1- Directional coupler (2 Students)

Goal

The goal of this project is to make a 2 by 2 optical directional coupler with a defined power ratio for the two output branches. The directional coupler should be optimized for the operating wavelength of λ = 1310 nm. In a first directional coupler design, the output power should be equally split between the two arms (50/50) with minimal overall losses. In a second design, the output splitting ratio should be 90/10. The general geometry of a directional coupler is shown in Figure 1.

Tasks

1. **Literature search.** The first task is to familiarize with the theory behind directional coupling. This should give you an idea of the geometry that a directional coupler should have, and which parameters are critical to achieve the specified goals.
2. **Single mode waveguide.** Directional couplers are based on guided wave, Si/SiO_2 waveguides for this project. Therefore, the design of a single mode Silicon waveguide (at λ = 1310 nm) using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis) is the first design goal. The material of the core is Silicon, while the cladding is SiO_2.
3. **Bending losses**. Bending of the waveguide is required for the coupling section. The bending has to be optimized for the smallest radius with a minimal loss per bending. The structure can be symmetric, so only one bending radius optimization is needed.
    a. **NOTE: if you want, you could do asymmetric structure, but that would require 2 bend loss calculation. However, if you have an idea and good reason to do it, you are welcome to try!**
4. **Coupling section**. The entire structure should be modeled, and the coupling section should be optimized for the specified power ratios.
    a. **NOTE**: Sweeping the length of the coupling section and/or distance between the waveguides and plot the two output power can reveal the ideal coupling section parameters.
5. **Convergence**. The final structure should be tested with smaller mesh size.
6. **Wavelength**. Check how the coupling section behaves for different wavelengths from 1450-1650 nm.
7. **90/10 directional coupler**. After the wavelength test, the design should be adapted for the power ratio in the two arms to be 10%/90%. Again, this design will be checked for its coupling spectrum.
8. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).
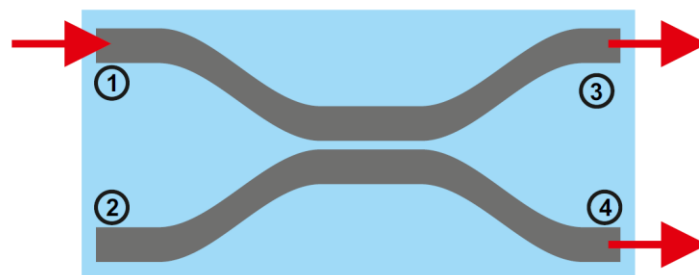

Figure 1: An illustration of a directional coupler.

2- Ring Resonator (2-3 Students)

Goal

The goal of this project is to design and simulate a Silicon-on-Insulator optical ring resonator. The device should act as a notch filter at the operating wavelength of 1550nm. In a second step, a cascaded multi ring resonators device has to be designed. In this configuration, rings with varying radii in series have to form an add/drop circuit with 50/50 power distribution. Fig. 2 shows an implementation example. The general geometry of an add/drop ring resonator and cascaded resonators are shown in Figure 1.

Milestones

1. **Literature search.** The first task is to familiarize with the theory behind ring resonators. The most important is to answer to questions of which parameters are playing the crucial roles. You should first calculate the ring parameters (radius) for the required resonance wavelength.

2. **Single Mode Waveguide.** Design a single mode Silicon waveguide (at λ = 1550 nm), using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis). The material of the core is Silicon, while the cladding is air.

3. **Ring Resonator.** Based on your calculation, the ring radius has to be optimized to have resonant behavior at 1550nm and minimal bending losses.

4. **Single Ring Filter.** The ring radius has to be further optimized not only to show resonance at 1550nm, but also have a Q factor and a FWHM of about 10'000 and 10nm, respectively. Additionally, the coupling between the waveguide and ring resonator has to be such that the extinction ratio is above 20dB.

5. **Cascaded Structure.** An add/drop filter design with cascaded ring resonators in series has to be designed. The power distribution should be optimized to 50/50 at the two forward outputs.

6. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).
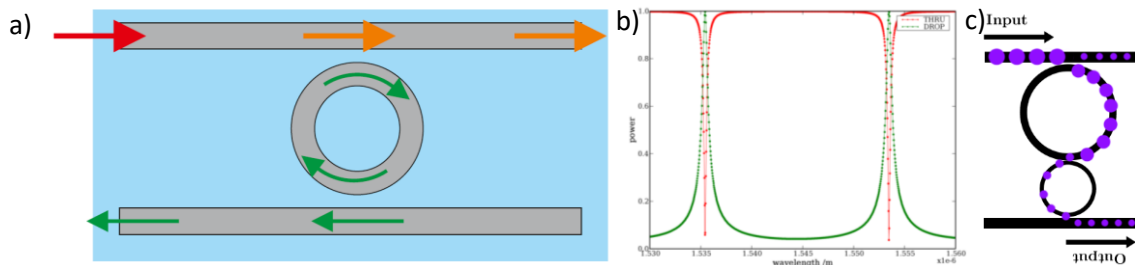

Figure 2: (a) The ring resonator structure is illustrated. (b) The expected transmission and reflection coefficients over a variation of the wavelength. (c) An illustration of two cascaded ring resonators.

3- Delay Interferometer (3 students)

Goal

The goal of this project is to design and simulate a delay interferometer based on a Mach-Zehnder configuration for the purpose of verifying the coherence of a light source. This project can be divided into two main parts. One is the design and optimization of the coupling section, which is the splitting and interference section of the interferometer. Second, an asymmetric delay line should be designed and optimized to induce a π-shift in one arm of the interferometer. Both designs should have minimal losses and be optimized for the operating wavelength of 1550nm. The general geometry of a Mach-Zehnder interferometer is shown in Figure 3.

Task

Milestones

1. **Literature search.** The first task is to familiarize with the theory behind Delay Interferometers, especially the Mach-Zehnder configuration. Important is also the theory about directional coupling. You can use theory to calculate the delay line length to achieve a specific relative phase shift.
2. **Single mode waveguide.** Next is to design a single mode Silicon waveguide (at λ = 1550 nm), using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis). The material of the core is Silicon, while the cladding is air. In both, the coupling scheme and the delay line, the waveguide dimension should be the constant.
3. **Splitting scheme.** A splitting scheme based on a directional coupler should be implemented with a splitting ratio of 50/50. The coupling length can be reduced by optimizing the waveguide separation. This reduces the overall dimension of the device. Similarly, the bending curvature should be optimized for low bending with minimum losses.
4. **Interference scheme.** For the coupling (interference), two options are possible. First option, you can use the same scheme as used for your splitting scheme. Based on the interference, the power will be split between the two outputs. Second option, you design a multi-mode interferometer (MMI), such as to observe interference behavior on a single output (a bit more effort, but you can collaborate with the MMI group).
5. **Symmetric interferometers**. In a first step, design and optimize the delay line with symmetric dimension. This step is useful to optimize the bending radius of the two arms. Note that, this should result in a constructive interference at the output.
6. **Asymmetric Delay line.** Based on your calculation, optimized the delay line length for a π-shift (wavelength of 1550nm). Do not forget the additional phase delay in the reference line!
7. **Putting the things together**. In the last step, the entire structure has to be assembled, and the π-shift should be verified by calculating the extinction ratio on the output lines (> 10dB). If possible, make a sweep of the delay line. With this, you can plot the output power as a function of the relative phase shift.
8. **Convergence**. The final structure should be tested for the mesh size.
9. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).
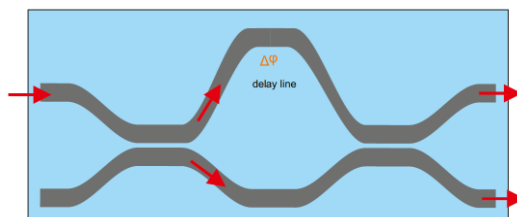

Figure 3: A Mach-Zehnder interferometer configuration is shown.

4- Bragg Mirror (2-3 students)

Goal

Goal of this project is to design a Bragg mirror with specified reflectivity R > 90% at the operating wavelength of λ = 1550 nm. In the first design, only one wavelength will be considered. In the second run, a parametric sweep of wavelengths will be performed, so that 3dB (half of the power) reflectivity can be achieved over a range of wavelengths. Figure 4 illustrates a general geometry of a Bragg reflector.

Milestones

1. **Literature search.** The first milestone is to familiarize with the theory behind the Bragg mirror. The most important is to answer to questions which parameters are playing the crucial role.
2. **Single mode waveguide (COMSOL).** The following milestone is to design a single mode Silicon waveguide (at λ = 1550 nm), using the eigenmode solver of COMSOL. The material of the core is Silicon, while the cladding is SiO$_2$.
3. **Infinite Bragg mirror.** The next milestone is to perform theoretical calculations of the infinite Bragg mirror (2 physical dimensions are infinite), so the starting design points (number of periods, filling factor and period) for COMSOL simulations could be chosen (see Figure).
4. **COMSOL simulation of the mirror.** Once the initial parameters are known, the Bragg mirror should be simulated in COMSOL with the following goals:
   a. **Reflection coefficient > 90% for $\lambda_c = 1550$ nm**
   b. **Reflection coefficient >3dB for $\lambda_c \pm 100$ nm (this result is optional)**
5. **Convergence test.** To make sure that results are realistic, you should simulate for different mesh sizes.
6. **Report and presentation.** The results of the project will be presented in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).
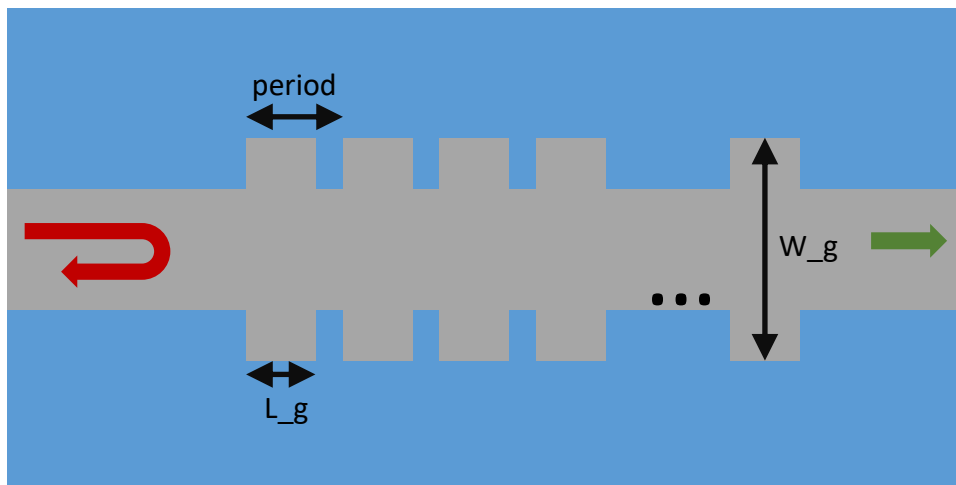

Figure 4: The Bragg mirror. The most important design parameters are the period, filling factor (L_g/period) and the thickness of the Si grating part (W_g). Number of periods N will determine the sharpness and strength of the mirror.

5- Multimode Interferometer (2-3 Students)

Goal

Goal of this project is to design a multi-mode interferometer (MMI) with specified output coupling operating at the wavelength of λ = 1310 nm. In the first design, a 1x2 configuration is considered with an output ratio of 50:50. In the second run, the MMI should be optimized for an output ratio of 10:90. The general geometry of a MMI is shown in Figure 5.

Task

1. **Literature search.** The first task is to familiarize with the theory behind the MMI. The most important is to answer to questions which parameters are playing the crucial role. Based on the theory you can estimate initial parameters.
2. **Single mode waveguide (COMSOL).** The following task is to design a single mode Silicon waveguide, using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis). The material of the core is Silicon, while the cladding is SiO_2.
3. **MMI.** Based on the estimated dimensions, you can design and simulate the MMI. From this point you can optimize the structure for a 50/50 coupling ratio. Make sure the overall losses are be below 1dB and minimize the reflections.
   a. **Note.** You can start by simulating a long interference section, and optimize only the width of the MMI. This allows you to then clearly see the 50/50 and 90/10 interference lengths.
   b. **Note.** You can use tapers to reduce scattering losses and reflection.
4. **Convergence test.** The results should be tested for different mesh sizes.
5. **Second MMI.** The 1x2 MMI should be optimized for the new goal:
   a. **Output ratio of 10:90 for** $\lambda_c = 1310$ nm
   b. **Overall losses below 1dB**
6. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).
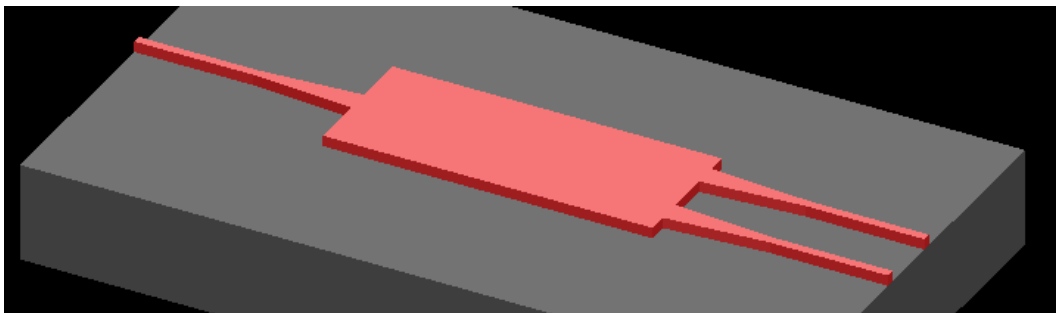

Figure 5: Multimode interferometer 1x2 configuration.

6- Waveguide to Fiber Coupling (3 Students)

Goal

One of the methods to extract the light from an optical chip is to use butt coupling from the end of the chip to a fiber that is held at a distance. Goal of this project is to design a taper to ease butt coupling from a Silicon waveguide to optical fiber with specified coupling operating at the wavelength of λ = 1550 nm. Also a dielectric layer (Silicon Dioxide) is used to facilitate the coupling. The general geometry of such a coupling structure is shown in Figure 1.

Task

1. **Literature search.** The first task is to familiarize with the theory behind the butt coupling. The most important is to answer to questions which parameters are playing the crucial role. Based on the theory you can estimate initial parameters.
2. **Single mode waveguide.** The input waveguide geometry is specified as in the figure. The following task is to check how many modes are supported by the waveguide, using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis).
3. **Taper & Low Index section.** Based on the estimated dimensions, you can design and simulate taper and the low index section. As light comes from the waveguide into the taper, the effective index of the mode will go down and the mode will couple into the dielectric section with lower refractive index. From that point, extracting light into the air and coupling it into a fiber would be easier with the correct geometry. And the structure can be optimized for 5dB coupling loss. Make sure the overall losses are as low as possible and minimize the reflections.
   a. **Note.** You can start by simulating a tapered Silicon waveguide and observe how light couples into the outside region. Then you can decide which parameters make difference for the coupling.
   b. **Note.** When using ports, check which mode(s) are launched/absorbed and make sure the output port will accept the incident light. In other words, the polarization of fiber mode should be aligned with the incident mode from the input.
4. **Convergence test.** The results should be tested for different mesh sizes.
5. **Wavelength**. Check how the coupling section behaves for different wavelengths from 1450-1650 nm.
6. **Specifications**
   a. $core\ diameter = 8\ \mu m$, $\quad n_{core} = 1.44$, $\quad n_{clad} = 1.43$,
   b. $waveguide\ width = 200\ nm$, $\quad gap > 5\ \mu m$,
   c. $S_{11} < -30\ dB$, $\quad S_{21} > -5\ dB$
7. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).
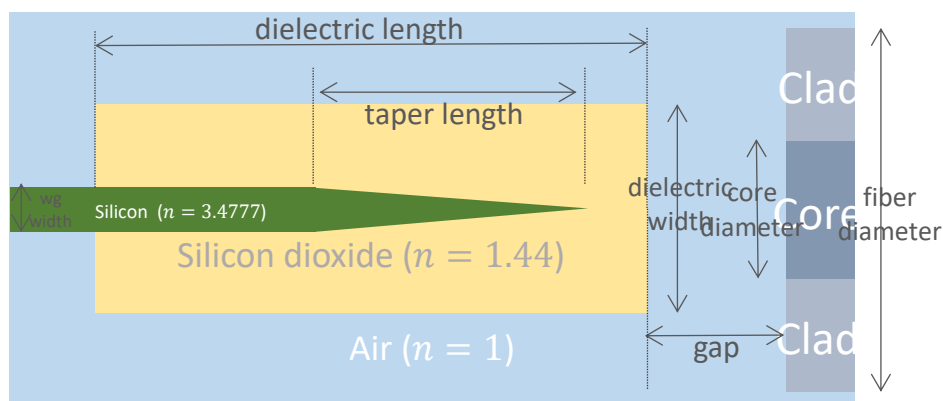

Figure 6: Butt coupling configuration (top view)

7- Waveguide to Waveguide Coupling (3 Students)

Goal

On optical chips sometimes different types of waveguides are used and light needs to couple from one type to the another one. Goal of this project is to design a taper/grating to facilitate coupling from a higher index (Silicon) waveguide to a lower index (Silicon Nitride) waveguide at the wavelength of λ = 1310 nm. The general geometry of such a coupling structure is shown in Figure 1.

Task

1. **Literature search.** The first task is to familiarize with the theory behind the tapering. The most important is to answer to questions which parameters are playing the crucial role. Based on the theory you can estimate initial parameters.

2. **Single mode waveguide.** Both the input and the output waveguide geometries are specified as below. The following task is to check how many modes are supported by each waveguide, using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis). The material of the core is Silicon on the input waveguide, and Silicon nitride for the output waveguide (lower one) while the cladding is SiO$_2$.

3. **Taper & Low Index section.** During the fabrication, it is possible to adjust the distance between the waveguides, also the geometry of the taper. Based on the estimated dimensions, you can design and simulate the taper between the waveguides. As light comes from the waveguide into the taper, the mode will enlarge, its effective index will go down and the mode will couple into the waveguide with lower refractive index. From this point, you can optimize the structure for low coupling loss and low reflections.

   a. **Note.** You can start by simulating a tapered Silicon waveguide and observe how mode shape and effective index changes. Also, you can change the distance between the waveguides to observe the effects.

   b. **Note.** When using ports, check which mode(s) are launched/absorbed and make sure the output port will accept the incident light. In other words, the polarization of output mode should match the incident mode from the input.

4. **Convergence test.** The results should be tested for different mesh sizes.

5. **Wavelength**. Check how the coupler behaves for different wavelengths from 1450-1650 nm.

6. **Specifications**

   a.

      i. $D_{wg_1} = 100 \, nm,$ $\qquad D_{wg_2} = 400 \, nm$
      ii. $gap > 10 \, nm,$ $\qquad taper \, length < 7.5 \mu m$
      iii. $S_{11} < -40 dB,$ $\qquad S_{21} > -0.3 dB$

   b. Same specifications as in part a with a sub-wavelength grating instead of a taper. Determine the fill factor and period of grating to facilitate the coupling.

7. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).
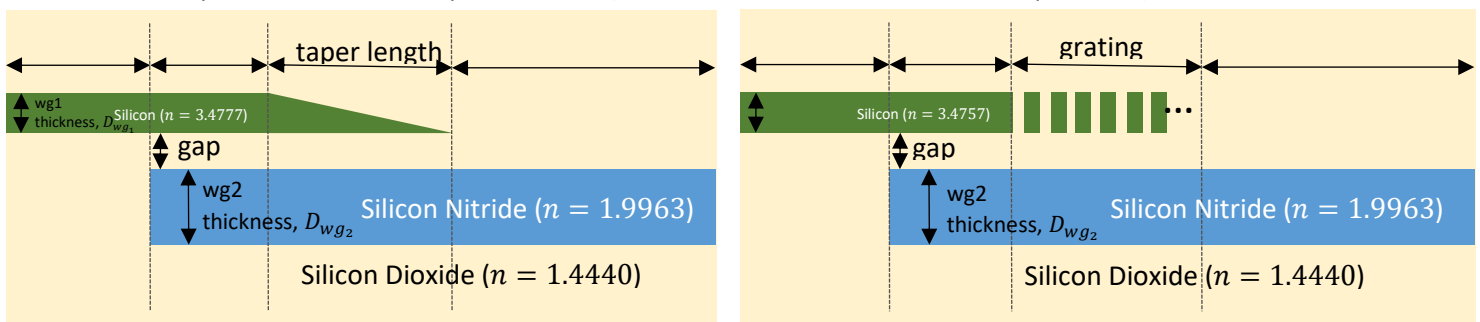

Figure 7: Coupling between waveguides (side view). Left: By tapering, Right: Using grating section

8- Waveguide Crossings (2-3 Students)

Goal

The goal of this project is to design a waveguide crossing with minimal transmission losses operating at the wavelength of λ = 1550 nm. In the first design, shown in Figure 8.a), a 2 (1x1) WG crossing configuration is considered with maximal transmission into the straight waveguide. Additionally, a 2x2 WG crossing configuration can be evaluated for maximal transmission and minimal crosstalk.

Task

1. **Literature search.** The first task is to familiarize with state-of-the-art waveguide crossings and the theory behind it. Based on the theory you can estimate initial parameters.
2. **Single mode waveguide (COMSOL).** The following task is to design a single mode Silicon waveguide (at λ = 1550 nm), using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis). The material of the core is Silicon, while the cladding is Air.
3. **Simple crossing.** As a reference, a simple straight crossing is simulated.
   a. **Note.** Make use of symmetries when building the model.
4. **Expanding crossing.** Based on the estimated dimensions, you can design and simulate the crossing with mode expanders. From this point you can optimize the structure for a maximal S21 transmission. Make sure the overall losses are below 0.3 dB and minimize the reflections.
   a. **Note.** Try to minimize the free parameters of the mode expanders for a more simple design and sweeping.
5. **Convergence test.** The results should be tested for different mesh sizes to make sure that the mesh is fine enough in order to get accurate results.
6. **Wavelength test.** Check for the optical bandwidth of your crossing.
7. **2x2 WG crossing.** Include additional waveguides without mode-expanders at the appropriate positions to maximize the through transmission while keeping a compact design.
8. **Report and presentation.** The results of the project should be summarized in the form of a short report and a 15 minutes presentation (10 minutes talk and 5 minutes for questions).
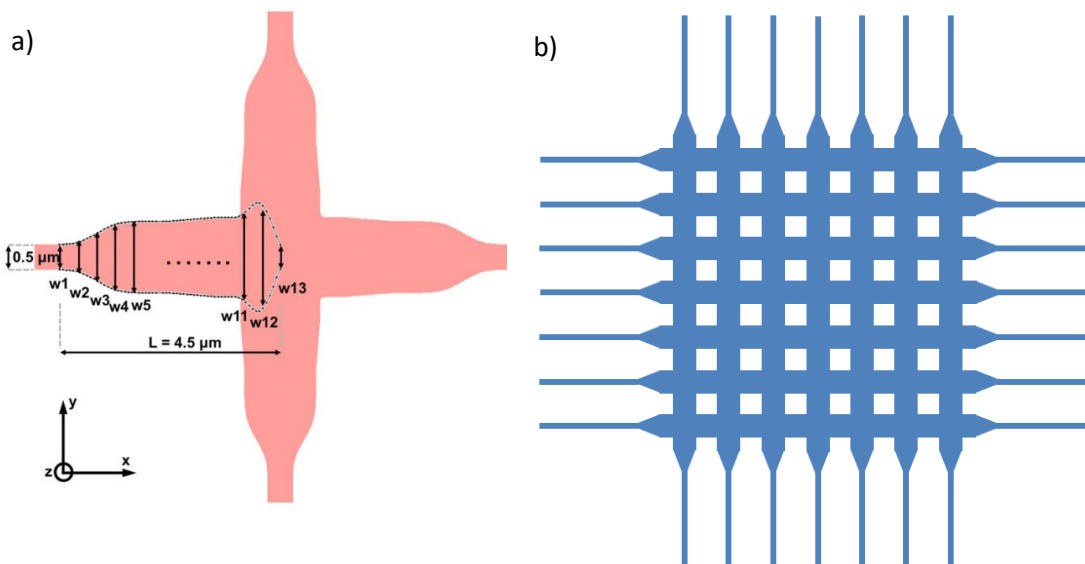

Figure 8: (a) A 2 waveguide crossing with mode expanders is shown (Ma, Yangjin, et al. "Ultralow loss single layer submicron silicon waveguide crossing for SOI optical interconnect." Optics express 21.24 (2013): 29374-29382).
(b) A Network of a 7x7 WG crossing is illustrated (Zhang, Yang, et al. "Ultralow-loss silicon waveguide crossing using Bloch modes in index-engineered cascaded multimode-interference couplers." Optics letters 38.18 (2013): 3608-3611).

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