ETH zürich

COMSOL ® Design Tool: Simulations of Optical Components Week 6: Waveguides and Propagation 3 – S Parameters

Taichiro Fukui, Maximilian Bosch

Content

- **Revision wave propagation**
  - Waveguide
  - Confinement
  - Modes
- **S-parameters**
  - Theory
- **Projects**
  - Outline
  - Short overview projects

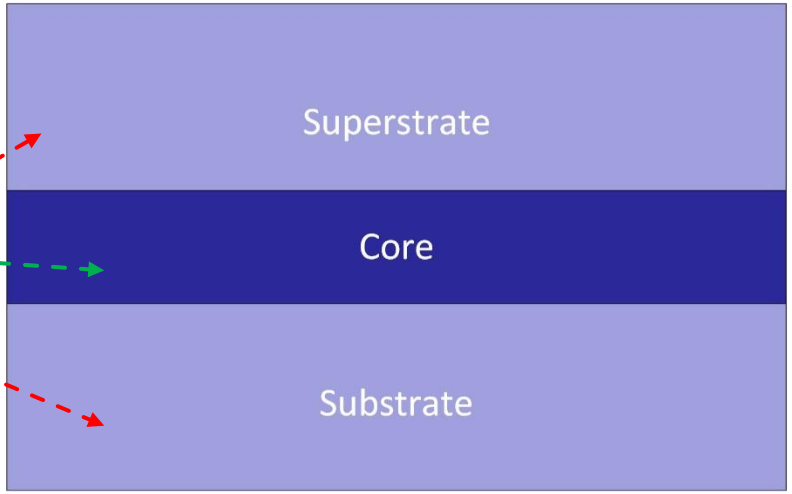
Theory

- **COMSOL examples**
  - Taper
  - Waveguide bend

Tutorial

Revision Wave Propagation

- Dielectric slab waveguide
- What we want
  - Propagation in core
  - Decay (exponential) in sub/superstrate
  - High confinement
- What we don’t want
  - Propagation in sub/superstrate
  - Low confinement (except in certain application - e.g. couplers)



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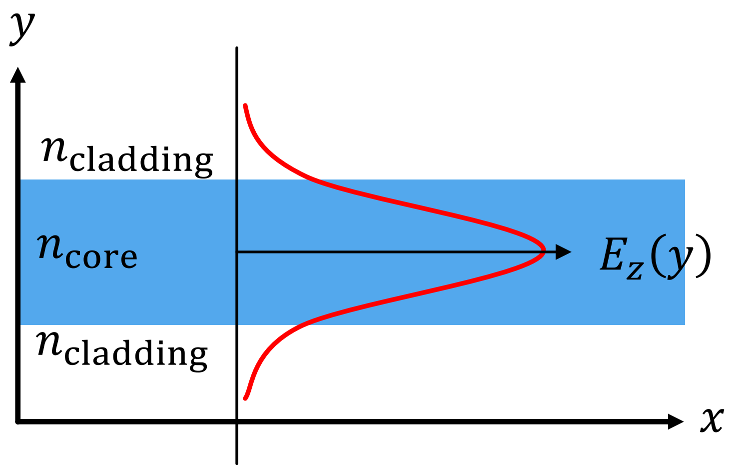
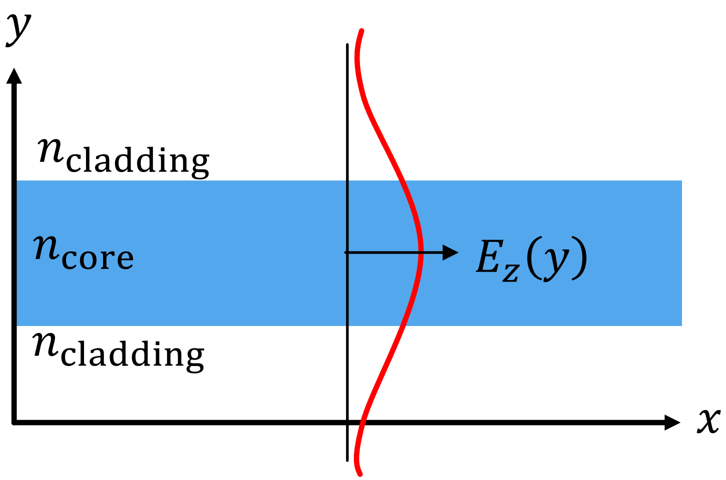
Revision Wave Propagation

- Confinement



Strongly confined
Wave mostly in the core



Weakly confined
Wave leaks into cladding

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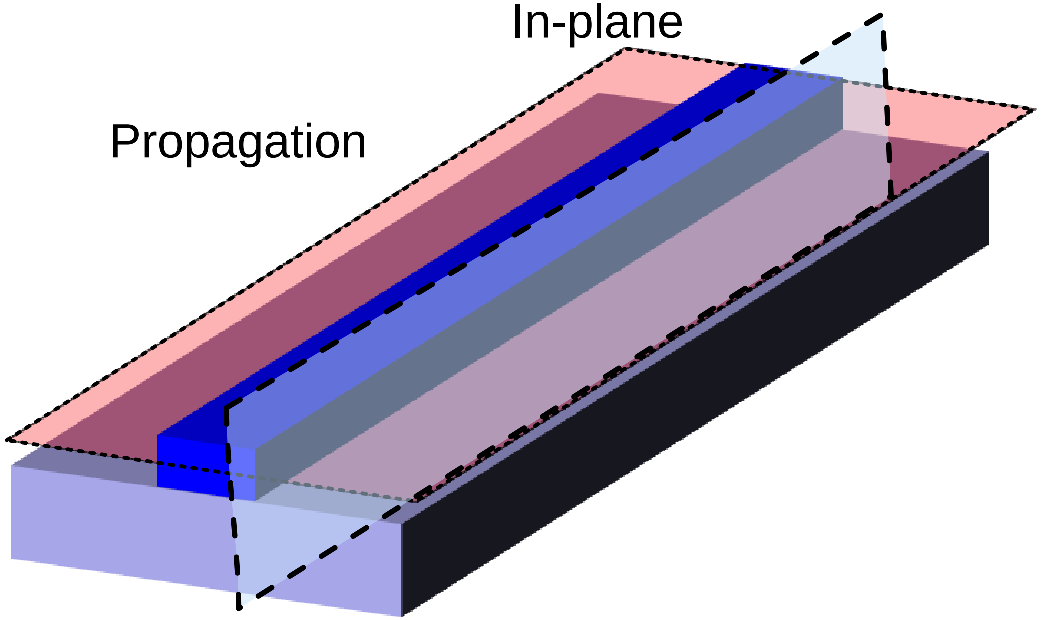
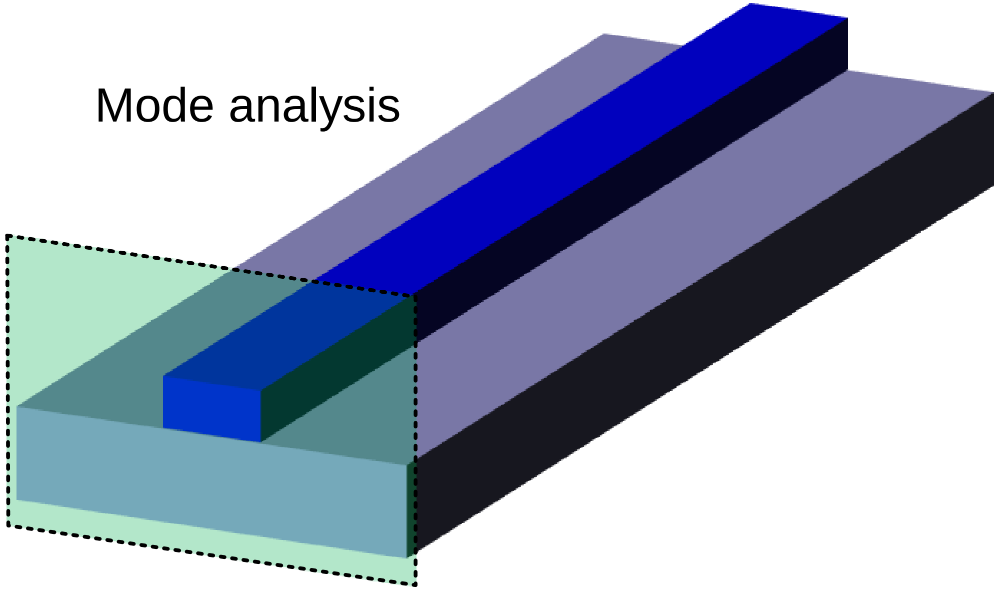
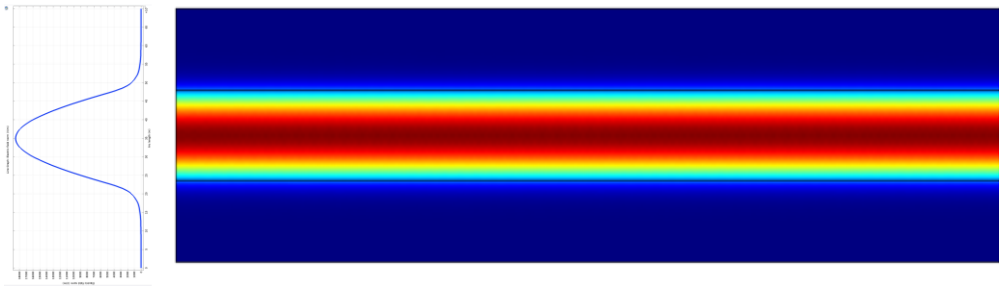
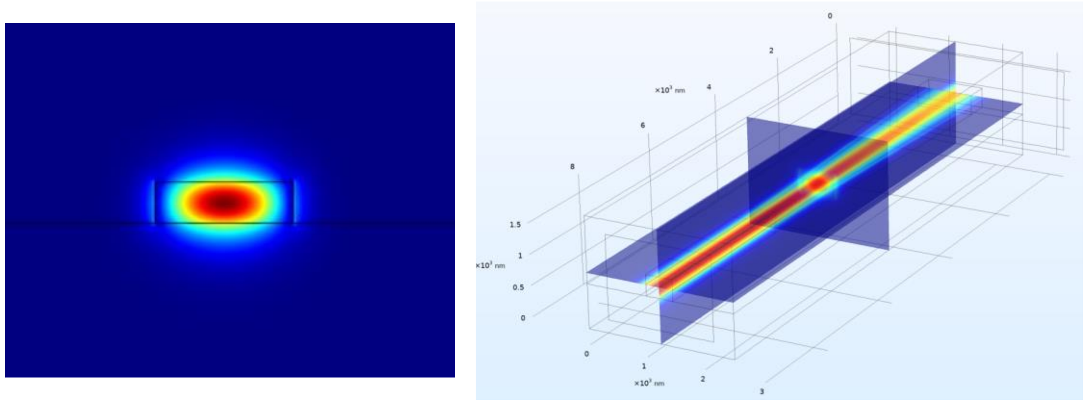
Revision Wave Propagation



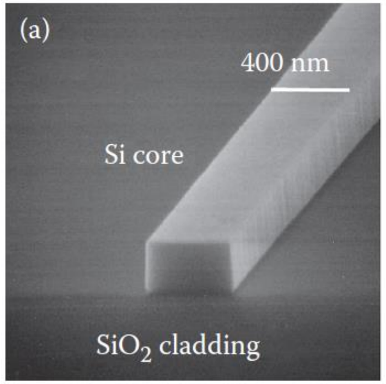


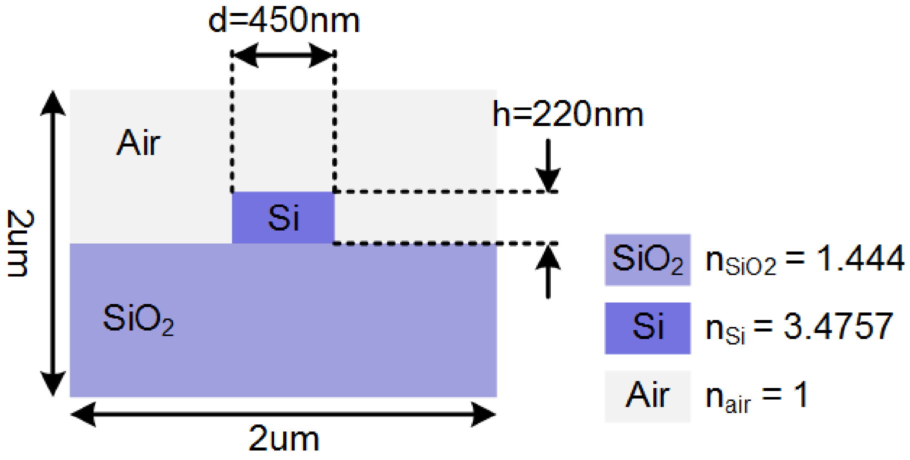




Revision Wave Propagation: Ridge Waveguide

- Multimode silicon ridge waveguide





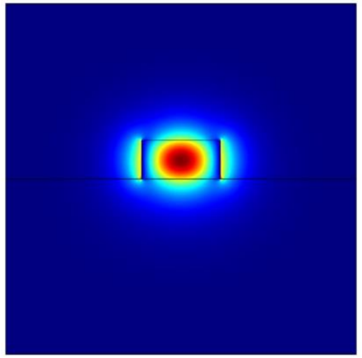
Given:
- $\lambda = 1550\ \text{nm}$
- $n_{\text{Si}} = 3.47$
- $\text{Si}_{\text{Height}} = 220\ \text{nm}$
- $\text{Si}_{\text{Width}} = [350{,}1000]\ \text{nm}$

Output:
- E-field (guided modes)
- Effective refractive index n_{eff}

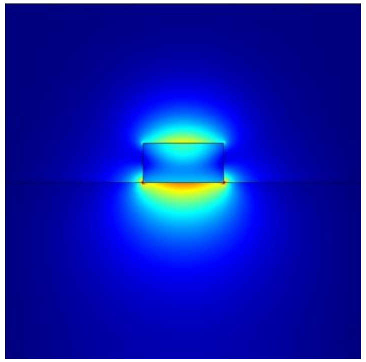
Revision Wave Propagation: Ridge Waveguide

$n_{\mathrm{Si}} = 3.4757$
$n_{\mathrm{SiO_2}} = 1.44$
$n_{\mathrm{air}} = 1$

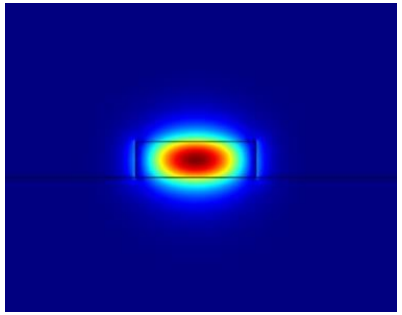
- Single-mode ridge
  - Solution 1: $n_{eff} = 2.2719$



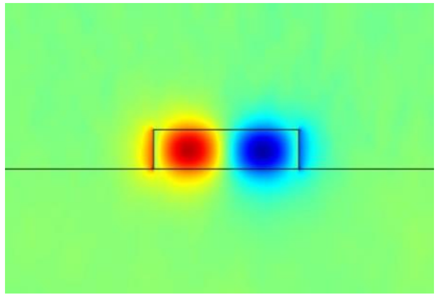
  - Solution 2: $n_{eff} = 1.5422$



- Multi-mode ridge (increased geometry)
  - Fundamental mode



  - Higher order mode



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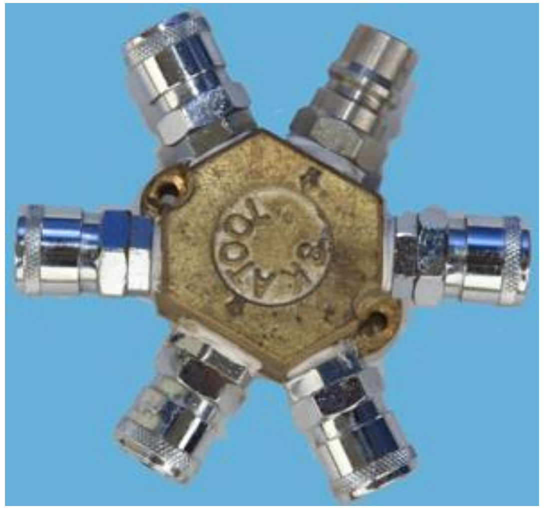
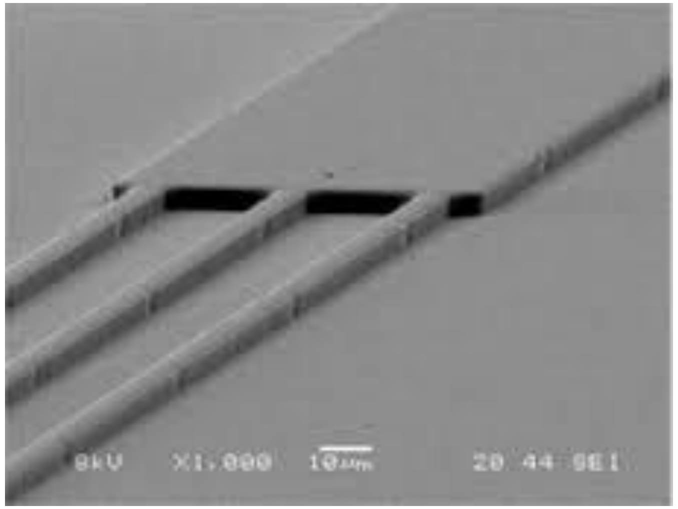
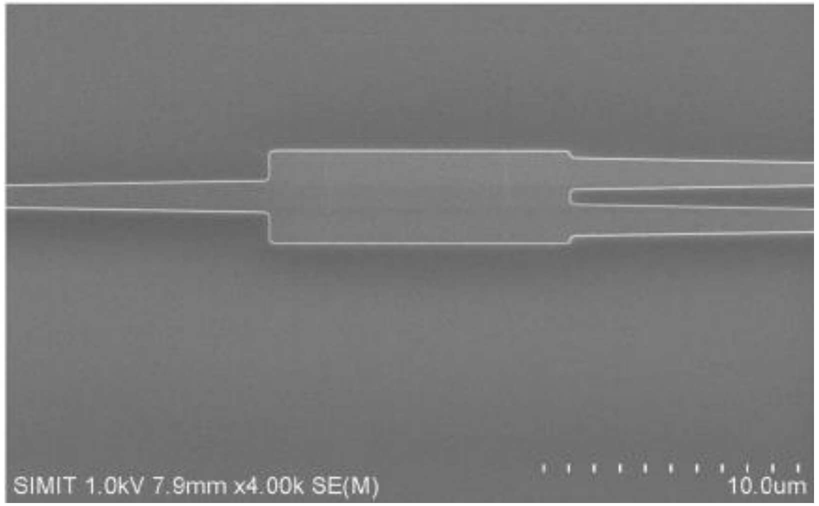
- **COMSOL examples**
  - Taper
  - Waveguide bend

S-Parameters: Motivation

- What happens with systems for multiple inputs and multiple outputs (MIMO)?
- How can it be described mathematically?



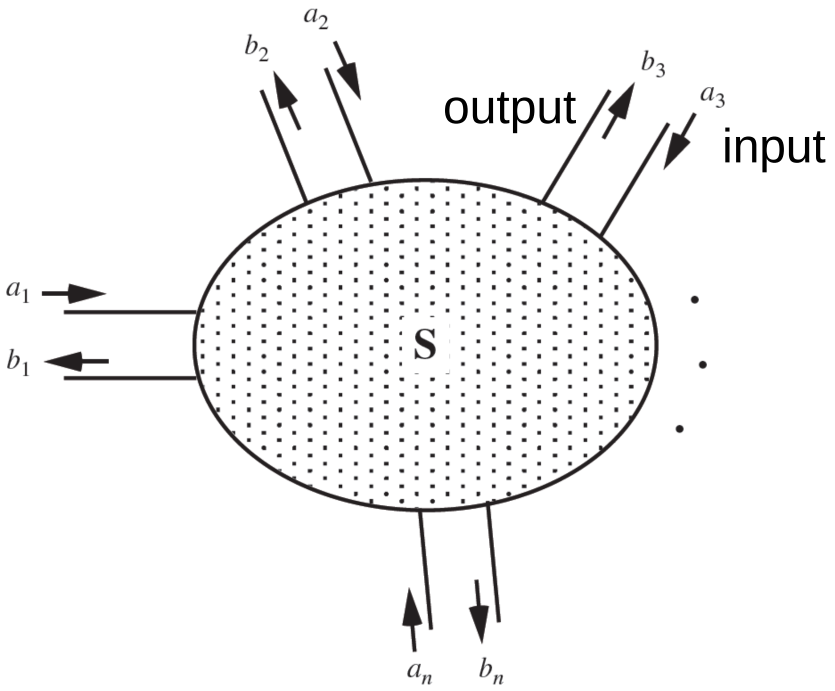




- → We use the S-matrix

S-Parameters for Photonics

- How to characterize our photonics system as whole?
  - Scattering matrix (so called S-matrix)



Superposition:

$$b_i = \sum_{j=1..n} S_{ij} a_j$$

$$\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}$$

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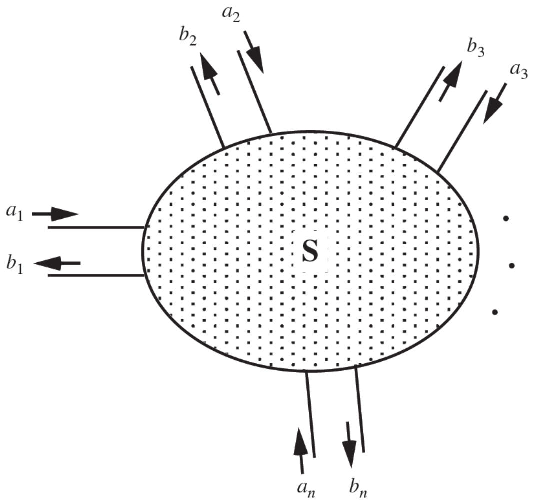
S-Parameters for Photonics

- How to characterize our photonics system as whole?
- S-matrix
  - Unitary in lossless systems
  - Diagonal S_{ii} terms are complex valued amplitude reflection coefficients



Superposition:

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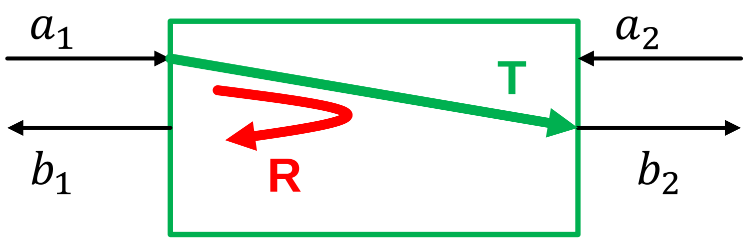
S-Parameters for Photonics

- How to characterize our photonics system as whole?
- S-matrix
  - Unitary in lossless systems
  - Diagonal S_{ii} terms are complex valued **amplitude reflection coefficients**

Two input/output ports:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$



$\boldsymbol{T} =$

$\boldsymbol{R} =$

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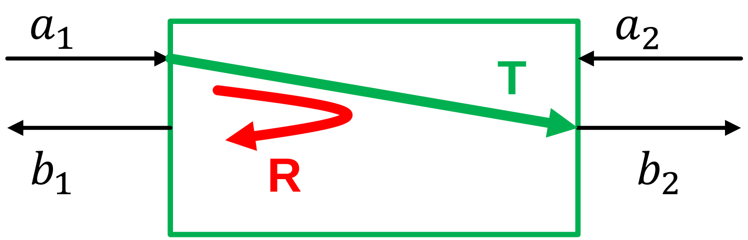
S-Parameters for Photonics

- How to characterize our photonics system as whole?
- S-matrix
  - Unitary in lossless systems
  - Diagonal S_{ii} terms are complex valued **amplitude reflection coefficients**

Two input/output ports:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$\boldsymbol{T} = |S_{21}|^2$$
$$\boldsymbol{R} = |S_{11}|^2$$



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S-Parameters for Photonics: COMSOL

- Can COMSOL help?
- S-matrix
  - Luckily, COMSOL has built-in calculation of these!

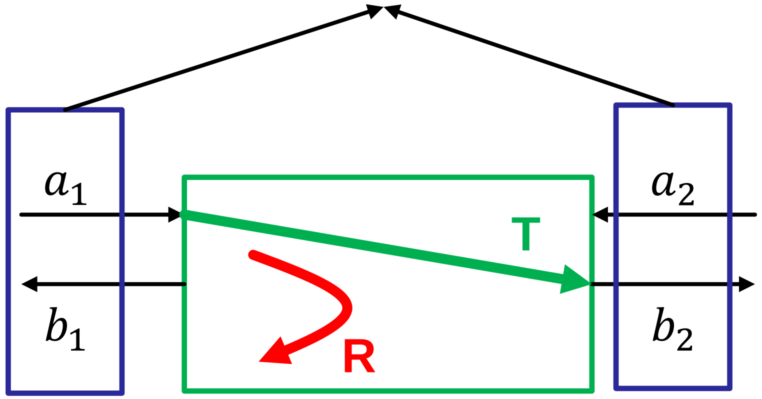
These are the ports we define in COMSOL!

Two input/output ports:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$\boldsymbol{T} = |S_{21}|^2$$
$$\boldsymbol{R} = |S_{11}|^2$$

COMSOL calculates this matrix!



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Projects – Outline

Date	Content
Nov 3rd	Description of all projects - Group Forming and start of projects
Nov 3rd - Dec 15th	Group work on projects (6 weeks)
Dec 15th	Presentations
Dec 22nd	Deadline for written report

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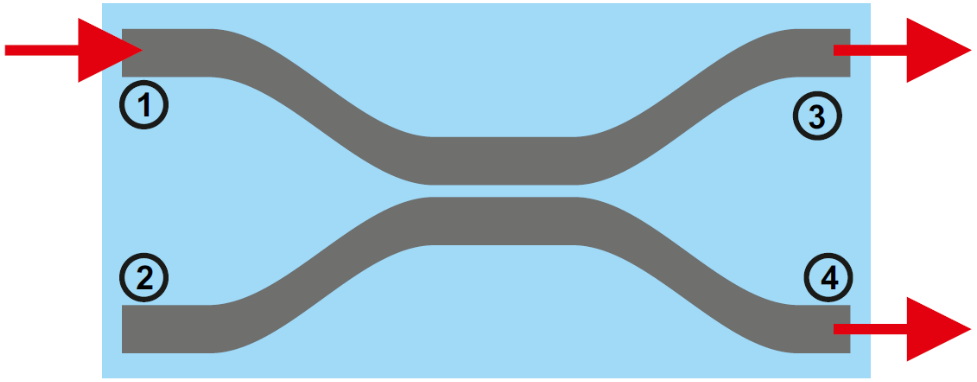
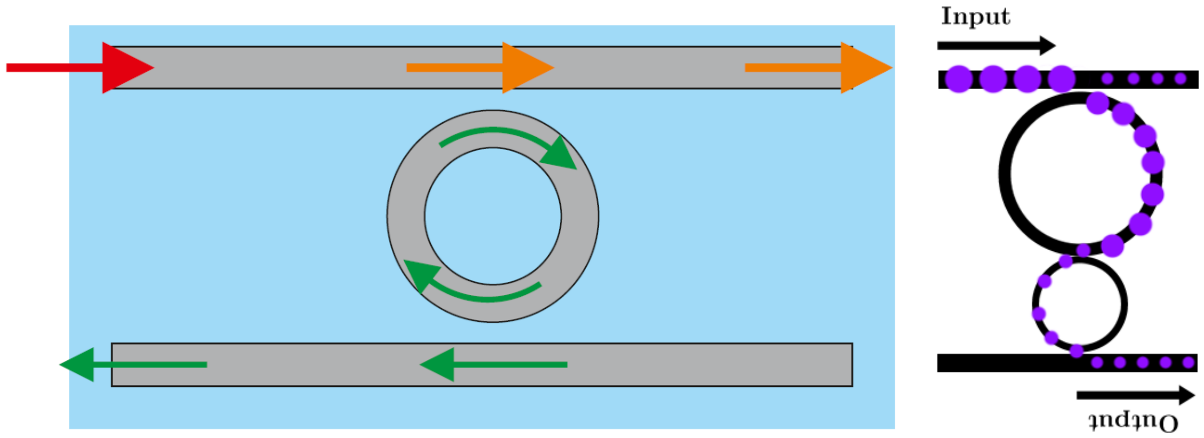
Projects Overview

- **Directional coupler**
  - 2-3 students
  - Goal
    - Analyze the Mode in 1D and 2D, discuss the difference
    - Wavelength: 1550 nm (C-Band)
    - Fix power ratio (to 50/50 and 90/10)
    - Minimize bending losses

- **Ring resonator**
  - 2-3 students
  - Goal
    - Find the resonant behavior at 1550 nm
    - Maximize Q factor and minimize losses
    - Cascaded ring resonators for 60/40 ratio

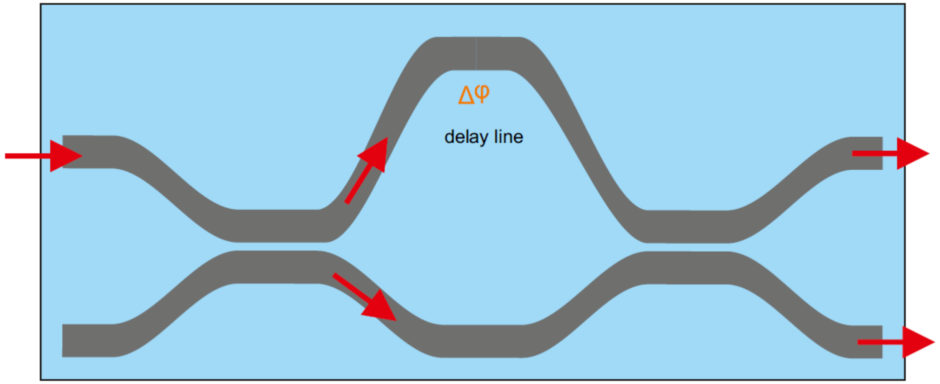


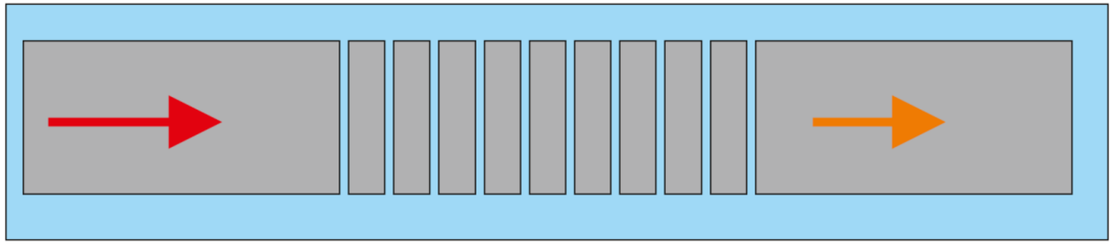


Projects Overview

- **Delay interferometer**
  - 3 students
  - Goal
    - Wavelength = 1550 nm
    - Minimize bending losses
    - Find delay line for $\frac{\pi}{2}, \pi, 2\pi$ phase shift
    - Directional coupler or MMI for 50:50 ratio

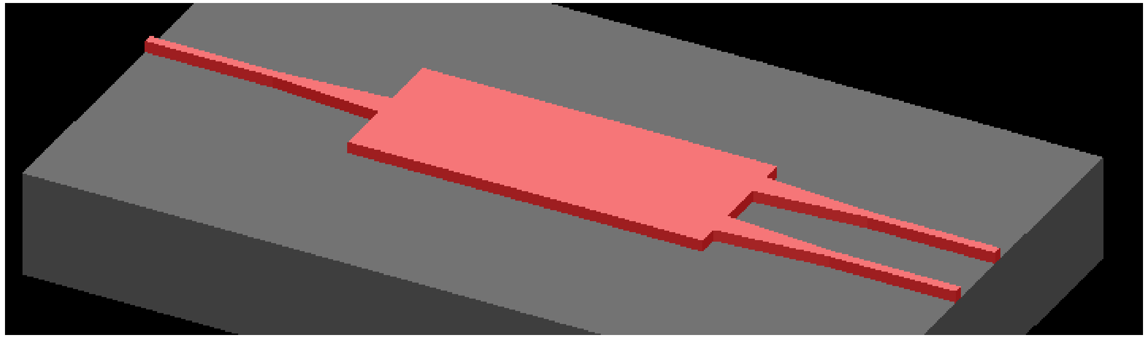
- **Bragg mirror**
  - 2-3 students
  - Goal
    - Operating wavelength: 1550 nm
    - Incoming wave should be reflected, R>0.9 at 1550 nm
    - Reflection coefficient >3 dB for 1450-1650 nm

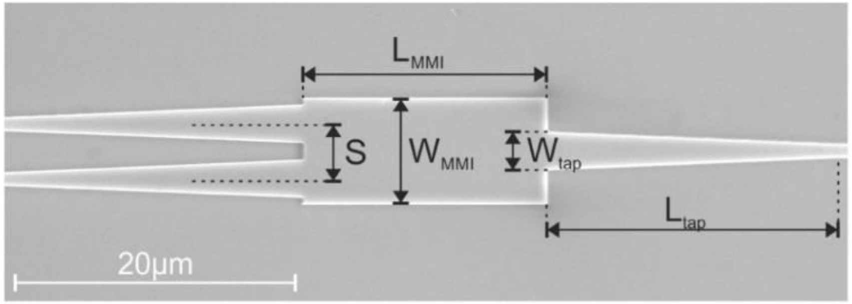




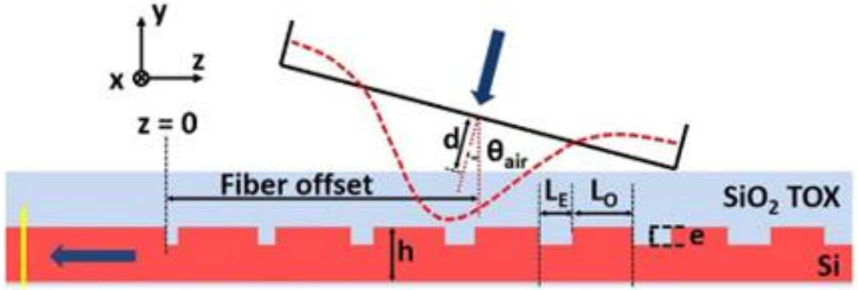
Projects Overview

- **Multimode interferometer**
  - 2-3 students
  - Goal
    - Find geometry such that output ratio is 50/50 and also 10/90



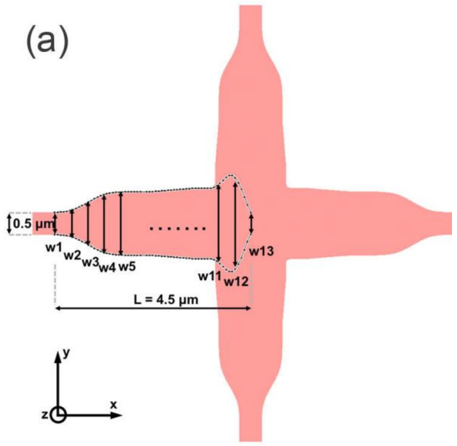


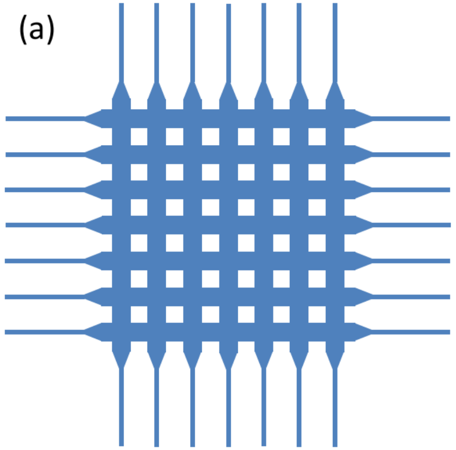
- **Grating Coupler**
  - 3 students
  - Goal
    - Simulate a grating coupler using the Bragg condition for a fiber incident angle of 10°.
    - Operating wavelength: 1550 nm
    - Maximize coupling efficiency from fiber to a certain mode inside the waveguide < 3 dB



Projects Overview

- **Waveguide Crossings**
  - 3 students
  - Goal
    - Minimize transmission losses
    - Total losses < 0.3 dB





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Projects Overview

- **Your own ideas**

  - They are WELCOME!

  - Please put together your ideas and make a small sketch by next week and let’s have a look together

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  - Taper
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Tutorial

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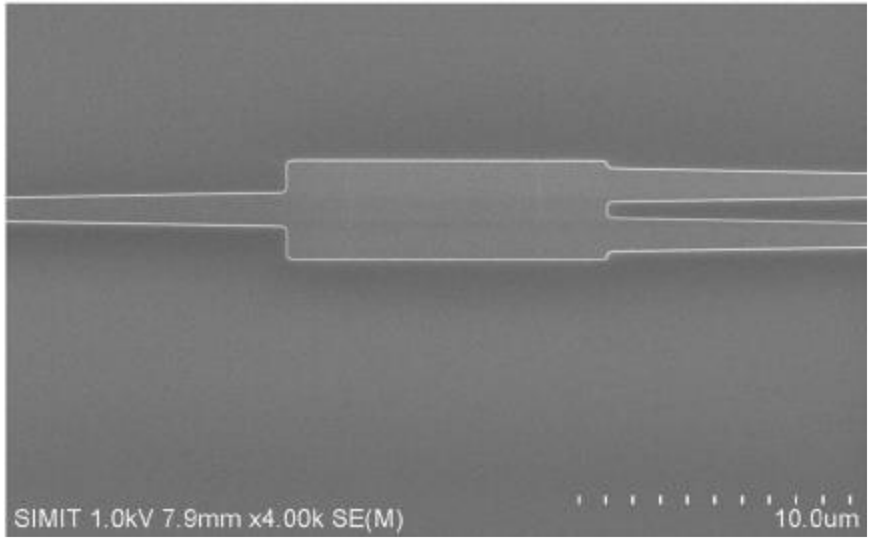
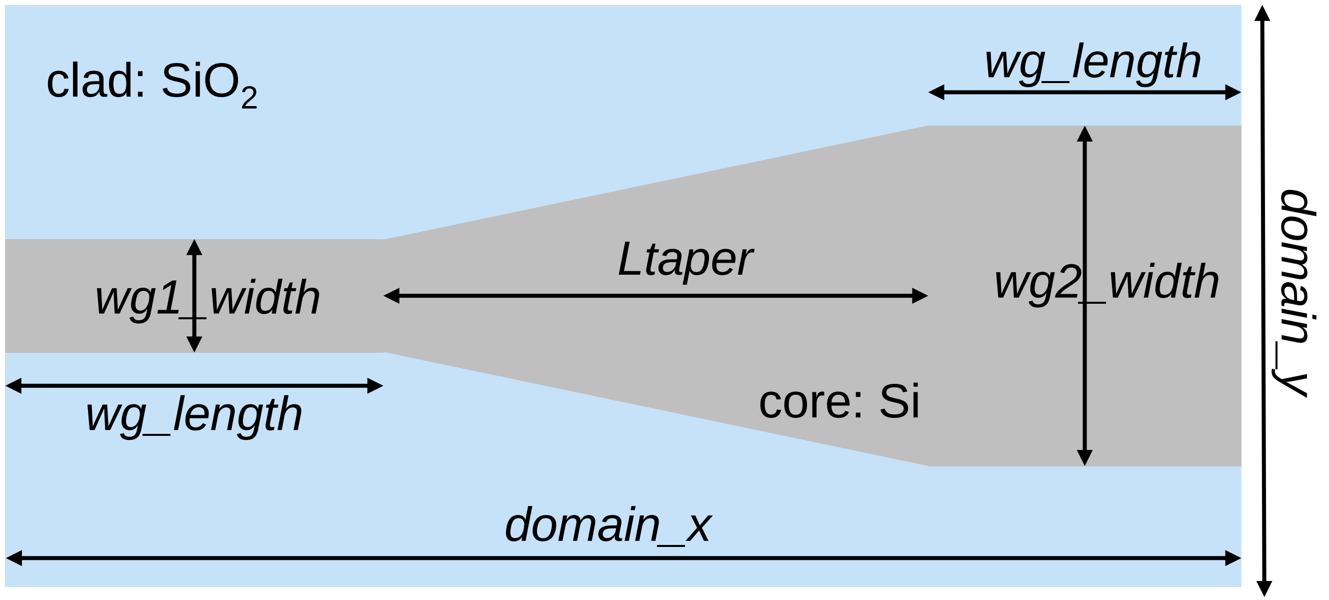
COMSOL Examples: Taper

- “Tapering”
- Sometimes, photonics design requires that waveguide also changes its width…
- Example is Multi – Mode – Interference coupler (one of the projects)

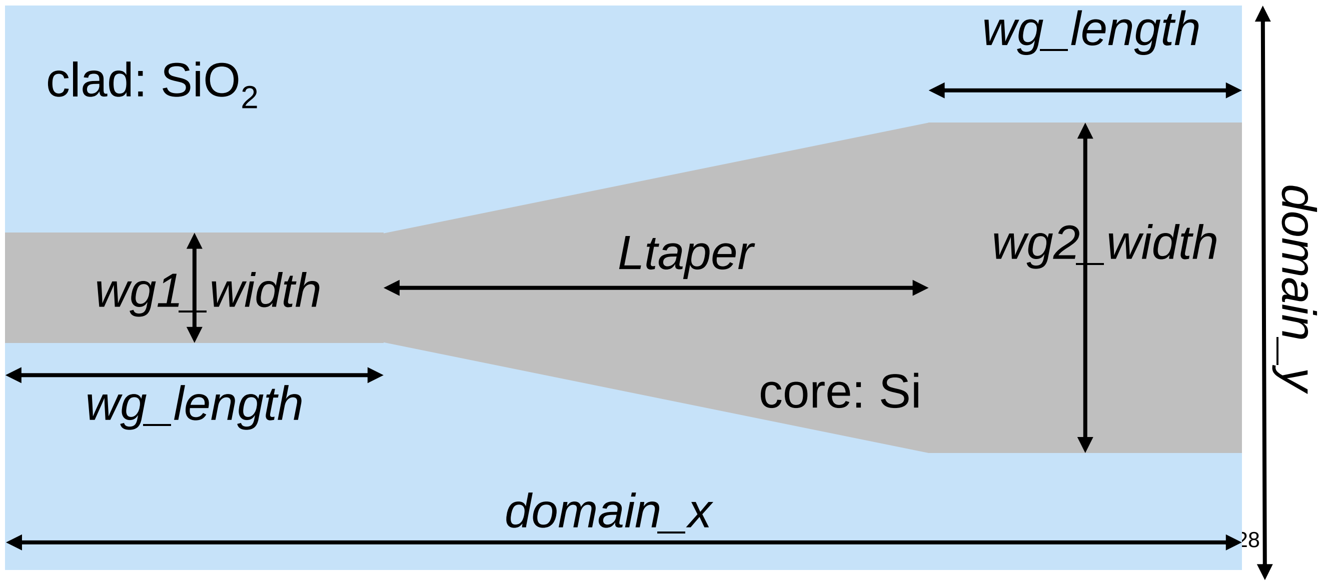


COMSOL Examples: Taper

- Tasks:
  - Plot transmission curve for different taper lengths
    - (*Note*: you can **add trapezoid or polygon** in COMSOL)
    - L_{taper} greater then 100 nm…



Name	Expression	Value	Description
lam0	1550[nm]	1.55E-6 m	wavelength
f0	c_const/lam0	1.9341E14 1/s	frequency
n_core	3.47	3.47	index of Silicon
n_clad	1.44	1.44	index of Silicon Dioxide
Ltaper	2[um]	2E-6 m	taper length
wg1_width	300[nm]	3E-7 m	1st wg width
wg2_width	2[um]	2E-6 m	2nd wg width
wg_length	2[um]	2E-6 m	waveguide straight lengths
domain_x	2*wg_length+Ltaper	6E-6 m	domain size in x
domain_y	5*wg2_width	1E-5 m	domain size in y



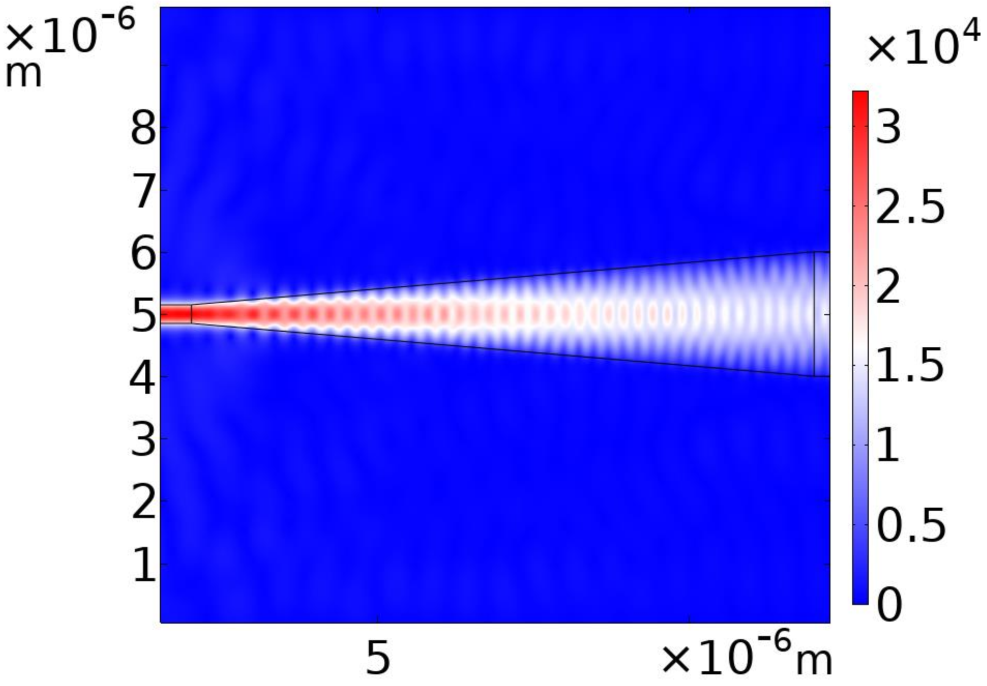
Next Steps

- Define Materials
  - Cladding
  - Core

- Define Ports
  - Don't forget : Numeric

- Define Mesh
  - Not to small → computationally intensive
  - To coarse → false results

- Select correct Study
  - Choose only one mode



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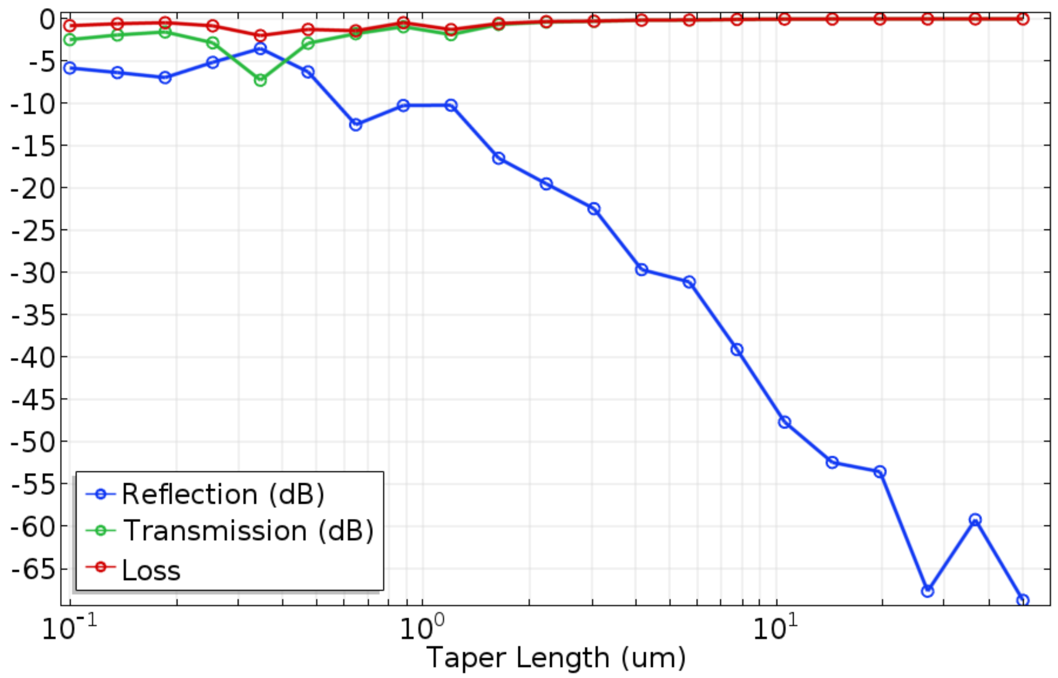
Next Steps: Analyze S- Parameters

- Parameter sweep taper length

- S-Parameters can be used to plot
  - Reflection
  - Transmission
  - Losses

- Hint:
  - Derive desired S-parameter values Sxx
  - Make a 1D- plot



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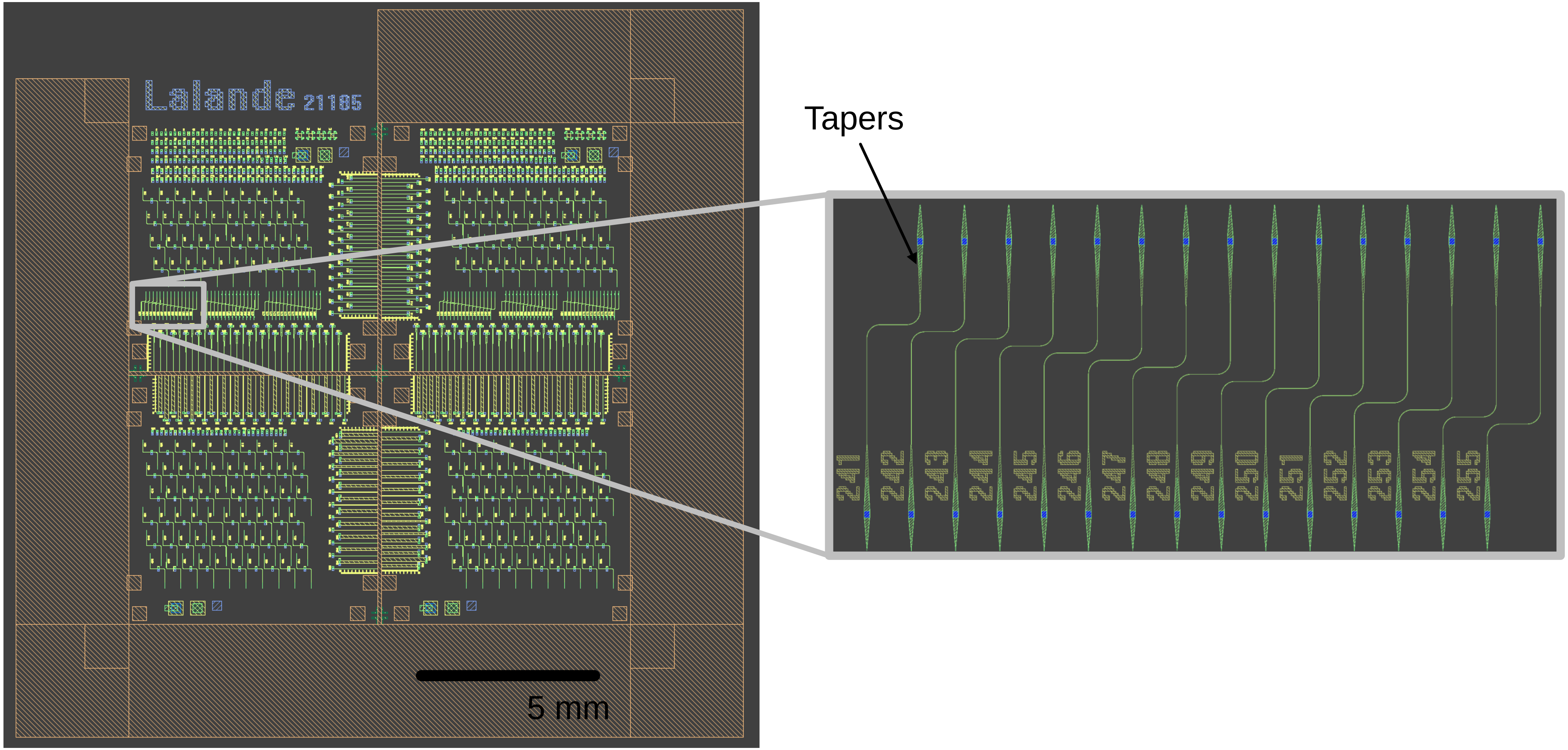
Waveguide bending



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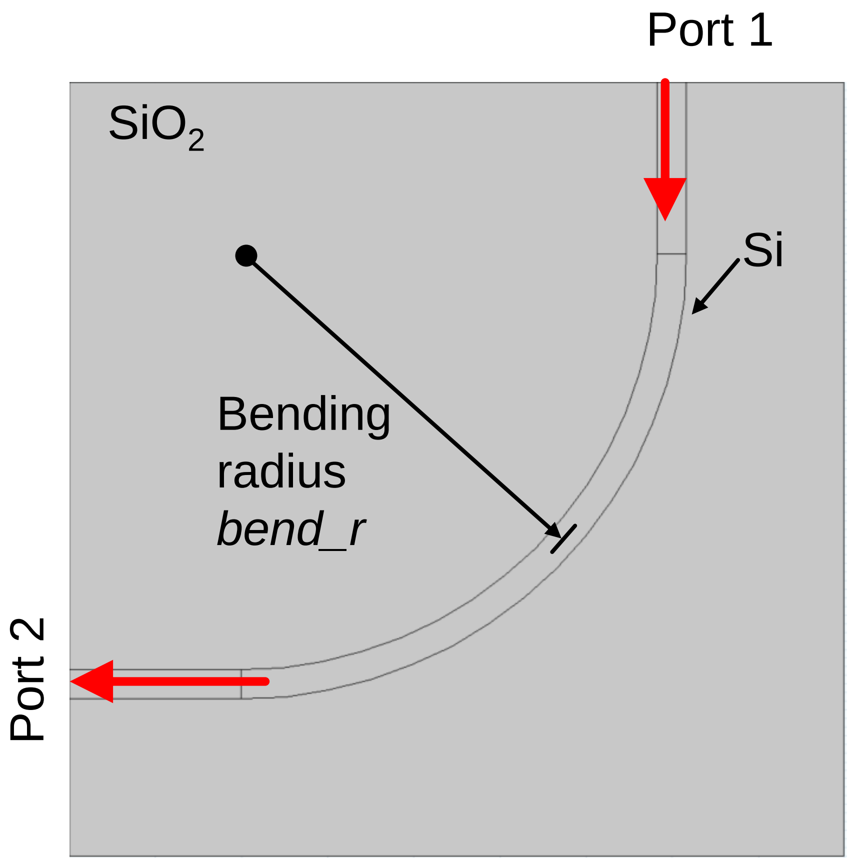
S-Parameters for Photonics: COMSOL Waveguide Bend



- WG bend with a circular segment with a radius *bend_r*
- *bend_r* goes to the center of the WG
- We collect the power at port 2
- We calculate the transmission

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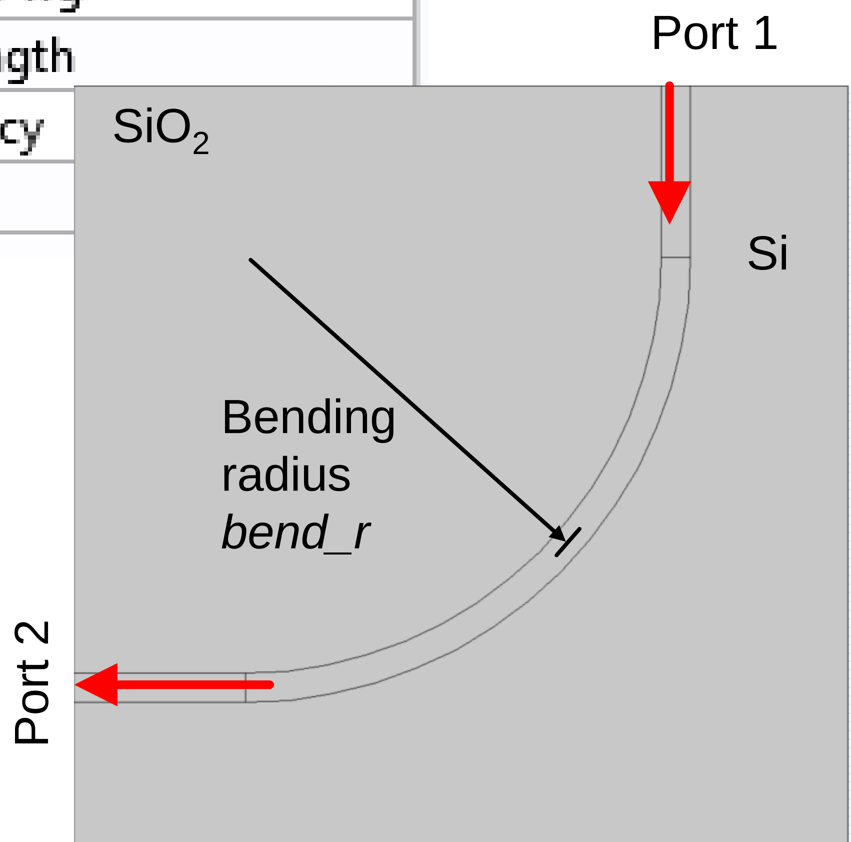
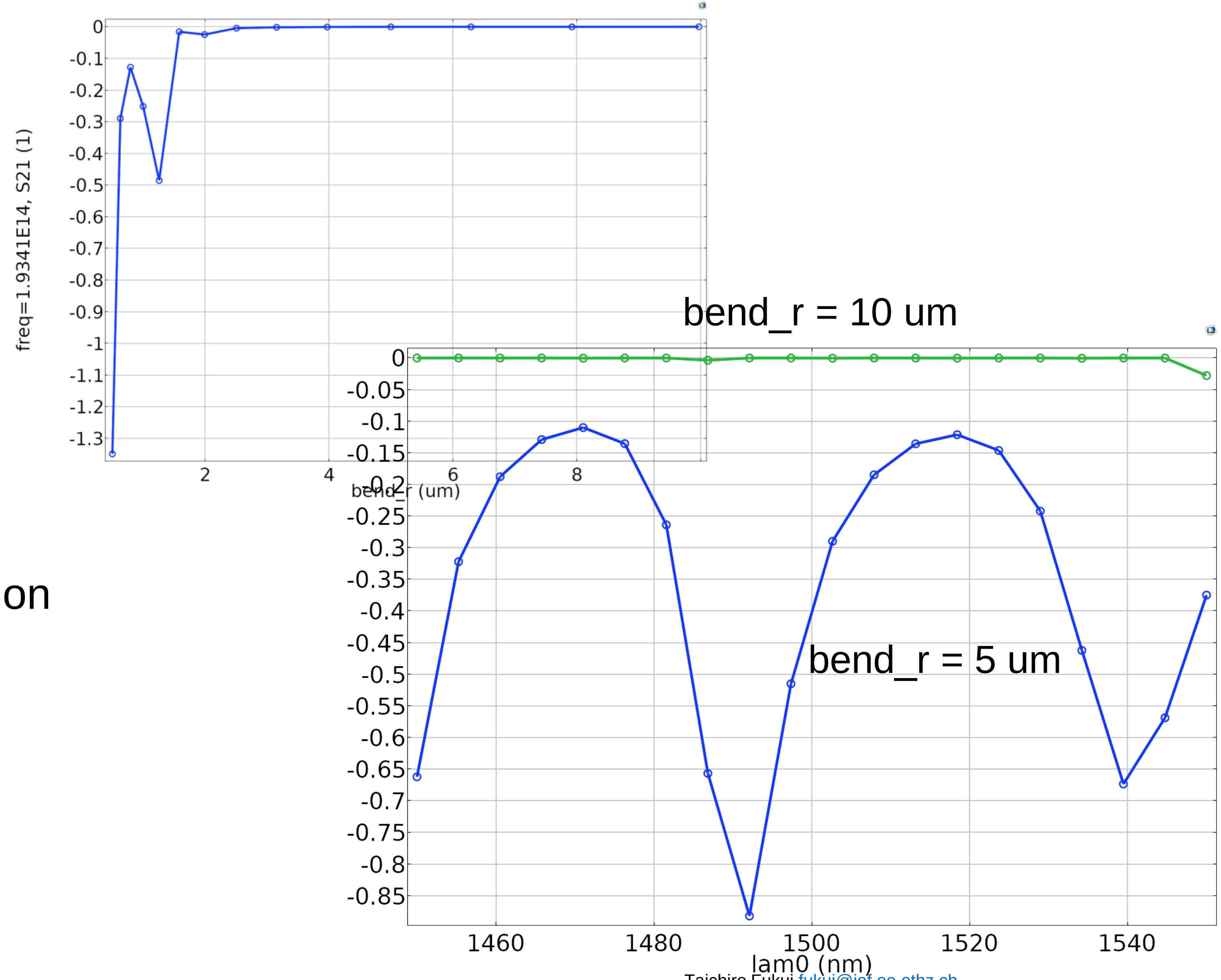
Name	Expression	Value	Description
bend_r	0.5[um]	5E-7 m	radius of bent
Dx	bend_r+2*si_in	4.5E-6 m	width domain
Dy	bend_r+2*si_in	4.5E-6 m	height domain
si_in	2[um]	2E-6 m	straight length
nSi	3.47	3.47	Si index
nSiO2	1.46	1.46	SiO2 index
wSi	450[nm]	4.5E-7 m	width of wg
lam0	1550 [nm]	1.55E-6 m	wavelength
f0	c_const/lam0	1.9341E14 1/s	frequency



Next Steps

- Assign
  - Materials
  - Mesh
- Run simulation
- Evaluate transmission depending on
  - Radius
  - Wavelength



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