ETH zürich

P&S COMSOL® Design: Simulations of Optical Components Lecture 4: Wave Optics and Waveguiding

Manuel Kohli & Raphael Schwanninger & Tobias Blatter

Content

- Last week
  - Young's single/double slit experiment

- Today
  Review on material properties
  - Waveguide
    - Motivation
    - Theory
    - COMSOL

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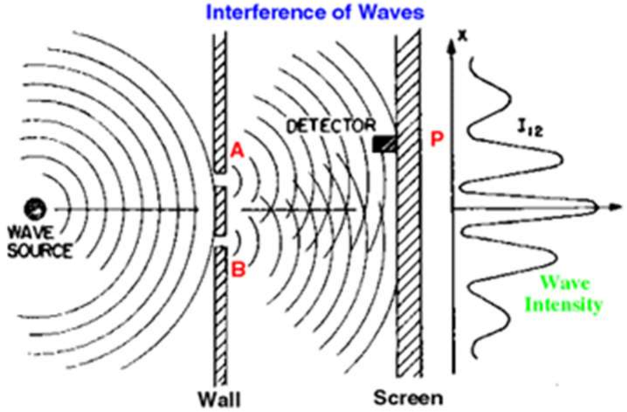
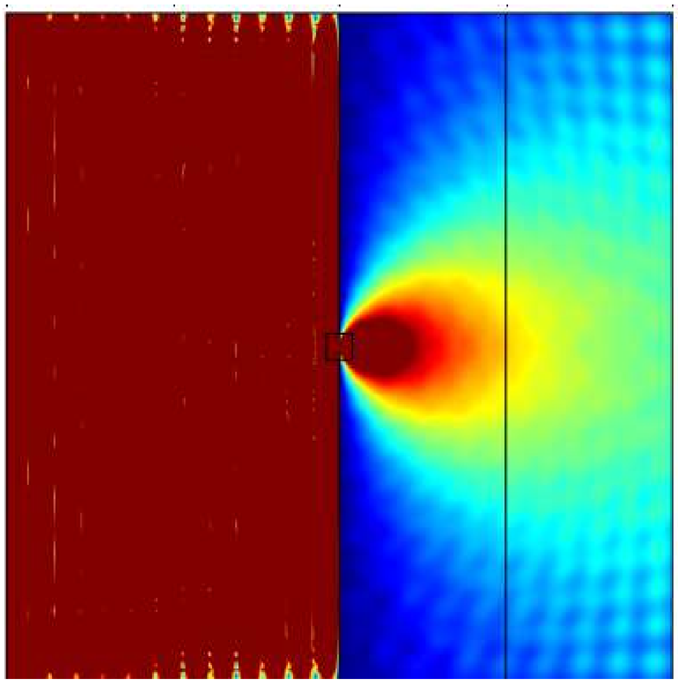
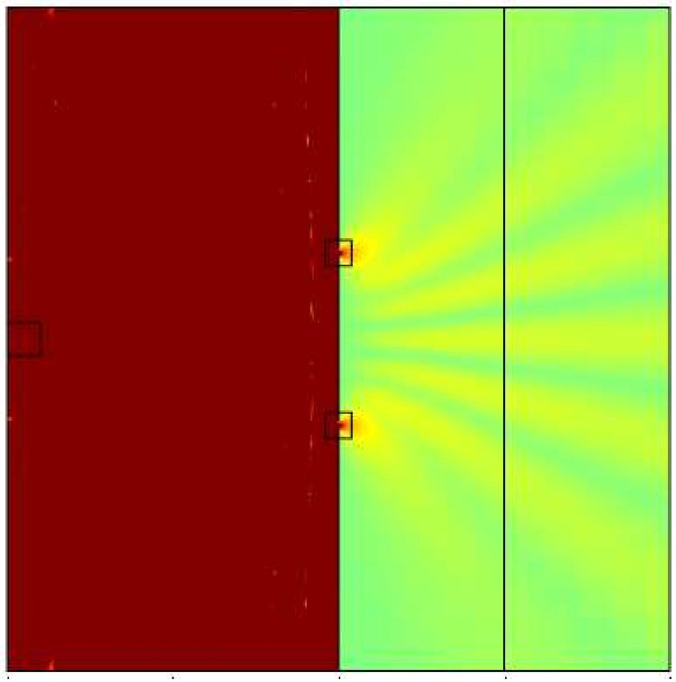
Last Week: Young's Slit Experiments



One Slit



Two Slits

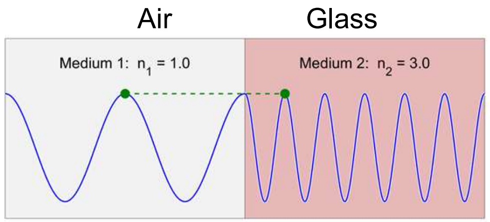


Review: Material Relations

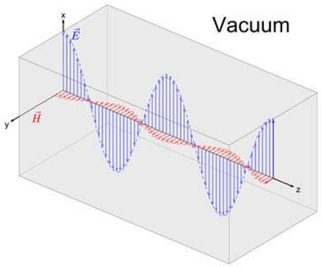
- In order to analyze an EM problem we need to define the **material properties** involved
- Materials are defined by their **refractive index $\boldsymbol{n}$** which is defined as
  - $\boldsymbol{n} = \sqrt{\boldsymbol{\mu_r \varepsilon_r}}$, for vacuum $n = 1$
  - n is a complex number $n = n' + ik$

Influences wavelength   Influences losses

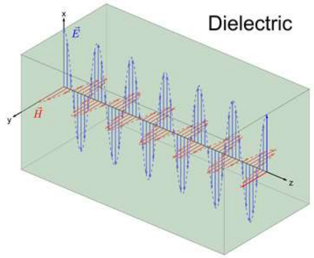
Antenna



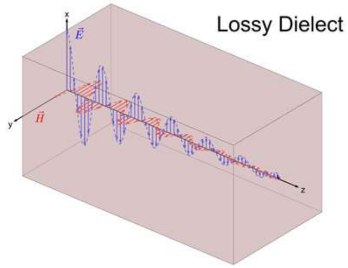
$n = 1$



$n = 3$

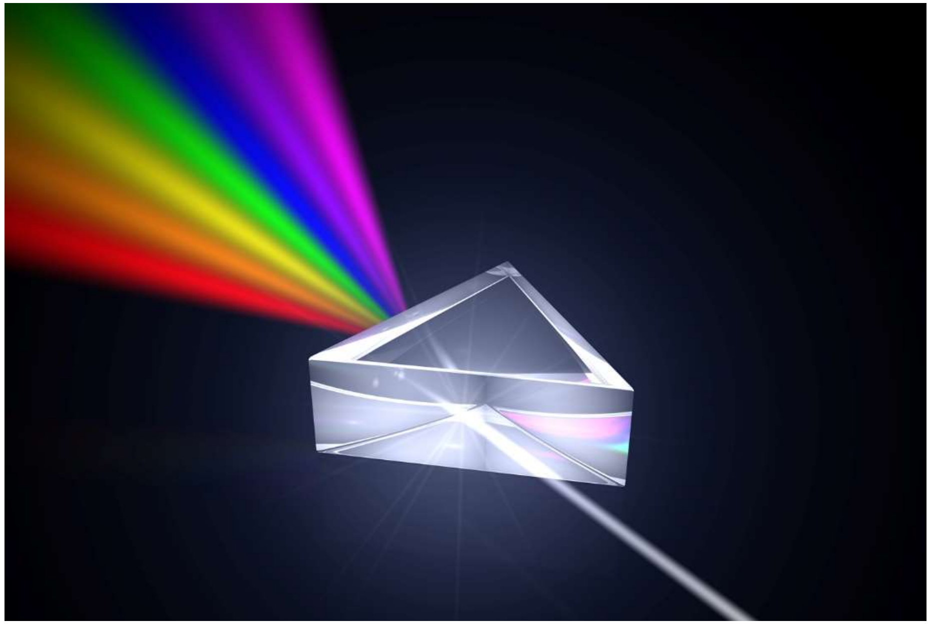


$n = 3 + 2i$



Material Properties

- What is the meaning of $n(\omega)$?
- Newton discovered that it changes with wavelength!



Waveguiding: Motivation

- How does the internet work?

- Data transfer
  - Wireless
  - By cable

Electrical (copper) or optical (glass fiber)

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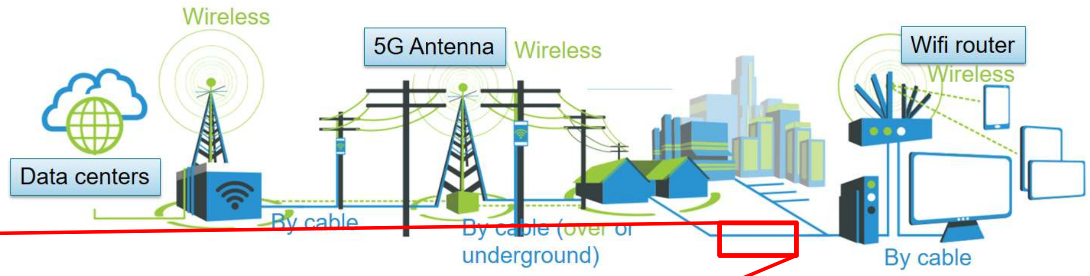
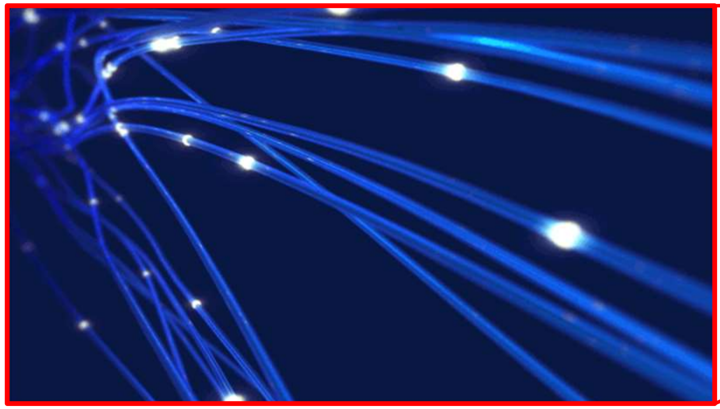
Waveguiding: Motivation

- Data transfer with an optical fiber





- Use the propagating light in the fiber to transmit information

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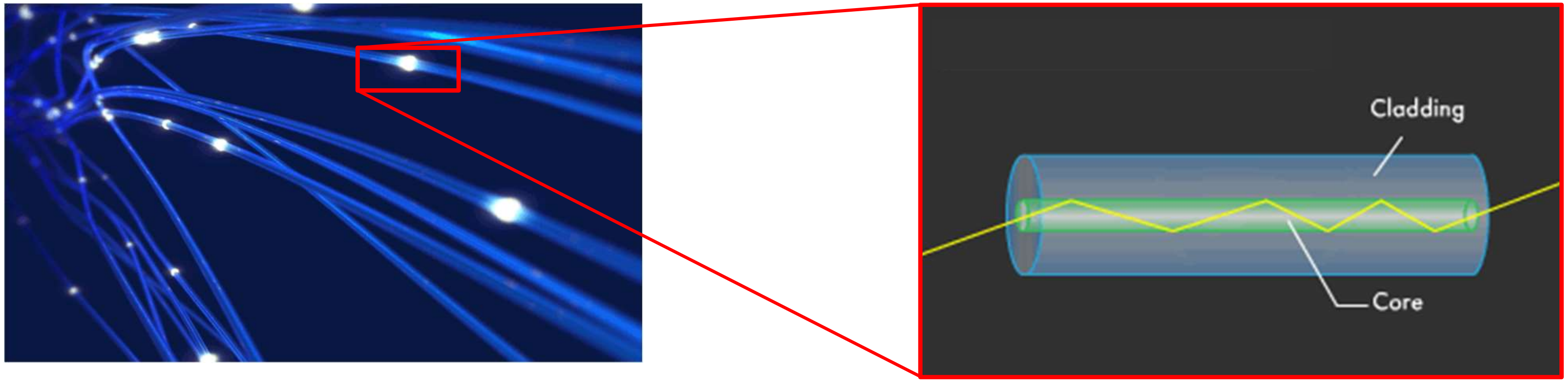
Waveguiding

- Optical data transmission → in the future maybe also in electronic devices (smartphones etc.)
- Our goal: learn how to simulate optical components used on-chip



How can we make this happen?

- Optical fiber often used terms:
  - Core
  - Cladding

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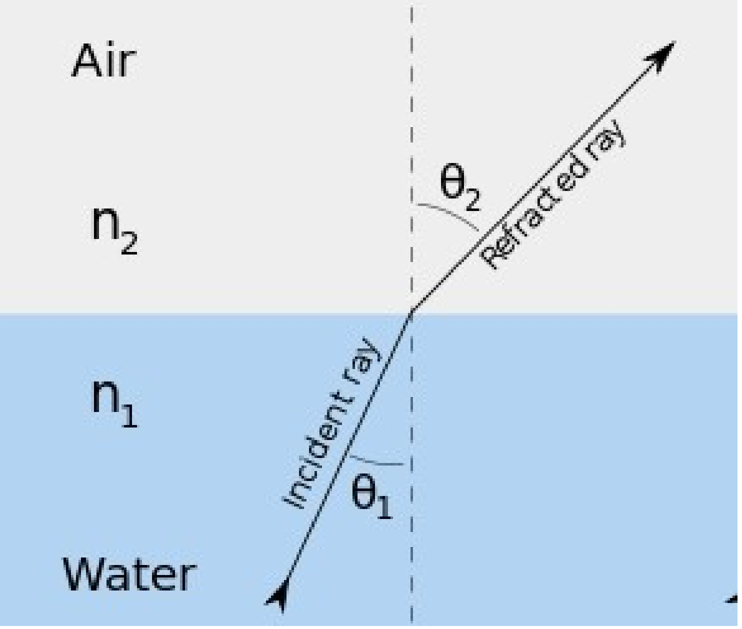
Waveguiding: Theory

- What happens at the boundary between two materials?

Snell's law

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



Waveguiding: Theory

Snell's law

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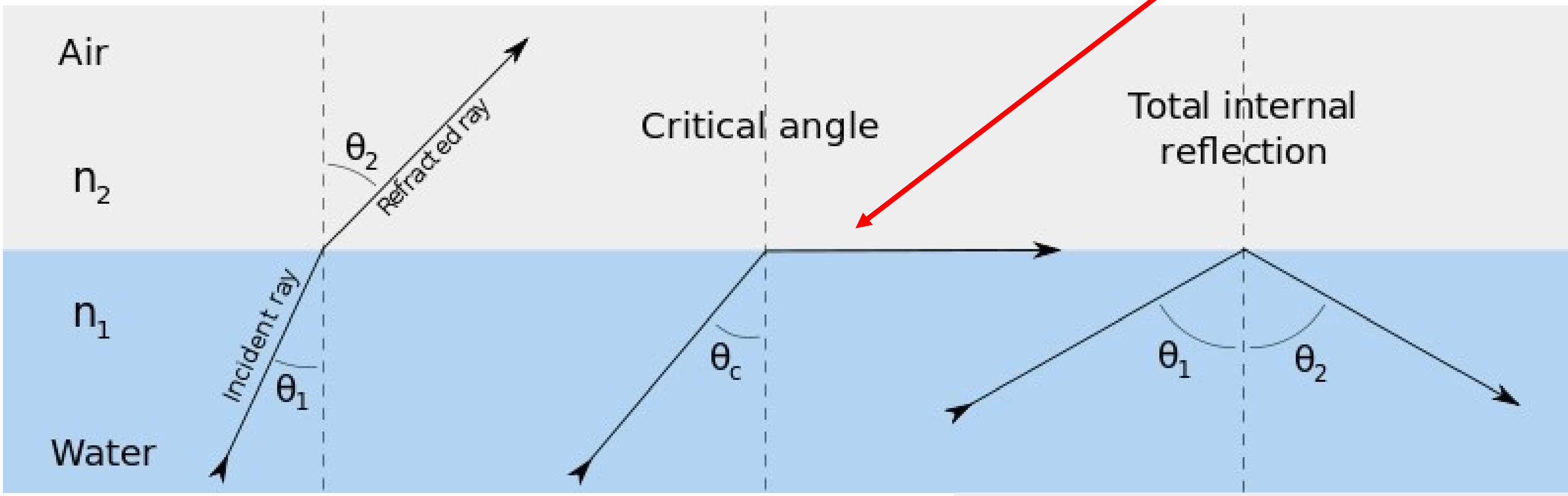
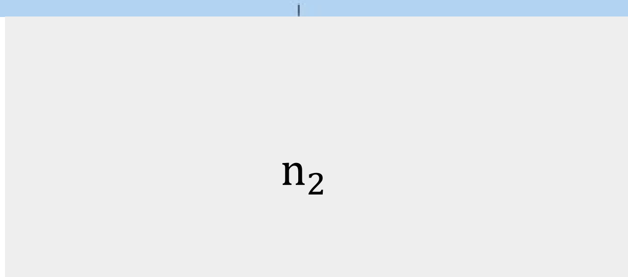
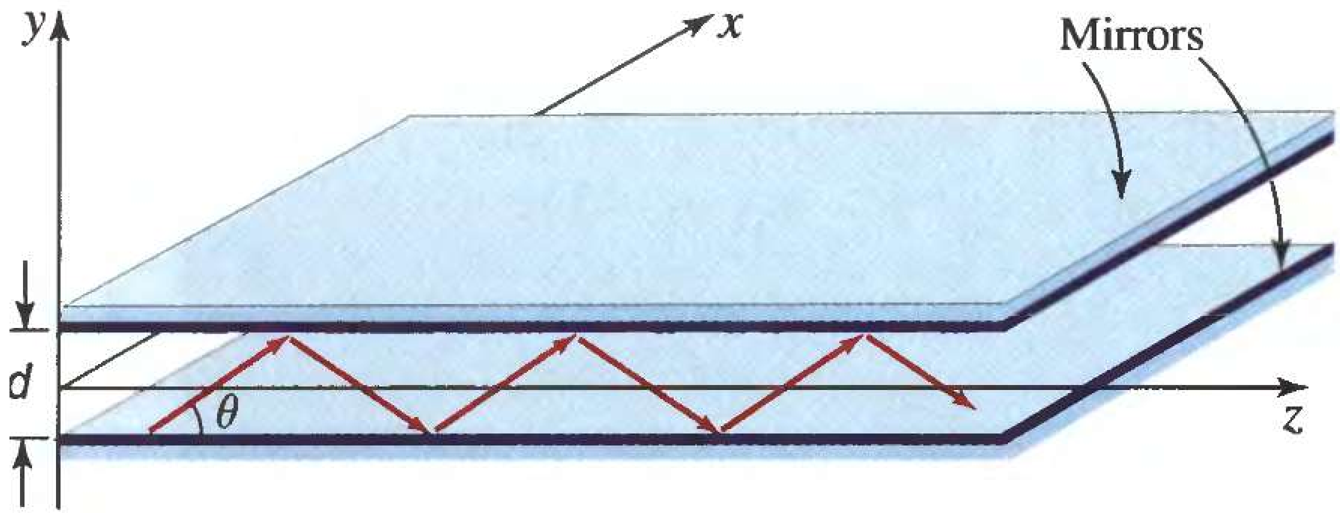


- What if $\sin\theta_2 \geq 1$?
  - There is critical angle $\theta_c = \arcsin n_2/n_1$!
    - $n_1 > n_2$
    - Light prefers to stay in higher index material!
    - Almost everything is reflected → **total internal reflection!**



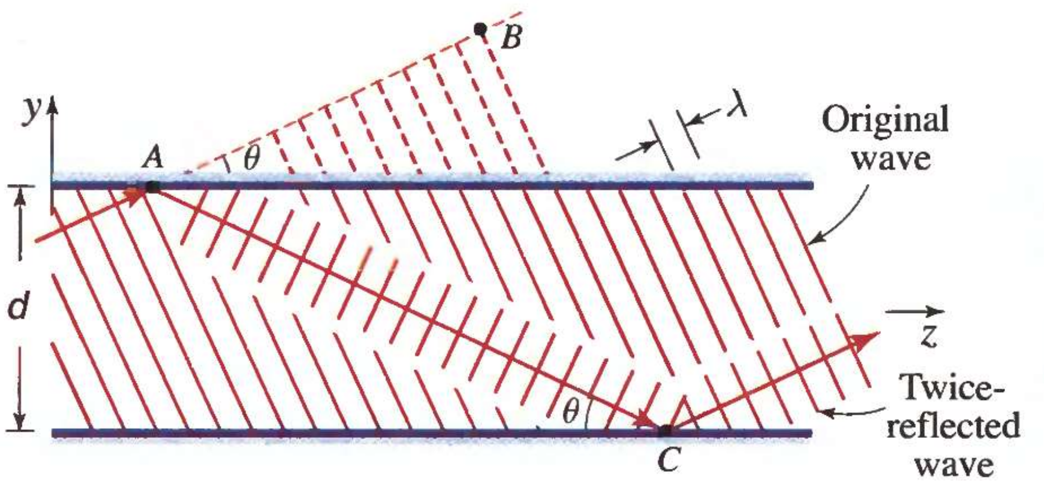
Waveguiding: Theory

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



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!

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

Waveguiding: Theory

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  - Interference after second reflection!
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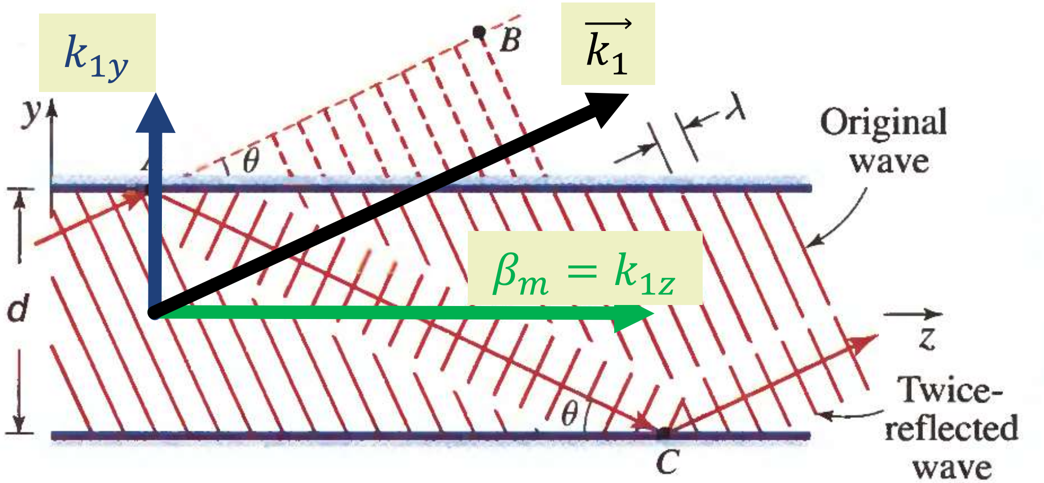

$$k_{1y} = k_1 \sin\theta_m$$

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

with $k_1 = k_0 * n_1$

Propagation constant — Effective refractive index

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

Waveguiding: Theory

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  - Interference after second reflection!
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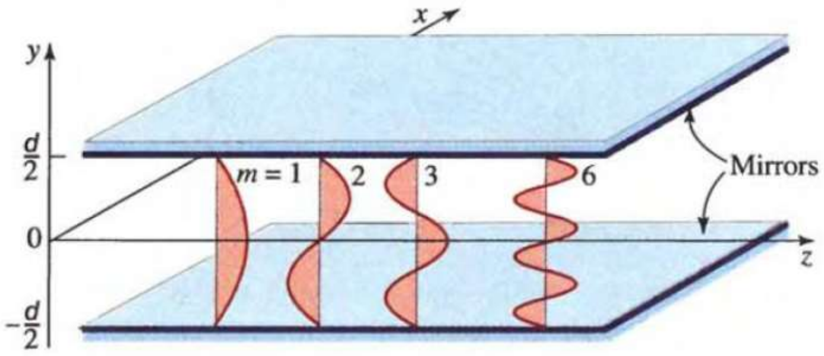

$$2d \cdot k_1 \sin\theta_m = 2\pi m$$

$$\sin\theta_m = \frac{\pi m}{d k_1} < 1$$

$$m < \frac{d k_1}{\pi} = \frac{2d}{\lambda} n$$

$$\omega_c \geq \pi \frac{c/n_1}{d}$$

Number of modes: $M < \frac{2d}{\lambda} n$

Cut-off frequency: $1 = \frac{2d}{\lambda_c} n \Rightarrow \lambda_c = 2dn$ $\qquad f_c = \frac{\frac{c}{n}}{2d}$

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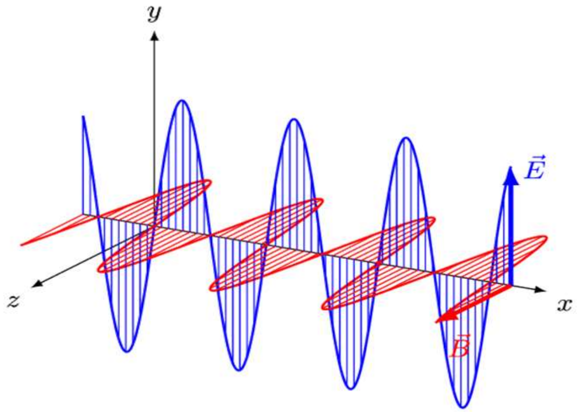
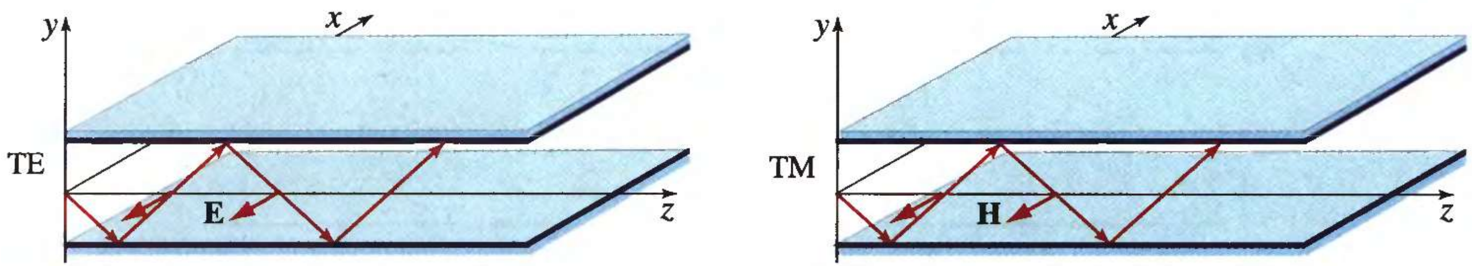
Waveguiding: Theory

- Planar dielectric waveguide
  - Core ($n_1, n_1 > n_2$)
  - Cladding (n_2)
- TE and TM modes

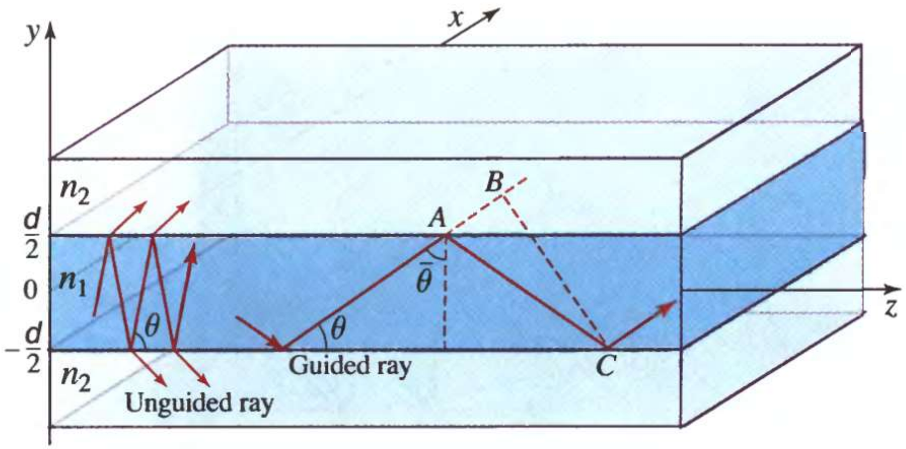


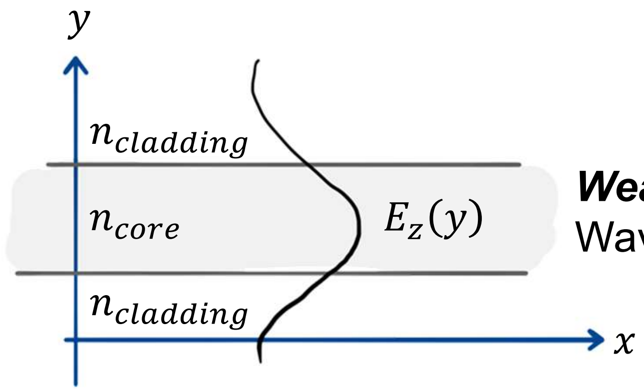


TE mode : *no electric field* in the propagation direction
TM mode: *no magnetic field* in the propagation direction

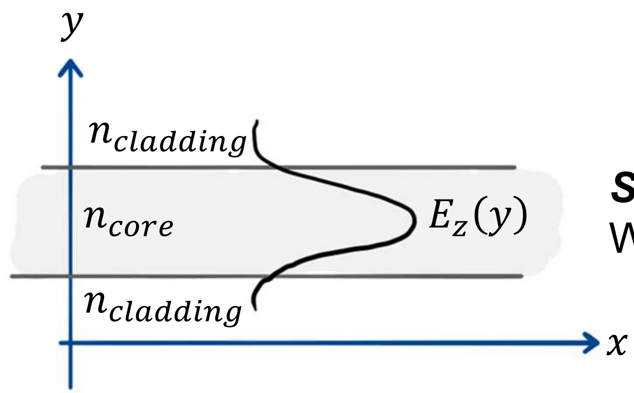
Waveguiding: Theory

- Planar dielectric waveguide
  - Core ($n_1, n_1 > n_2$)
  - Cladding (n_2)





Weakly confined
Wave leaks into cladding



Strongly confined
Wave mostly in the core