ETH zürich

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

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Content

- Revision on waveguiding theory
  - Confinement
  - TE and TM modes

- COMSOL
  - Silicon ridge waveguide
  - Glass fiber

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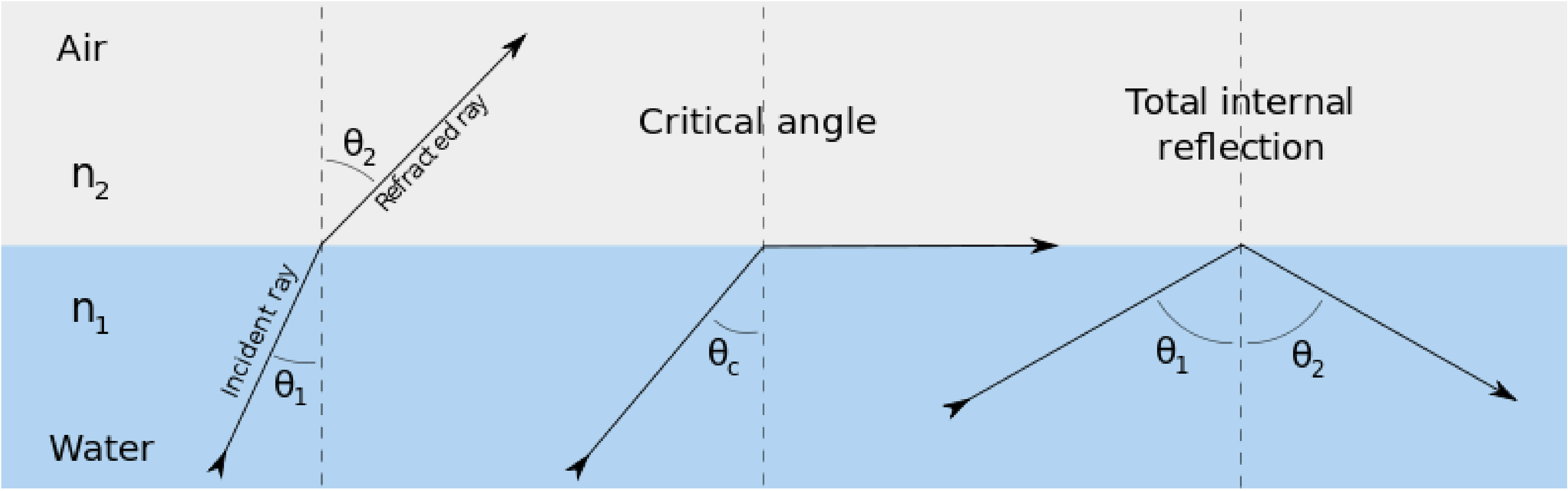
Snell's Law and total internal reflection

- 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

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

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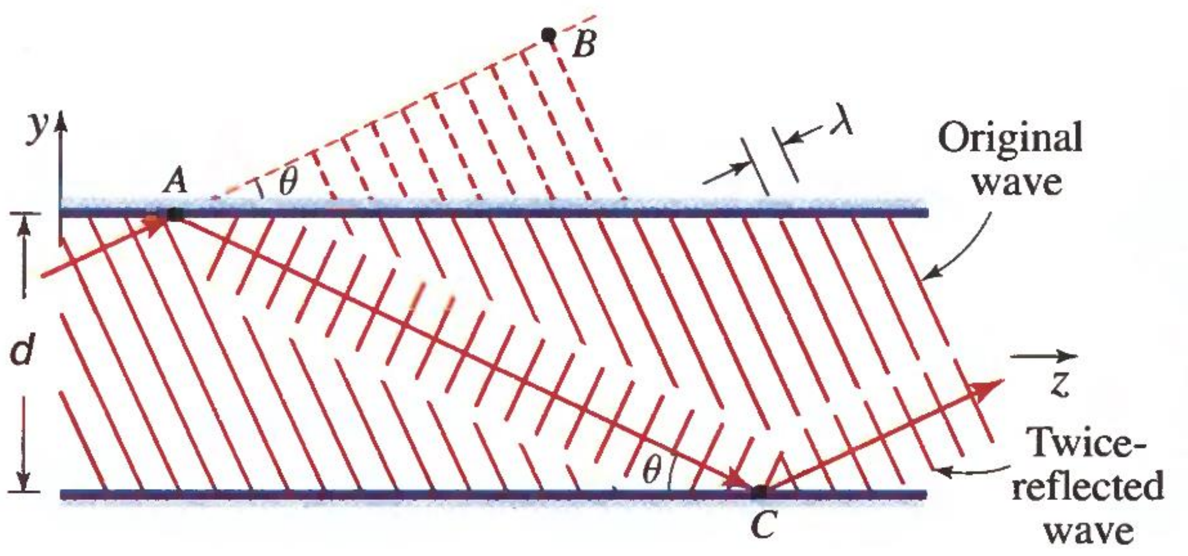
Waveguiding: Theory

- 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
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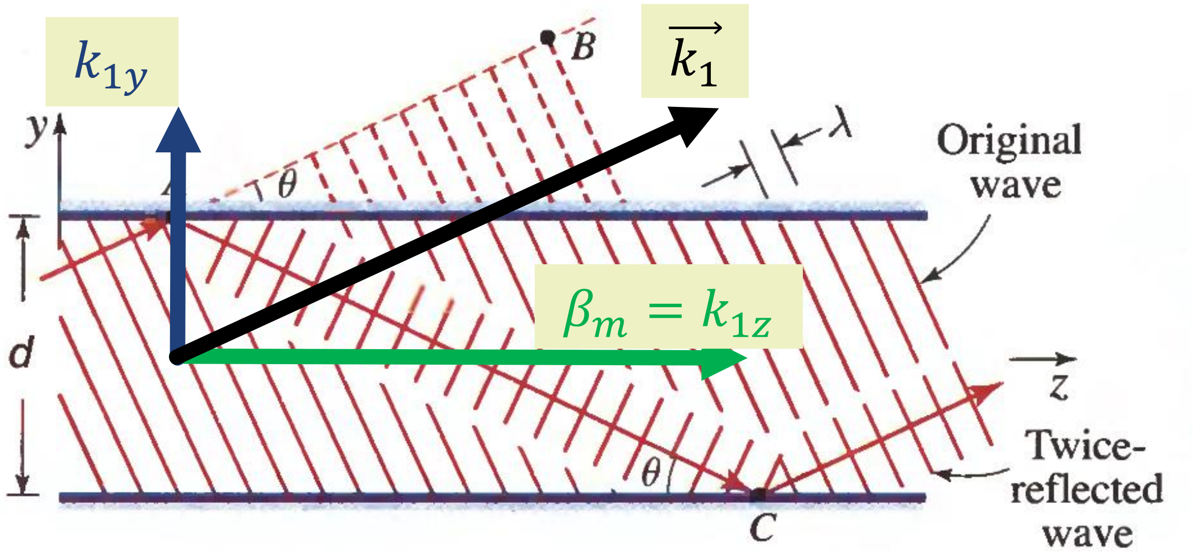


$$k_{1y} = k_1 \sin\theta_m$$
$$k_{1z} = k_1 \cos\theta_m$$
$$\sin(\theta_m) = \frac{\lambda m}{2dn}$$

Propagation constant

Effective refractive index

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

Mode in a Waveguide

Maxwell Equations

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

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

With $\boldsymbol{E} = \boldsymbol{E_0}(x, y)e^{j(\omega t - \beta z)}$ and $\boldsymbol{H} = \boldsymbol{H}_0(x, y)e^{j(\omega t - \beta z)}$

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

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

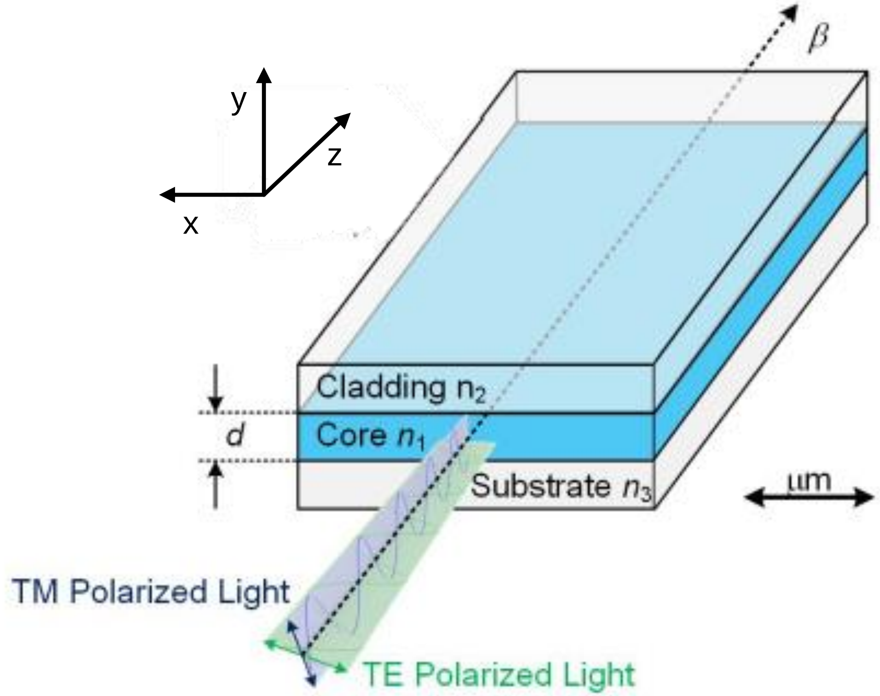
$$H_{0z} = \frac{1}{j\omega\mu_0}\frac{\partial E_{0x}}{\partial y}$$

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

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

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

6 equations, 6 unknown



Mode in a Waveguide

Hemlholtz equations

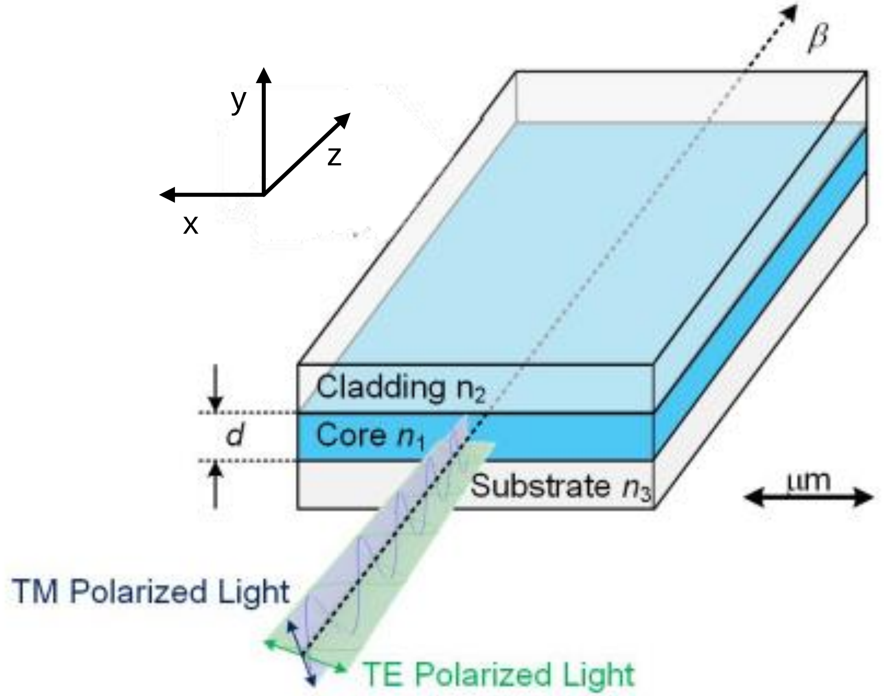
2 sets of equations, **TE and TM**

TE: no E field in the propagation direction

$$E_{0z} = E_{0y} = H_{0x} = 0$$
$$H_{0y} = \frac{\beta}{\omega\mu_0} E_{0x}$$
$$H_{0z} = \frac{1}{j\omega\mu_0}\frac{\partial E_{0x}}{\partial y}$$
$$E_{0x} = -\frac{1}{j\omega\mu_0}\left(\frac{\partial E_{0z}}{\partial z} + j\beta E_{0y}\right)$$
…
$$\frac{\partial^2 E_{0x}}{\partial y^2} + E_{0x}(\varepsilon_r k_0^2 - \beta^2) = 0$$

TM: no H field in the propagation direction

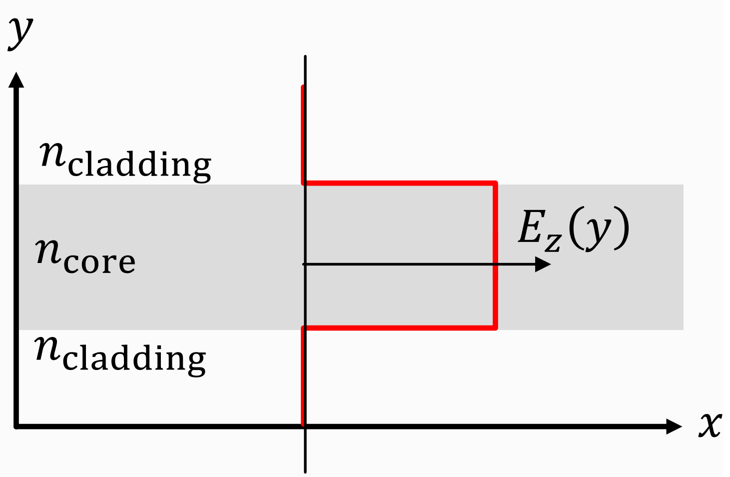
$$H_{0z} = H_{0y} = E_{0x} = 0$$
$$H_{0x} = -\frac{1}{j\omega\mu_0}\left(\frac{\partial E_{0z}}{\partial y} + j\beta E_{0y}\right)$$
$$E_{0y} = -\frac{\beta}{\omega\varepsilon_0\varepsilon_r} H_{0x}$$
$$E_{0z} = -\frac{1}{j\omega\varepsilon_0\varepsilon_r}\frac{\partial H_{0x}}{\partial y}$$
…
$$\frac{\partial^2 H_{0x}}{\partial y^2} + H_{0x}(\varepsilon_r k_0^2 - \beta^2) = 0$$



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

Waveguiding: Theory

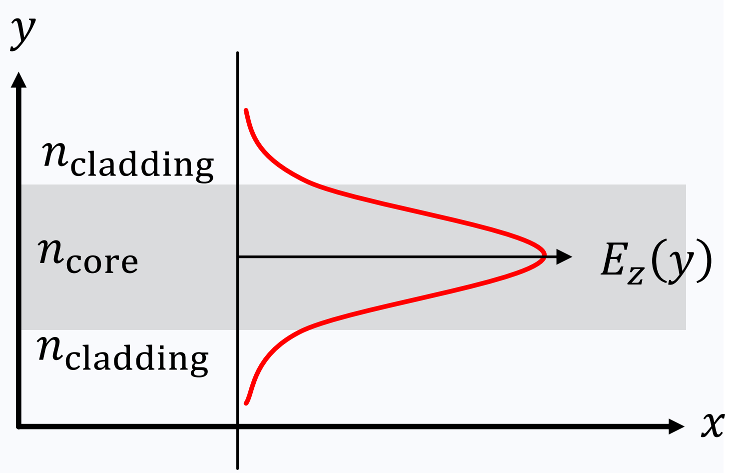
Completely confined



Wave only in the core

$n_{\text{eff}} = n_{\text{core}}$

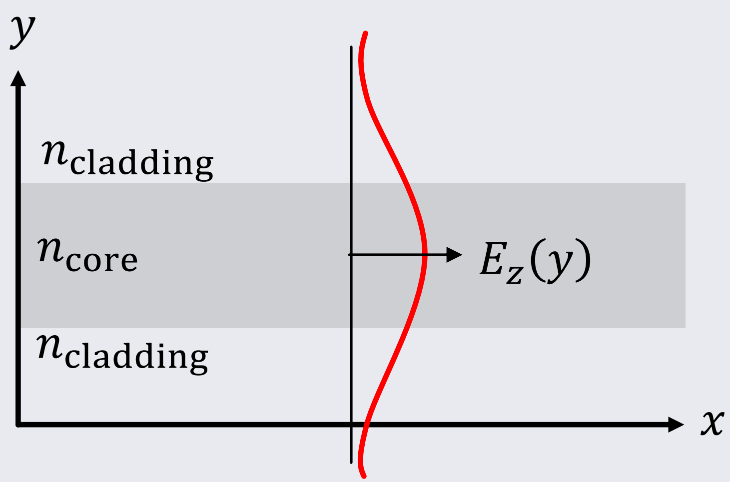
Strongly confined



Wave mostly in the core

$n_{\text{eff}} \approx n_{\text{core}}$

Weakly confined



Wave leaks into cladding

$n_{\text{eff}} \approx n_{\text{cladding}}$

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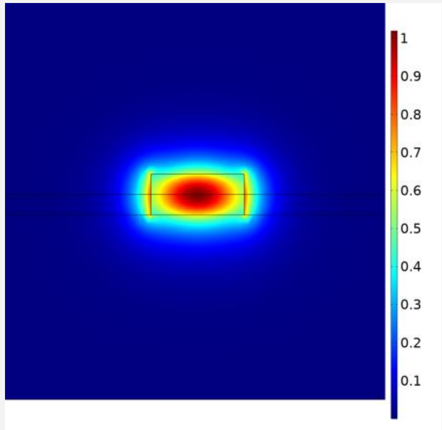
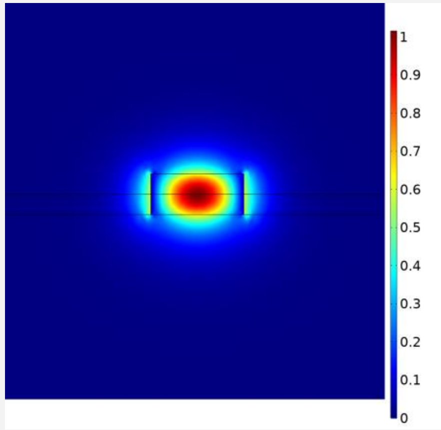
Mode in a Waveguide

TE Mode

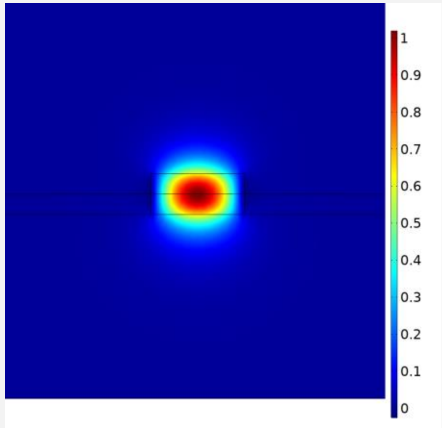
$|\boldsymbol{E}|$

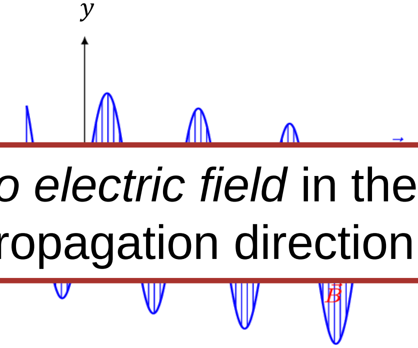


E_{0x}



H_{0y}

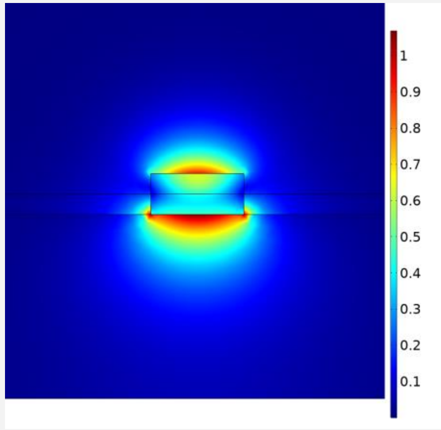




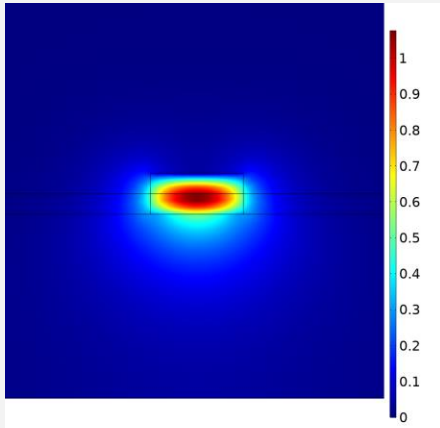
no electric field in the propagation direction

no magnetic field in the propagation direction

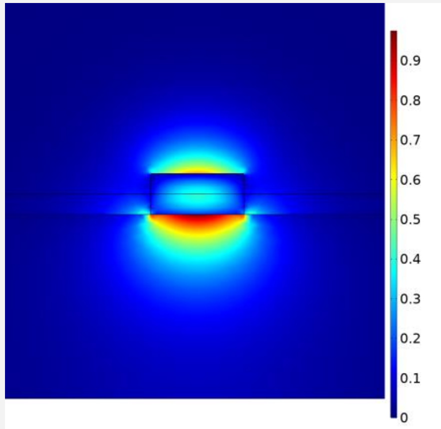
$|\boldsymbol{E}|$



H_{0x}



E_{0y}

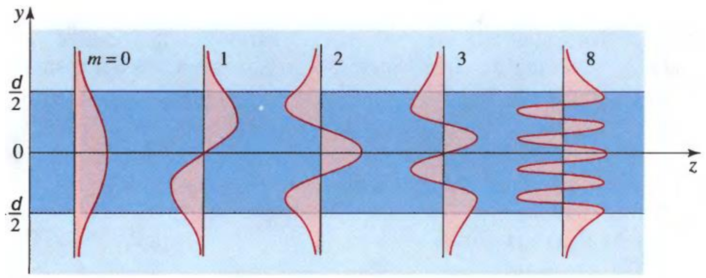


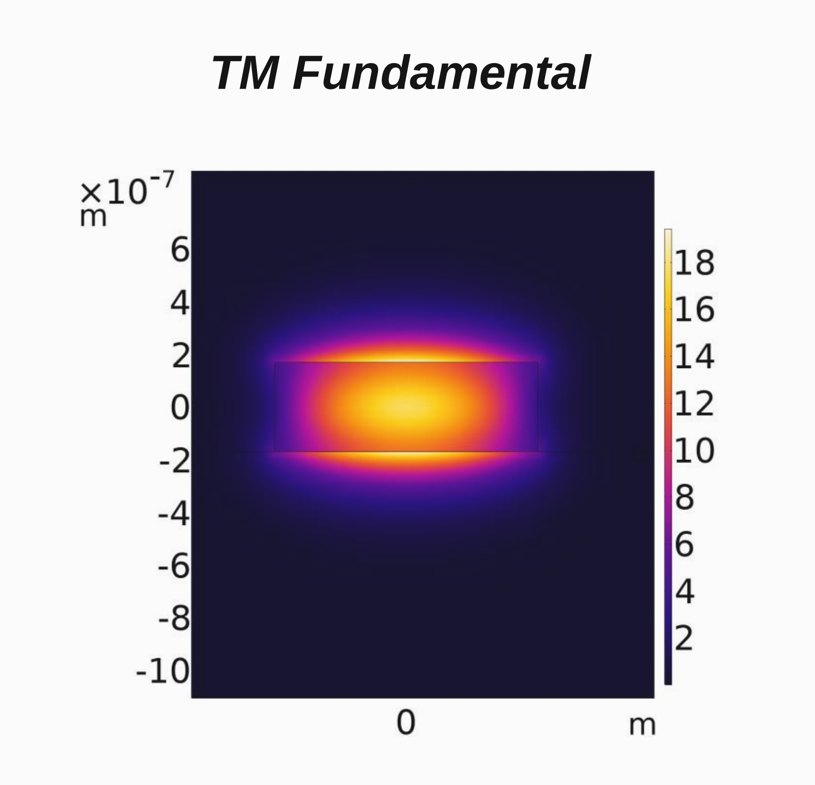
TM Mode

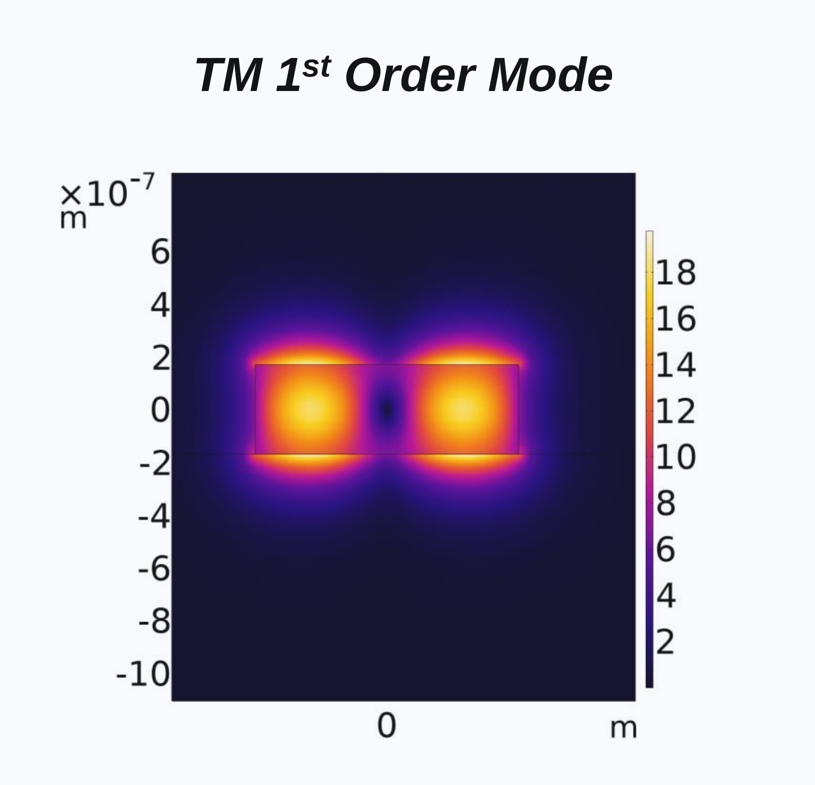
Multimoded Waveguide

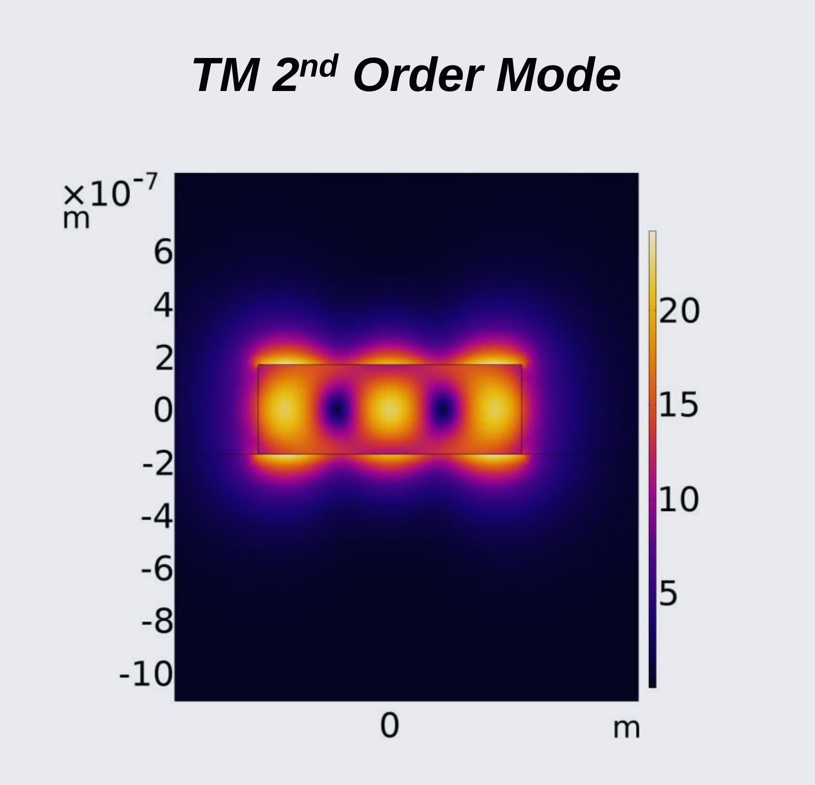
$$\frac{\partial^2 E_{0x}}{\partial y^2} + E_{0x}(\varepsilon_r k_0^2 - \beta_m^2) = 0 \text{ with } \beta_m = k_0 n \cos(\theta_m) = k_0 n_{eff}$$

There exist discrete number of modes









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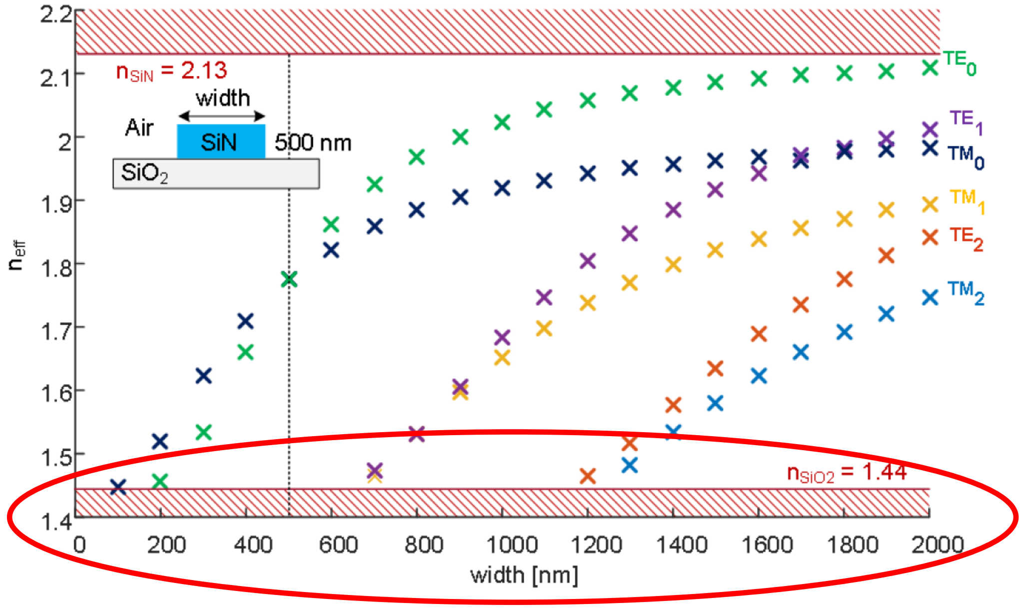
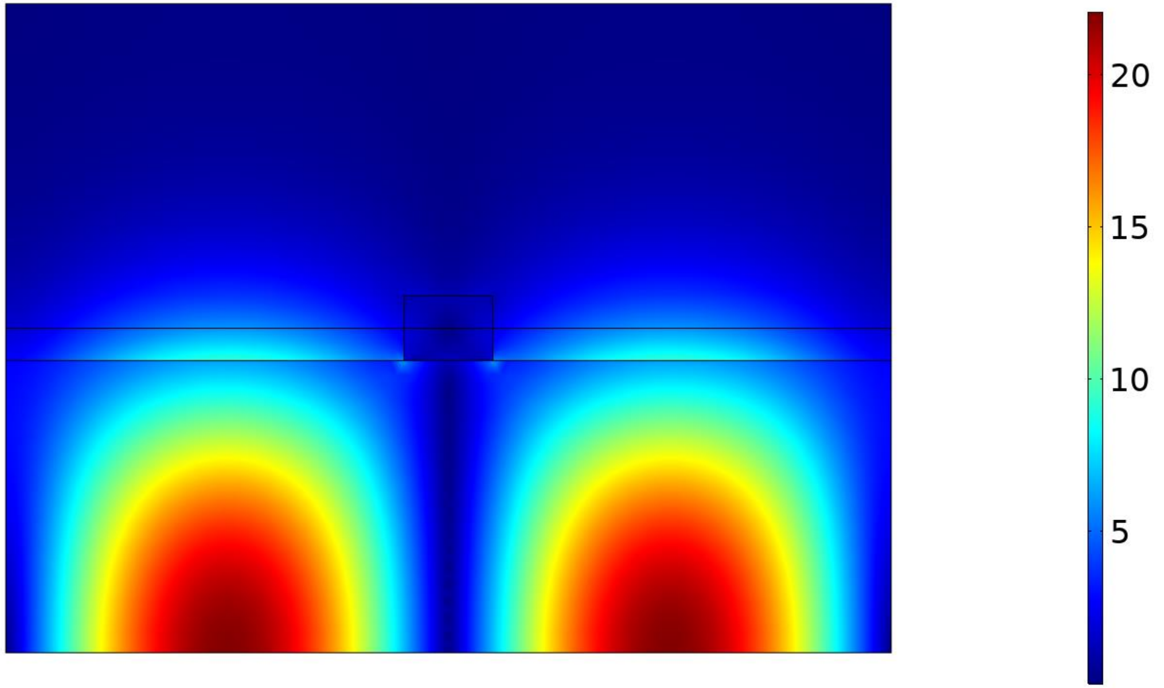
Multimoded Waveguiding



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



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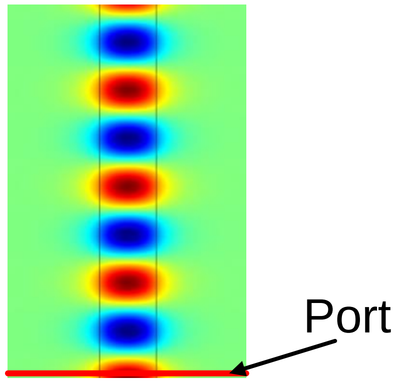
Waveguiding in COMSOL

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

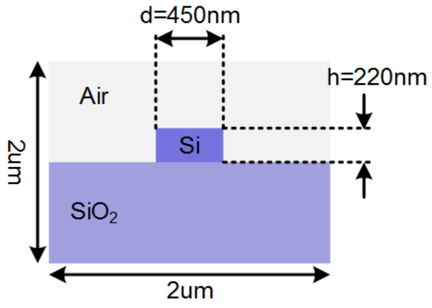
Last week



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*

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

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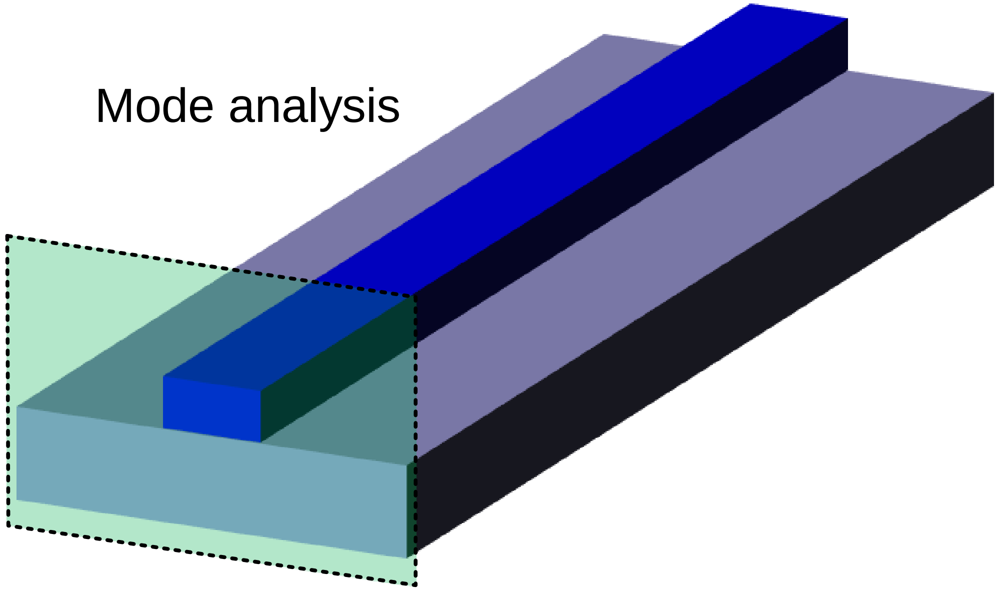
Waveguiding in COMSOL

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



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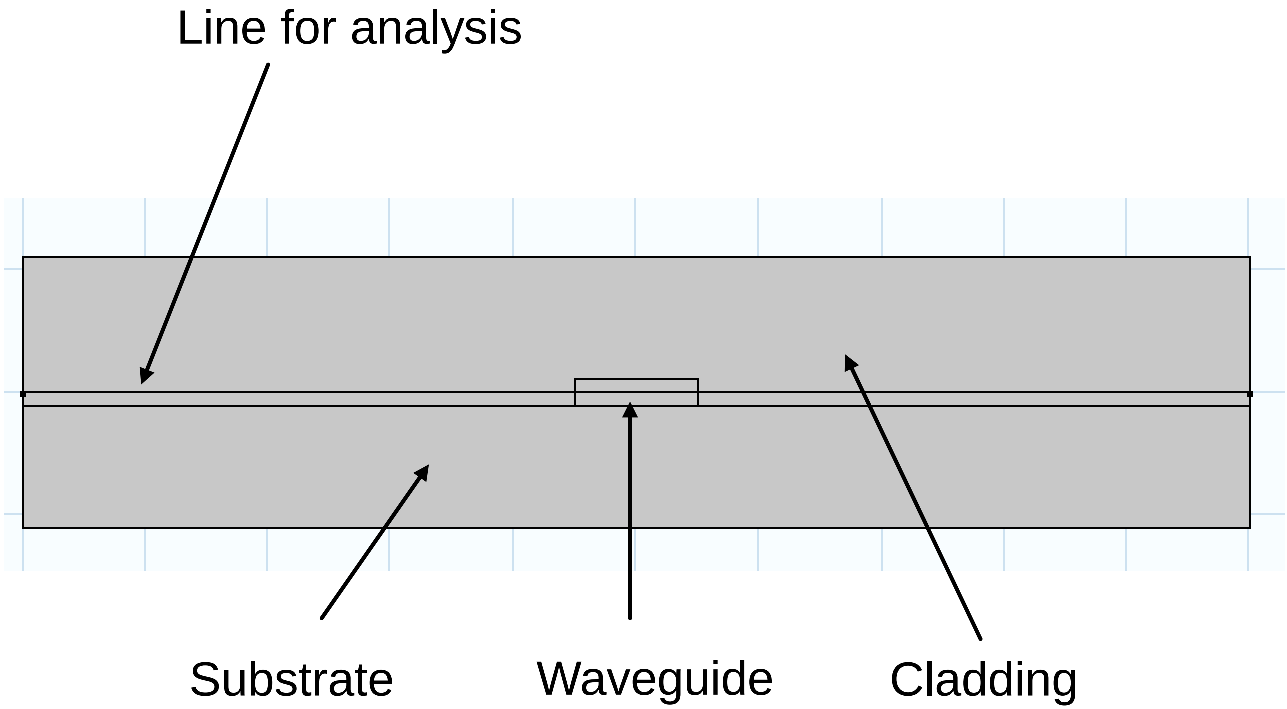
Design Geometry

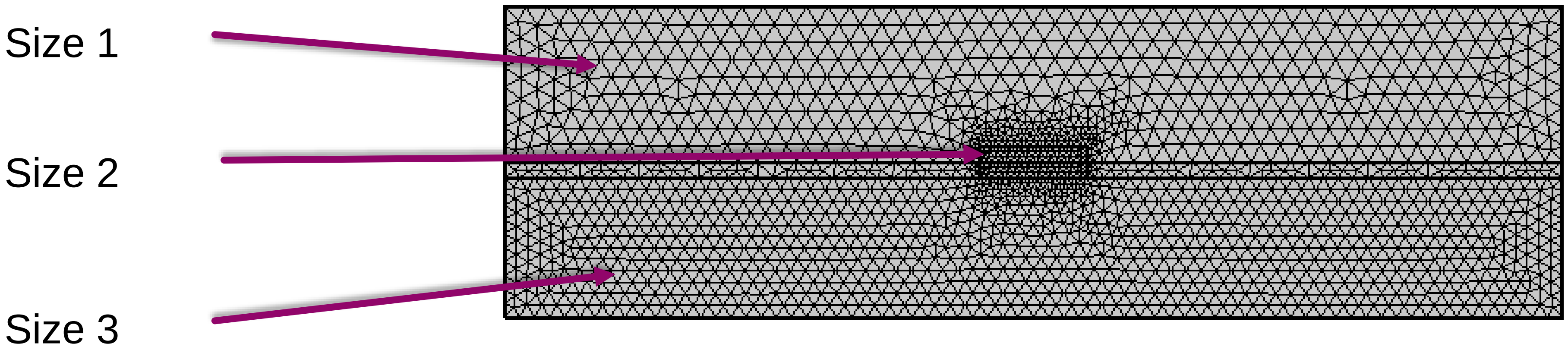
Parameter	Value
f0	c_cons/wl
n_clad	1
n_core	3.47
n_sub	1.45
sim_height	10*wg_height
sim_width	10*wg_width
wg_height	220[nm]
wg_width	750[nm]
wl	1550[nm]
mesh_size	??



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 core/10)



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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

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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

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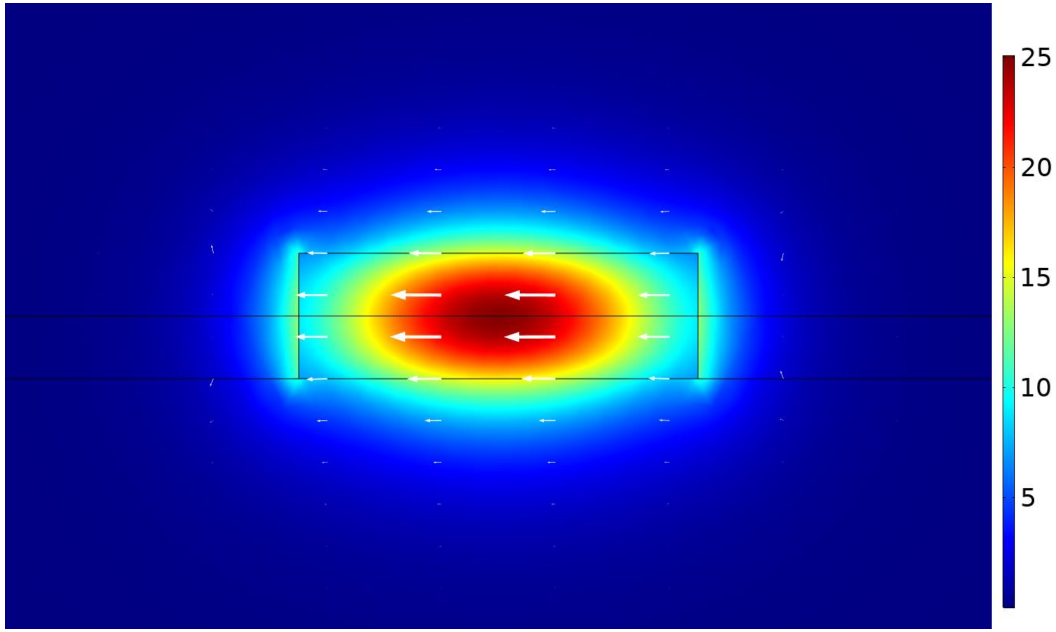

- To which mode does it correspond? TE or TM?
- How would the field look like in the x and y direction?
- Why are there discontinuities at the edges?

- 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

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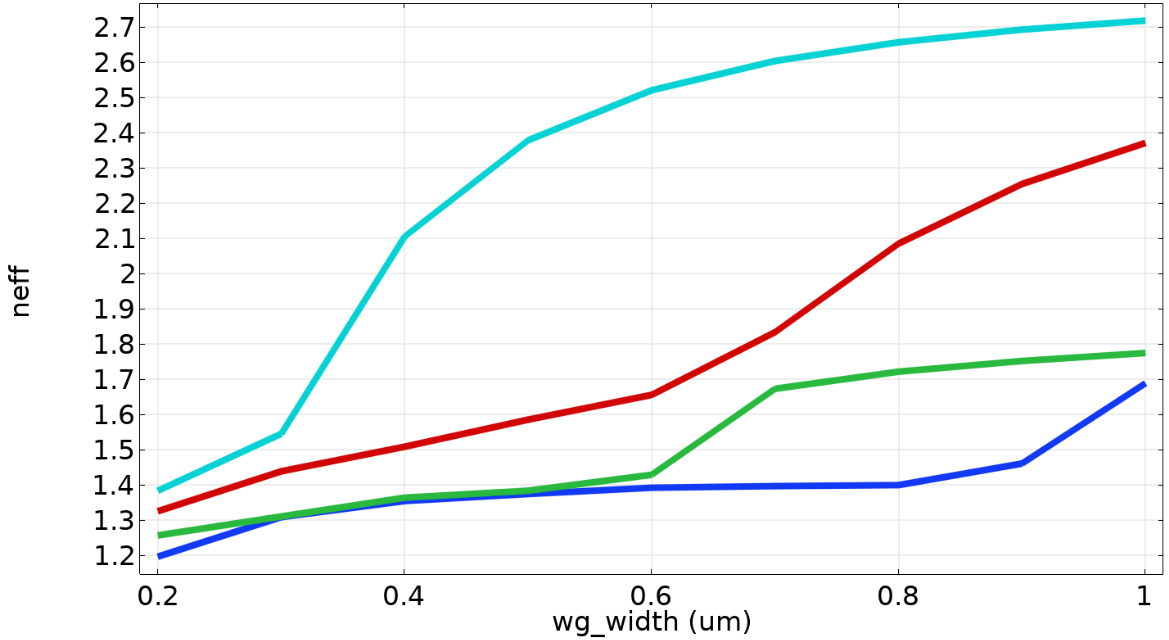

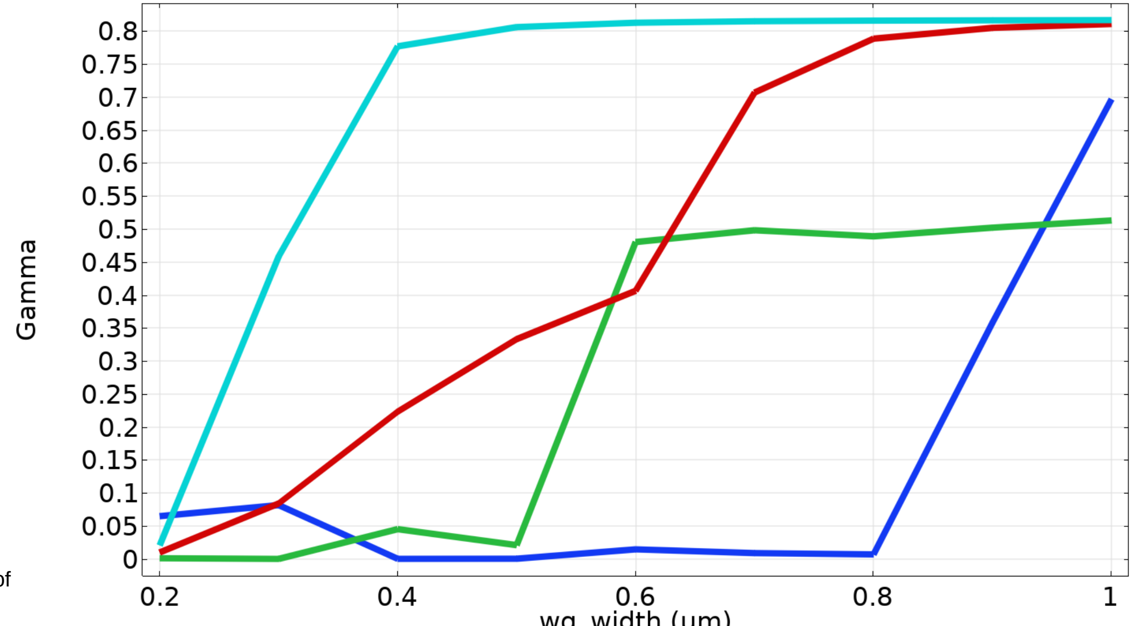

- Which mode is associated to which curve?
- Is every mode confined in the waveguide? If not where is the threshold?
- Can you adjust the confinement factor with another parameter or property than the waveguide's width?