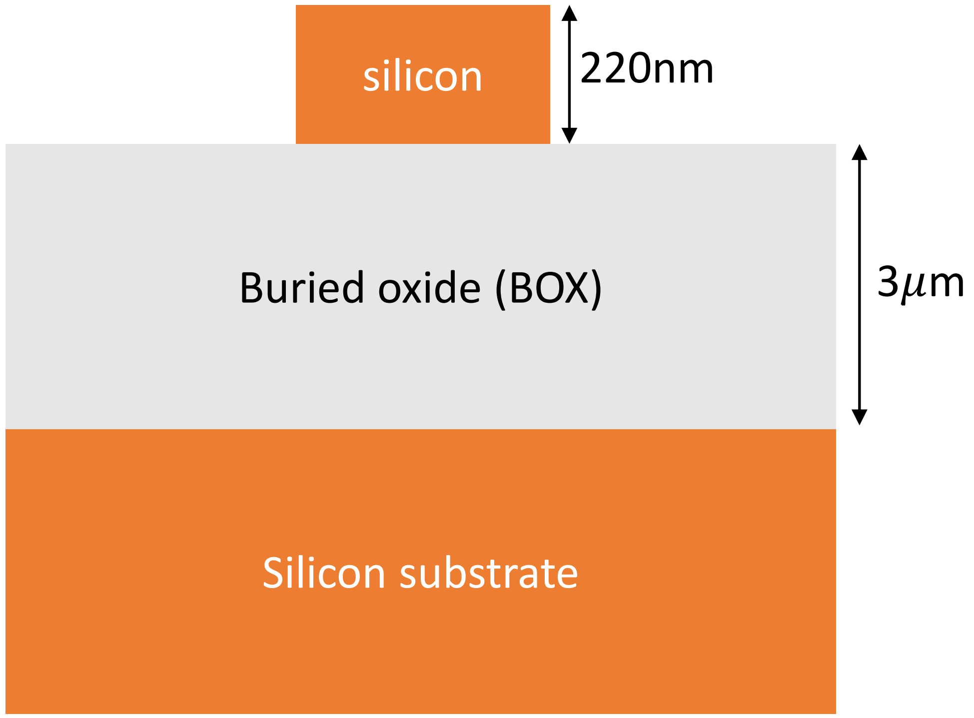
Rectangular waveguide



Cross-section

- 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)

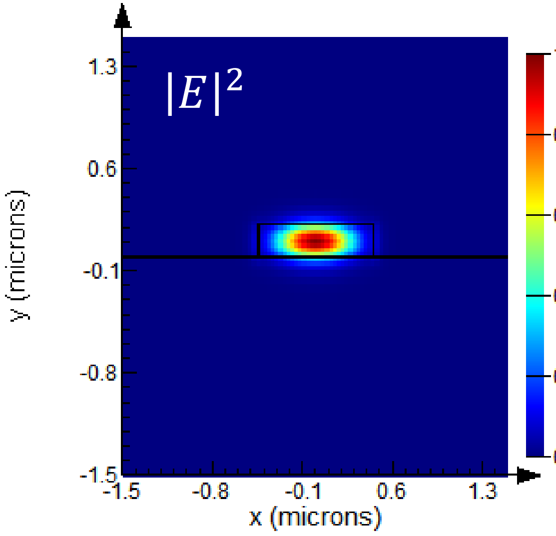
Silicon photonic ridge waveguide



Waveguide modes

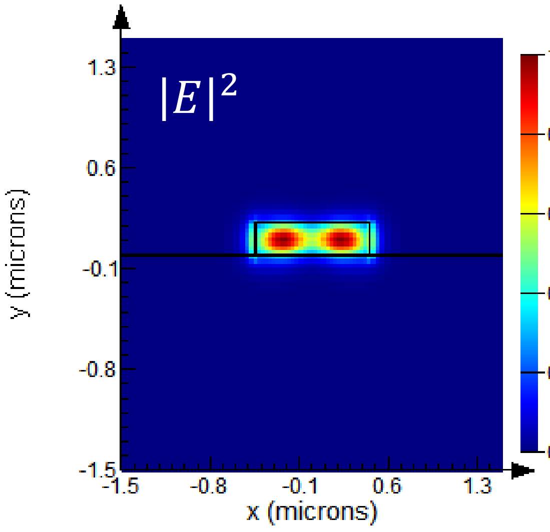
- Silicon thickness of 220nm for silicon-on-substrate (SOI) substrate is somewhat standardized
- We often desire waveguide to contain only a single mode
- Our goal is to determine the silicon ridge width such that that waveguide is single mode
- Open **Silicon_Photonic_Ridge_Waveguide.lms** from the 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



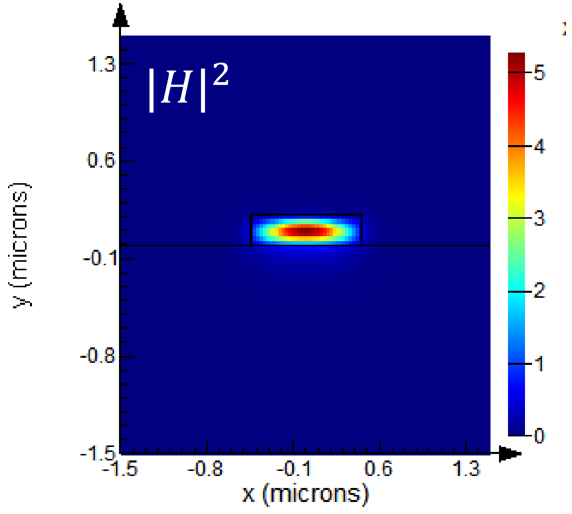
Quasi-TE_{00}

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



Quasi-TE_{10}

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



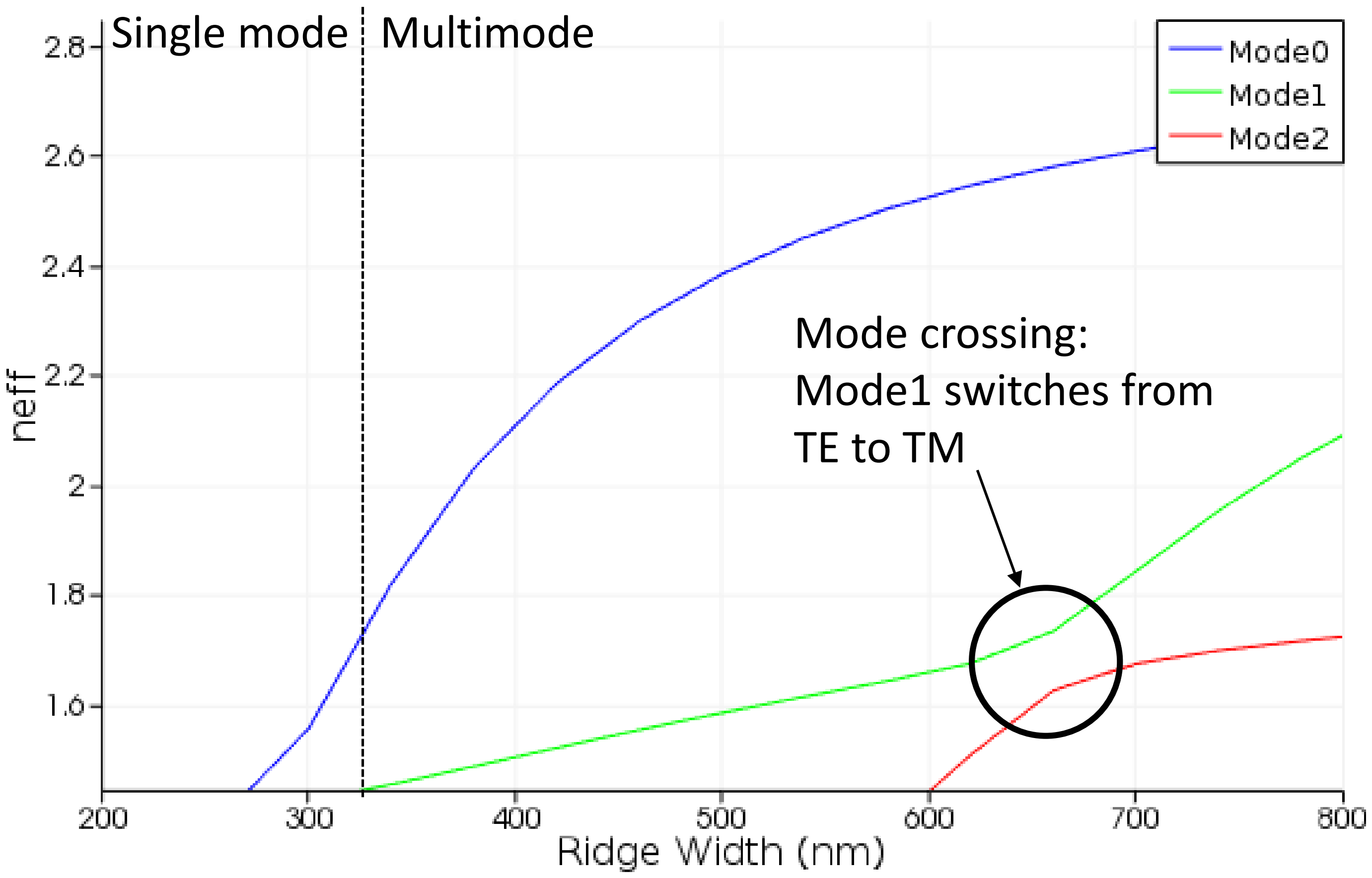
Quasi-TM_{00}

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

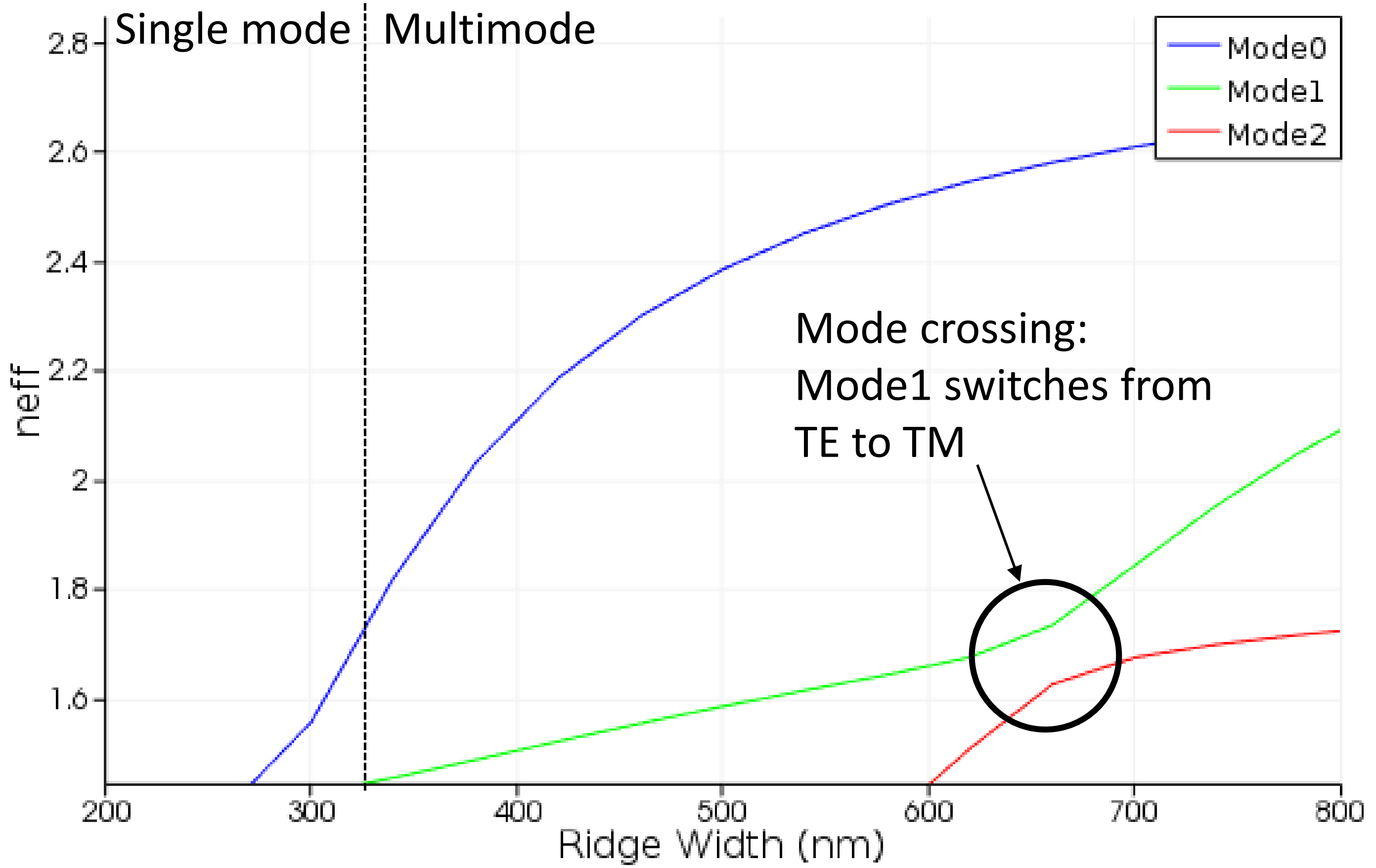
Single-mode waveguide

- 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



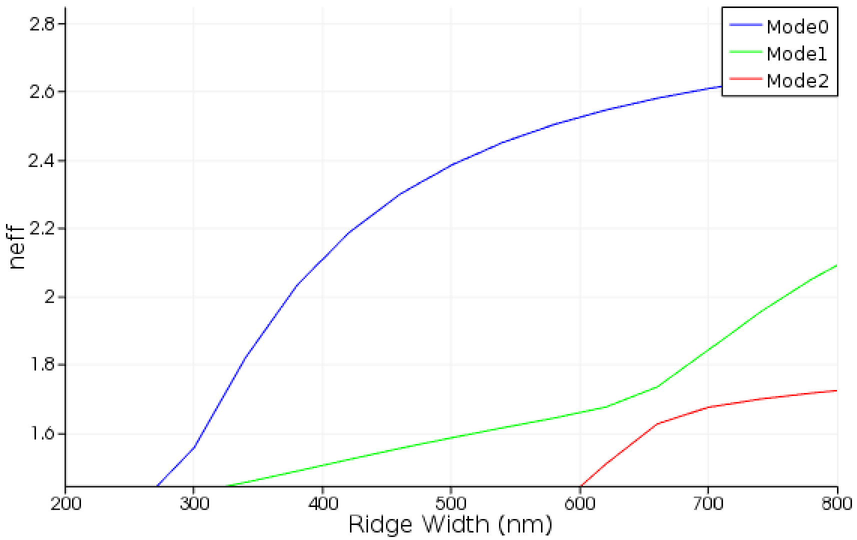
Single-mode waveguide



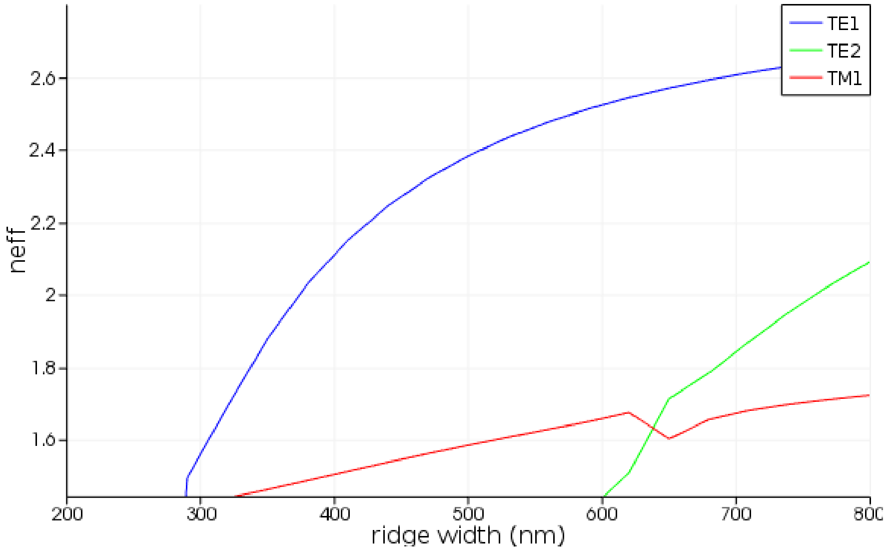
Note: Lumerical indexes modes by effective index, while we usually want to sort by spatial distribution

Single-mode waveguide

Index mode by eigenmode



Index mode by spatial distribution

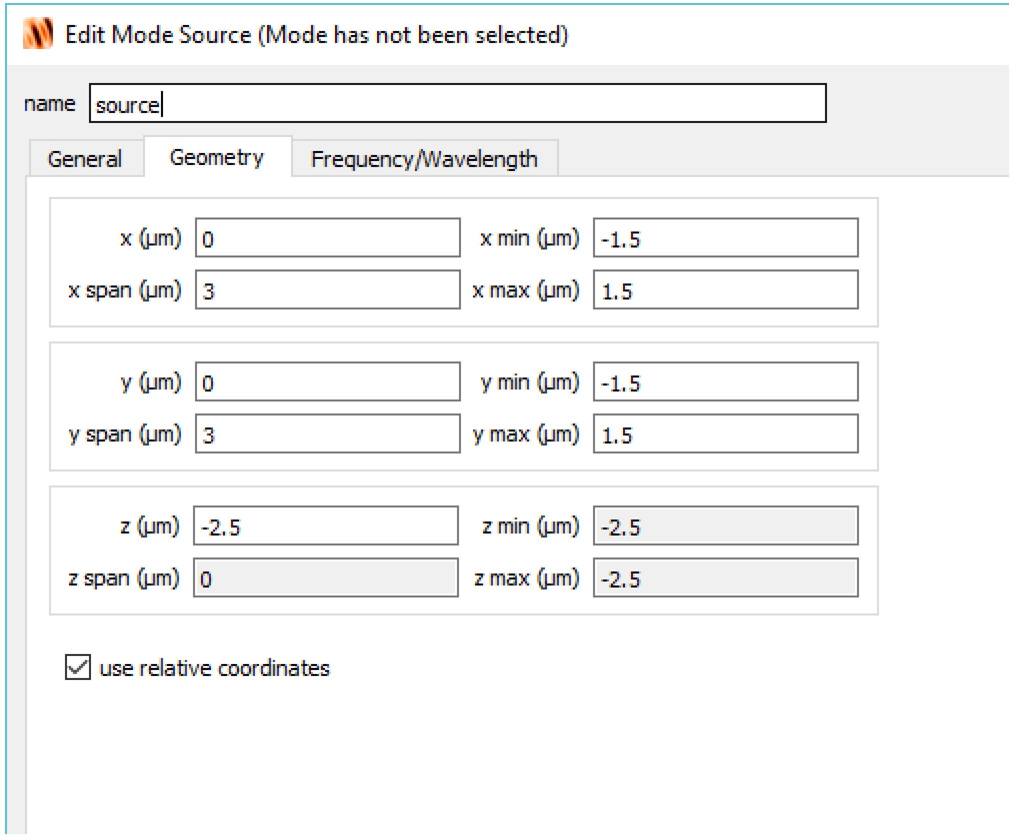


Mode source in FDTD

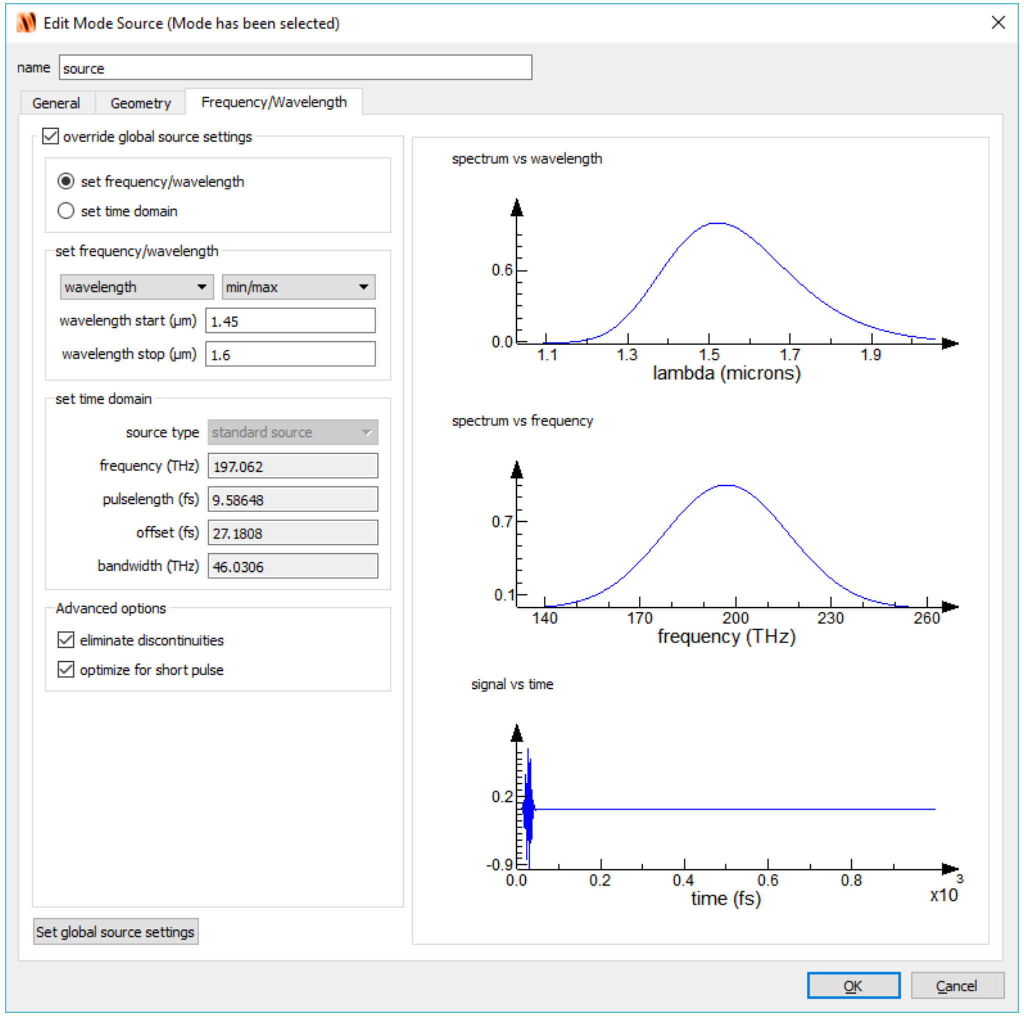
- When running FDTD simulation we often want to excite a particular waveguide mode
- This can be done using a *mode source* in Lumerical FDTD.
- Open the file Silicon_Photonic_Waveguide_Port_Source.fsp from bcourses
- This Lumerical FDTD simulation file contains 3D silicon photonic ridge waveguide that 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

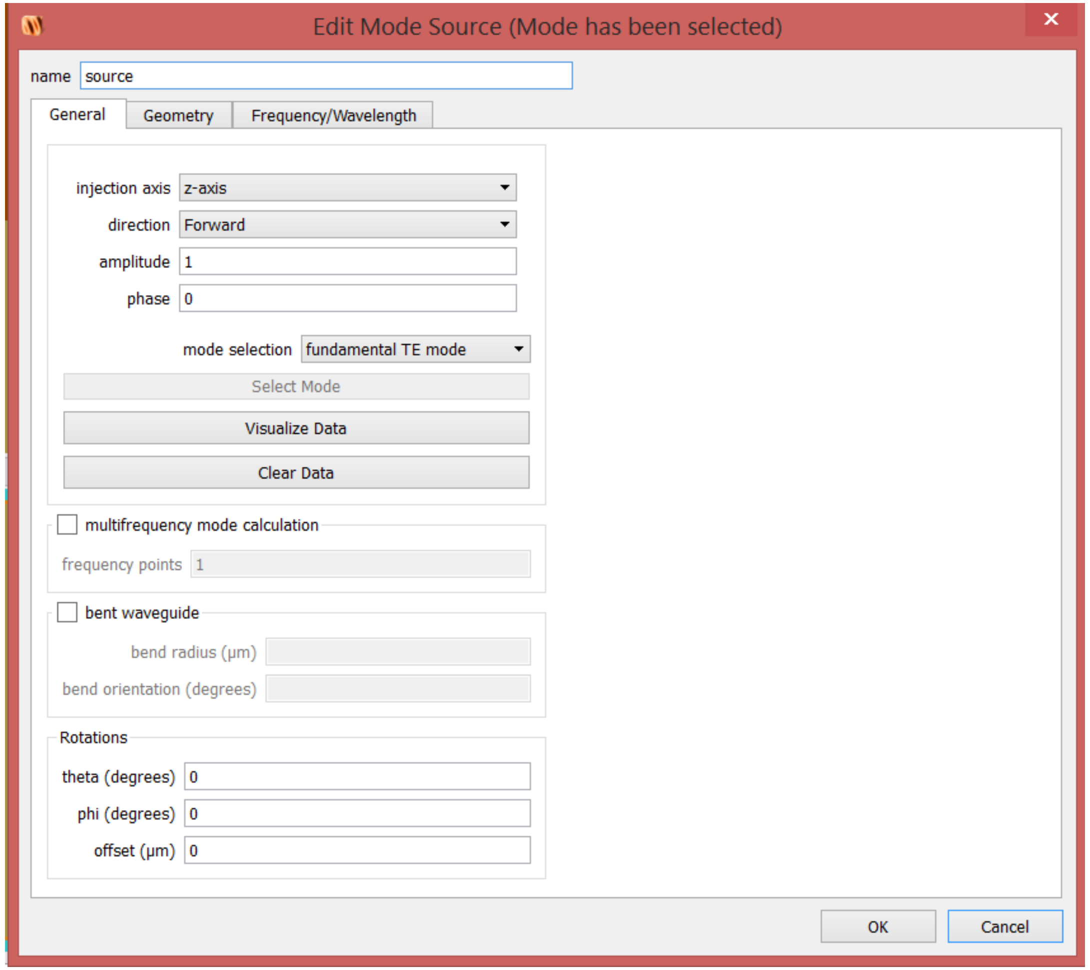


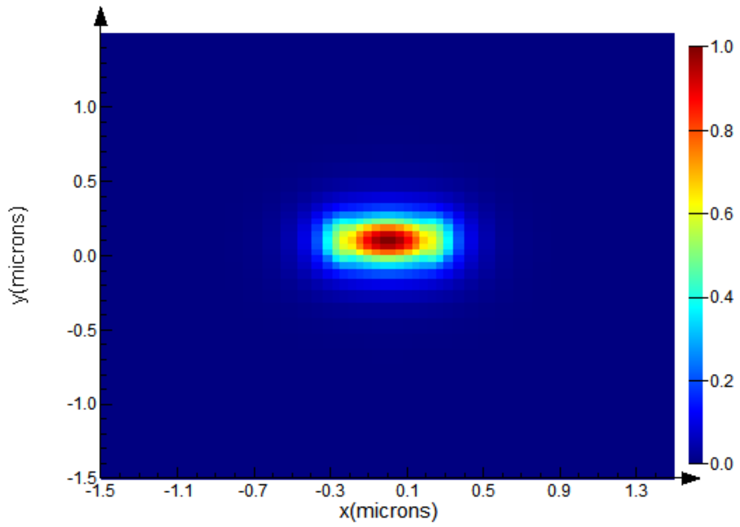
Mode source in FDTD



Mode source in FDTD

- Click ***Visualize Data***

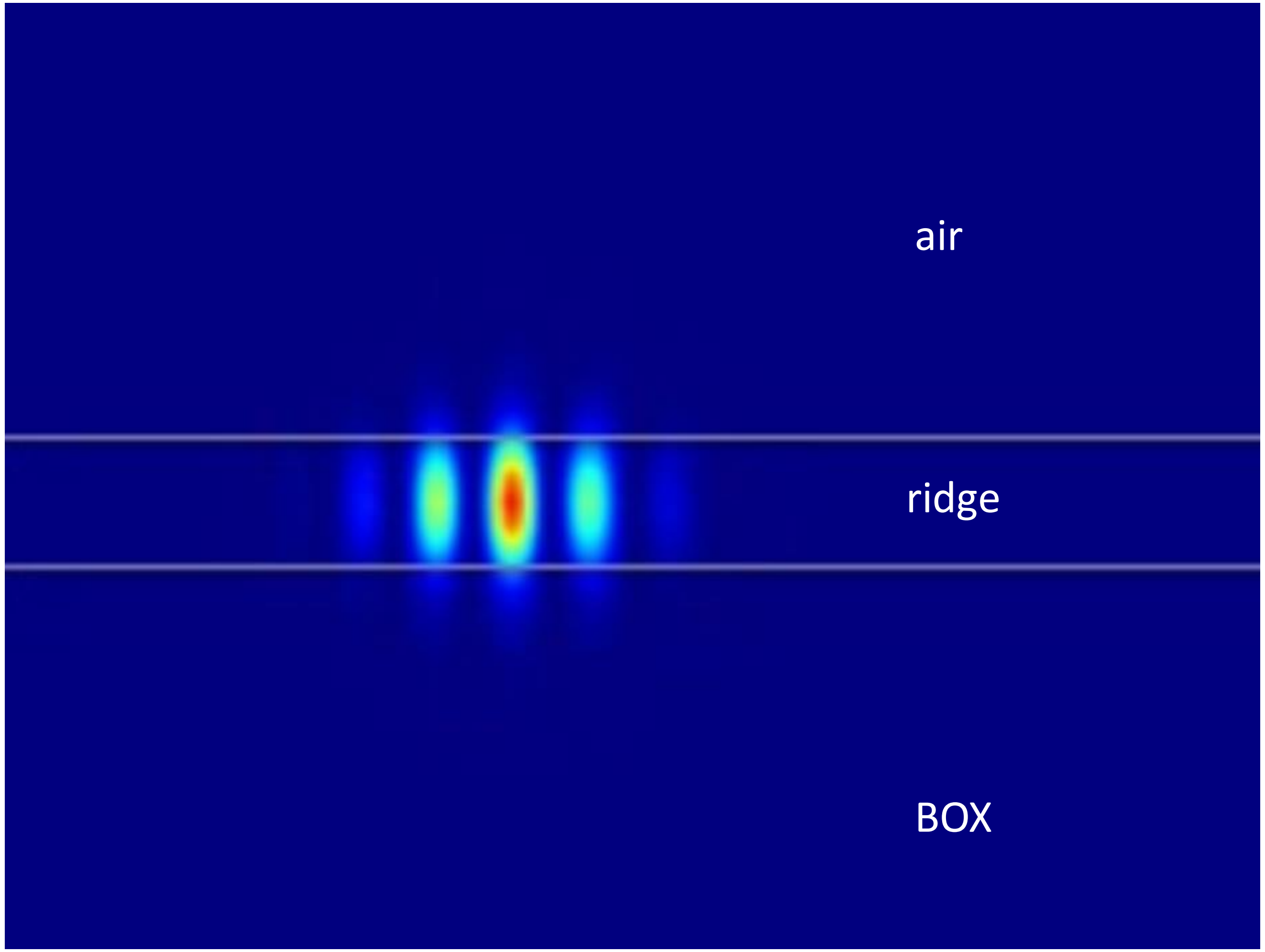


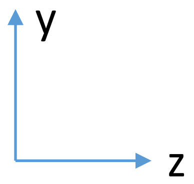


Mode source in FDTD

- 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.