



COMSOL® Design Tool: Simulations of Optical Components Week 5: Waveguides – Mode Solver

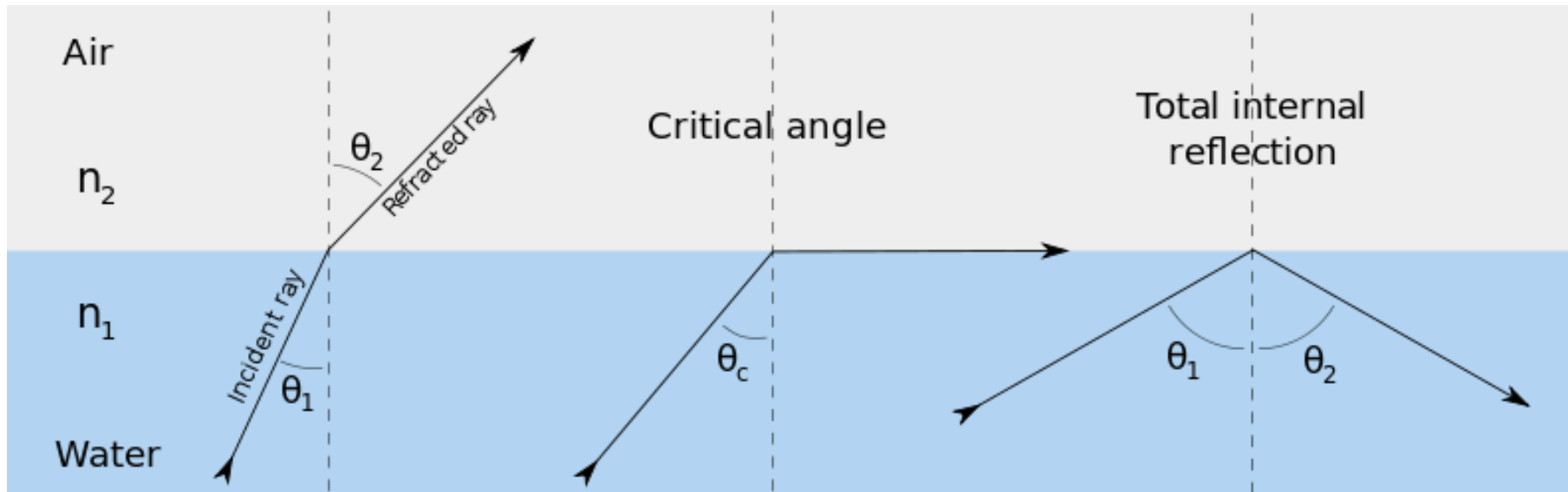
Taichiro Fukui, Maximilian Bosch

Content

- Revision on waveguiding theory
 - Confinement
 - TE and TM modes
- COMSOL
 - Silicon ridge waveguide
 - Glass fiber (Homework)

Snell's Law and total internal reflection

- What happens at the boundary between two materials?



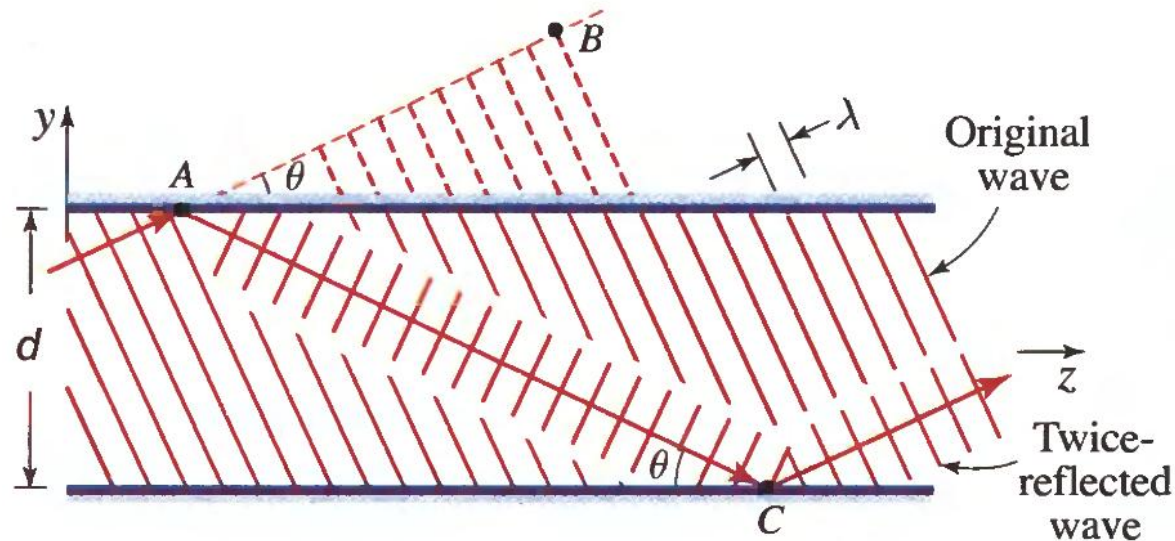
- What if $\sin \theta_2 \geq 1$?
 - There is critical angle $\theta_c = \arcsin n_2/n_1$
 - $n_1 > n_2$
 - Light prefers to stay in higher index material!
 - Almost everything is reflected → **total internal reflection!**

Snell's law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Waveguiding: Theory

- EM field in between two perfect mirrors
 - Interference after second reflection!
 - Self consistency: after second reflection, wave duplicates itself

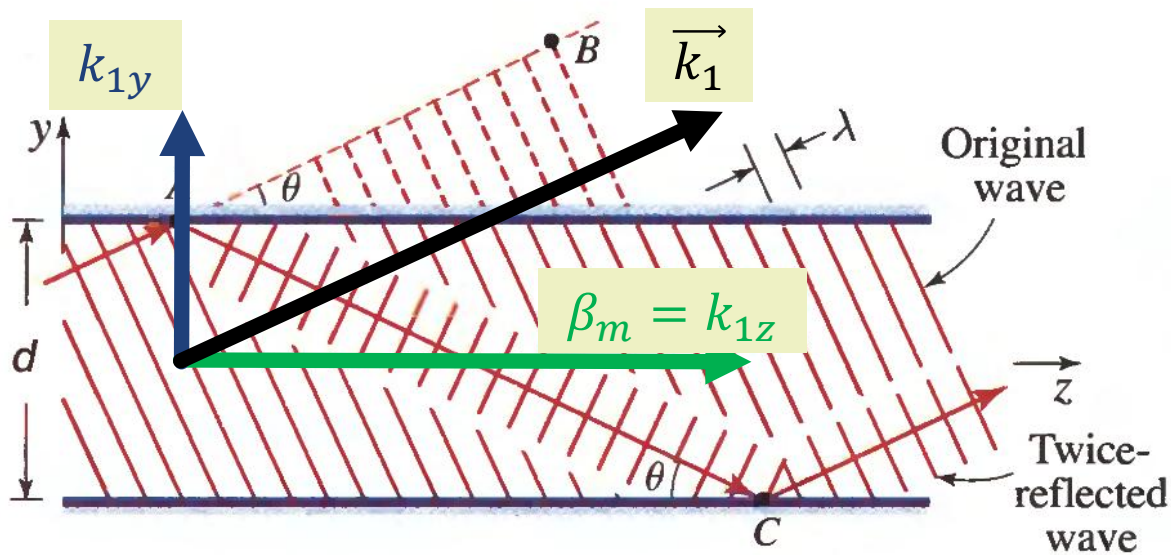


Definition: EM fields which satisfy this condition, we call (eigen)modes!

$$E(x, y, z) = E(x, y)e^{j\beta z}$$

Waveguiding: Theory

- EM field in between two perfect mirrors
 - Interference after second reflection!
 - Self consistency: after second reflection, wave duplicates itself



$$k_{1y} = k_1 \sin \theta_m$$

$$k_{1z} = k_1 \cos \theta_m$$

$$\sin(\theta_m) = \frac{\lambda m}{2dn}$$

Propagation constant

Effective refractive index

$$\beta_m = k_1 \cos \theta_m = \frac{2\pi}{\lambda} n_{\text{eff},m}$$

Mode in a Waveguide

Maxwell Equations

$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}$$

$$\nabla \times \mathbf{H} = \varepsilon_0 \varepsilon_r \frac{\partial \mathbf{E}}{\partial t}$$

With $\mathbf{E} = \mathbf{E}_0(x, y)e^{j(\omega t - \beta z)}$ and $\mathbf{H} = \mathbf{H}_0(x, y)e^{j(\omega t - \beta z)}$

No dependency in the x direction (in this case)

$$H_{0x} = -\frac{1}{j\omega\mu_0} \left(\frac{\partial E_{0z}}{\partial y} + j\beta E_{0y} \right)$$

$$H_{0y} = \frac{\beta}{\omega\mu_0} E_{0x}$$

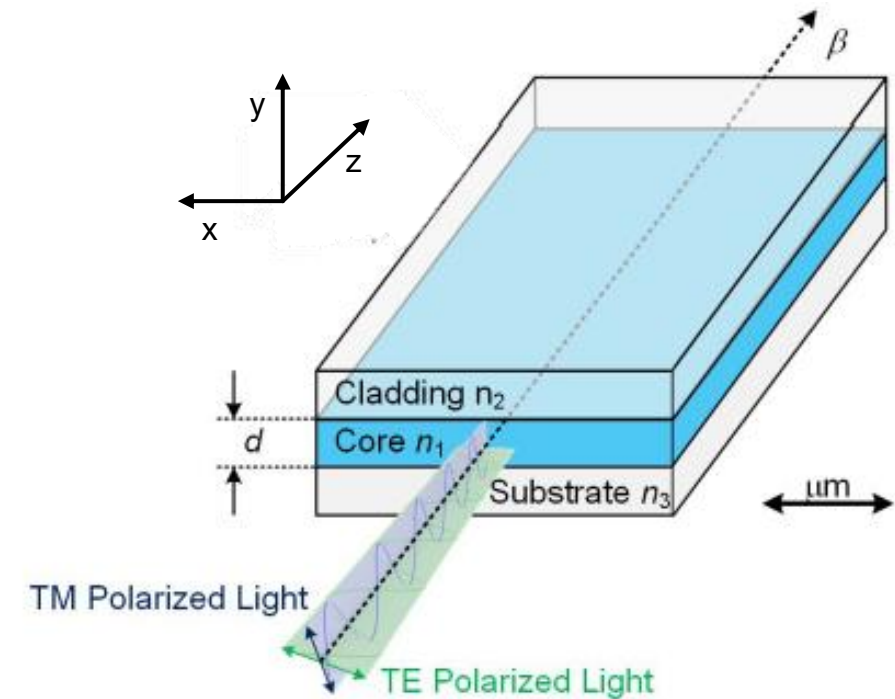
$$H_{0z} = \frac{1}{j\omega\mu_0} \frac{\partial E_{0x}}{\partial y}$$

$$E_{0x} = \frac{1}{j\omega\varepsilon_0\varepsilon_r} \left(\frac{\partial H_{0z}}{\partial y} + j\beta H_{0y} \right)$$

$$E_{0y} = -\frac{\beta}{\omega\varepsilon_0\varepsilon_r} H_{0x}$$

$$E_{0z} = -\frac{1}{j\omega\varepsilon_0\varepsilon_r} \frac{\partial H_{0x}}{\partial y}$$

6 equations, 6 unknown



Mode in a Waveguide

Helmholtz equations

2 sets of equations, **TE** and **TM**

TE: no E field in the propagation direction

$$E_{0z} = E_{0y} = H_{0x} = 0$$

$$H_{0y} = \frac{\beta}{\omega\mu_0} E_{0x}$$

$$H_{0z} = \frac{1}{j\omega\mu_0} \frac{\partial E_{0x}}{\partial y}$$

$$E_{0x} = -\frac{1}{j\omega\mu_0} \left(\frac{\partial E_{0z}}{\partial z} + j\beta E_{0y} \right)$$

...

$$\frac{\partial^2 E_{0x}}{\partial y^2} + E_{0x}(\epsilon_r k_0^2 - \beta^2) = 0$$

TM: no H field in the propagation direction

$$H_{0z} = H_{0y} = E_{0x} = 0$$

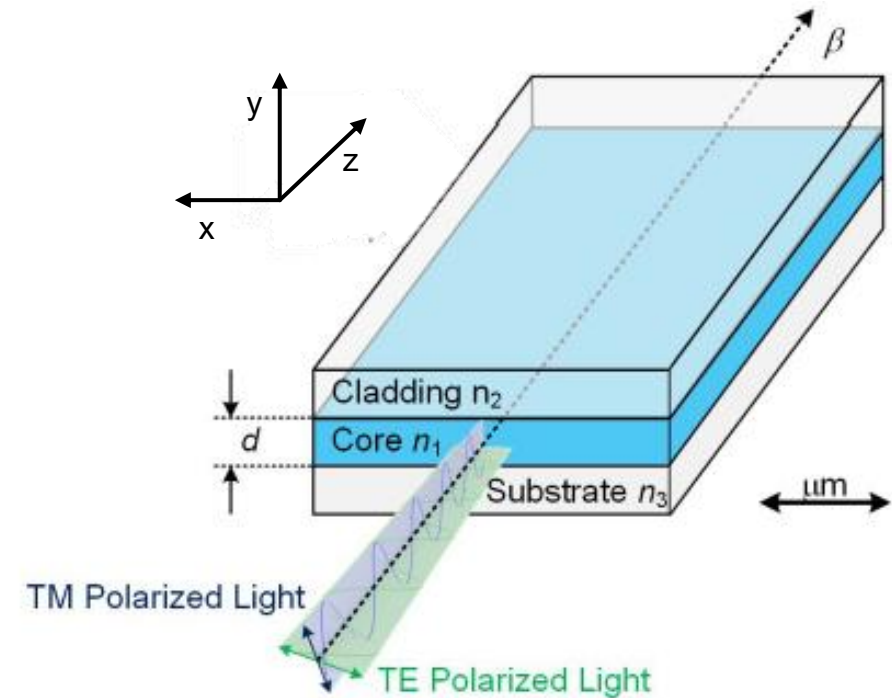
$$H_{0x} = -\frac{1}{j\omega\mu_0} \left(\frac{\partial E_{0z}}{\partial y} + j\beta E_{0y} \right)$$

$$E_{0y} = -\frac{\beta}{\omega\epsilon_0\epsilon_r} H_{0x}$$

$$E_{0z} = -\frac{1}{j\omega\epsilon_0\epsilon_r} \frac{\partial H_{0x}}{\partial y}$$

...

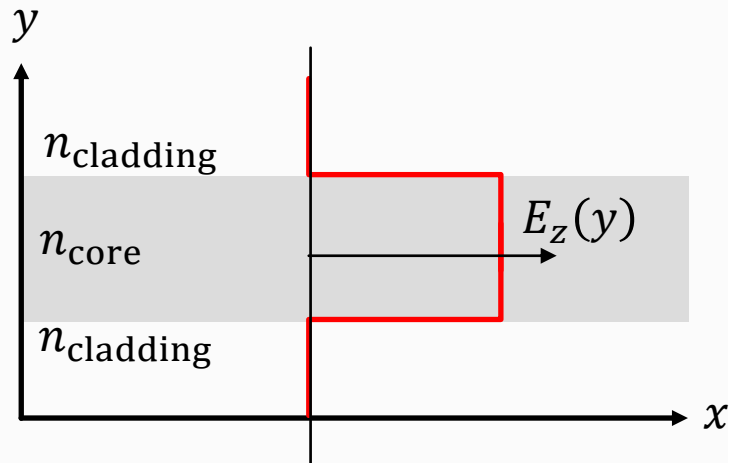
$$\frac{\partial^2 H_{0x}}{\partial y^2} + H_{0x}(\epsilon_r k_0^2 - \beta^2) = 0$$



Need to solve the equations for every layer, and apply BC

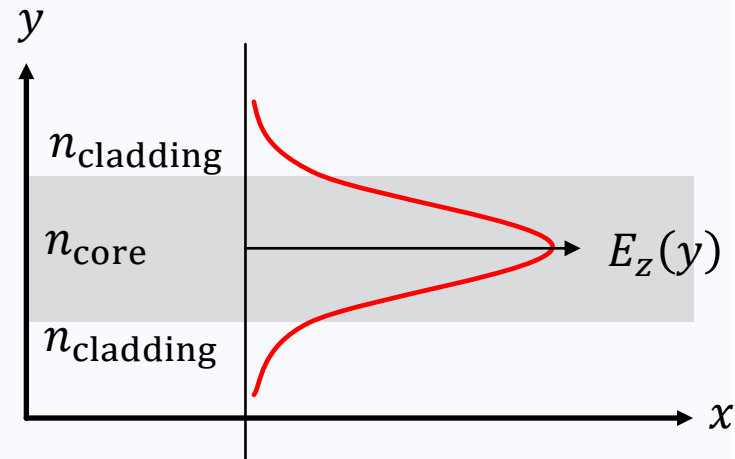
Waveguiding: Theory

Completely confined



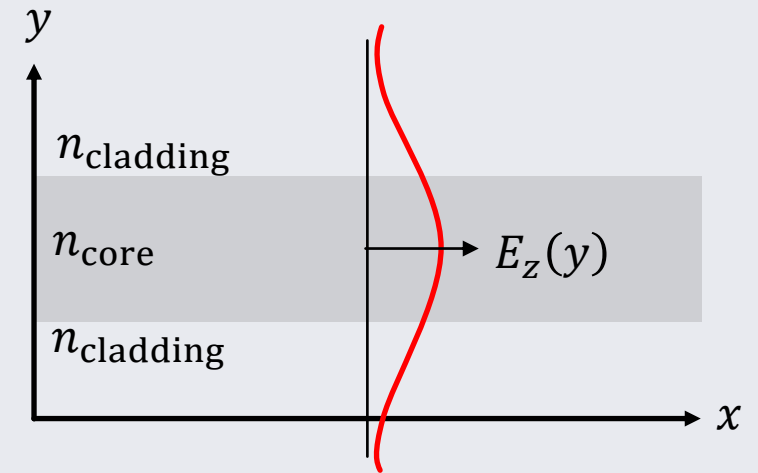
Wave only in the core
 $n_{\text{eff}} = n_{\text{core}}$

Strongly confined



Wave mostly in the core
 $n_{\text{eff}} \approx n_{\text{core}}$

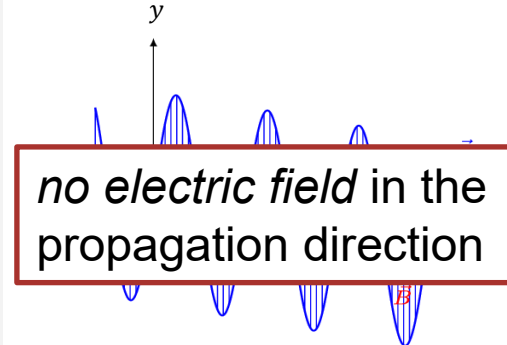
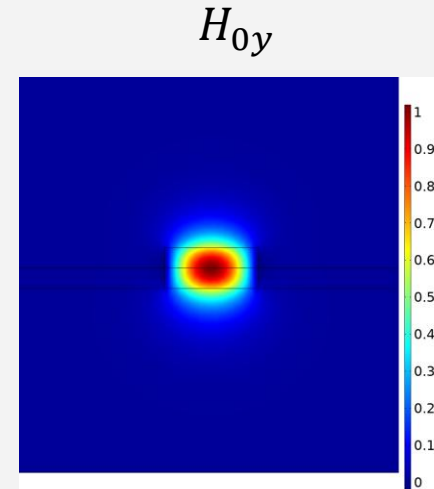
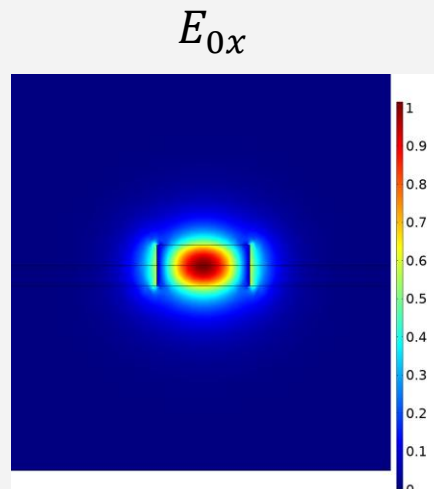
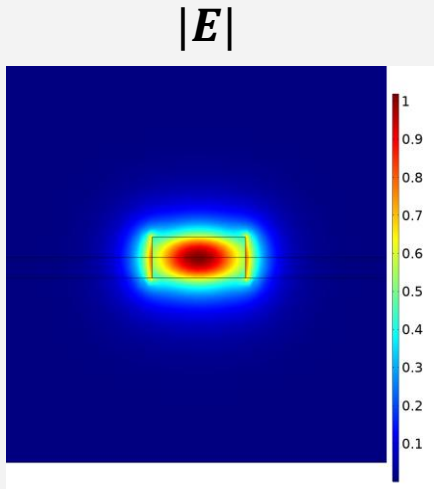
Weakly confined



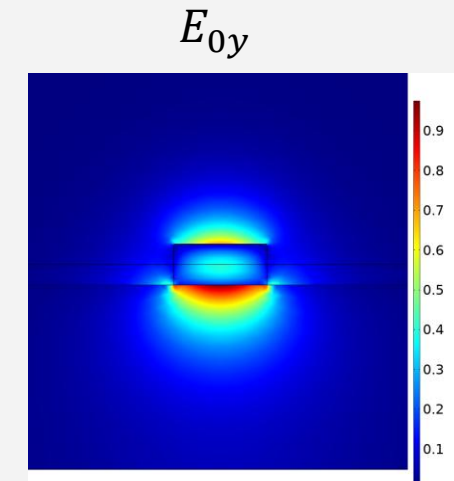
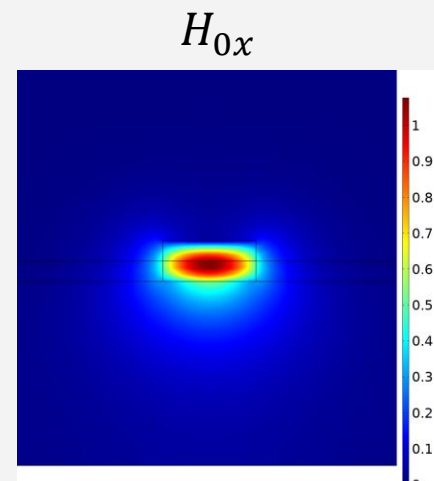
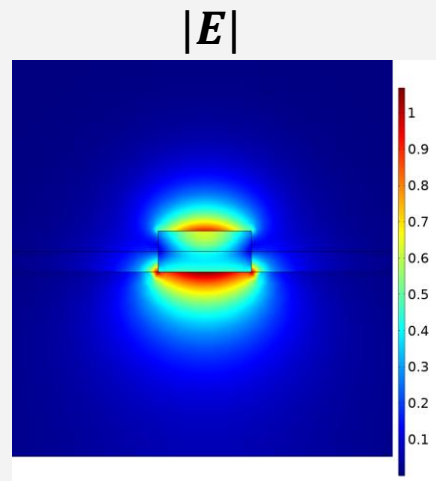
Wave leaks into cladding
 $n_{\text{eff}} \approx n_{\text{cladding}}$

Mode in a Waveguide

TE Mode



no magnetic field in the propagation direction

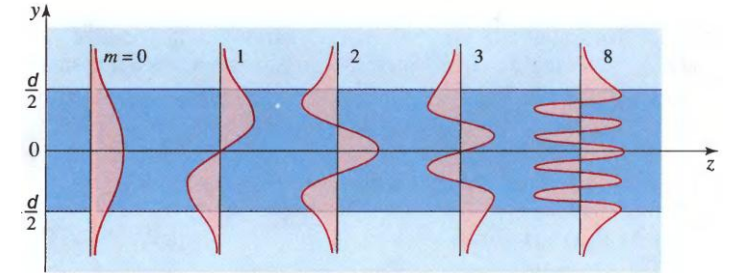


TM Mode

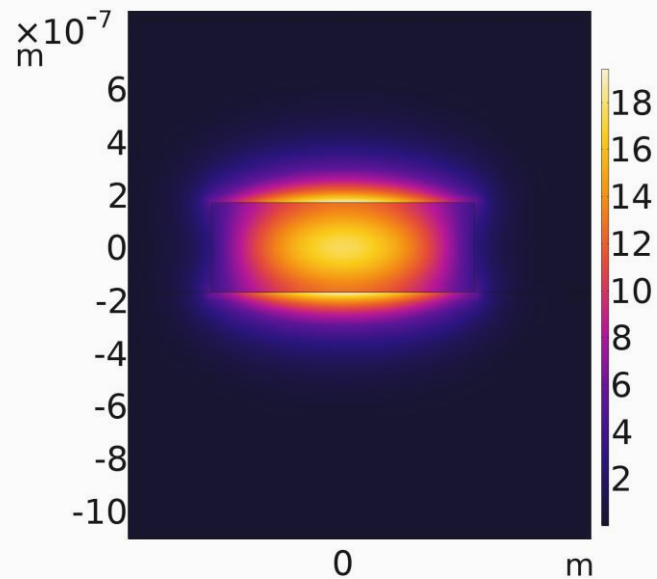
Multimoded Waveguide

$$\frac{\partial^2 E_{0x}}{\partial y^2} + E_{0x}(\epsilon_r k_0^2 - \beta_m^2) = 0 \text{ with } \beta_m = k_0 n \cos(\theta_m) = k_0 n_{eff}$$

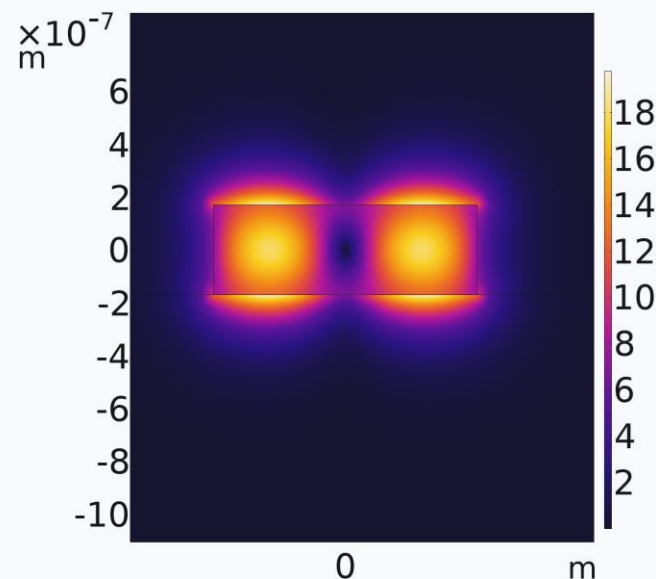
There exist discrete number of modes



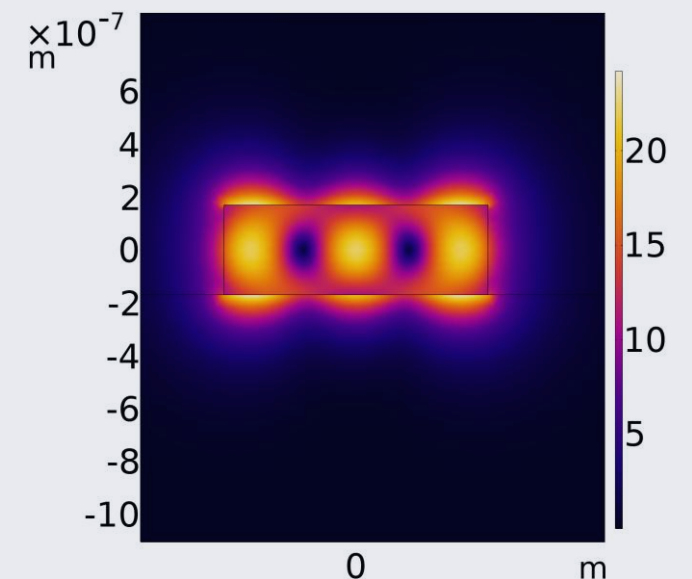
TM Fundamental



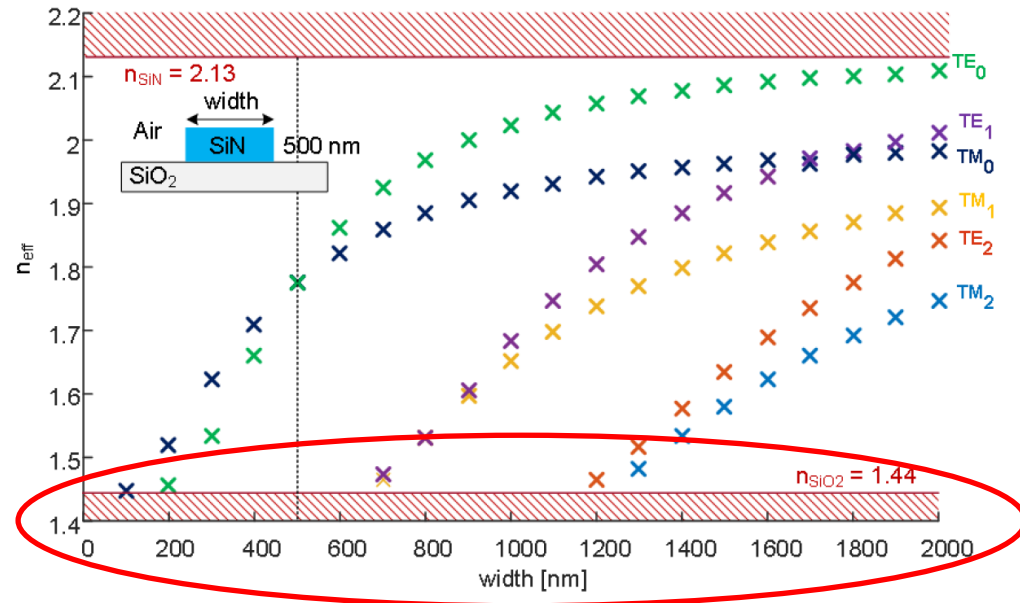
TM 1st Order Mode



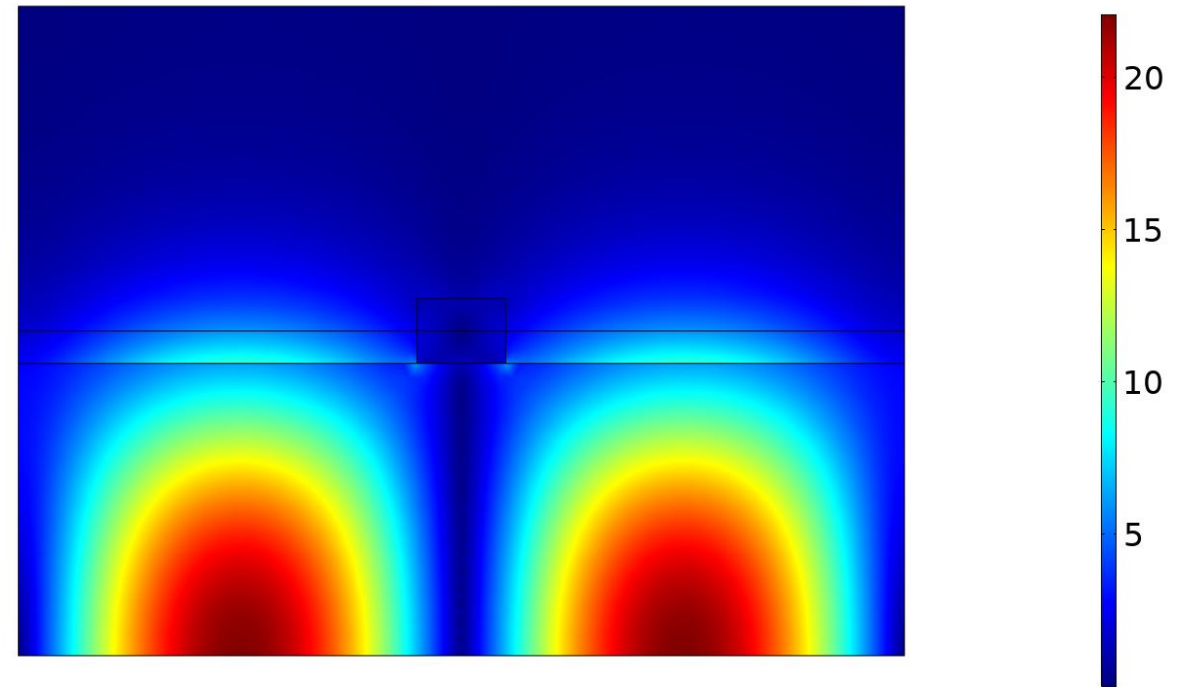
TM 2nd Order Mode



Multimoded Waveguiding



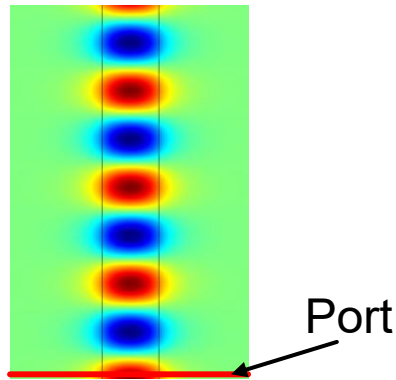
No guided mode exists for $n_{\text{eff}} < n_{\text{sub}}$



Waveguiding in COMSOL

- Propagation
 - *In-plane*: Ports need to be defined (eigenvalue solution to the defined port)

Last week



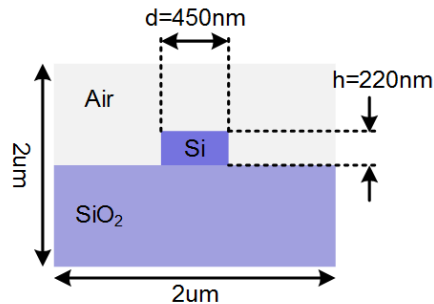
In-plane

Excitation
from boundary

Electromagnetics
node: TE or TM

- *Out-of-plane*: Ports are not defined (eigenvalue solution to the whole geometry)

Today



Out-of-plane

Excitation
from surface
plane

Electromagnetics
node: NO PORT



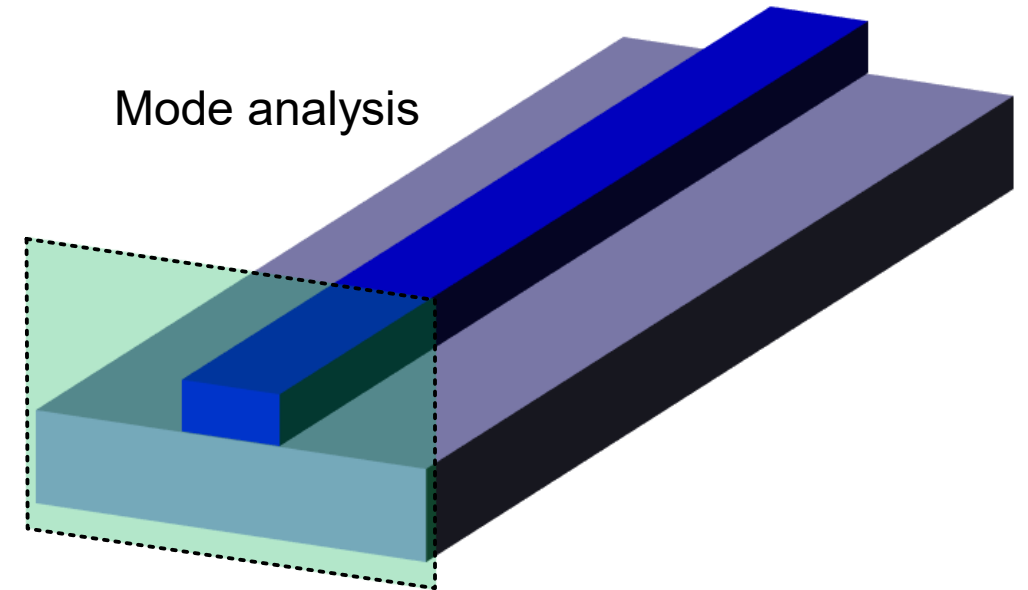


P&S COMSOL® Design: Simulations of Optical Components Tutorial 5: Optical Waveguide II

Taichiro Fukui, Maximilian Bosch

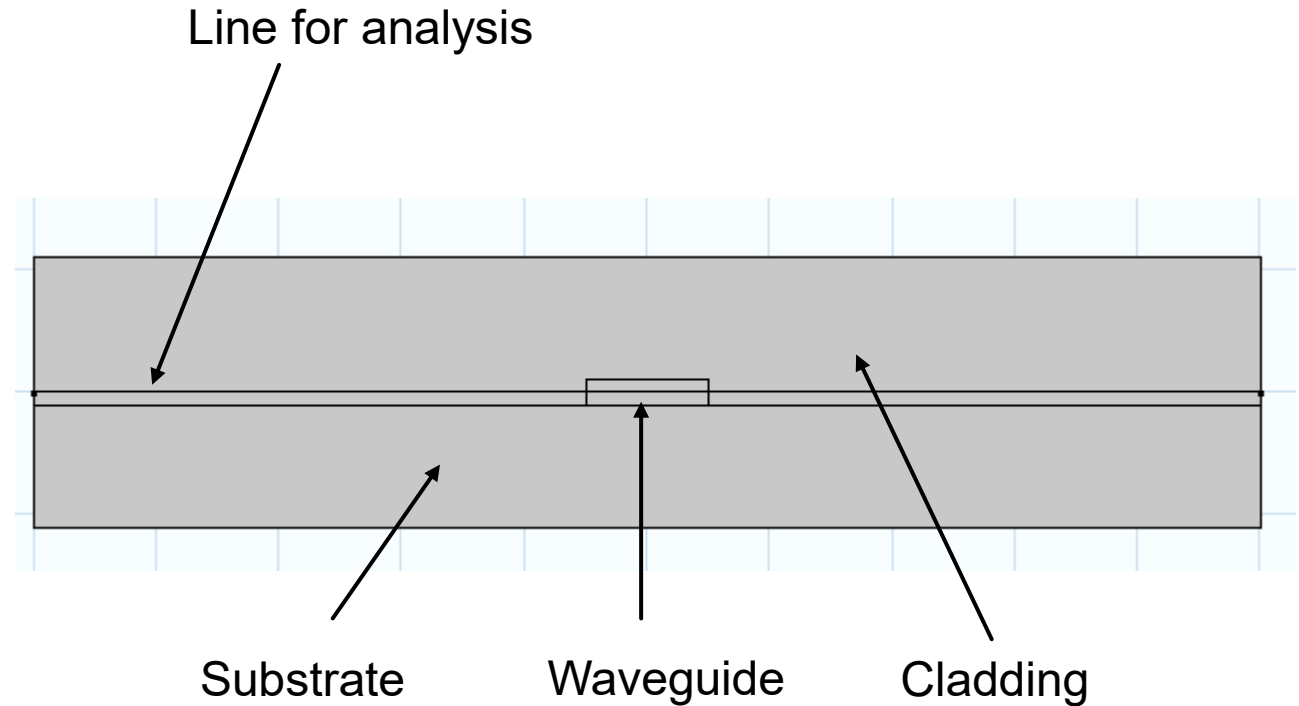
Waveguiding in COMSOL

- Goal of todays tutorial
- Simulate modes in waveguide cross section
- Analyse geometric influence on modes
- Get an understanding of effective refractive index



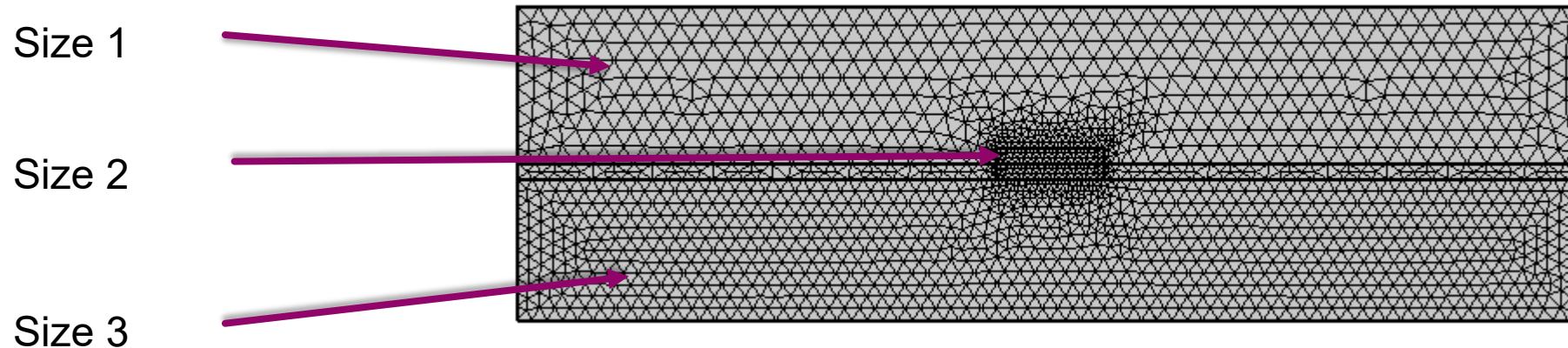
Design Geometry

Parameter	Value
f0	c_{cons}/w_l
n_clad	1
n_core	3.47
n_sub	1.45
sim_height	$10 \cdot w_g_{\text{height}}$
sim_width	$10 \cdot w_g_{\text{width}}$
wg_height	220[nm]
wg_width	750[nm]
wl	1550[nm]
mesh_size	??



Define Materials & Mesh

- Materials
 - Define materials using the refractive index in the parameter definition
 - Hint: Change Wave Equation, electric Displacement Field to : Refractive Index
- Mesh
 - Define a mesh size for each material (3 sizes total)
 - Make the mesh size dependent on the wavelength and refractive index ($l/n_{\text{core}}/10$)



Study

- Study needed for this tutorial
 - Mode analysis
 - Define frequency
 - Desired number of modes: 4
 - Search for modes around shift : ??? (Hint: For which effective refractive index is the mode confined)
- Parameter Sweep for geometrical analysis

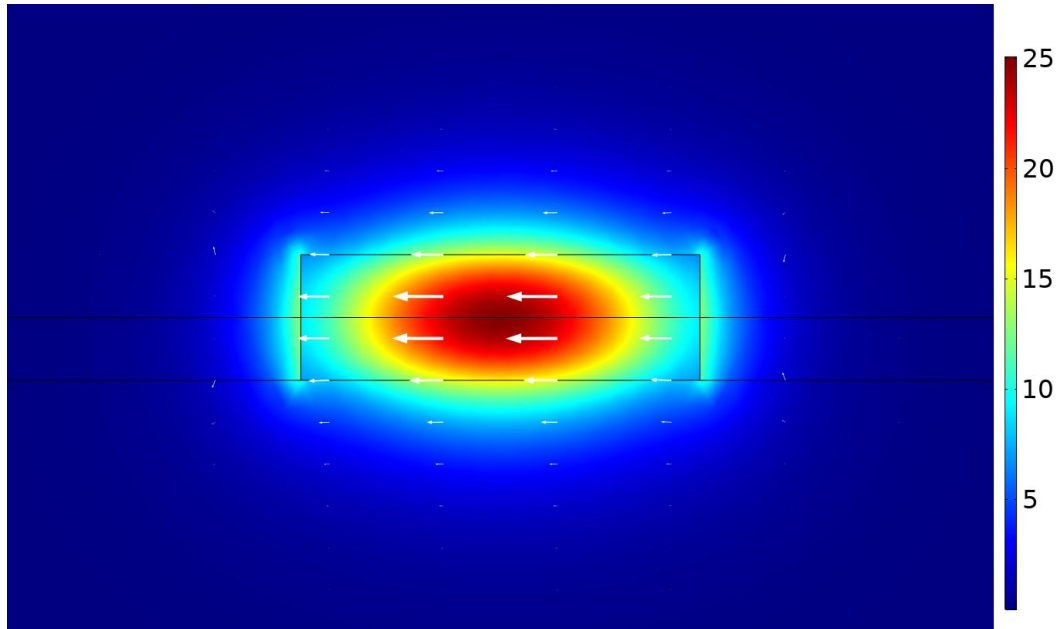
What should be Analysed ?

1) Get a feeling for structure:

- Vary waveguide geometry and analyse modes
 - Analyse E & H Fields (2 D plots)
- Understand correlation confinement of wave and effective mode index

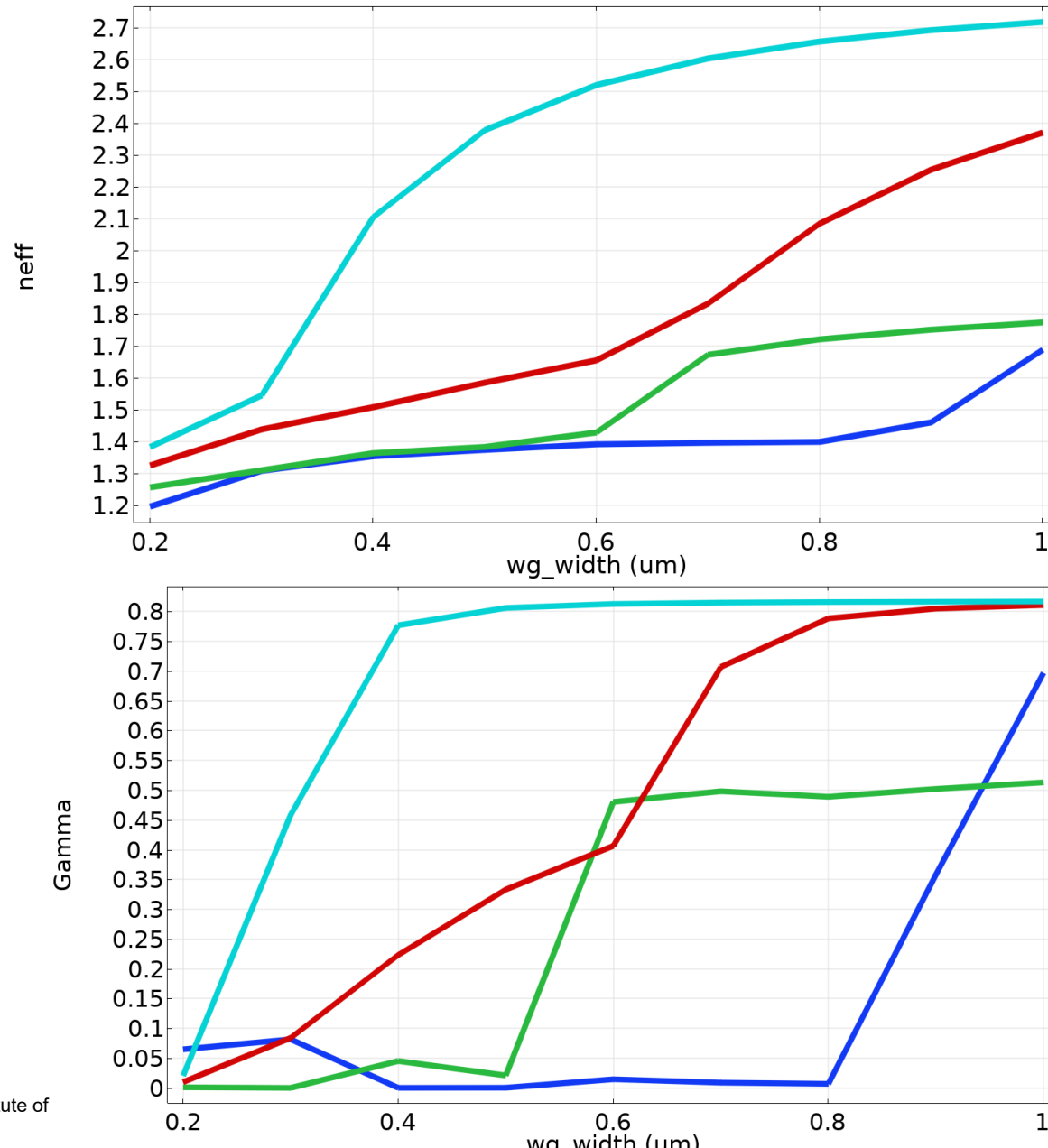
2) Plot Fields along line through waveguide

- 1D plot → Line Graph
- Select line along which should be plotted



- To which mode does it correspond? TE or TM?
- How would the field look like in the x and y direction?
- Why are there discontinuities at the edges?

- 3) Analyse effective mode index dependency of wg_width
 - Derive values from Simulation
 - Derived Values → Global Evaluation 1 →
Select correct Dataset
Table columns: Inner solutions
Expression: select the effective mode index
 - Evaluate will create a table with the solutions
 - Create plot wg_width vs effective mode index
 - 1D plot → Table Graph → Select correct table



- Which mode is associated to which curve?
- Is every mode confined in the waveguide? If not where is the threshold?
- Can you adjust the confinement factor with another parameter or property than the waveguide's width?