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

Manuel Kohli, Raphael Schwanninger, Tobias Blatter & Shadi Nashashibi

Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Content

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

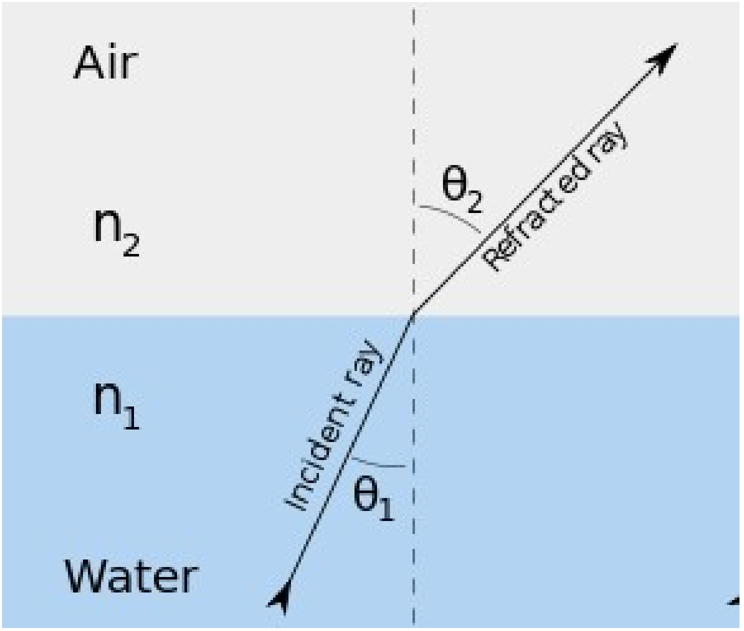
- COMSOL
  - Silicon ridge waveguide
  - Glass fiber

Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Snell's Law

Snell's law

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



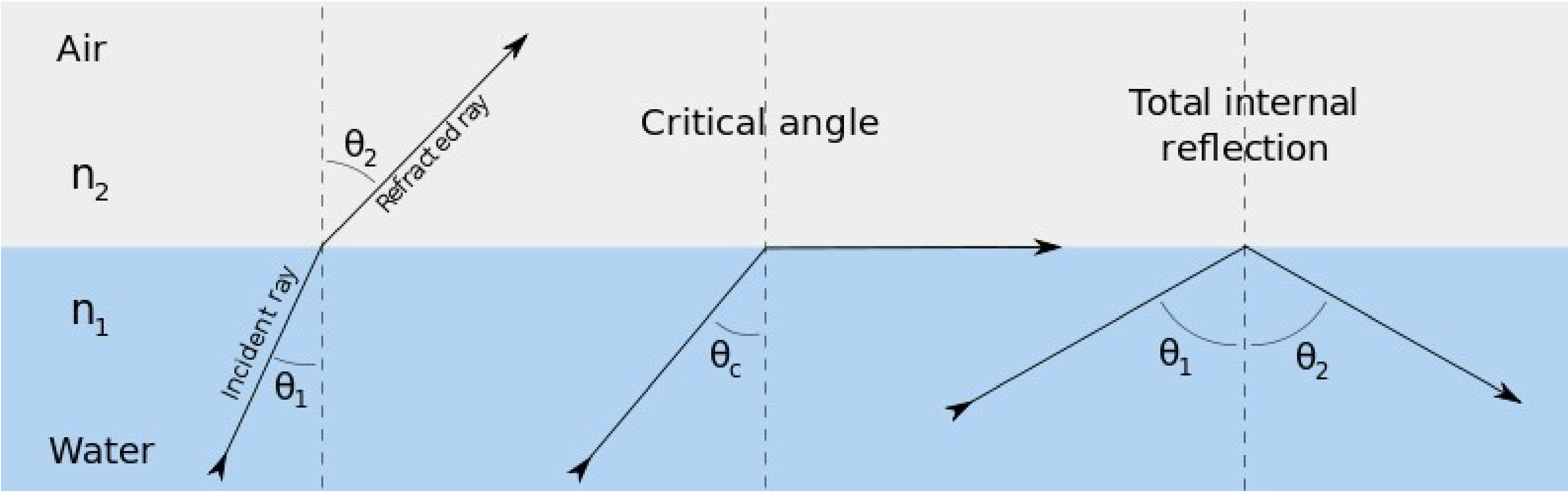
Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Snell's Law

- What happens at the boundary between two materials?

Snell's law

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

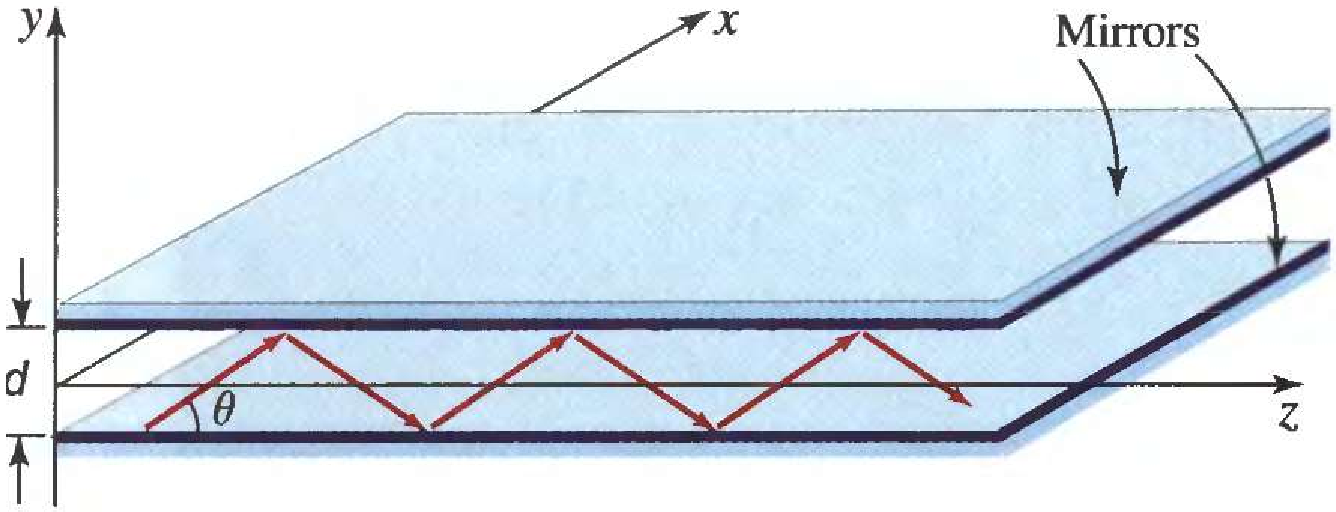


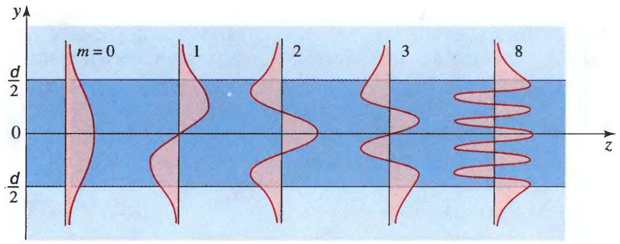
- What if $\sin\theta_2 \geq 1$?
  - There is critical angle $\theta_c = \arcsin n_2/n_1$
    - $n_1 > n_2$
    - Light prefers to stay in higher index material!
    - Almost everything is reflected → **total internal reflection!**

Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Waveguiding: Theory

- EM field in between two perfect metallic mirrors
  - After each reflection, there is π phase shift

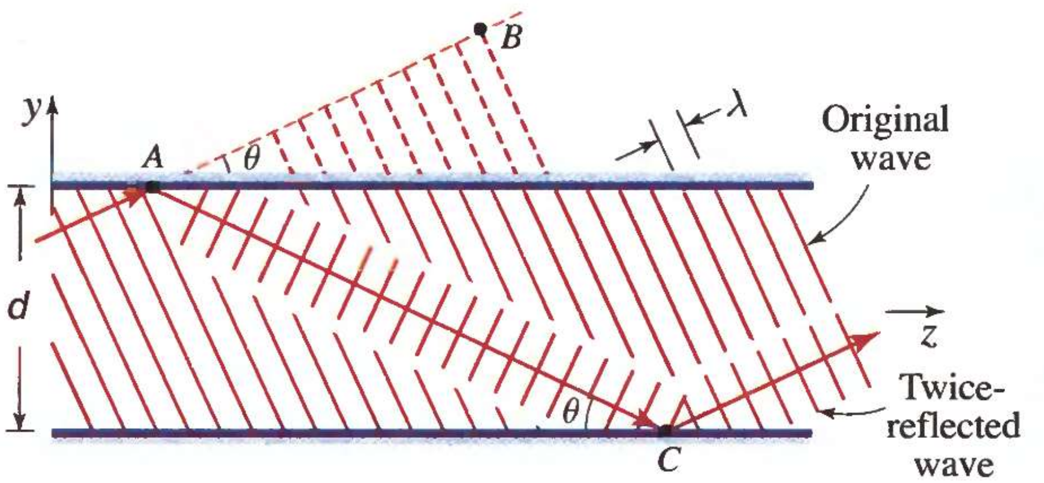




Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Waveguiding: Theory

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



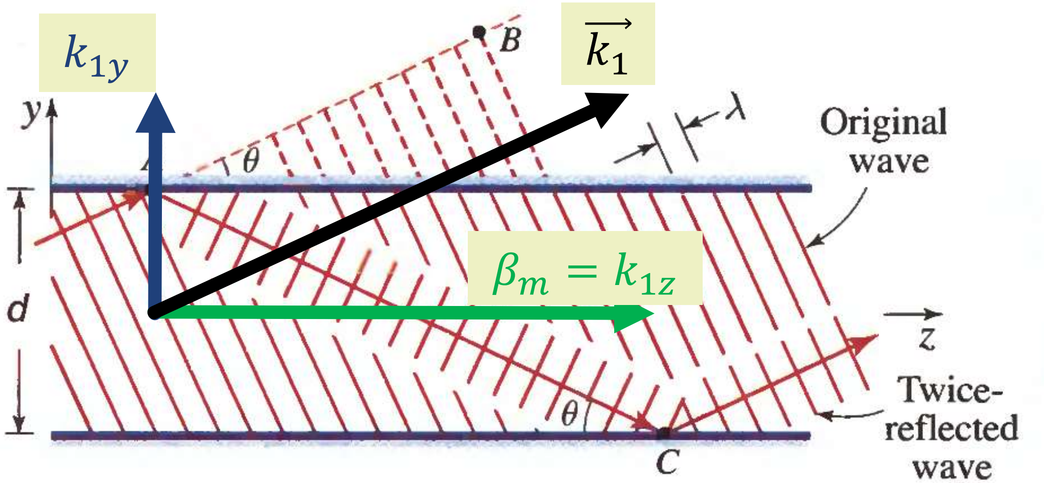
Definition: EM fields which satisfy this condition, we call (eigen)modes!

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

Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Waveguiding: Theory

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



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

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

with $k_1 = k_0 * n_1$

Propagation constant

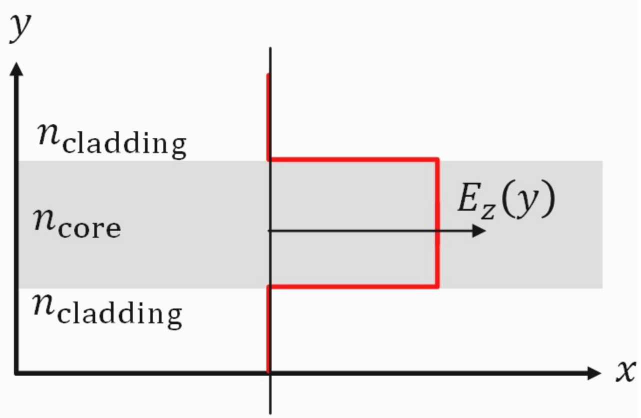
Effective refractive index

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

Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

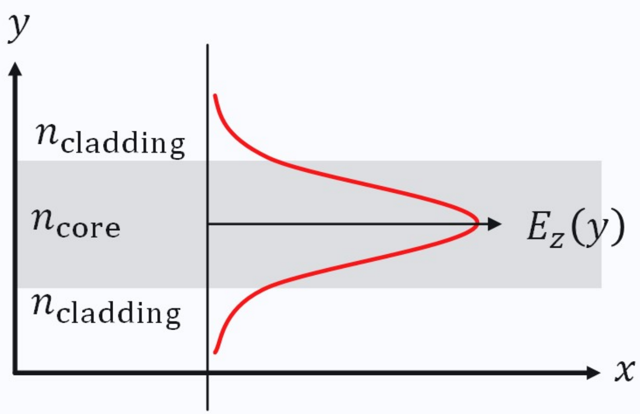
Waveguiding: Theory

Completely confined



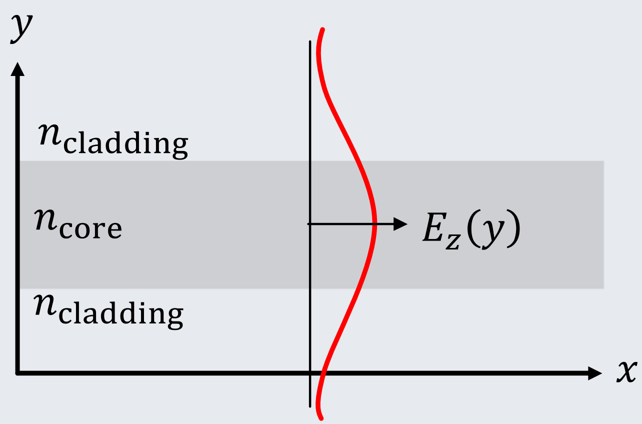
Wave only in the core
$n_{\text{eff}} = n_{\text{core}}$

Strongly confined



Wave mostly in the core
n_{eff} close to n_{core}

Weakly confined

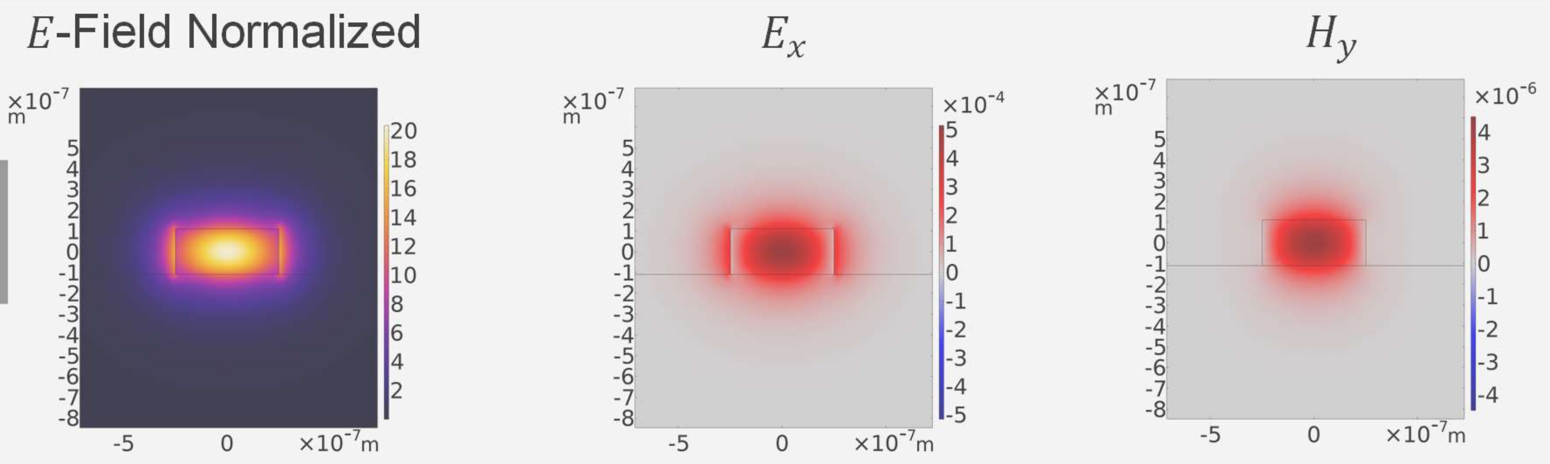


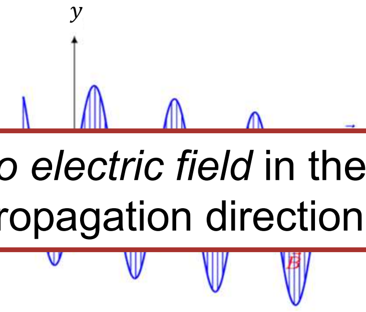
Wave leaks into cladding
n_{eff} close to n_{cladding}

Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Mode in a Waveguide

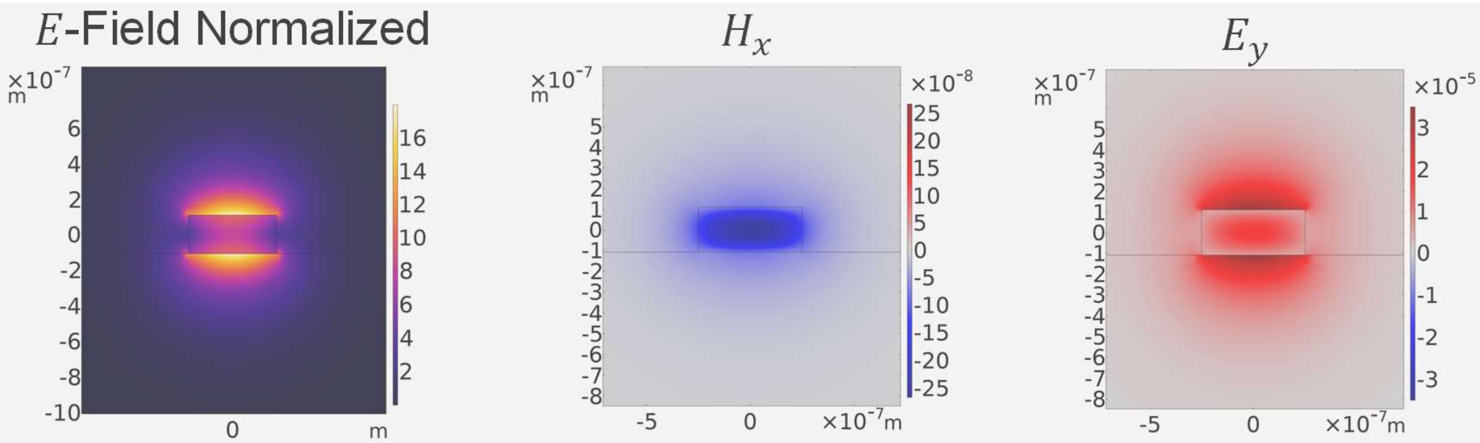
TE Mode





no electric field in the propagation direction

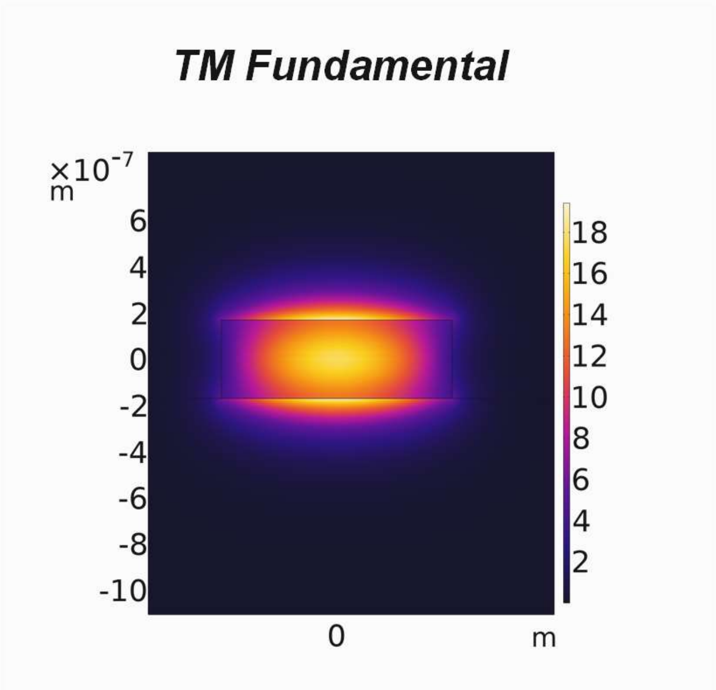
no magnetic field in the propagation direction

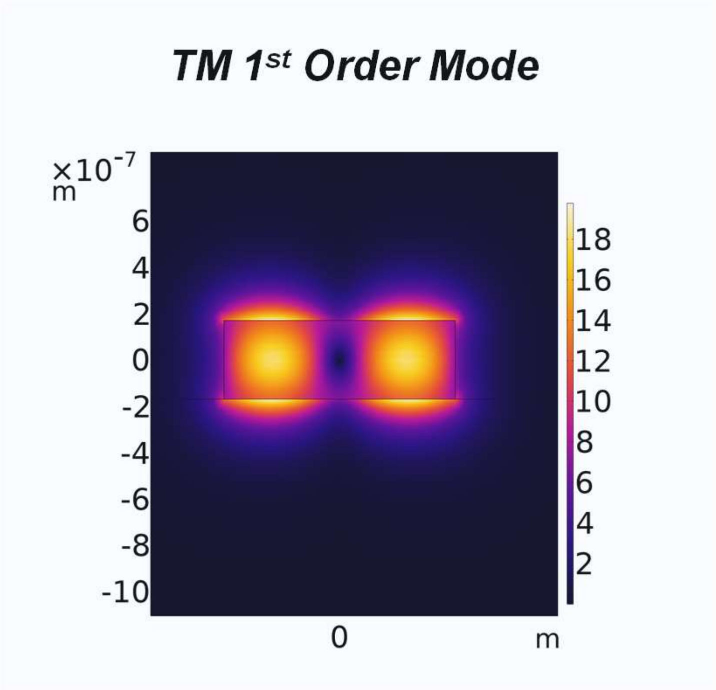


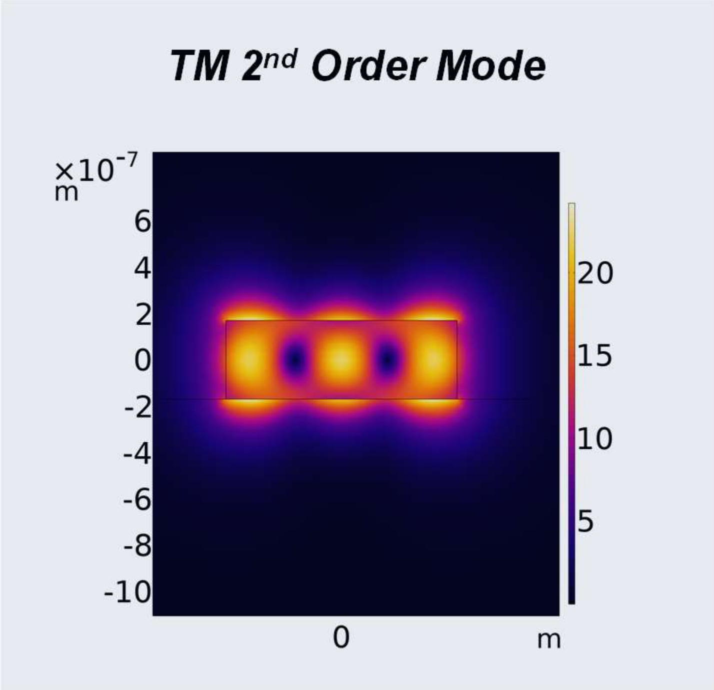
TM Mode

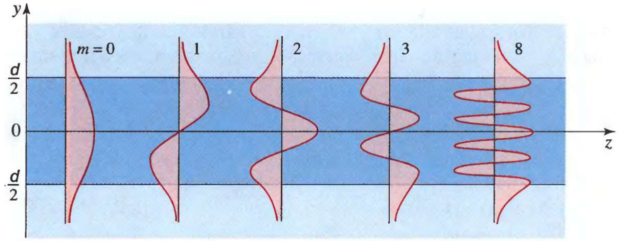
Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Multimoded Waveguide







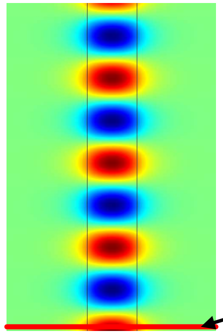


Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Waveguiding in COMSOL

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

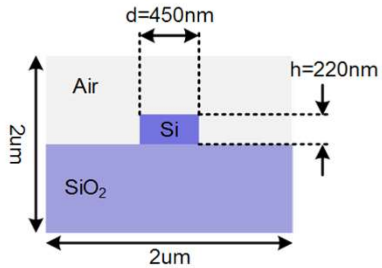
Last week



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*

Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Tobias Blatter – tobias.blatter@ief.ee.ethz.ch
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Shadi Nashashibi– shadi.nashashibi@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch