Basic structures in photonic integrated circuits

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UNIVERSITAT POLITÈCNICA DE VALÈNCIA

NANOPHOTONICS TECHNOLOGY CENTER

Outline

- Waveguide bend
- Y-junction
- Directional coupler
- Multimode interference coupler
- Mach-Zehnder interferometer
- Ring resonator
- Fiber coupling structures

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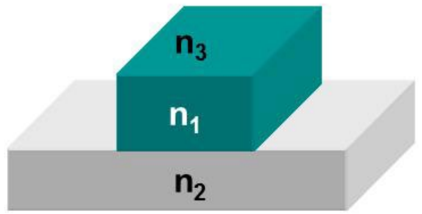
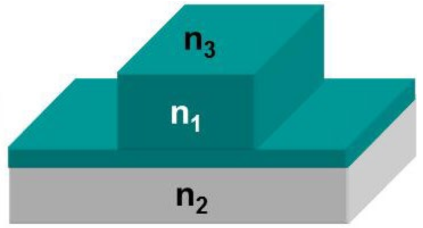
Photonic waveguide

WORKING PRINCIPLE

- Confinement and guiding of light is achieved by **total internal reflection**
  - Refractive index of core higher than refractive index of claddings
  - Light confinement in the transversal dimensions of the propagation direction
  - Higher contrast index → stronger light confinement → smaller size of the waveguide
- **Modes of the waveguide**: finite set of propagation modes
  - Different for each polarization (TE and TM)
  - Singlemode transmission is usually desired (m_{max}=1)
- **Singlemode** condition
  - Depends on the index contrast, waveguide dimensions, polarization and wavelength



Stripe/ridge waveguide

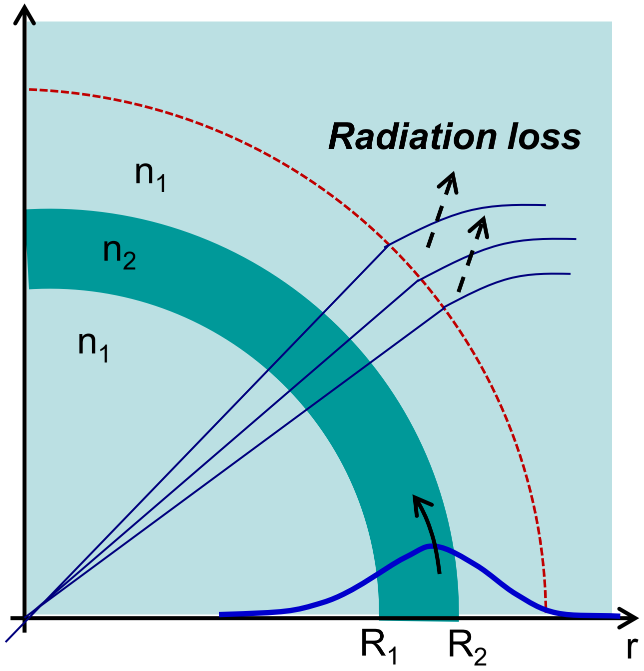


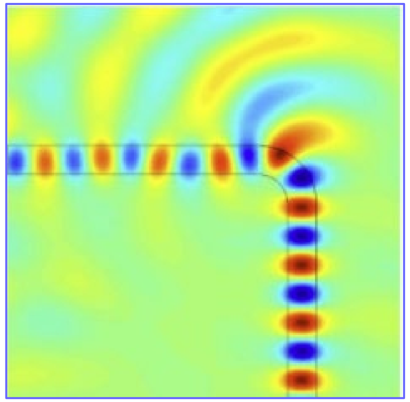
Rib waveguide

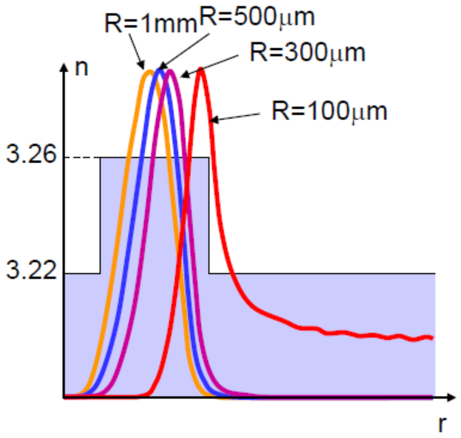
Waveguide bend

WORKING PRINCIPLE

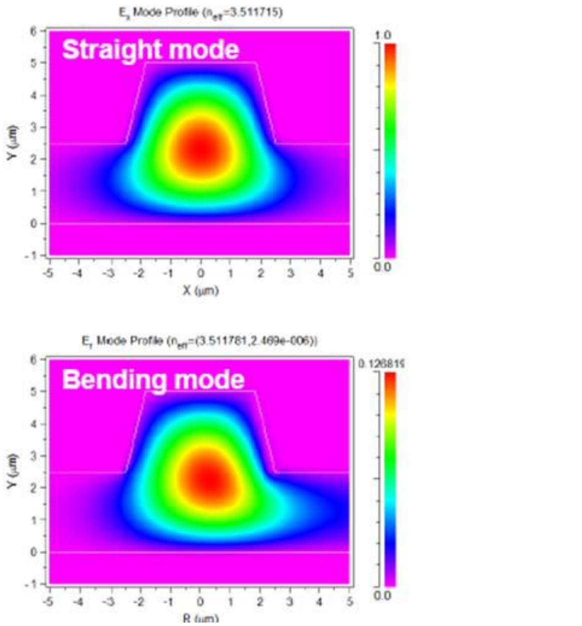
- Bending of a waveguide leads to optical loss as the mode propagates around the bend due to **radiation loss** from its modal field in the cladding
  - Evanescent light at the outer cladding must propagate more quickly than light at the inner cladding to keep the phase relationship across the mode
  - At a certain radius, light would need to exceed the velocity of unguided light → this is not possible so light is radiated and lost from the mode







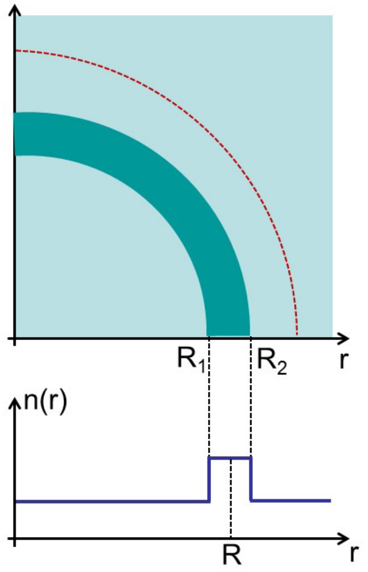
- Bend mode is shifted outwards
- Higher scattering losses due to roughness at the outer interface
- Optical losses at transition due to mode profile mismatch



Waveguide bend

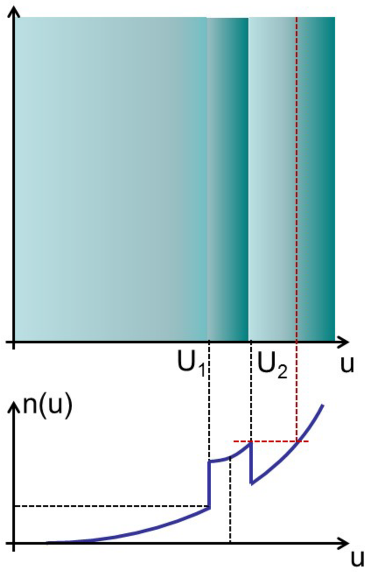
DESIGN PARAMETERS

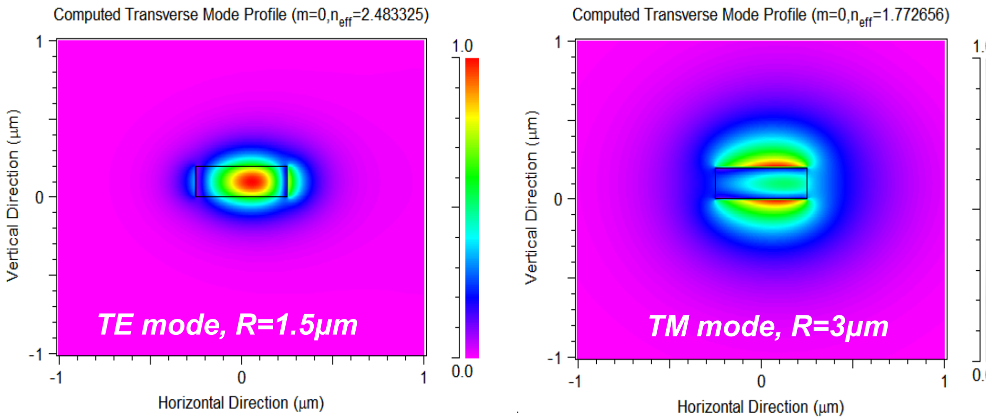
- The design parameters are:
  - **Radius** to minimize radiation loss
  - **Straight-to-bend interface** to minimize mode profile mismatch loss
- Conformal transformation method
  - An equivalent index profile is calculated which allows to obtain the mode profile and bend losses by using standard mode solvers
  - Design depends on polarization, index contrast and waveguide geometry



$$\boxed{n(u) = n(r)e^{u/R}}$$

$$r = Re^{\frac{u}{R}}$$





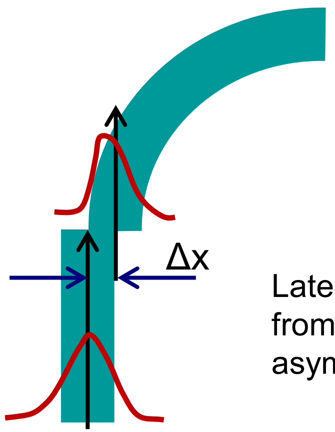
M. Heiblum et al., "Analysis of curved optical waveguides by conformal transformation," *IEEE J. Quantum Electron.*, no. 2, pp. 75–83, 1975

Waveguide bend

DESIGN PARAMETERS

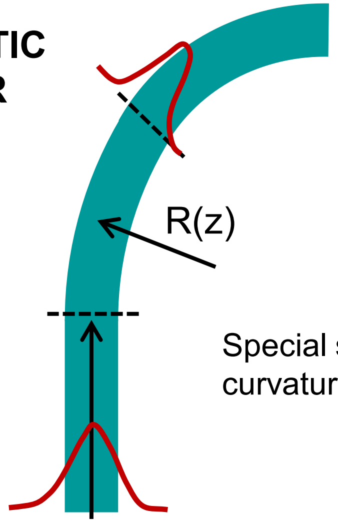
- Straight-to-bend transition
  - Optical loss at transition **unless the bend radius is large**
  - Two main approaches to minimize loss: lateral offset and adiabatic taper

LATERAL OFFSET



Lateral shift for efficiently coupling from the symmetrical to the asymmetrical mode profile

ADIABATIC TAPER



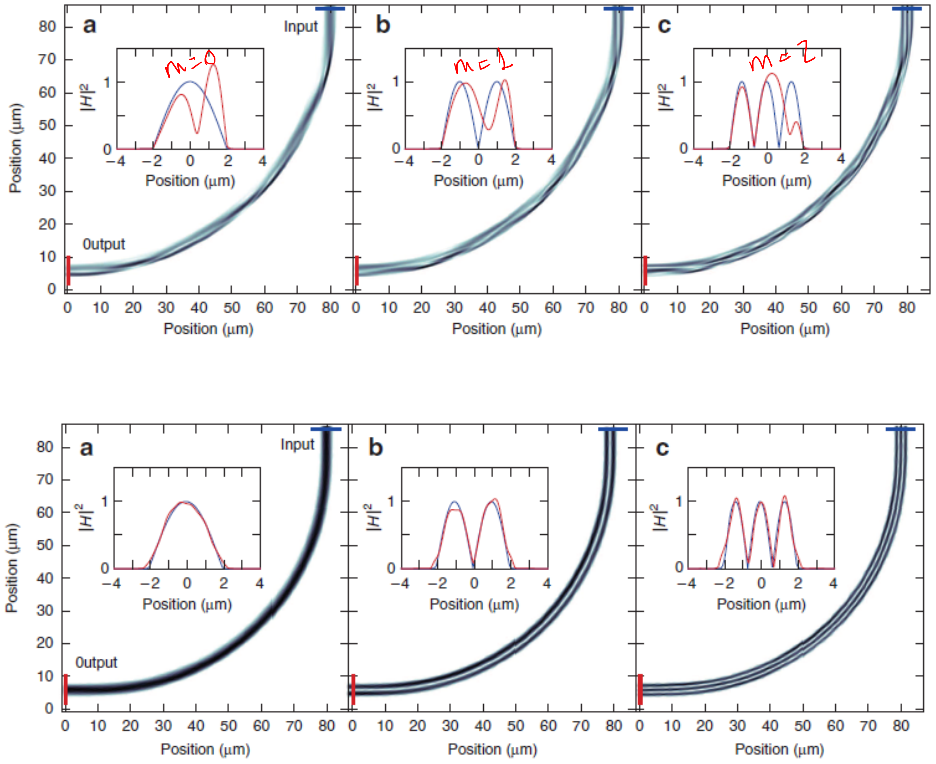
Special section where the curvature is gradually changed

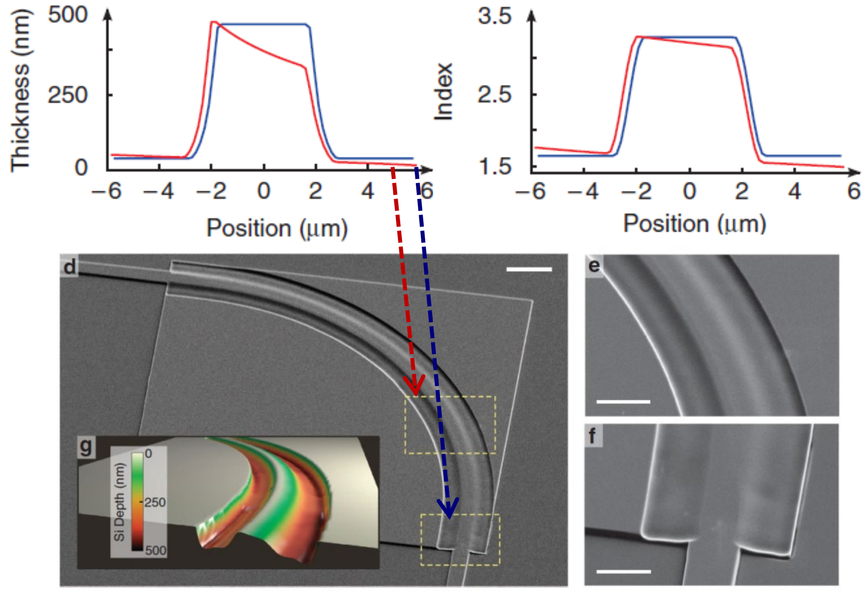
Lateral offset provides more compact low-loss transitions but gives rise to **polarization and wavelength dependence** as well as **stronger sensitivity to fabrication deviations**

Waveguide bend

APPLICATIONS

- Optimized waveguide bend for multimode waveguides
  - Design to minimize inter-mode coupling
  - Each mode travels along the curve as it would on the straight waveguide





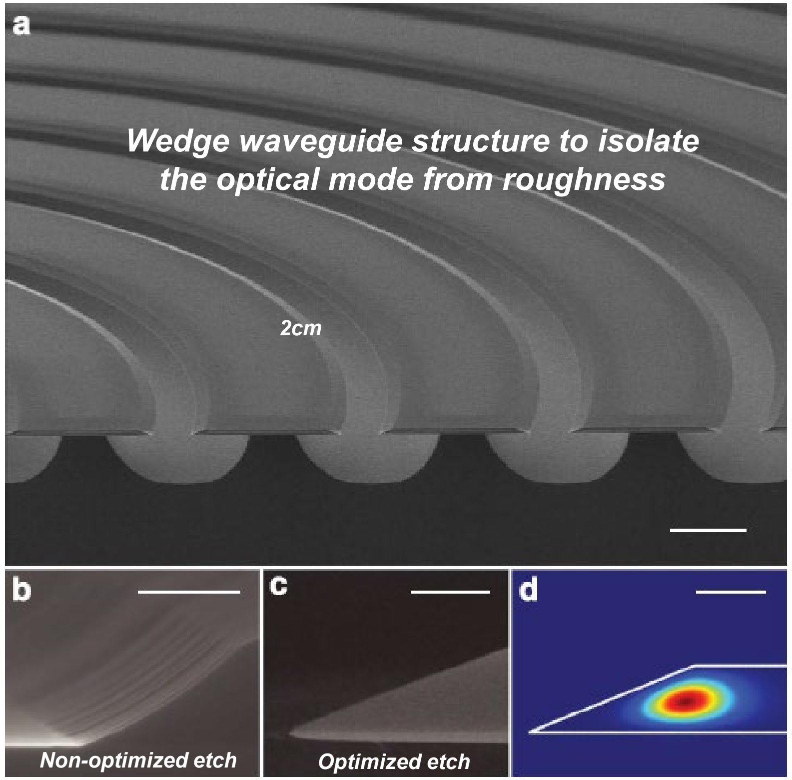
Refractive index and thickness are gradually changed along the bend

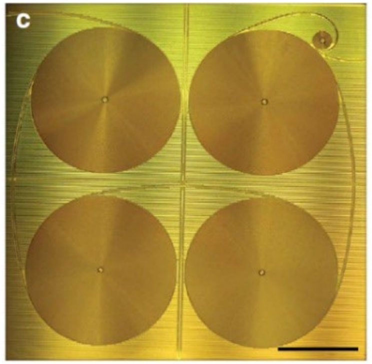
L. H. Gabrielli et al., “On-chip transformation optics for multimode waveguide bends,” *Nat. Commun.*, vol. 3, p. 1217, Jan. 2012

Waveguide bend

APPLICATIONS

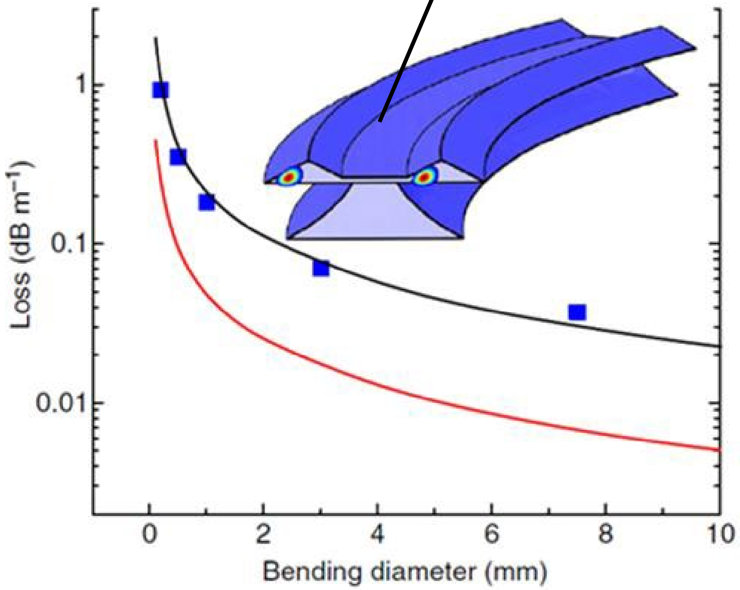
- Optimized waveguide bend for ultra-long distance transmission
  - Propagation losses of 0.08dB/cm → optical transmission in a **27 meter long** photonic waveguide





Interleaved Archimedean spirals

Modified design to provide both interior and exterior guiding



H. Lee et al., "Ultra-low-loss optical delay line on a silicon chip", *Nat. Commun.*, vol. 3, no. May, p. 867, Jan. 2012

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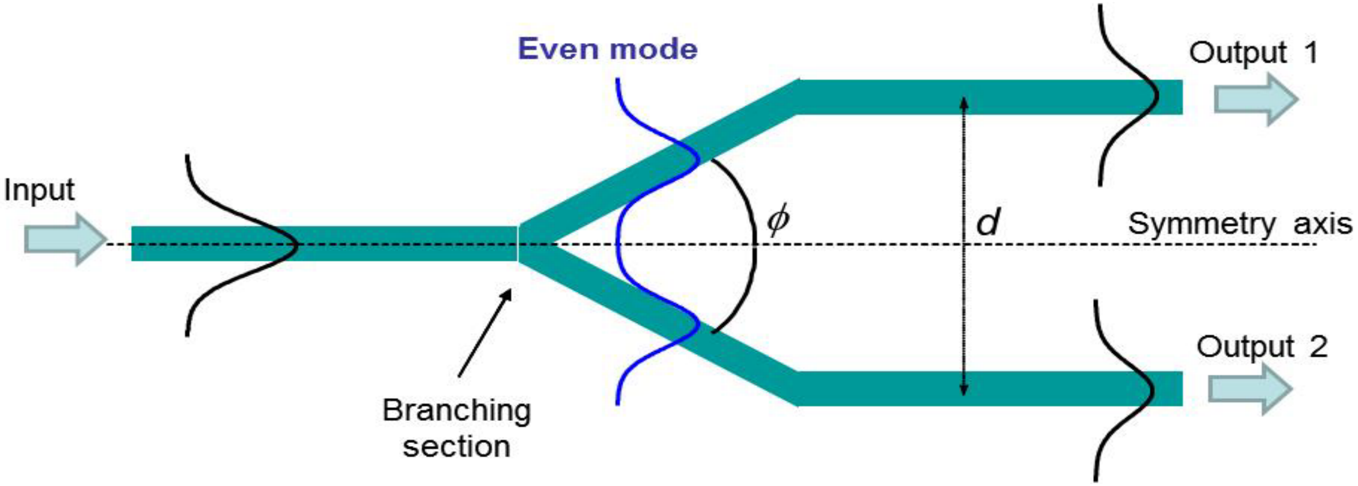
Y-junction

WORKING PRINCIPLE

- The Y-junction is a structure in which an input waveguide is divided into two output waveguides
- The **branching section** must be designed to achieve an efficient coupling from the guided mode in the input waveguide to the guided modes in the output waveguides



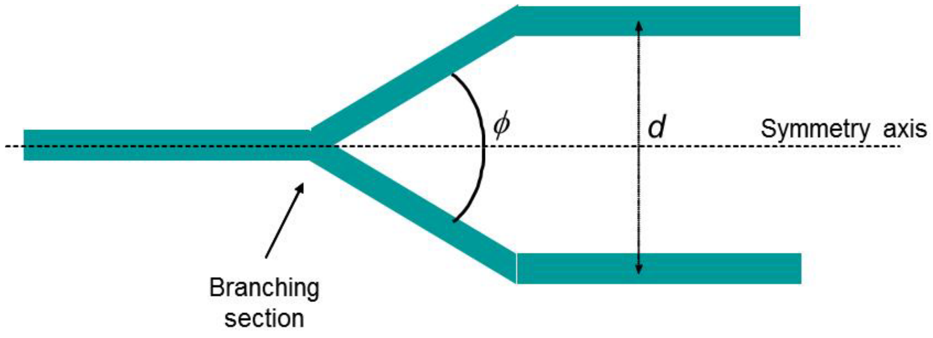
An inefficient coupling will give rise to **radiation losses** at the branching section

- The two output waveguides must be enough separated (d↑↑) to avoid coupling between them

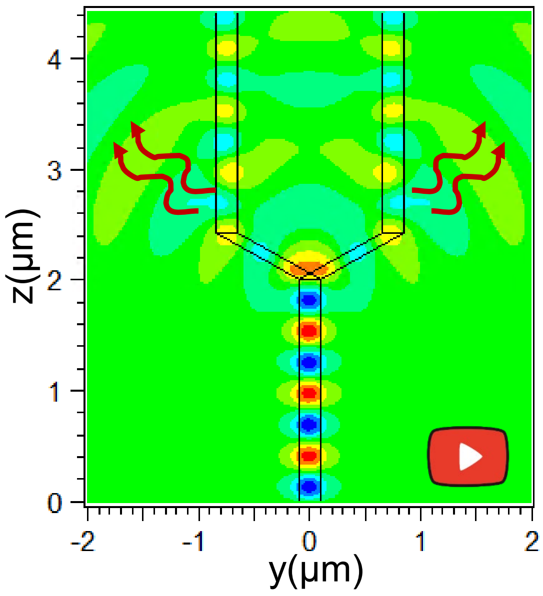
Y-junction

DESIGN PARAMETERS

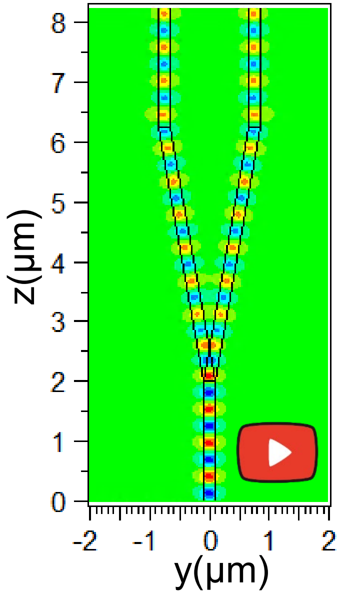
- The design is focused on the branching section
- The simplest approach is using an aperture angle (*Φ*)
  - A larger aperture angle will result in a more compact structure but with radiation losses
  - A higher contrast index will allow larger aperture angles without increasing radiation losses



The Y-junction performance is **broadband** and usually has a very **low polarization dependence**



Φ=60º



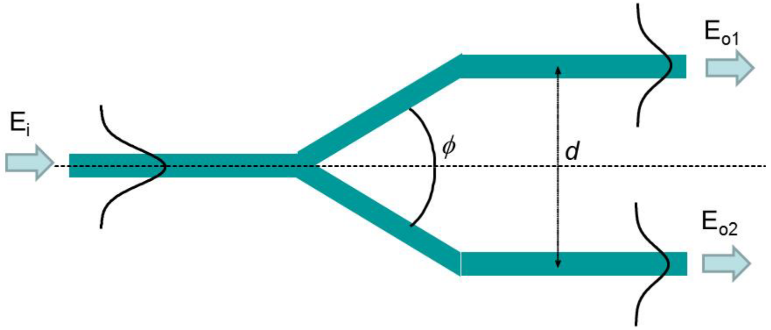
Φ=10º

Y-junction

APPLICATIONS

- The typical application is as power splitter/combiner
  - Identical input and output waveguides
  - Branching section is symmetric with respect to the horizontal axis

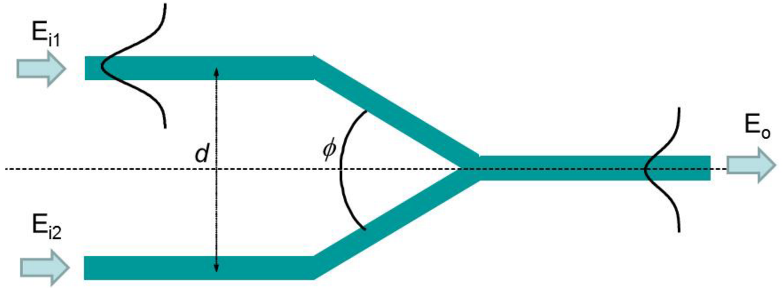
POWER SPLITTER



$$E_{o1} = E_{o2} = \frac{1}{\sqrt{2}} E_i$$

3dB power splitter

POWER COMBINER

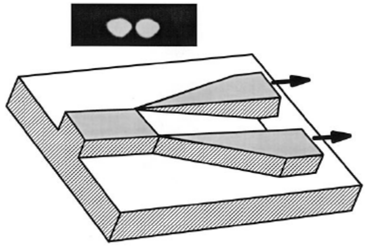


$$E_o = \frac{1}{\sqrt{2}} (E_{i1} + E_{i2})$$

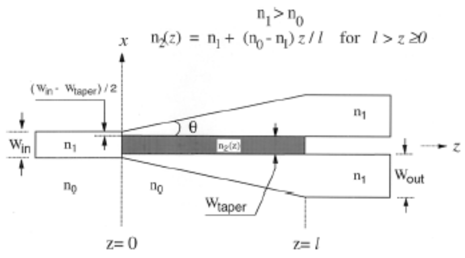
Y-junction

APPLICATIONS

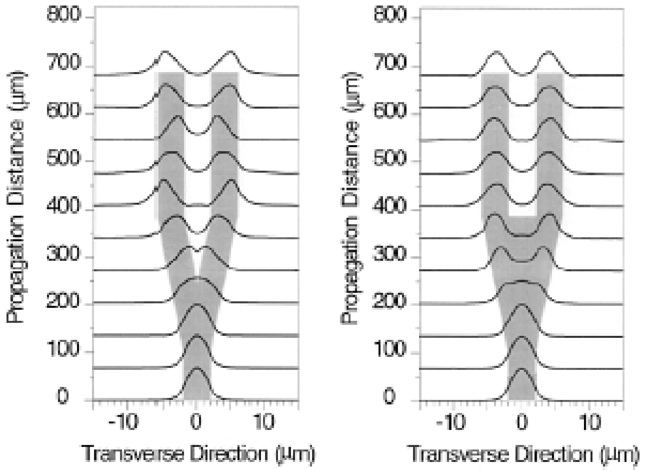
Novel designs with optimized branching region



Conventional Y-branch

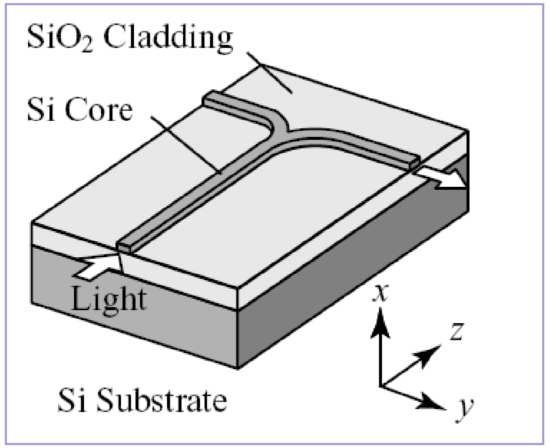


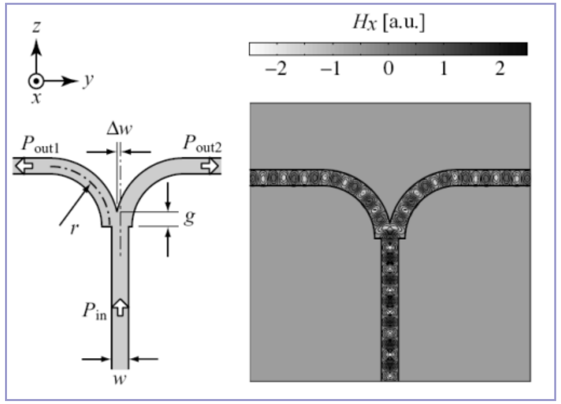
Index-Tapered Y-branch

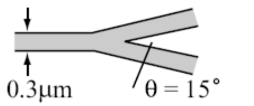
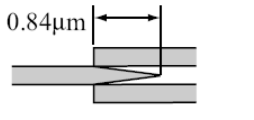
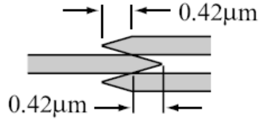
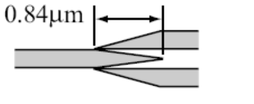
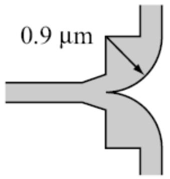
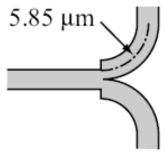


M.H. Hu et al., “A Low-Loss and Compact Waveguide Y-Branch Using Refractive-Index Tapering”, IEEE Photo. Tech. Lett., vol. 9, 203-205, 1997

Y-junction designs in silicon waveguides





	Schematic	Loss
(a)		2.0 dB
(b)		0.5 dB
(c)		0.5 dB
(d)		< 0.1 dB
(e)		0.3 dB
(f)		< 0.1 dB

A. Sakai et al., “Low Loss Ultra-Small Branches in a Silicon Photonic Wire Waveguide,” IEICE Trans. Electron. 2002

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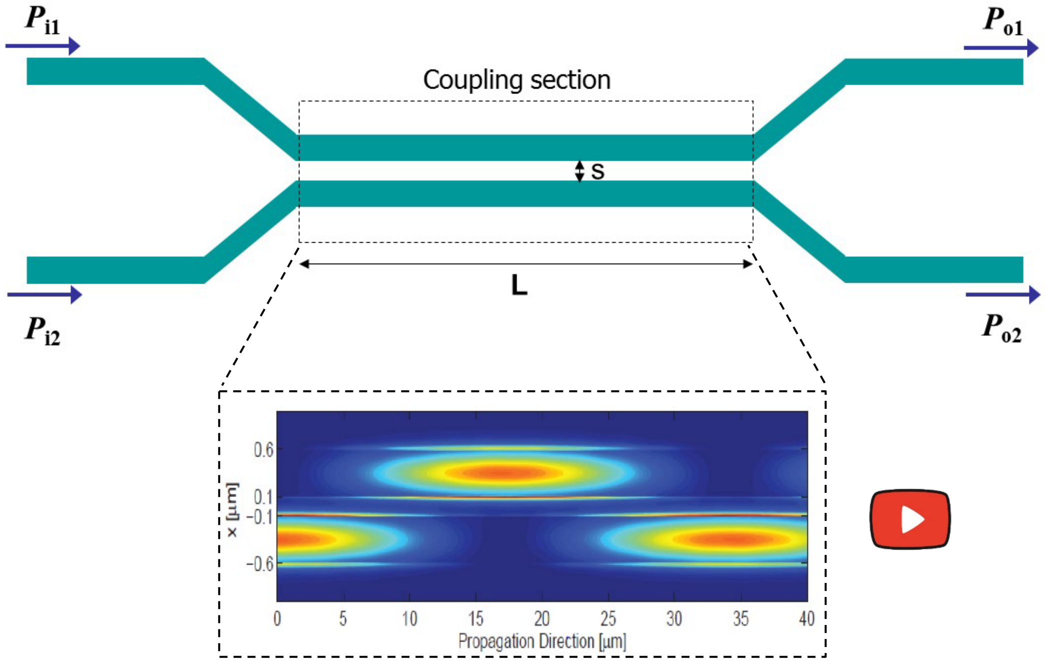
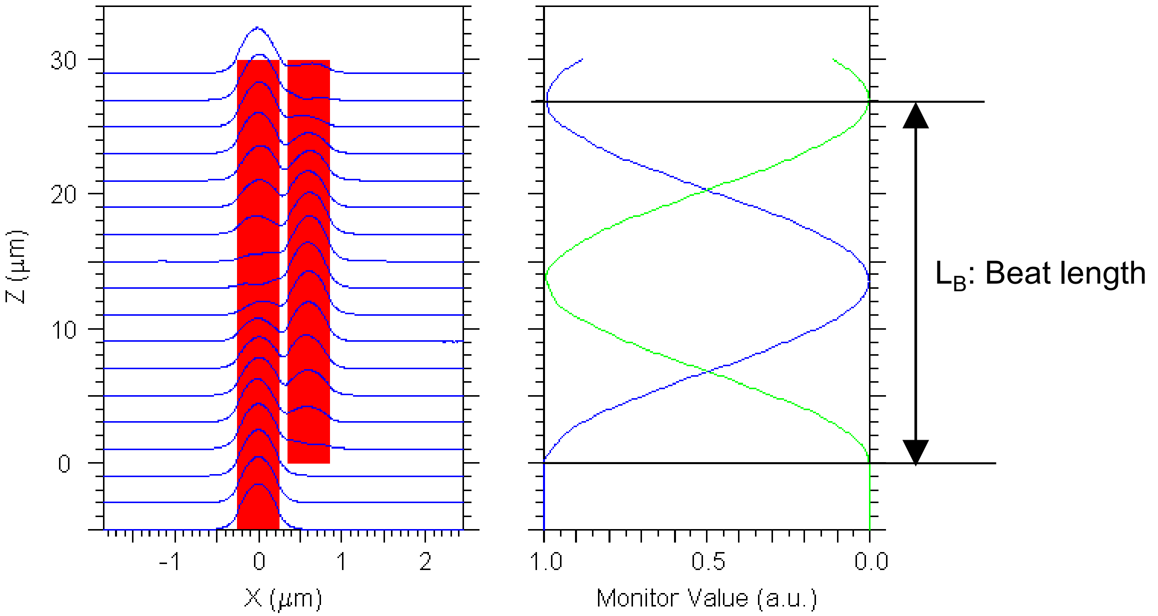
Directional coupler

WORKING PRINCIPLE

- The directional coupler consists of two photonic waveguides placed **closed together**
  - Most usual case → identical waveguides and singlemode
- A coupling section appears where a **periodic power exchange** occur between the two waveguides
- There are different theories to model the performance





Directional coupler

COUPLED MODE THEORY

- The coupling between the guided modes of the two waveguides is described by an amplitude factor

$$E_1(r) = A(z)E_o(x,y)e^{j\beta z} \qquad E_2(r) = B(z)E_o(x,y)e^{j\beta z}$$

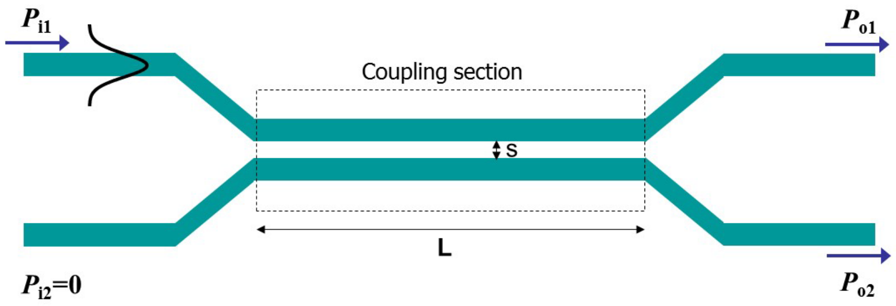
- The amplitude factors are calculated by resolving a set of coupled mode equations

$$\frac{\partial A(z)}{\partial z} = -j\kappa B(z) \qquad \frac{\partial B(z)}{\partial z} = -j\kappa A(z)$$

- If we assume that only one of the input waveguides is excited (P_{i2}=0)

$$\left.\begin{aligned} A(z) &= cos(\kappa z) \\ B(z) &= -jsin(\kappa z) \end{aligned}\right\}$$

κ: coupling coefficient



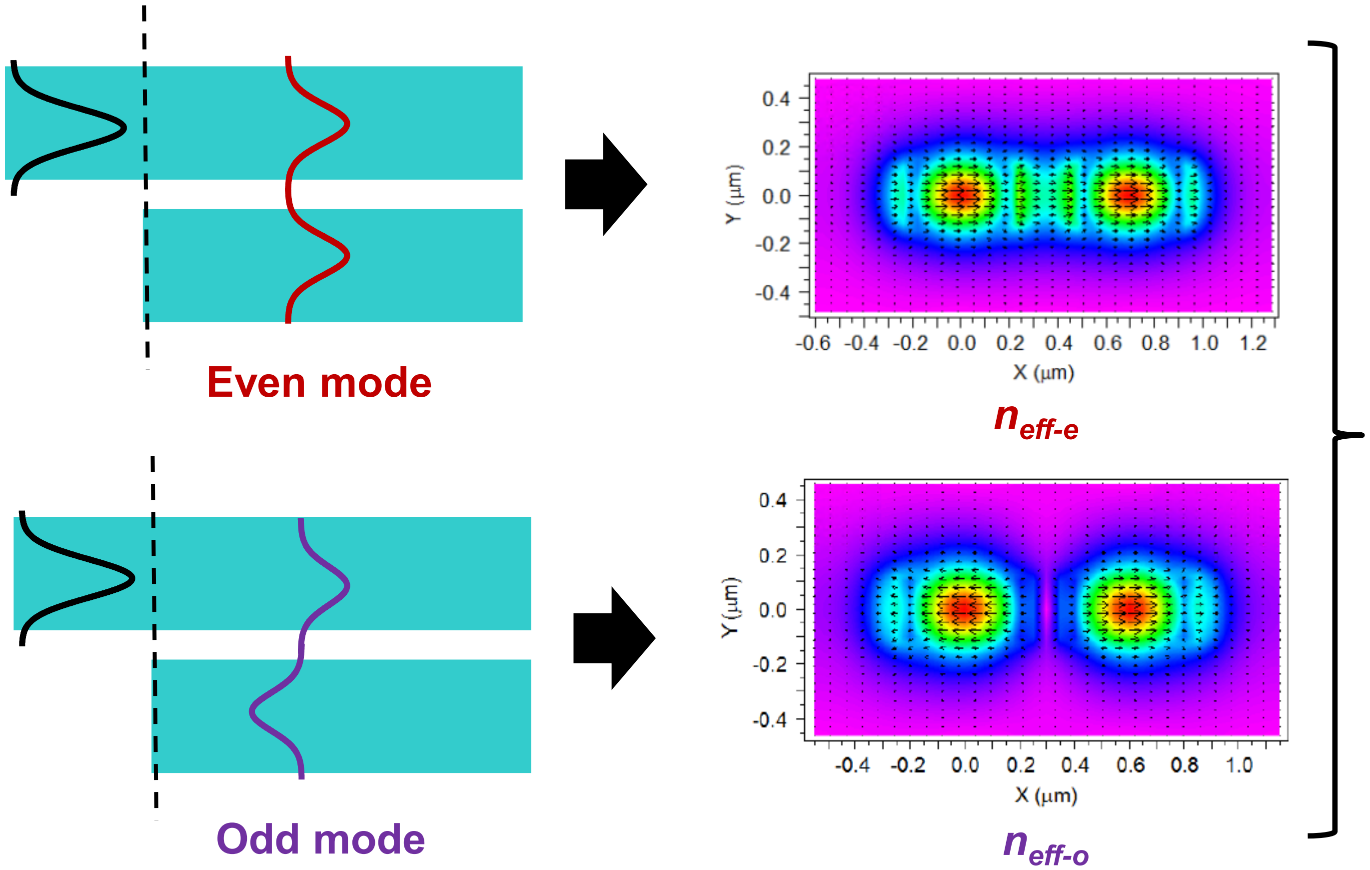
$$\boxed{P_{o1} = \cos^2\left(\frac{\pi L}{L_B}\right)P_{i1}}$$

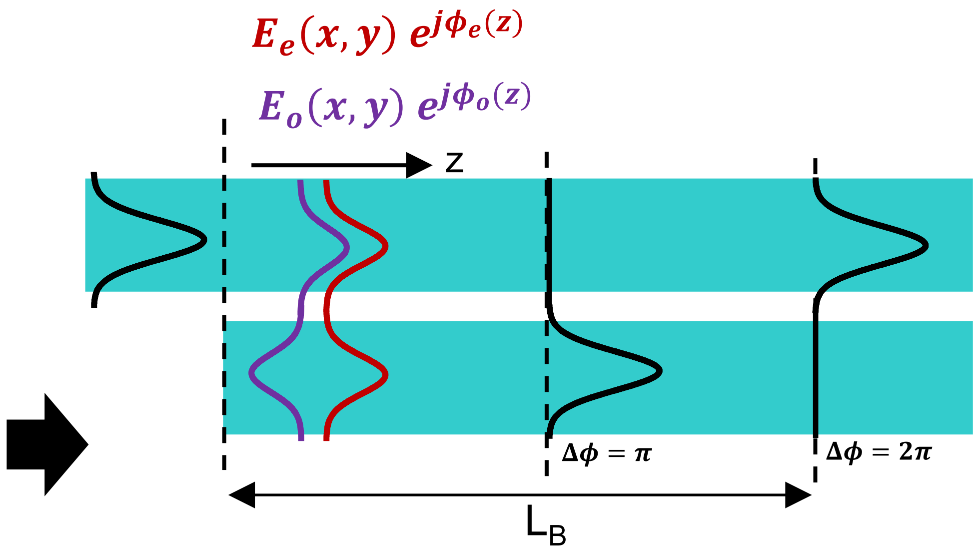
$$\boxed{P_{o2} = \sin^2\left(\frac{\pi L}{L_B}\right)P_{i1}}$$

Directional coupler

SUPERMODES THEORY

- The two coupled waveguides are regarded as one waveguide → two **supermodes** appear





$$\boxed{L_B = \frac{\lambda}{|n_{eff-e} - n_{eff-o}|}}$$

The beat length depends on the **wavelength** and **polarization**

Directional coupler

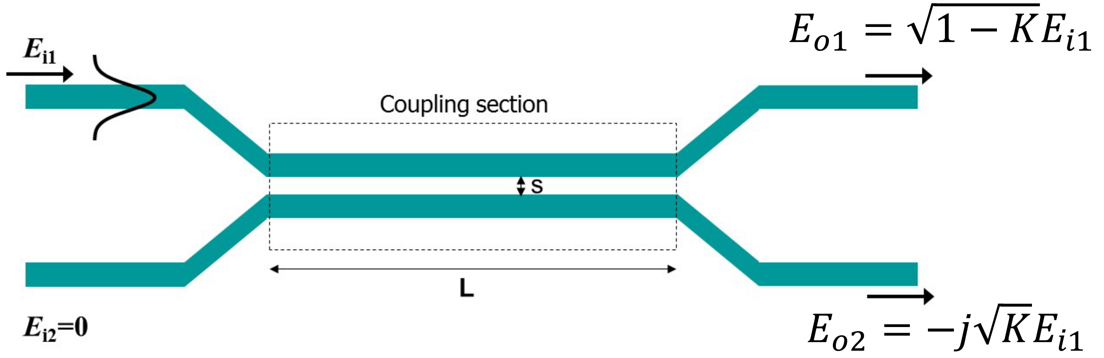
DESIGN PARAMETERS

- Coupling section:
  - **Waveguides separation** (*s*): determines L_B
  - **Waveguides length** (*L*)*:* determines the power at the output ports
- Transfer function

$$\begin{pmatrix} E_{o1} \\ E_{o2} \end{pmatrix} = \begin{pmatrix} \sqrt{1-K} & -j\sqrt{K} \\ -j\sqrt{K} & \sqrt{1-K} \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix}$$

$$\boxed{K = \sin^2\left(\frac{\pi L}{L_B}\right)}$$

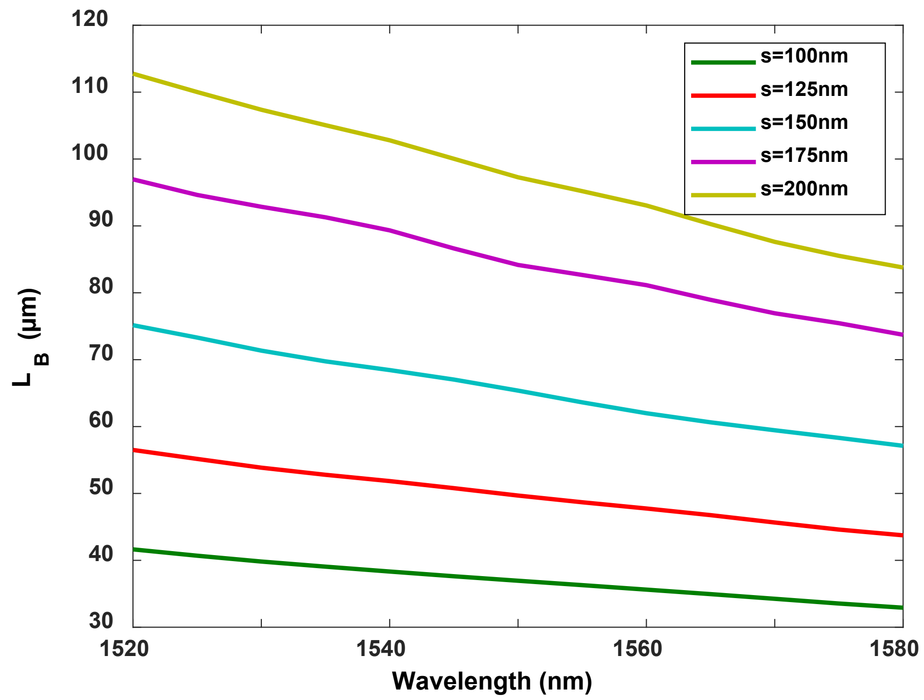
$$0 \leq K \leq 1$$



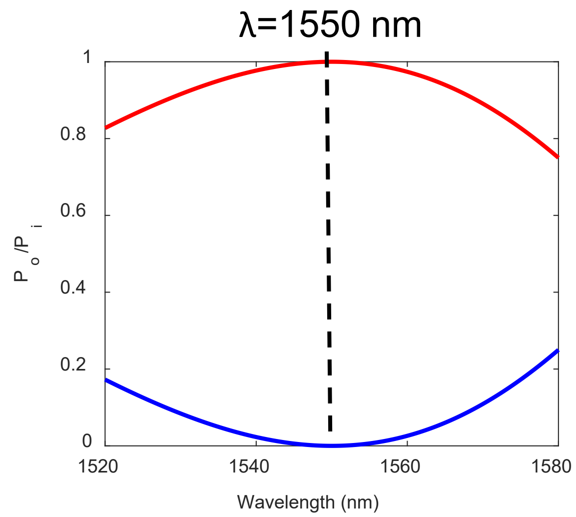
A relative **phase shift** of π/2 is introduced between the two output ports when signal is injected at only one of the input ports

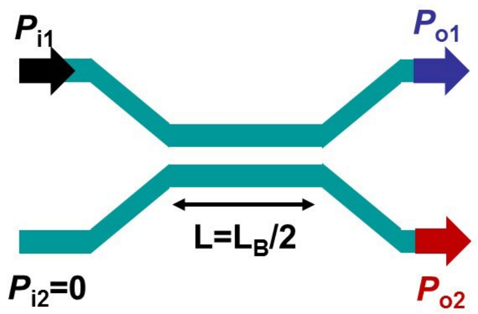
Directional coupler

DESIGN PARAMETERS



SILICON WAVEGUIDES
(λ=1550 nm, TE polarization)





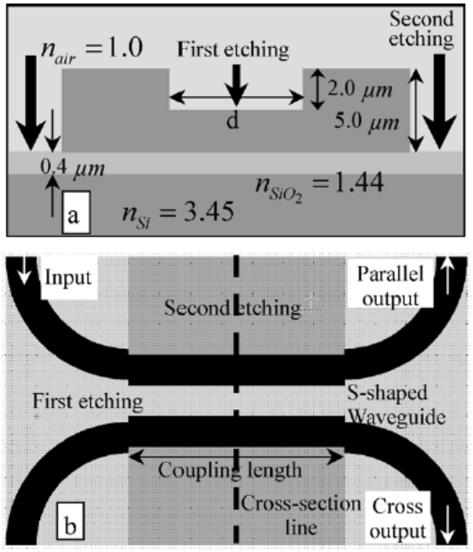
$$K = 1$$

- The coupling between waveguides will be stronger for lower separations (**s**↓↓) yielding to smaller beat lengths → **shorter directional couplers**
- The wavelength dependence of the beat length will also be smaller for closer waveguides → **directional couplers with broader optical bandwidth**

Directional coupler

APPLICATIONS

- **Independent of the wavelength**
  - 3dB power splitter/combiner (K=0.5)
  - 1:99 power splitter for monitoring (K=0.01 or K=0.99)



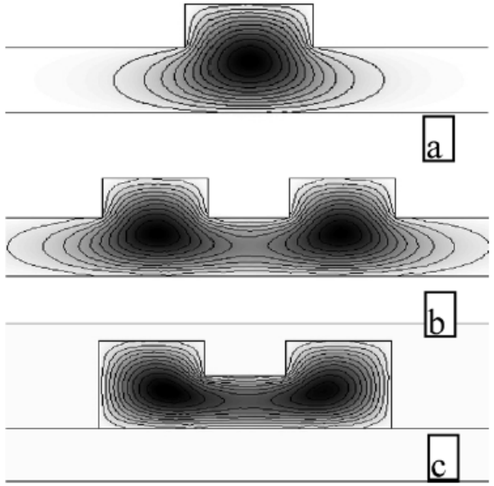
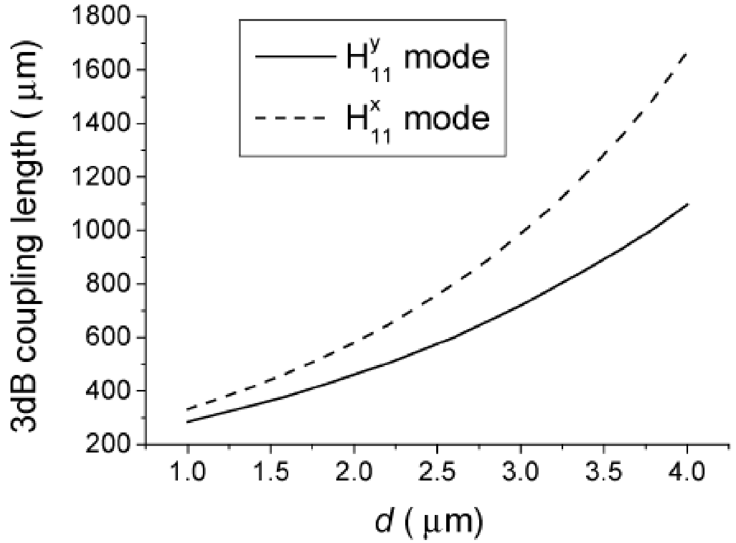


Fig. 2. H_{11}^{y} mode field profiles (H_y) of (a) the symmetrical rib waveguide, (b) the symmetrical coupler, and (c) the asymmetrical couplers, with $d = 3\ \mu$m.

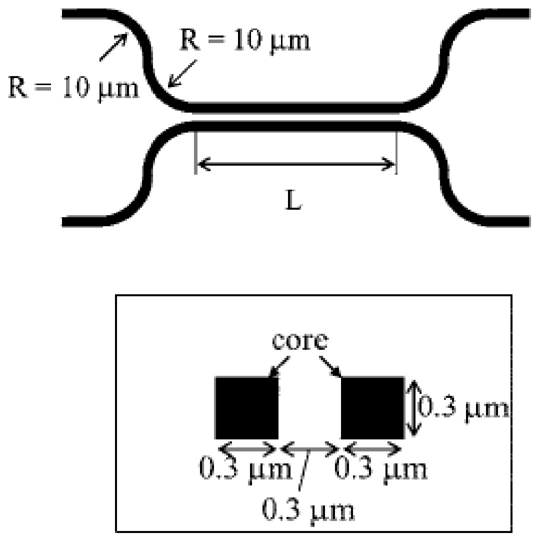


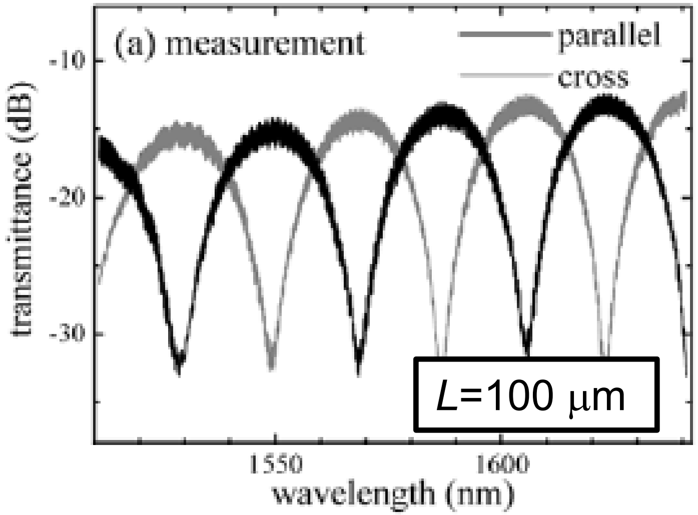
G. B. Cao et al., “Directional couplers realized on Silicon-on-Insulator”, IEEE Photonics Technology Letters Vol. 17, 8, pp.1671-1673, 2005.

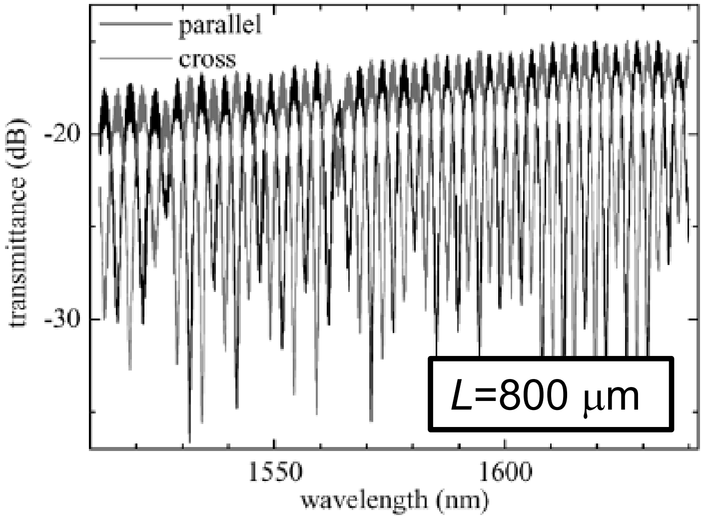
Directional coupler

APPLICATIONS

- **Dependent of the wavelength**:
  - Multiplexer / demultiplexer or optical filter







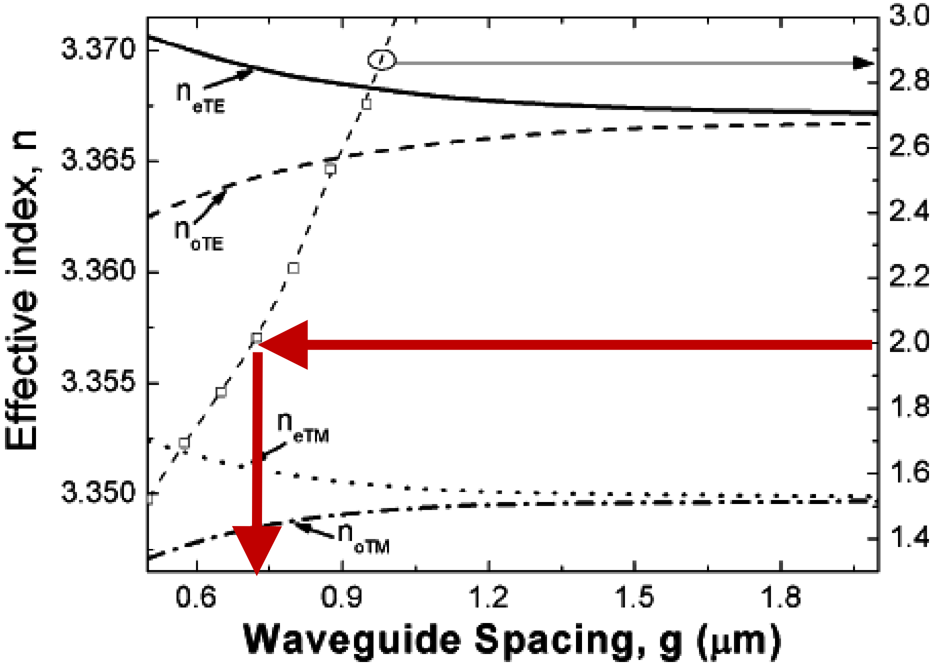
The channel spacing is lower as the length of the direction coupler increases

H. Yamada et al., "Optical directional coupler based on Si-wire waveguides", IEEE Photonics Technology Letters, vol.17, 3, pp. 585 – 587, 2005.

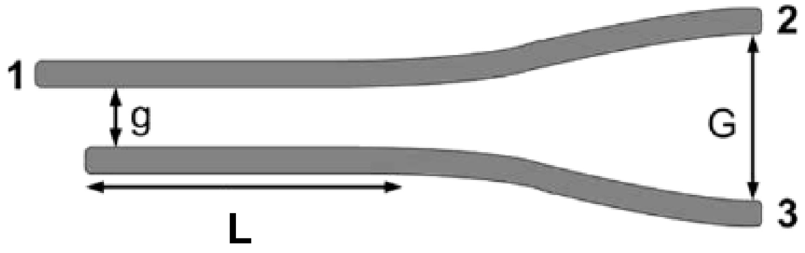
Directional coupler

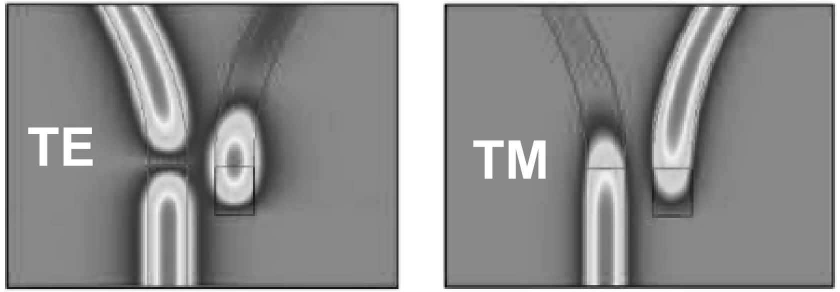
APPLICATIONS

- **Dependent of the polarization**:
  - Polarization splitter



$$\frac{L_B^{TM}}{L_B^{TE}}$$





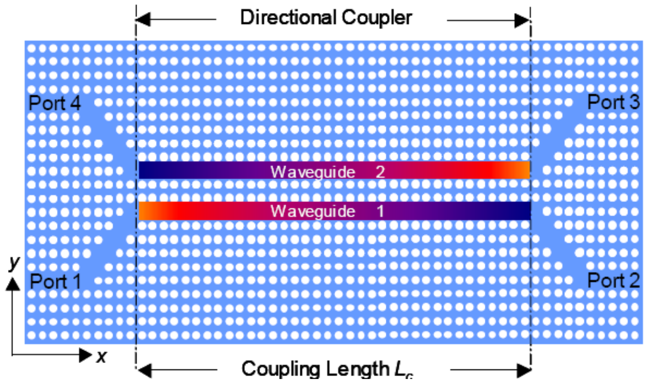
$$\boxed{L = 0.5L_B^{TM} = L_B^{TE}}$$

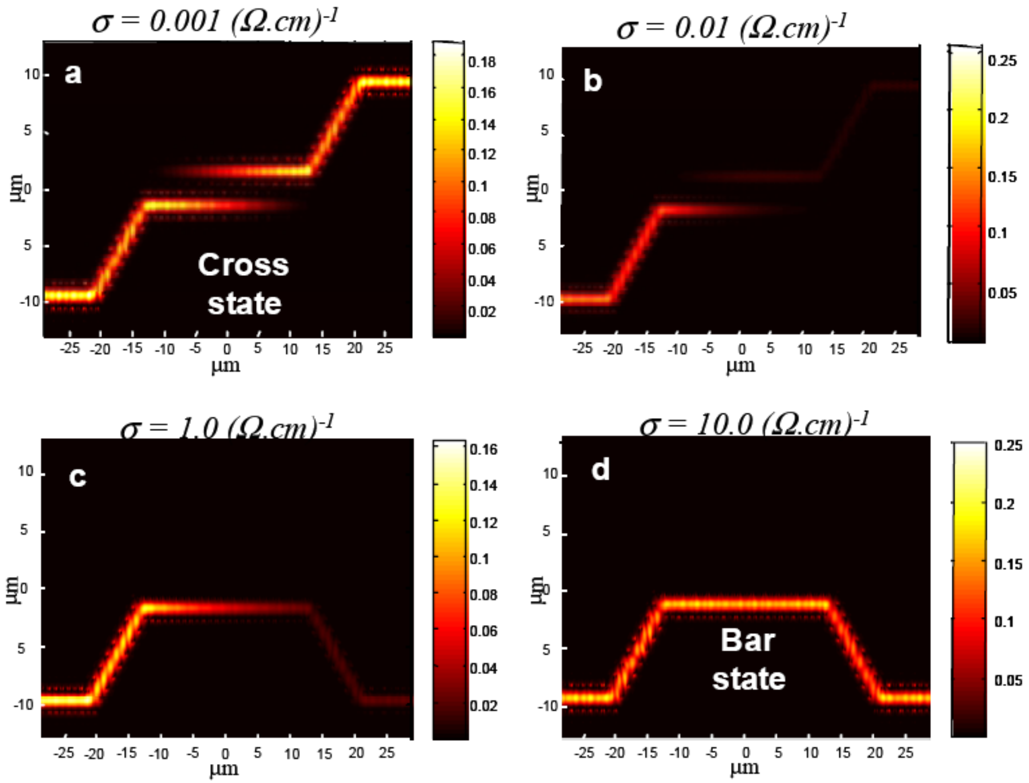
I. Kiyat et al., "A Compact Silicon-on-Insulator Polarization Splitter", IEEE Photonics Technology Letters Vol.17, 1, pp. 585 – 587, 2005.

Directional coupler

APPLICATIONS

- **Active directional couplers**:
  - Switches





The properties of the coupling section (optical absorption or refractive index) are modified via an external signal (e.g. electrical) thus changing the performance of the directional coupler

A. Sharkawy et al., " Electro-optical switching using coupled photonic crystal waveguides," Opt. Express, vol. 10, 1048-1059, 2002

Homework #3

- A directional coupler must be designed for different applications. The effective index of the even and odd supermodes are 3.37 and 3.36, respectively, for TE polarization:
  1. Determine the minimum length of the directional coupler to implement a 3dB power splitter at 1550nm wavelength.
  2. Determine the length of the directional coupler to implement a 1:99 power splitter at 1550nm wavelength for monitoring purposes being the monitored signal extracted at the cross port. The length must be higher than 10μm.
  3. Determine the length of the coupler to demultiplex a WDM input signal with wavelengths at $\lambda_1 \approx 1520$nm, $\lambda_2 \approx 1540$nm, $\lambda_3 \approx 1560$nm and $\lambda_4 \approx 1580$nm so that λ_1 and λ_3 are demultiplexed to the cross port while λ_2 and λ_4 are demultiplexed to the parallel port.
  4. Design a polarization splitter having TE in the cross port and TM in the parallel port. Determine the minimum length of the coupler and the effective index of the even TM supermode if the effective index of the odd TM supermode is 3.32.
- Use the virtual laboratory "Performance of directional coupler for photonic applications" (https://laboratoriosvirtuales.upv.es/eslabon/directionalcoupler) to obtain and justify the results

PDF file. 2 pages maximum. Include key plots from virtual laboratory to support the obtained results

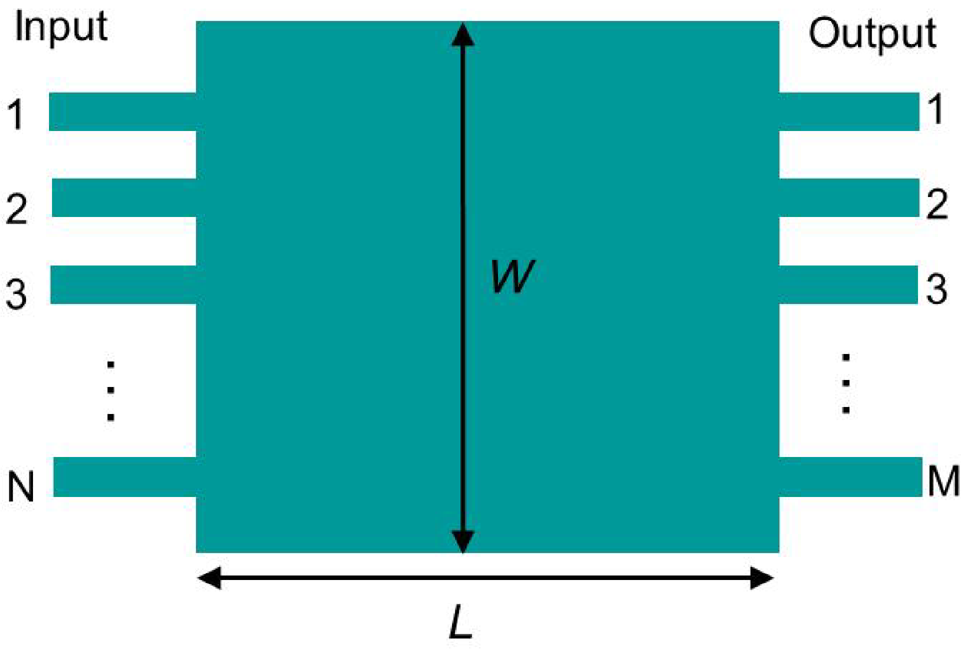
Outline

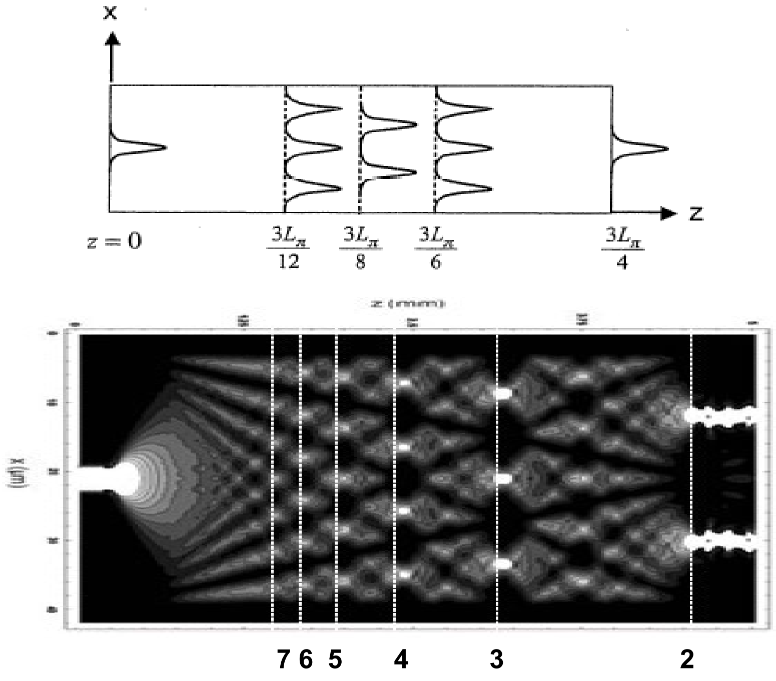
- Waveguide bend
- Y-junction
- Directional coupler
- Multimode interference coupler
- Mach-Zehnder interferometer
- Ring resonator
- Fiber coupling structures

Multimode interference coupler

WORKING PRINCIPLE

- A multimode interference coupler (MMI) is a structure with N input and M output ports connected with a **multimode waveguide** that can support a large number of guided modes (typically more than three)
- The working principles is based on the **self-imaging effect**
  - The input excitation is periodically repeated in one or multiple images along the propagation direction

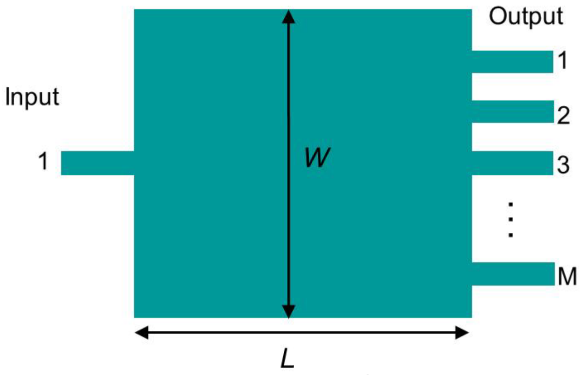




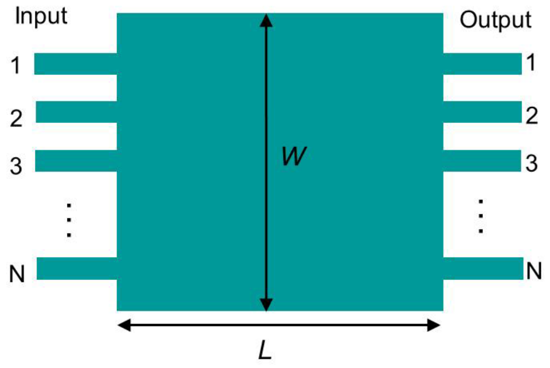
Multimode interference coupler

DESIGN PARAMETERS

- The **width of the multimode waveguide** (*W*) depend on the number of input and output waveguides, the separation between them and their width
  - A small separation between waveguides is desired to minimize *W* and so *L*
  - But a too small separation can give rise to an undesired coupling between ports
- Once *W* is fixed, the main design parameter will be the **length of the multimode waveguide** (*L*) that will depend on the ports configuration
  - Typical configurations:1x*M o NxN*



$$L_{1xM} = \frac{3L_\pi}{4M}$$



$$L_{NxN} = \frac{3L_\pi}{N}$$

$$L_\pi = \frac{\lambda}{2(n_{eff0} - n_{eff1})}$$

MMI beat length

L.B. Soldano et al, “Optical multimode interference devices based on self-imaging: principles and applications”, IEEE J. Light. Techn., vol. 13, pp. 615-627, 1995

Multimode interference coupler

DESIGN PARAMETERS

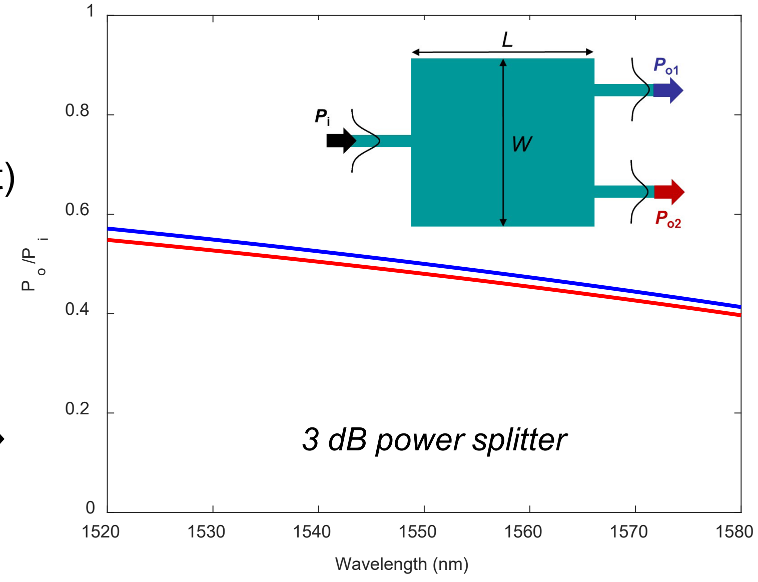
- The **MMI beat length** can also be calculated as

$$\boxed{L_\pi = \frac{4 n_c W_{eff}^2}{3\lambda}} \qquad W_{eff} = W + \frac{\lambda}{\pi}\left(\frac{n_{cd}}{n_c}\right)^{2\sigma}\left(n_c^2 - n_{cd}^2\right)^{-1/2}$$

  - n_c y n_{cd}: refractive index of core and cladding
  - σ=0 for TE and σ=1 for TM

- These expressions are obtained from a 2D analysis
  - Starting point for 3D structures (better approximation → W>>h and low index contrast)
  - 3D numerical simulations are recommended for high index contrast structures

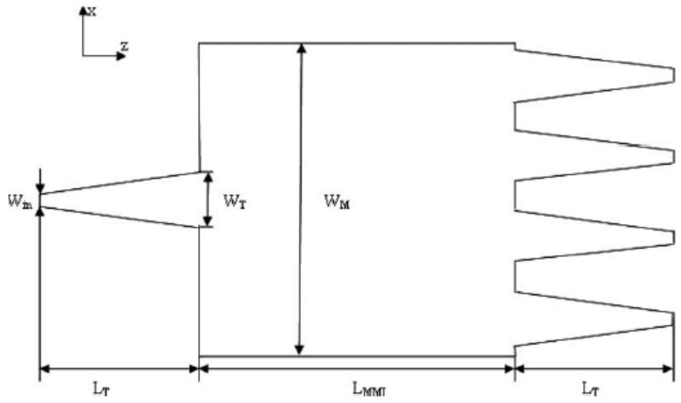
- The main **advantages** of the MMI are
  - **Broadband performance and low polarization dependence**
  - **High tolerance to fabrication deviations**

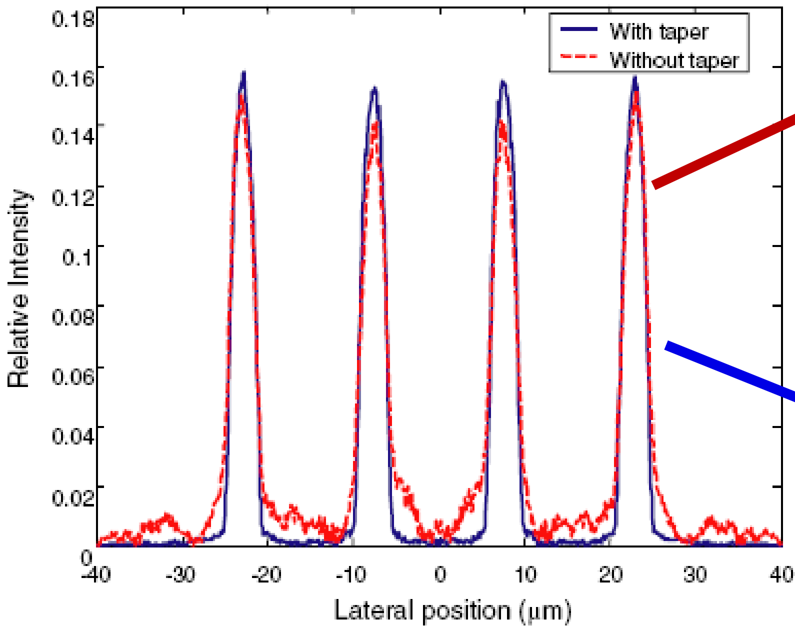


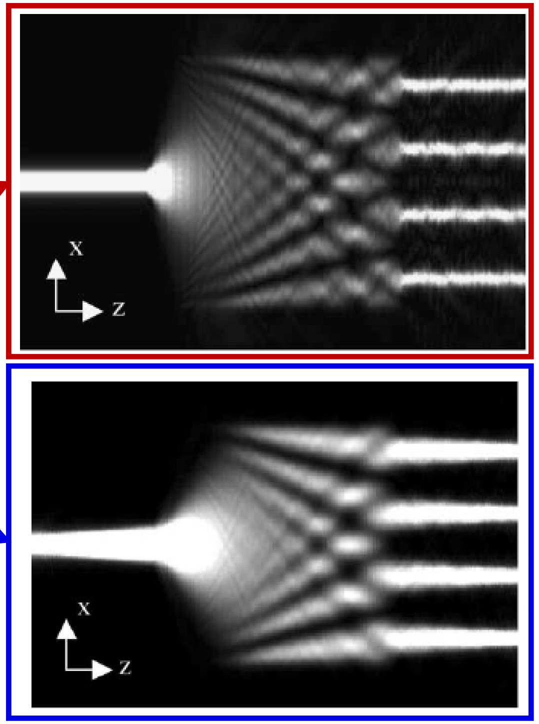
Multimode interference coupler

DESIGN PARAMETERS

- Optimization of coupling to input/output waveguides:
  - Minimize reflections
  - Reduce insertion losses





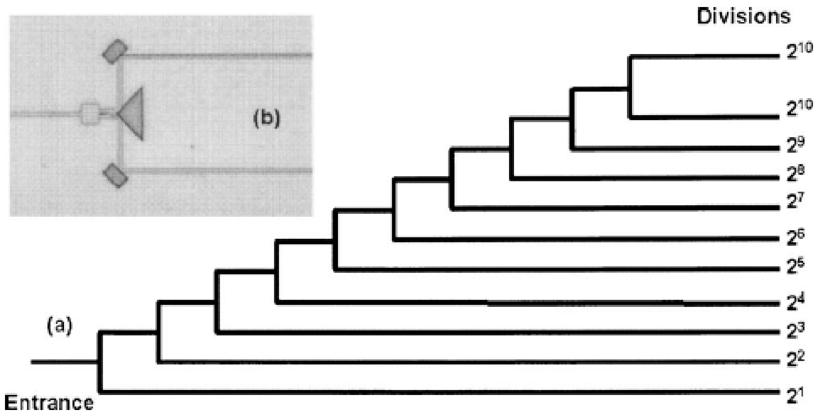


Y. Shi et al, “Improved performance of a silicon-on-insulator-based multimode interference coupler by using taper structures”, Opt. Communications, vol. 253, pp. 276–282, 2005

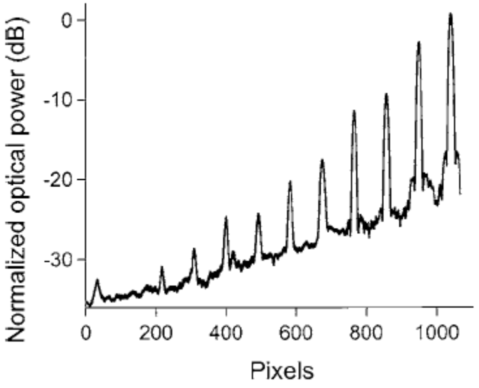
Multimode interference coupler

APPLICATIONS

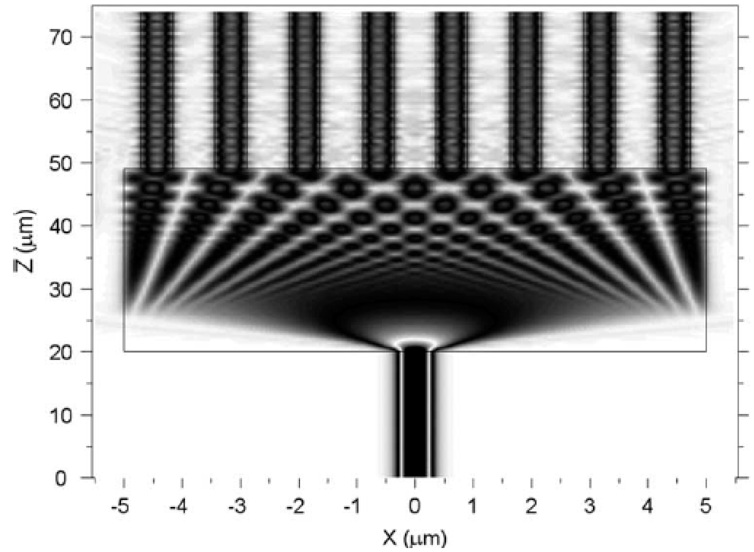
- Compact power splitter/combiner with multiple inputs/outputs



1:N splitter with Y-junctions



Power is unbalanced at output ports due to bad design



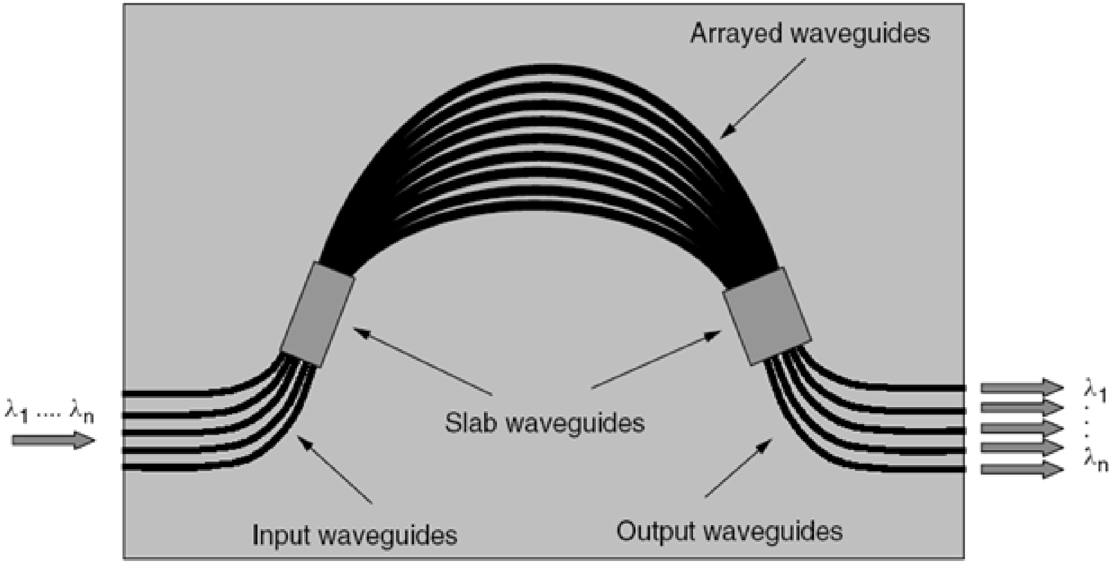
A more compact solution: MMI

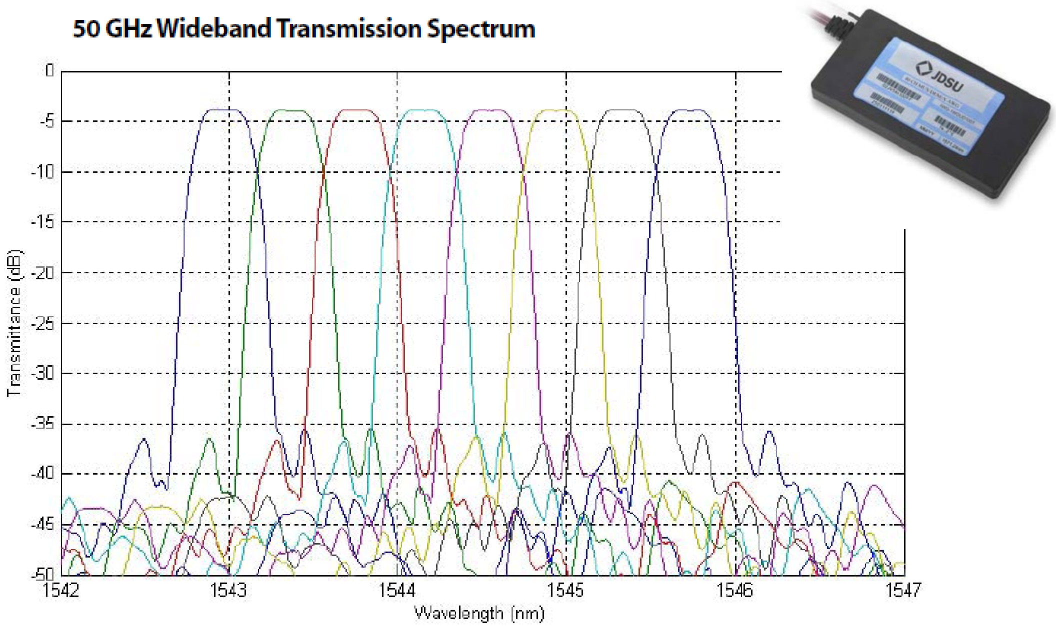
D. Marris, et al., “Ultralow loss successive divisions using silicon-on-insulator microwaveguides ,” Appl. Phys. Lett. 87, 211102 (2005)

Multimode interference coupler

APPLICATIONS

- Arrayed waveguide gratings (AWG) are usually employed as (de)multiplexers in WDM applications
- They are formed by two MMI couplers with a star geometry that connects a set of photonic waveguides with slightly different lengths





M. K. Smit and C. van Dam, "PHASAR-Based WDM-Devices: Principles, Design and Applications", *IEEE J. of Sel. Topics in Q.E.*, vol. 2, no. 2, pp. 236-250, 1996.

Questions to review

- What polarization can give rise to more compact bends in high-index contrast photonic waveguides? Why?
- What will be the power of the output signal from a combiner based on Y-junction if we have two input signals with power of 0.5W and 1W?
- How can be achieved more compact directional couplers?
- What is the phase shift between the output ports of a directional coupler when signal enters only at one of the input ports? Does this phase shift depend on the coupling coefficient?
- What is the required condition for using the directional coupler as a polarization splitter?
- What are the main advantages of implementing a 3 dB power splitter with a MMI with respect to a directional coupler?

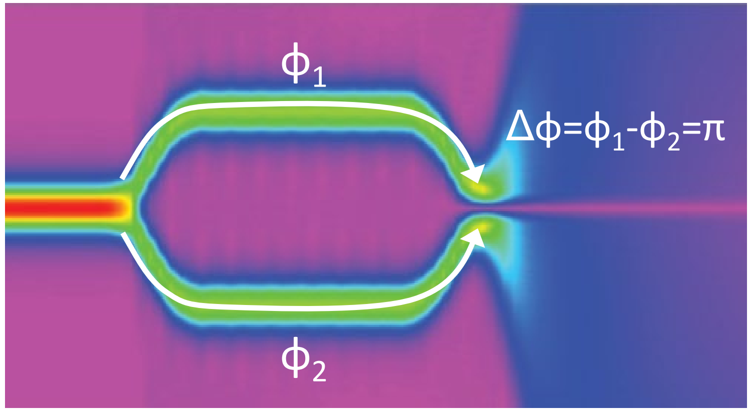
Outline

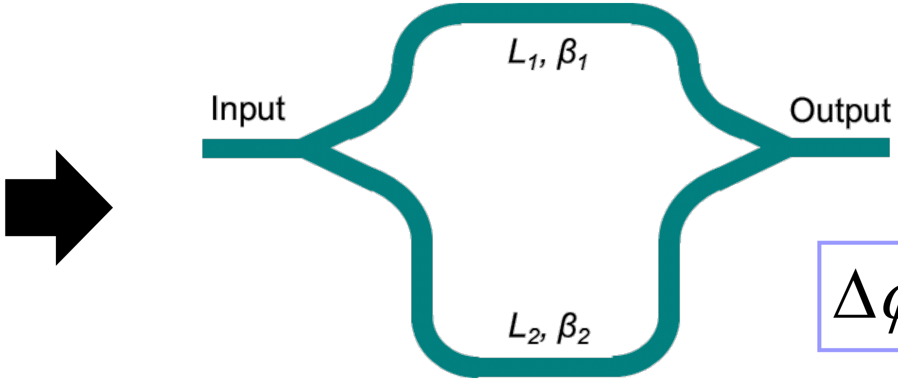
- Waveguide bend
- Y-junction
- Directional coupler
- Multimode interference coupler
- Mach-Zehnder interferometer
- Ring resonator
- Fiber coupling structures

Mach-Zehnder interferometer

WORKING PRINCIPLE

- The Mach-Zehnder Interferometer (MZI) is based on the **interference** between two optical signals coming from the same origin and travelling a **different effective length**
- The different effective length creates a **phase difference** that is converted into a **change in output power** as the two signals are combined at the end



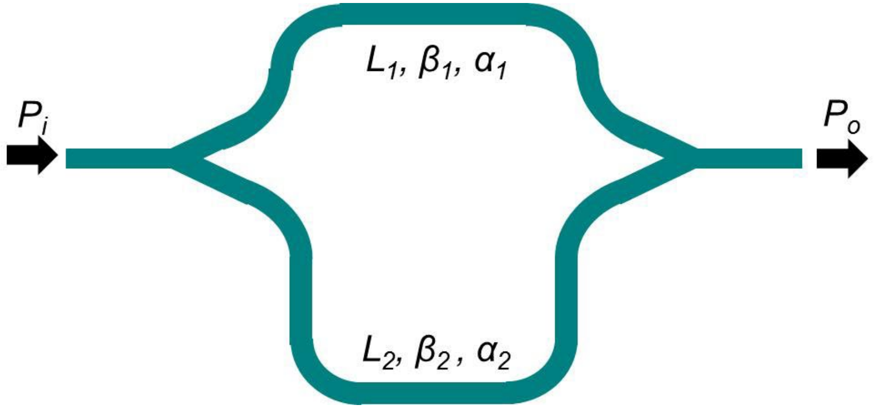


$$\boxed{\Delta\phi = \beta_2 L_2 - \beta_1 L_1}$$

- The **phase difference**, and therefore the MZI response, depends on the **wavelength** and **polarization** of the input signal

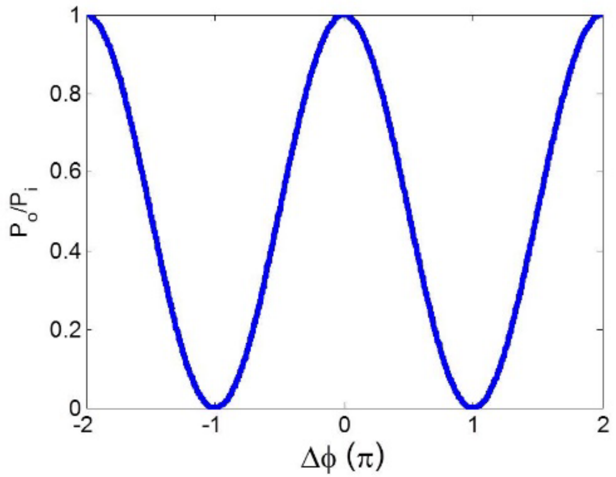
Mach-Zehnder interferometer

1x1 MZI DESIGN: Transfer function

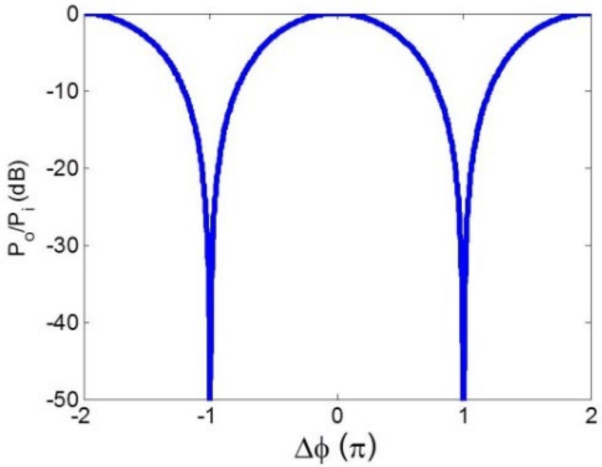


$$\frac{E_o}{E_i} = \left(\frac{1}{2}e^{(-\alpha_1+j\beta_1)L_1} + \frac{1}{2}e^{(-\alpha_2+j\beta_2)L_2}\right)$$

$$\boxed{\Delta\phi = \beta_2 L_2 - \beta_1 L_1}$$



Response in linear units

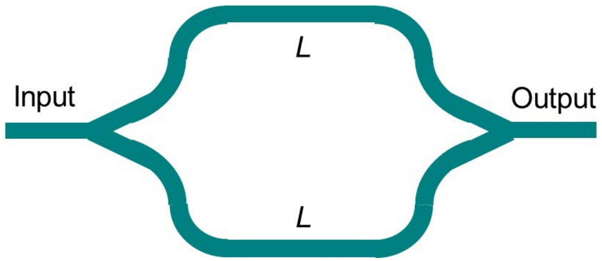


Response in dB units

$$\boxed{\frac{P_o}{P_i} = \cos^2\left(\frac{\Delta\phi}{2}\right)}$$ ($\alpha_1 = \alpha_2 = 0$)

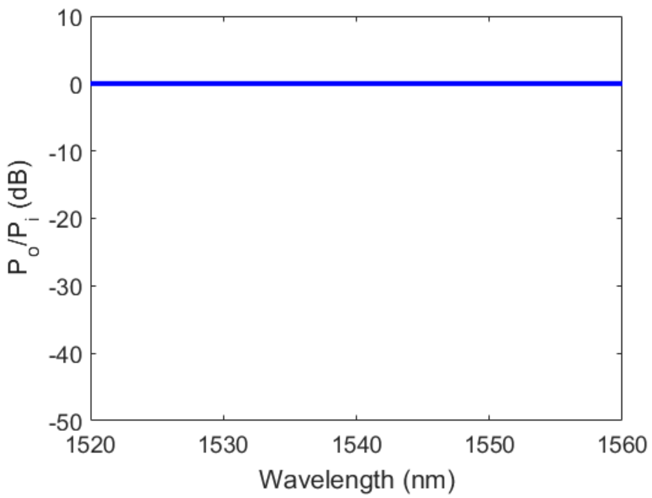
Mach-Zehnder interferometer

1x1 MZI DESIGN: Passive performance

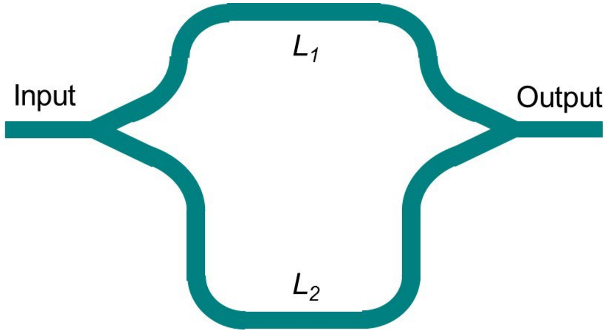


Symmetric MZI

$$\boxed{\Delta\phi = 0}$$

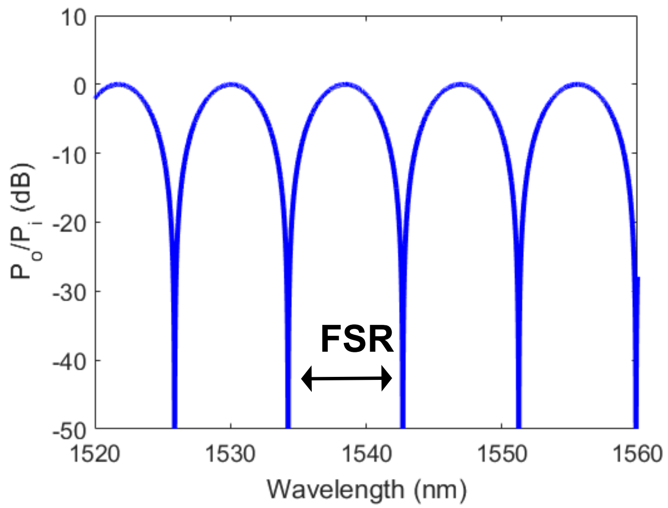


$$P_o = P_i$$



Asymmetric MZI

$$\boxed{\Delta\phi = n_{eff}\frac{2\pi}{\lambda}(L_2 - L_1)}$$



$$P_o = \cos^2\left(\pi\frac{n_{eff}\Delta L}{\lambda}\right)P_i$$

Free Spectral Range

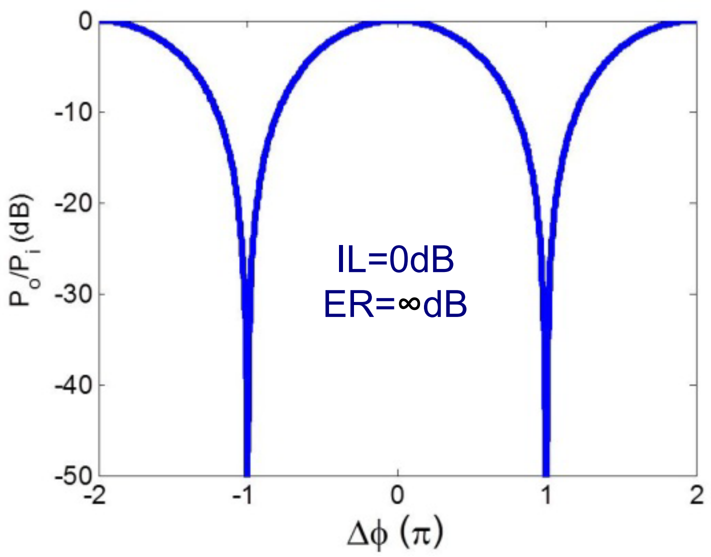
$$FSR = \frac{\lambda^2}{n_g \Delta L}$$

Mach-Zehnder interferometer

1x1 MZI DESIGN: Effect of optical losses

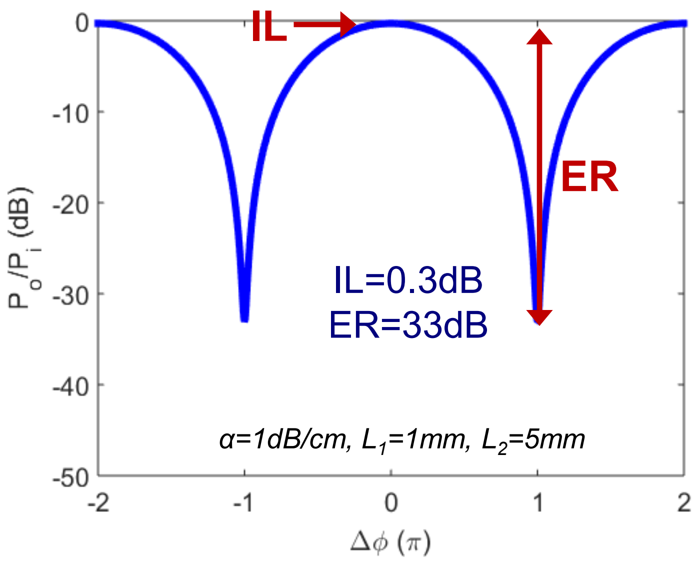
- **Insertion losses** (IL) increase and the **extinction ratio** (ER) decreases

Without losses (α_1=α_2=0)



$$\frac{P_o}{P_i} = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

With losses (α_1, α_2)

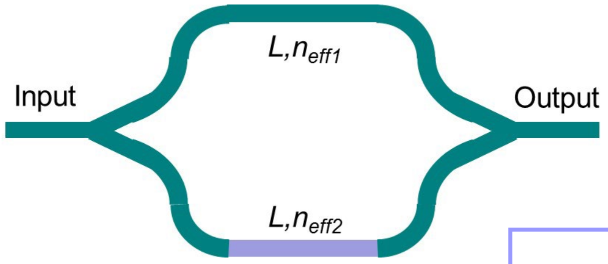


$$\frac{P_o}{P_i} = \frac{1}{4}[\tau_1^2 + \tau_2^2 + 2\tau_1\tau_2\cos(\Delta\phi)]$$

$$\tau_i = e^{-\alpha_i L_i}$$

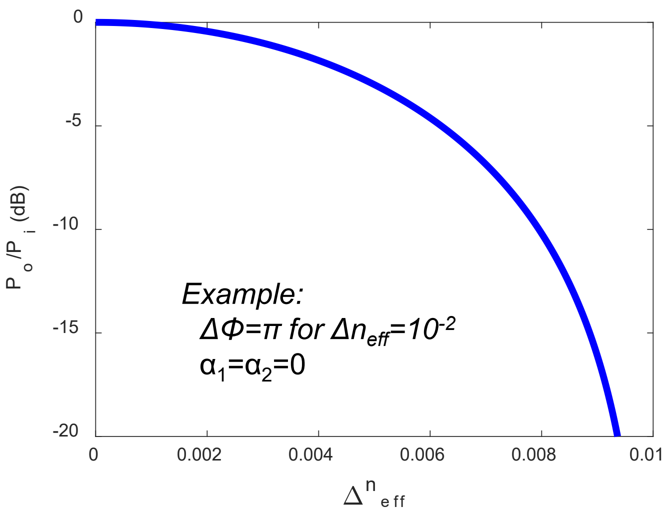
Mach-Zehnder interferometer

1x1 MZI DESIGN: Active performance



Symmetric MZI

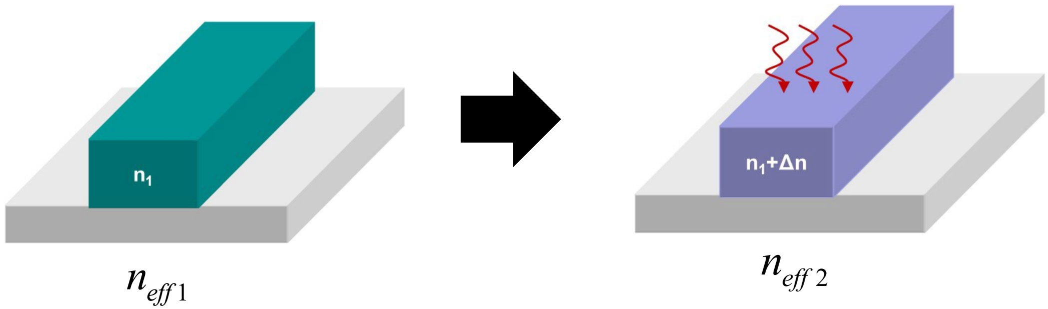
$$\boxed{\Delta\phi = \left(n_{eff\,1} - n_{eff\,2}\right)\frac{2\pi}{\lambda}L}$$



$$P_o = \cos^2\left(\pi\frac{\Delta n_{eff} L}{\lambda}\right) P_i$$

Fixed wavelength

$\alpha_1=\alpha_2=0$

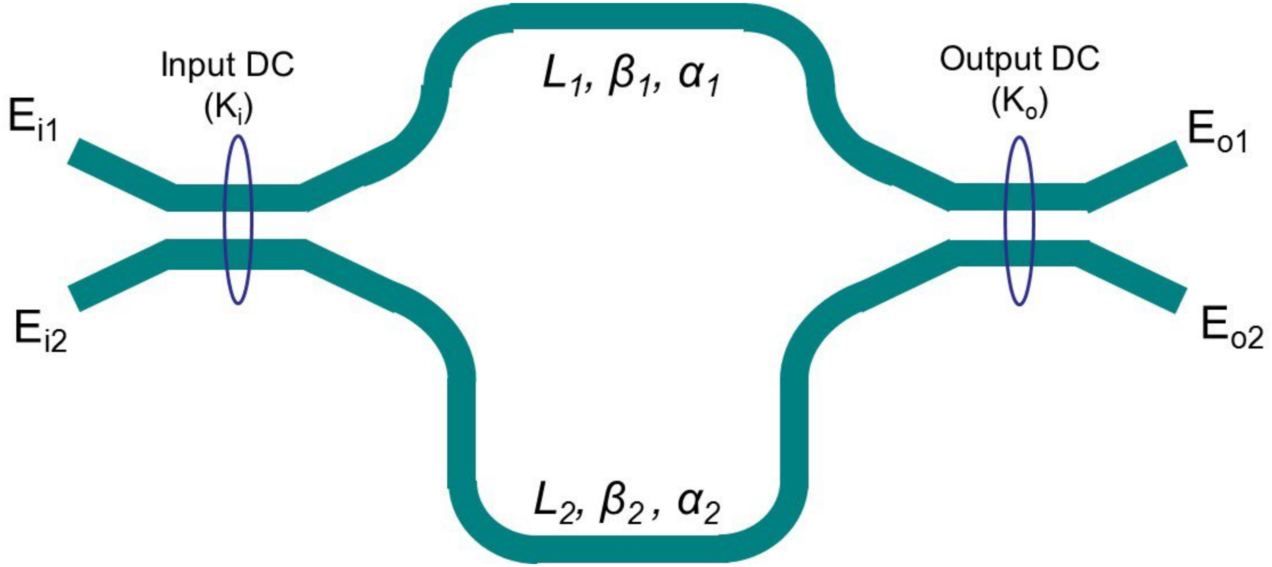


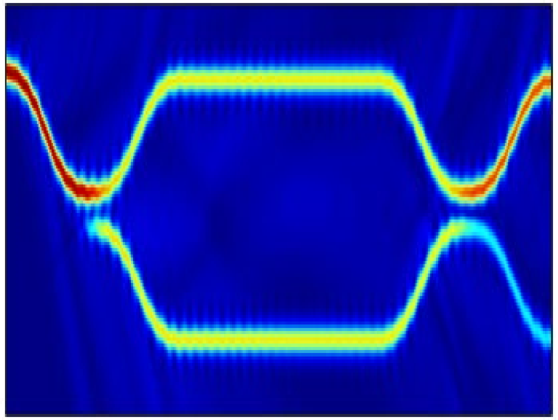
A change of refractive index (*Δn*) is induced in one of the MZI arms by an external excitation (thermal, electrical, optical)

Mach-Zehnder interferometer

2x2 MZI DESIGN: Transfer function

$$\begin{pmatrix} E_{o1} \\ E_{o2} \end{pmatrix} = \begin{pmatrix} \sqrt{1-K_o} & -j\sqrt{K_o} \\ -j\sqrt{K_o} & \sqrt{1-K_o} \end{pmatrix} \begin{pmatrix} e^{(-\alpha_1+j\beta_1)L_1} & 0 \\ 0 & e^{(-\alpha_2+j\beta_2)L_2} \end{pmatrix} \begin{pmatrix} \sqrt{1-K_i} & -j\sqrt{K_i} \\ -j\sqrt{K_i} & \sqrt{1-K_i} \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix}$$

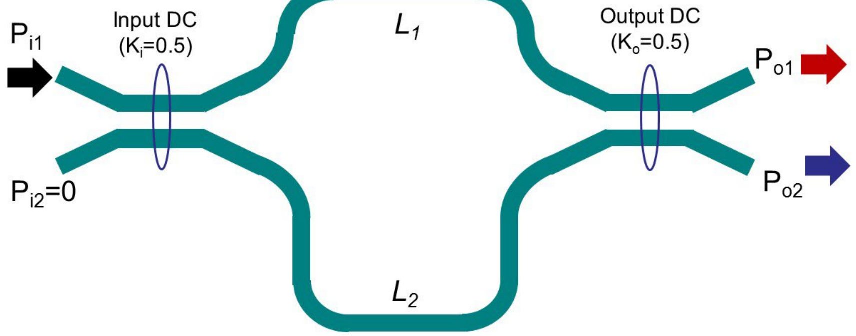




Simulation of a 2x2 MZI

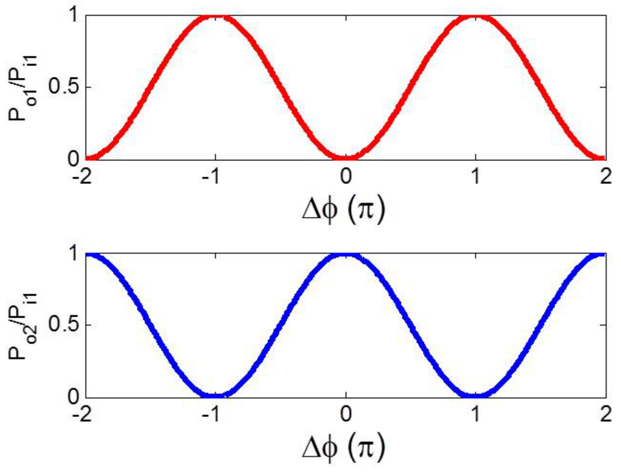
Mach-Zehnder interferometer

2x2 MZI DESIGN: Passive performance



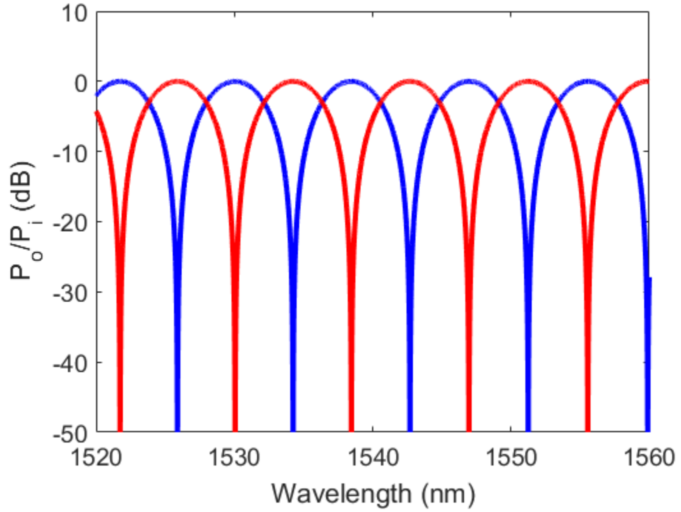
α_1= α_2 =0, 3dB-DC (K_i=K_o =0.5) and P_{i2}=0

$$\Delta\phi = n_{eff}\frac{2\pi}{\lambda}(L_2 - L_1)$$



$$\frac{P_{o1}}{P_{i1}} = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

$$\frac{P_{o2}}{P_{i1}} = \cos^2\left(\frac{\Delta\phi}{2}\right)$$



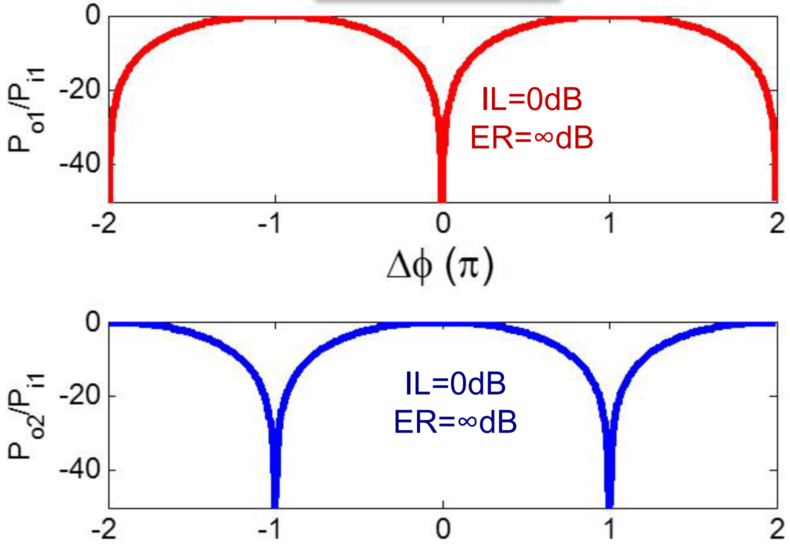
$$P_{o1} = \sin^2\left(\pi\frac{n_{eff}\Delta L}{\lambda}\right)P_{i1}$$

$$P_{o2} = \cos^2\left(\pi\frac{n_{eff}\Delta L}{\lambda}\right)P_{i1}$$

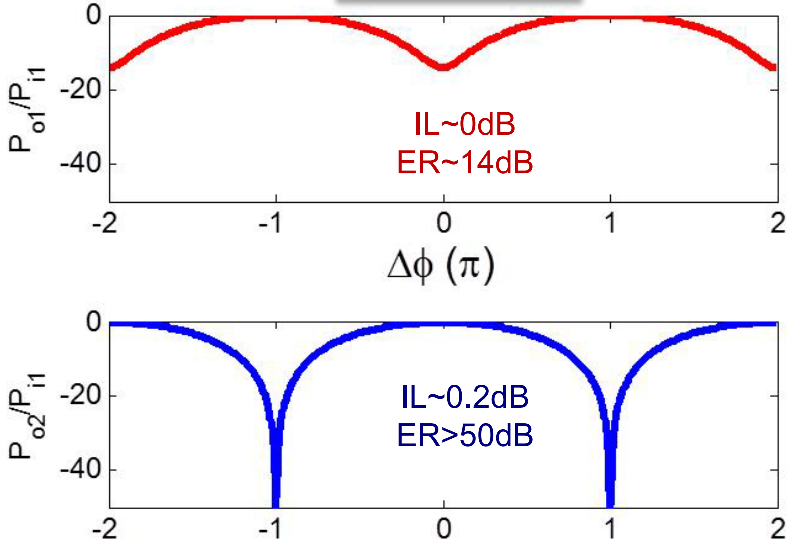
Mach-Zehnder interferometer

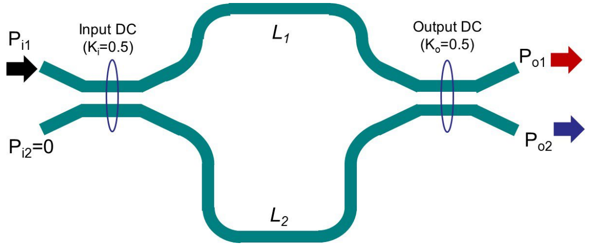
2x2 MZI DESIGN: Effect of equal DCs but not necessarily 3dB couplers

K_i=K_o=0.5



K_i=K_o=0.4



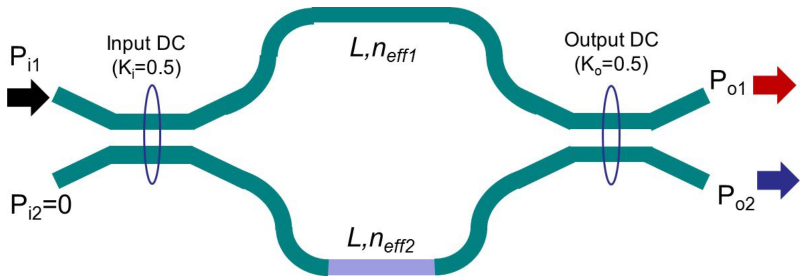


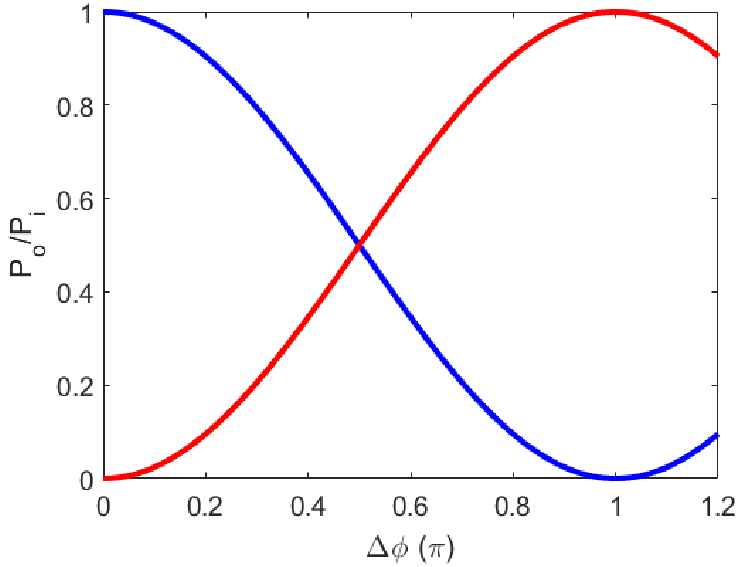
α_1= α_2 =0, K_i=K_o and P_{i2}=0

- The MZI response in cross port (P_{o2}/P_{i1}) is more stable to coupling ratio variations when input and output DCs are equal (K_i=K_o)
- Therefore, the response in cross port has a **lower wavelength dependence** and **higher tolerance to process variations**

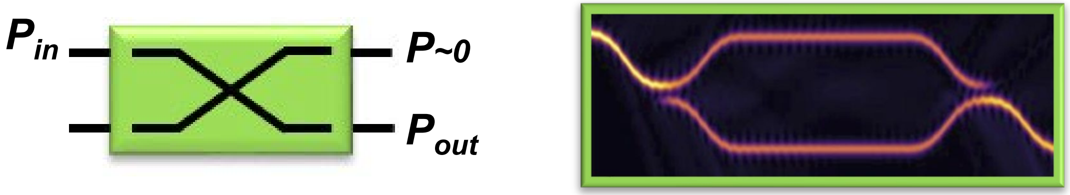
Mach-Zehnder interferometer

2x2 MZI DESIGN: Active performance

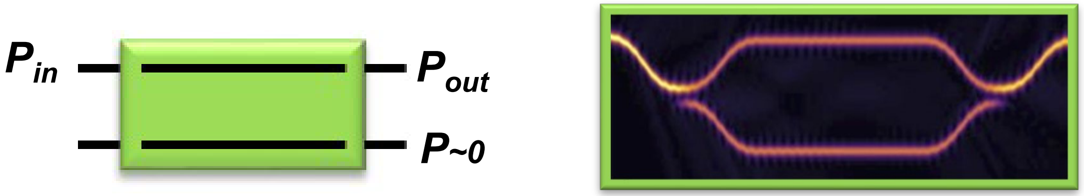




PHOTONIC 2x2 SWITCH



CROSS STATE (ΔΦ~0)

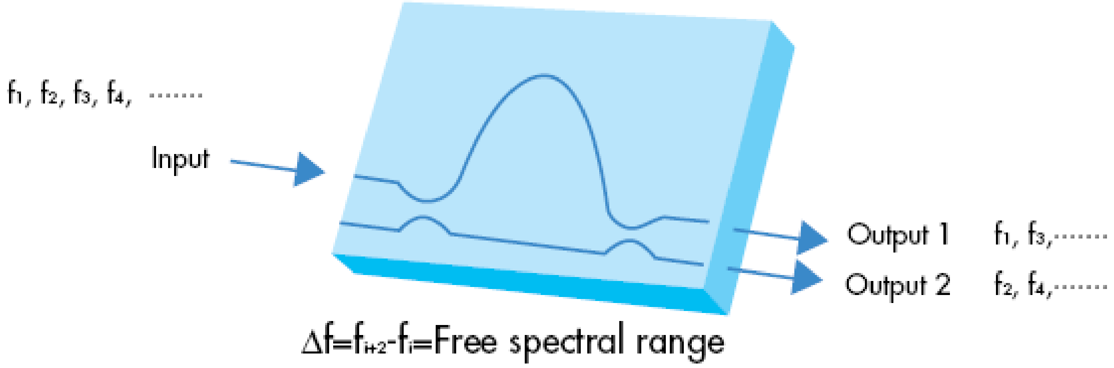


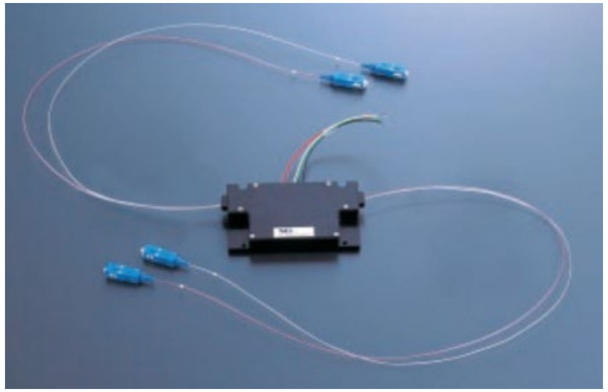
BAR STATE (ΔΦ~π)

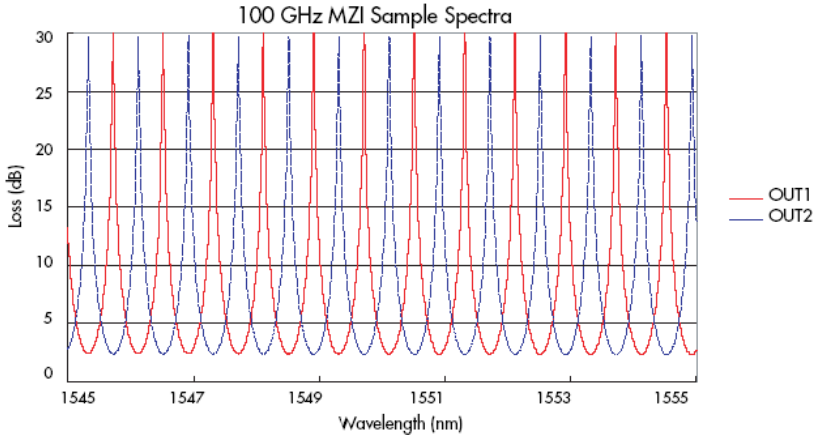
Mach-Zehnder interferometer

APPLICATIONS

- Multiplexer / demultiplexer







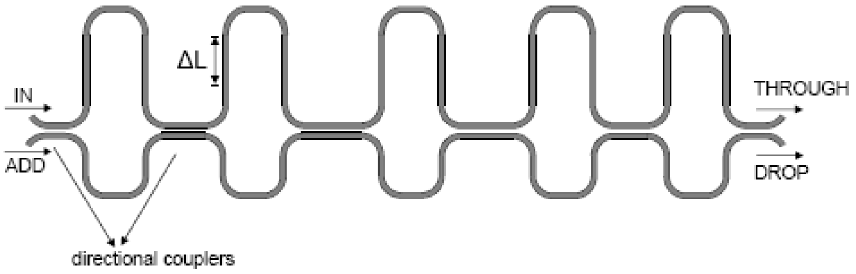
FSR Accuracy	< 1/1000
Insertion Loss	< 3.5 dB
Insertion Loss Uniformity	< 0.5 dB
Extinction Ratio *	< -15 dB
PDL	< 0.4 dB
Temperature Coefficient **	~0.011nm/deg

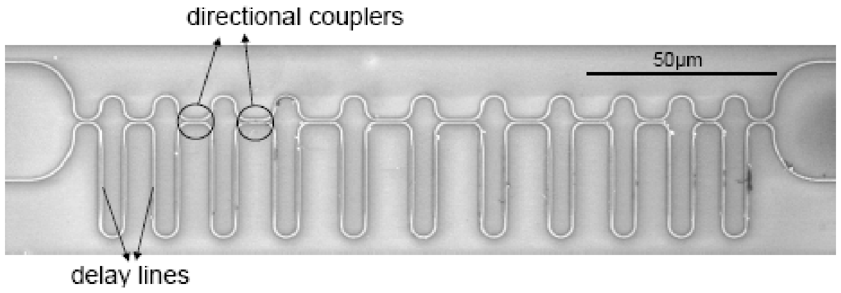
Commercial MZI in silica technology (NTT)

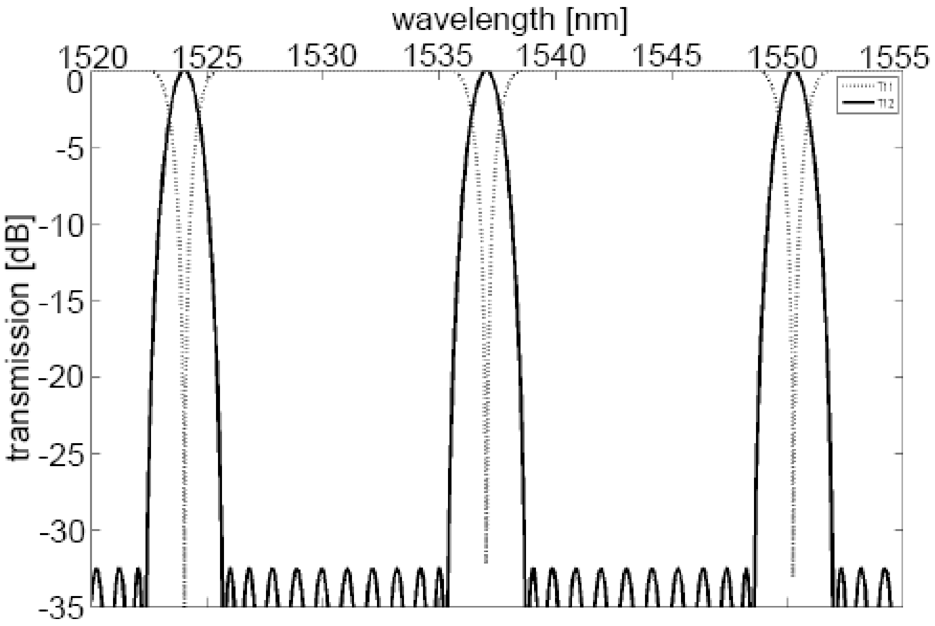
Mach-Zehnder interferometer

APPLICATIONS

- Optical filters
  - Array of cascaded MZIs to design a specific filter response





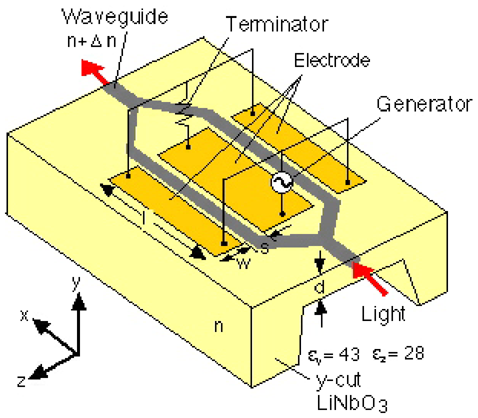


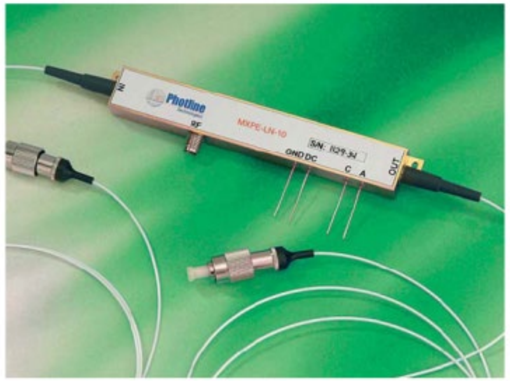
P. Dumon, “Ultra-Compact Integrated Optical Filters in Silicon-on-insulator by Means of Wafer-Scale Technology”, PhD, March 2007

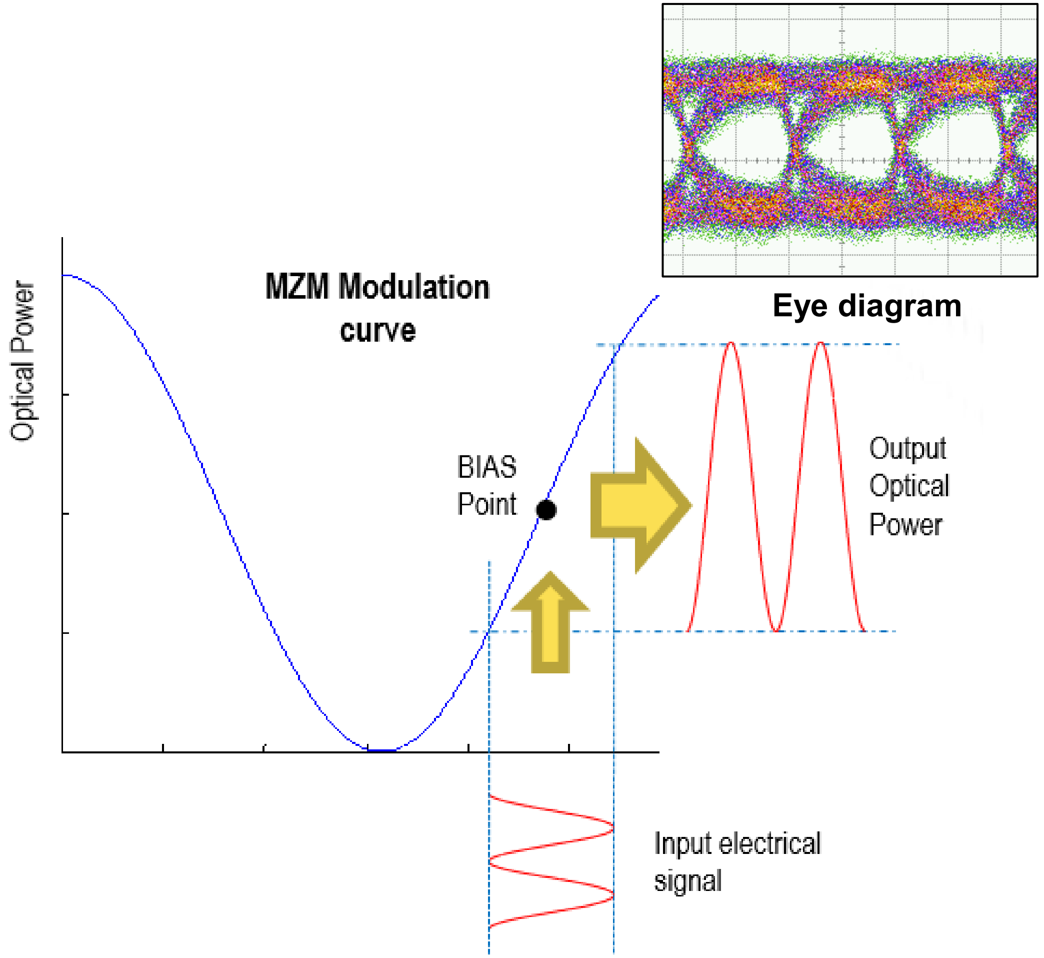
Mach-Zehnder interferometer

APPLICATIONS

- Electro-optical modulator





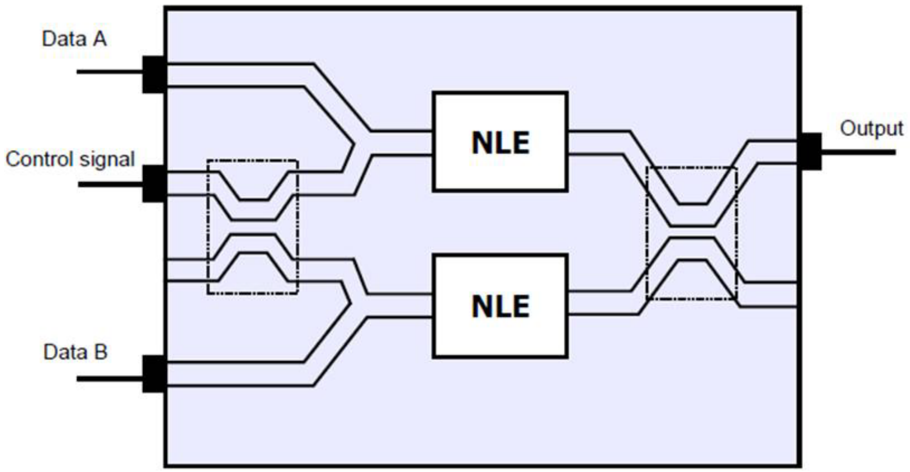


Electro-optical MZI commercial modulator in $LiNbO_3$ technology

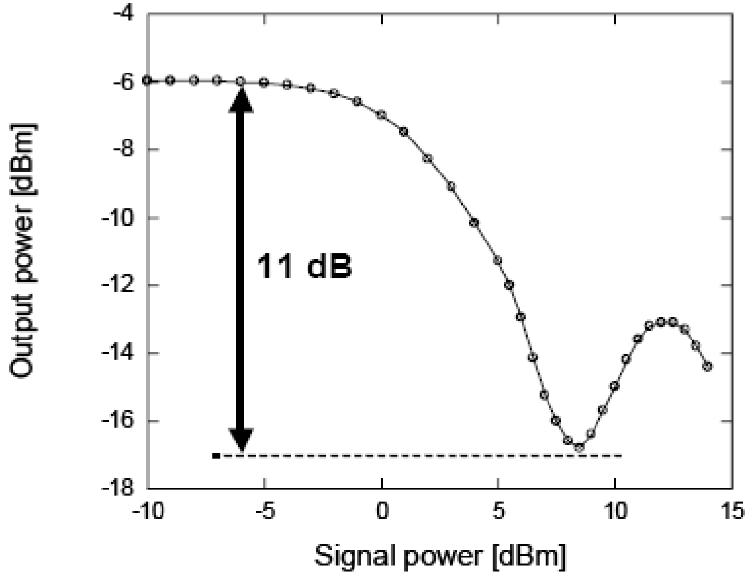
Mach-Zehnder interferometer

APPLICATIONS

- All-optical switch
  - Refractive index is modified by injecting high power optical pulses (non-linear effects)
  - Very high speed can be achieved (all-optical logic gates)



NLE: non-linear effect



M. Takenaka, et al, "All-optical switching of 40 Gb/s packets by MMI-BLD optical label memory," Opt. Express 14, 10785-10789 (2006)

Homework #4-Part 1

- Design a 2x2 switch based on a Mach-Zehnder interferometer. The specifications of the switch are insertion losses lower than 3dB and an extinction ratio higher than 10dB at both output ports.
  1. If optical losses are the same in both arms, what are the maximum allowed losses to fulfill the specifications?, what is the extinction ratio in this case?, why?
  2. If optical loses in the parallel arm are 2dB. What are the maximum allowed losses in the cross arm?, what specifications are not met if losses increase above this value?
  3. If optical loses in the cross arm are 0.5dB. What are the maximum allowed losses in the parallel arm?, what specifications are not met if losses increase above this value?
  4. If optical losses are 3dB in the cross arm and 0 dB in the parallel arm. Explain how would you design the input and output couplers and calculate the coupling coefficient values to have an extinction ratio higher than 50dB at both output ports of the Mach-Zehnder interferometer. What will be the insertion losses in that case?
- Use the virtual laboratory "Performance of Mach-Zehnder interferometer for photonic applications" (https://laboratoriosvirtuales.upv.es/eslabon/mzinterferometer) to obtain and justify the results

Single PDF file for Part 1 and Part 2 with 4 pages maximum. Include key plots from virtual laboratory

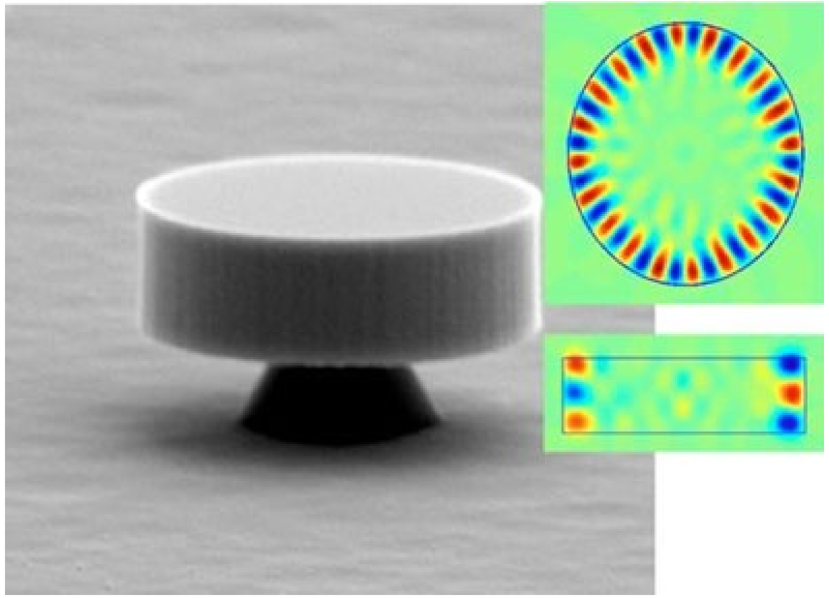
Outline

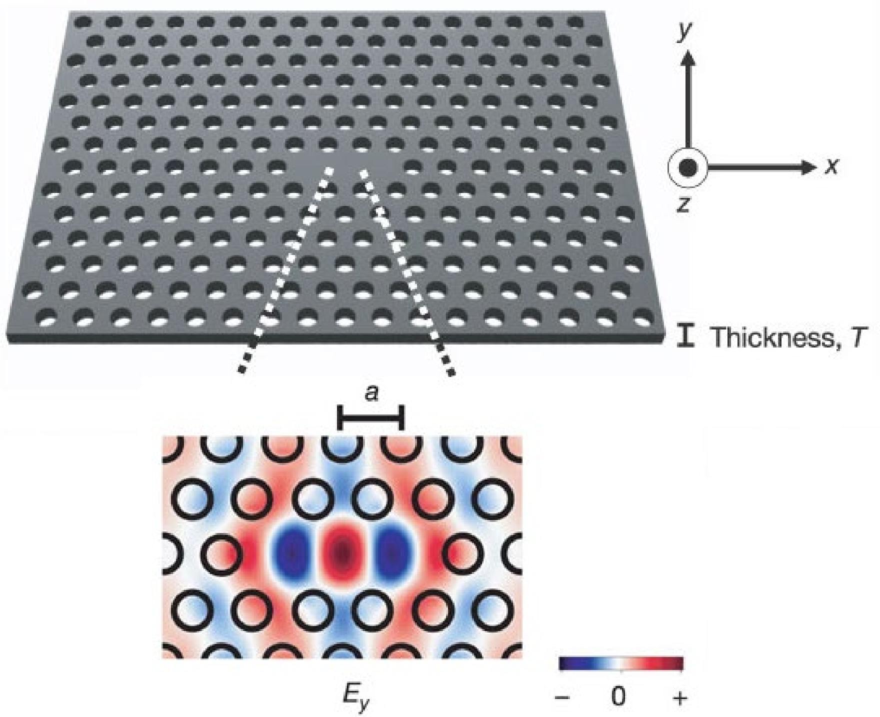
- Waveguide bend
- Y-junction
- Directional coupler
- Multimode interference coupler
- Mach-Zehnder interferometer
- Ring resonator
- Fiber coupling structures

Ring resonator

WORKING PRINCIPLE

- Optical cavities confine light to small volumes by resonant recirculation
- Light is only confined at some wavelengths: **resonant modes**
- An **ideal cavity** (that is, without loss) would confine light indefinitely



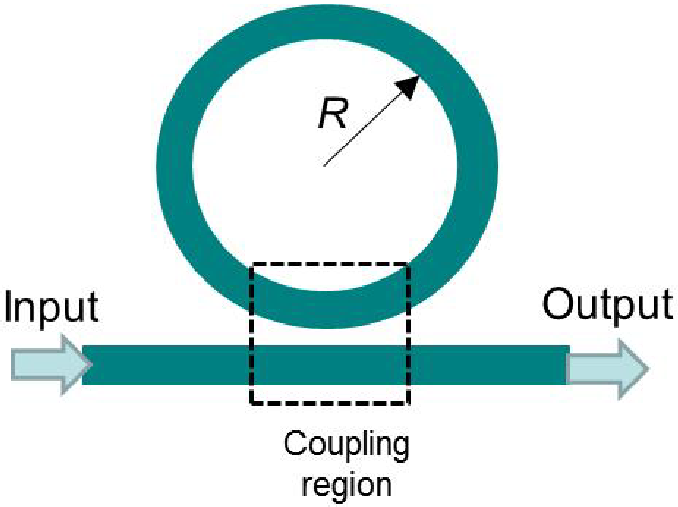


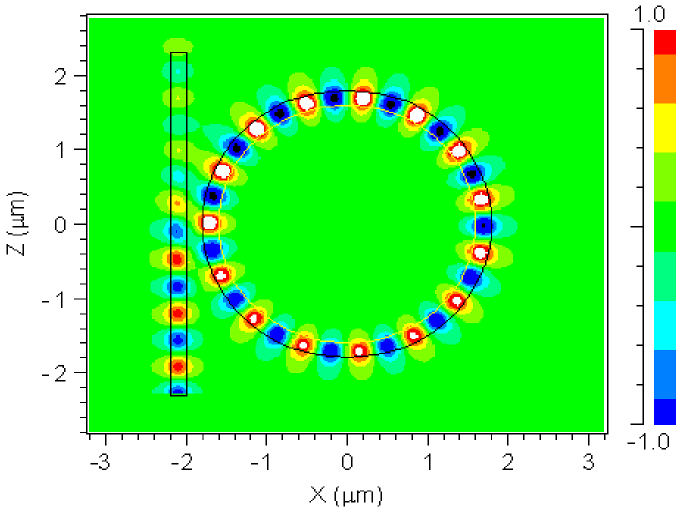
K. J. Vahala, "Optical microcavities", Nature 424, 839-846 (14 August 2003).

Ring resonator

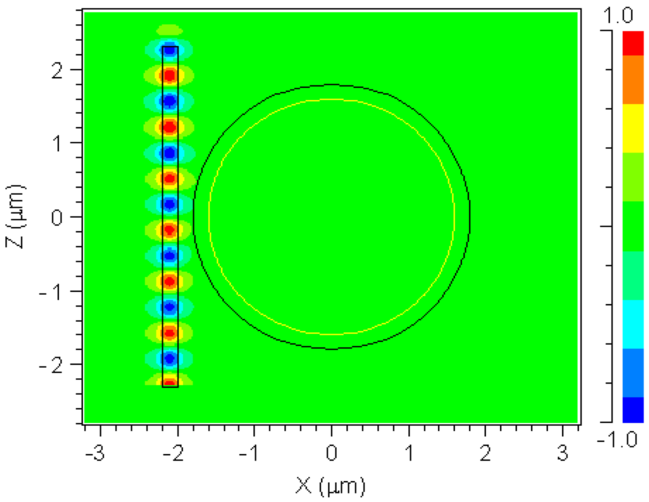
WORKING PRINCIPLE

- A **ring resonator consists** of a waveguide in a close loop coupled to another waveguide
- The structure will be resonant for light which after each full trip around the ring **constructively interferes** with the input light
- Optical intensity in the ring is **built up** and hence significantly increased





Resonant wavelength (λ_{RES})



Non resonant wavelength

Ring resonator

RING DESIGN: Transfer function

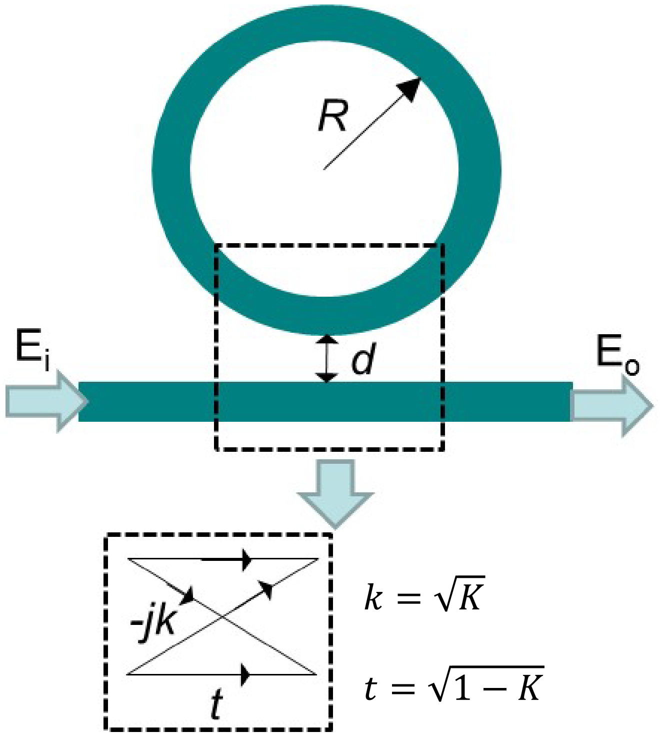
$$\frac{E_o}{E_i} = t - k^2 A e^{j\phi} - tk^2\left(Ae^{j\phi}\right)^2 - t^2k^2\left(Ae^{j\phi}\right)^3 \ldots$$

$$\downarrow$$

$$\boxed{\frac{E_o}{E_i} = \frac{t - Ae^{j\phi}}{1 - tAe^{j\phi}}}$$

$\phi = \beta L$ *Single-pass phase shift*

$A = e^{-\alpha L}$ *Single-pass losses*



$k = \sqrt{K}$

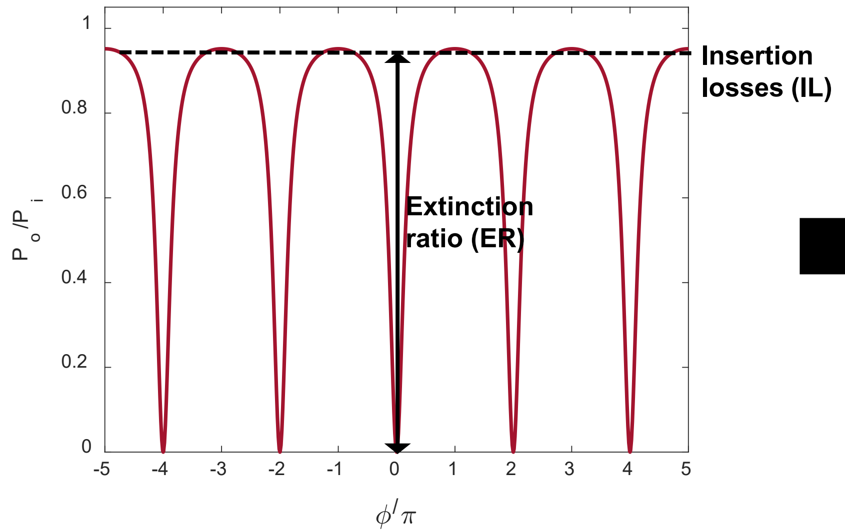
$t = \sqrt{1 - K}$

- **Resonant wavelengths occur at ϕ=0, 2π, 4π…**
- **The loss factor, *A*, may change from 0 (α=∞) to 1 (α=0) → *A*(dB)=-20·log$_{10}$ (*A*)**
- **We assume that there are no losses in the coupling region → $t^2+k^2=1$**

Ring resonator

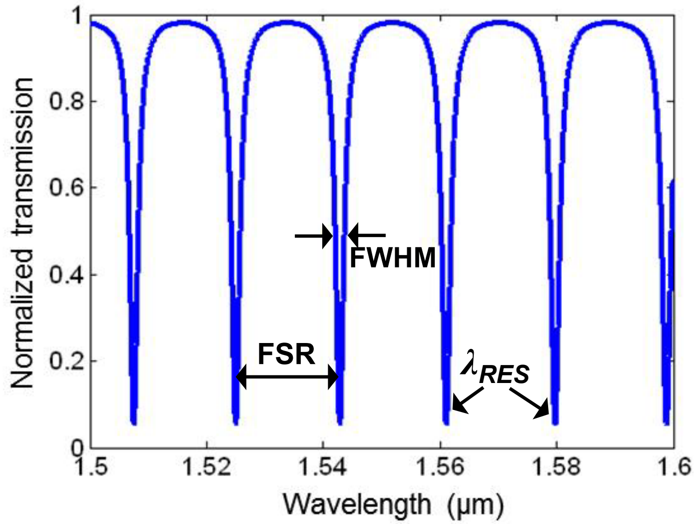
DESIGN PARAMETERS

- The design parameters are
  - **Radius** (*R*): determines the length (*L=2πR)* of the resonant cavity → λ_{RES}, FSR
  - **Waveguides separation** (*d*): determines the transmission coefficient (*t)* → FWHM



$$\boxed{\phi = n_{eff}\frac{2\pi}{\lambda}L}$$

Single-pass phase shift



$$\boxed{\lambda_{RES} = \frac{n_{eff}L}{N}, N = 1,2,3\ldots}$$

$$\boxed{FSR = \frac{\lambda_{RES}^2}{n_g L}}$$

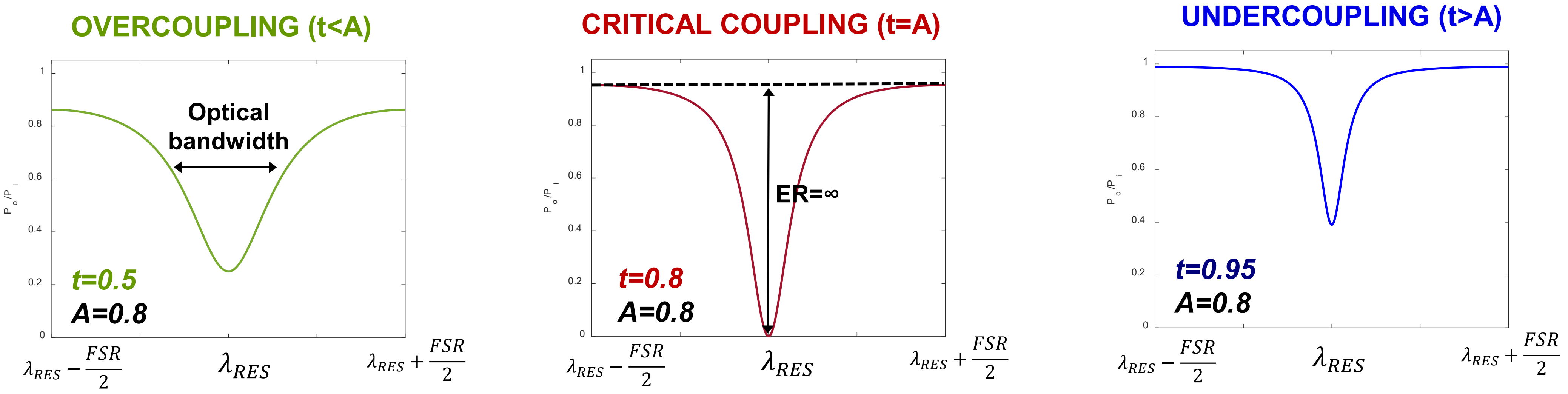
Free spectral range (FSR): separation between adjacent resonant wavelengths

Full width at half maximum (FWHM): 3dB optical bandwidth of resonant wavelength

Ring resonator

OPTICAL TRANSMISSION RESPONSE

- Effect of transmission coefficient for a given ring loss

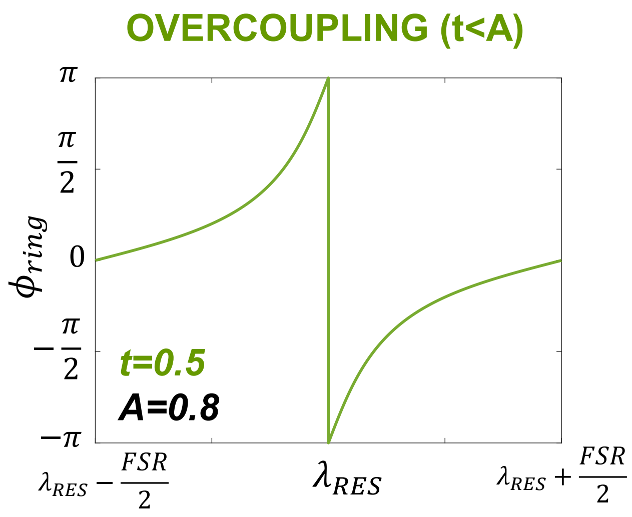


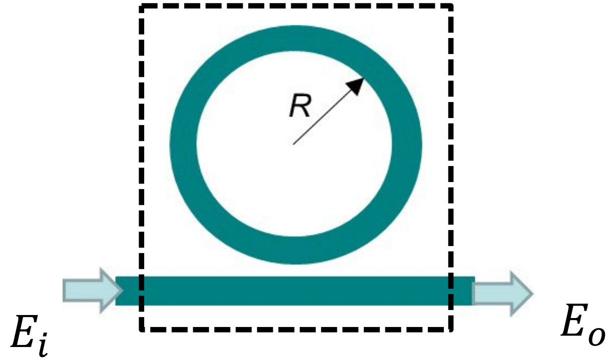
- The optical power is highly attenuated at the resonant wavelength (λ_{RES})
- The **maximum extinction ratio (ER=∞) is always achieved for critical coupling**
- The optical bandwidth (FWHM) of the resonance decreases when the transmission coefficient is increased or the ring losses decrease

Ring resonator

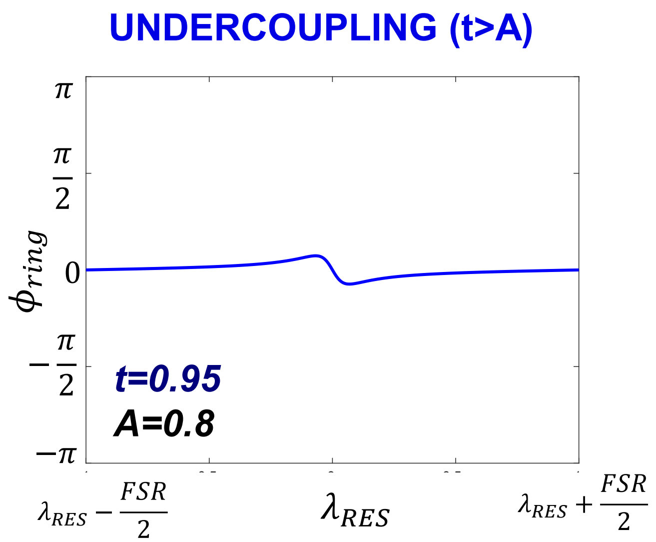
OPTICAL PHASE RESPONSE

- Effect of transmission coefficient for a given ring loss





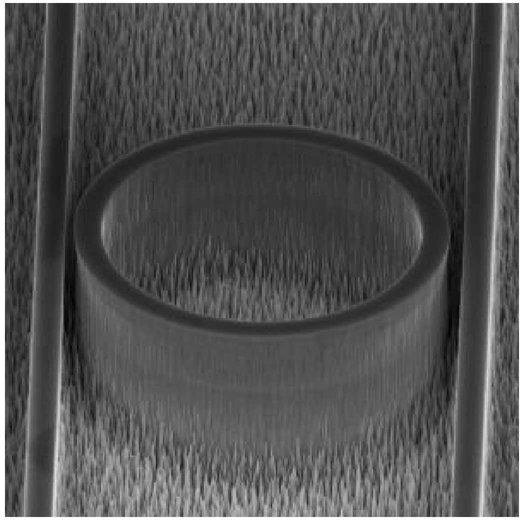
$$\boxed{\frac{E_o}{E_i} = A_{ring} e^{j\phi_{ring}}}$$

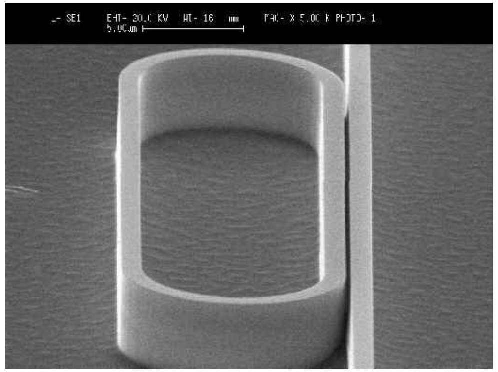


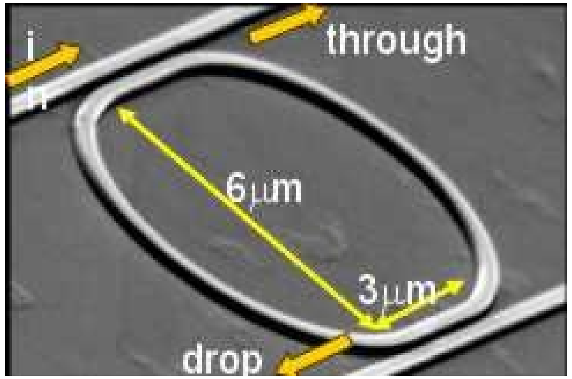
- The optical phase introduced by the ring **at the resonant wavelength** is $\phi_{ring}=\pi$ in the overcoupling regime and $\phi_{ring}=0$ in the undercoupling regime. At critical coupling it makes no sense because there is no optical power ($A_{ring}=0$) at the output.
- The variation of phase response is steeper when closer to critical coupling → influence on the **group delay**

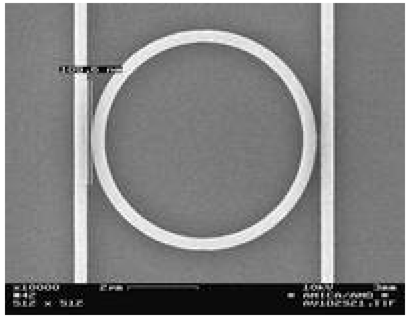
Ring resonator

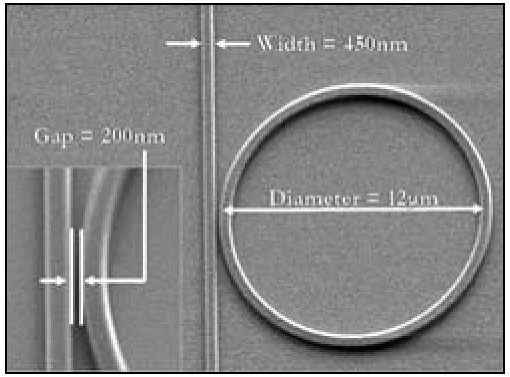
SEM IMAGES OF RING RESONATORS

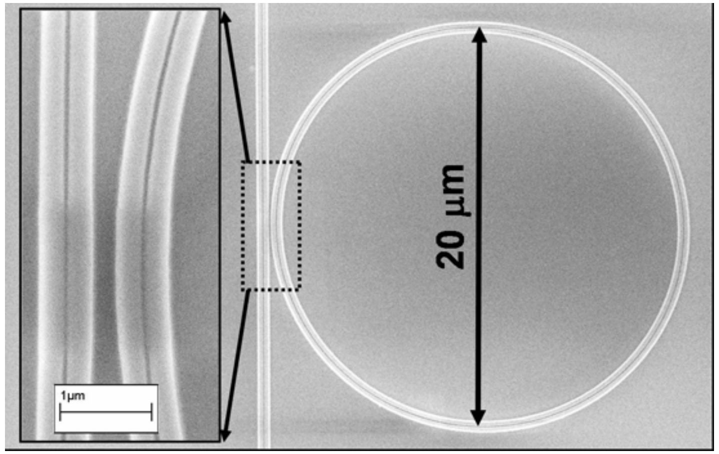








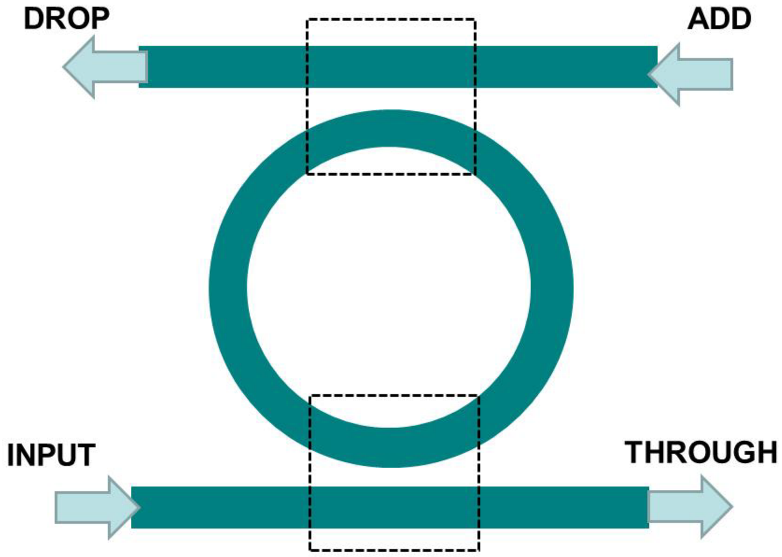




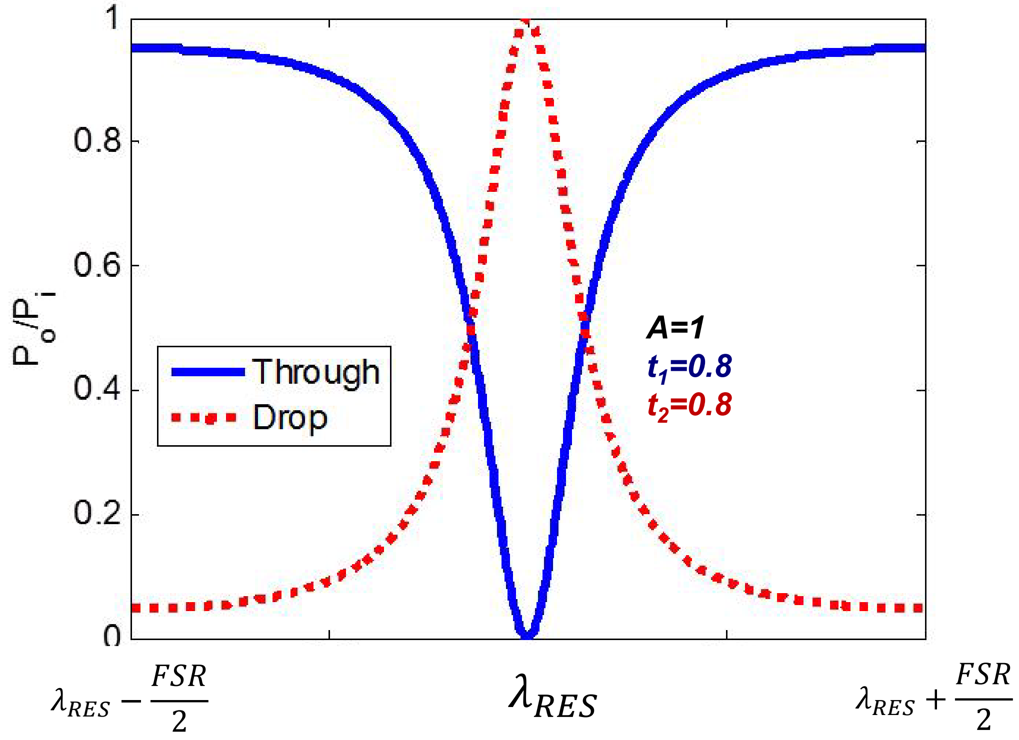
Ring resonator

APPLICATIONS

- Add-drop multiplexer/demultiplexer
  - Ring resonator coupled to two waveguides



P. Dumon, "Ultra-Compact Integrated Optical Filters in Silicon-on-insulator by Means of Wafer-Scale Technology", PhD, March 2007

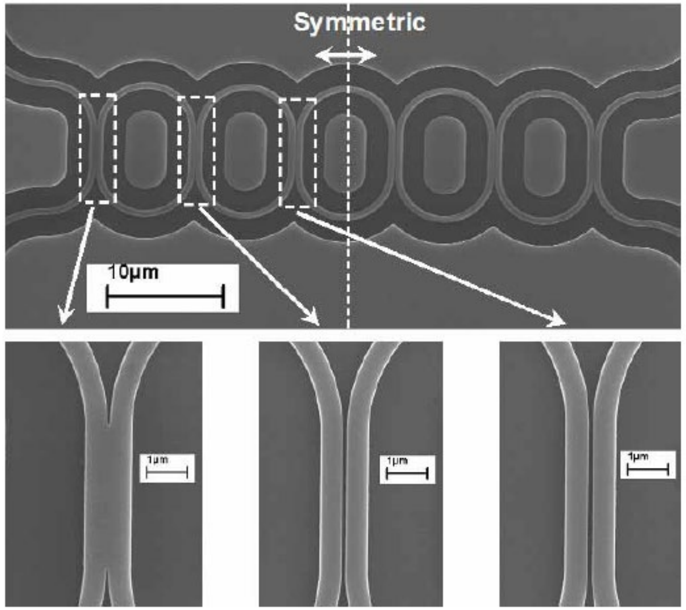


$\boxed{t_1=t_2A}$ for critical coupling at through port

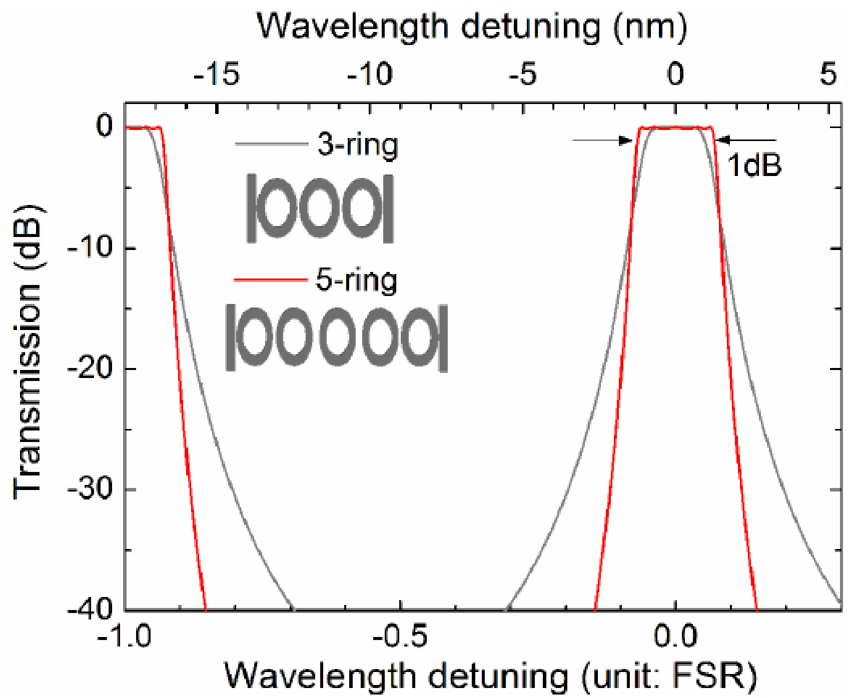
Ring resonator

APPLICATIONS

- Optical filters
  - Exploit the **transmission response** of the ring
  - Based on multiple coupled or cascaded ring resonators



F. Xia, et al. "Ultra-compact high order ring resonator filters using submicron silicon photonic wires for on-chip optical interconnects," Opt. Express 15, 11934-11941 (2007)

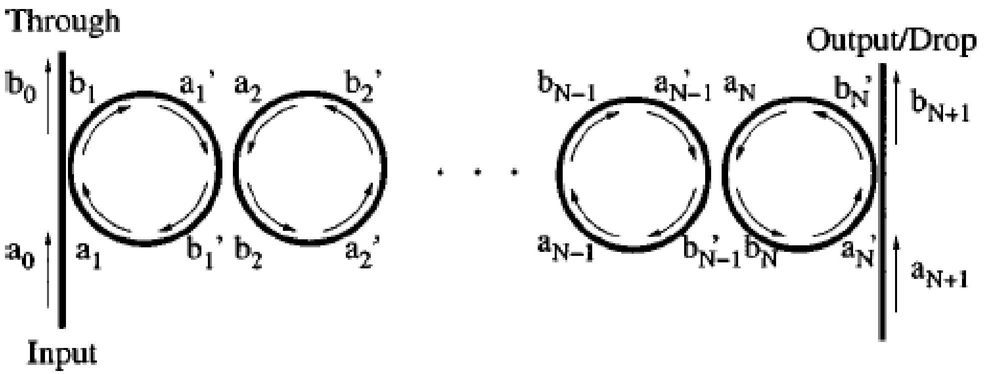


Flat transmission band, high rejection (classical filter theory)

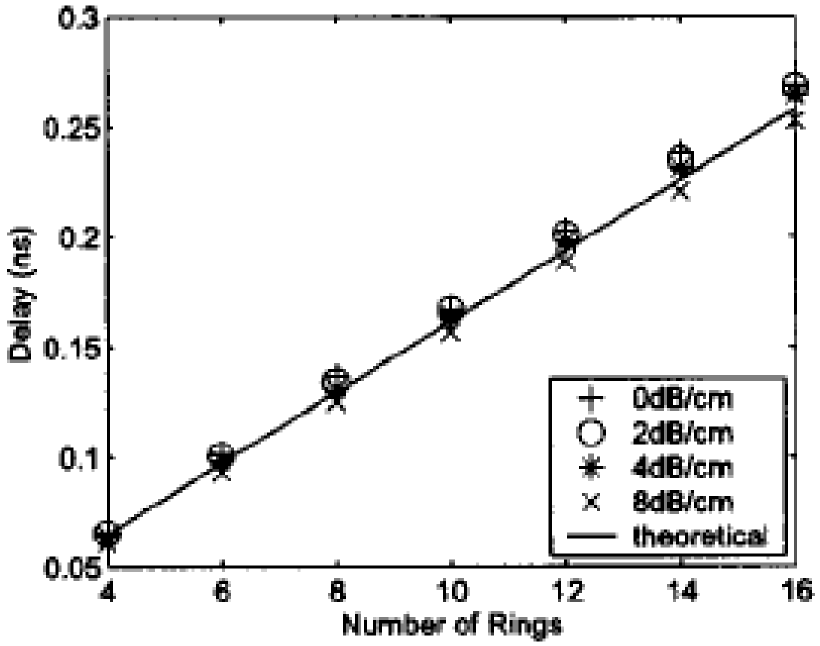
Ring resonator

APPLICATIONS

- Optical delay lines or dispersion compensators
  - Exploit the **phase response** of the ring
  - Based on multiple coupled or cascaded ring resonators



J. Poon et al, “Designing coupled-resonator optical waveguide delay lines”, J. Opt. Soc. Am. B, vol. 21, no. 9, pp. ,1665-1673, 2004



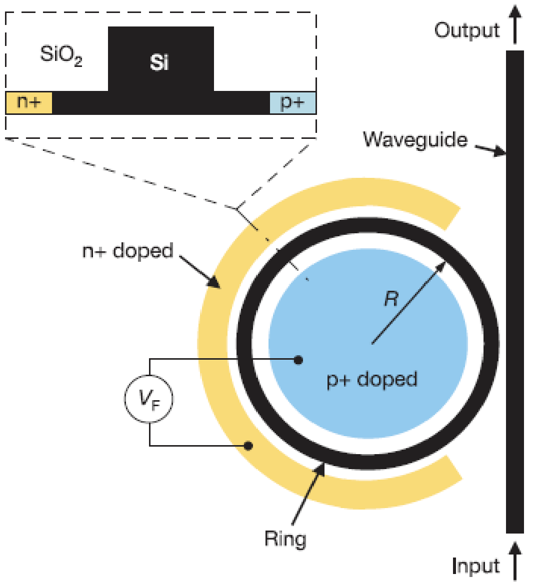
(b) Delay vs. N for $|\kappa| = 0.1$.

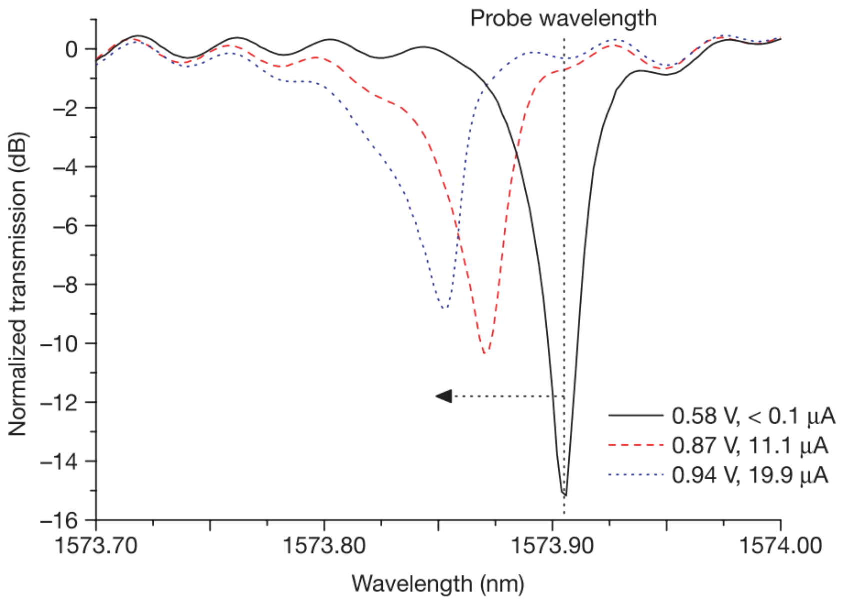
Trade-off between delay, bandwidth and losses

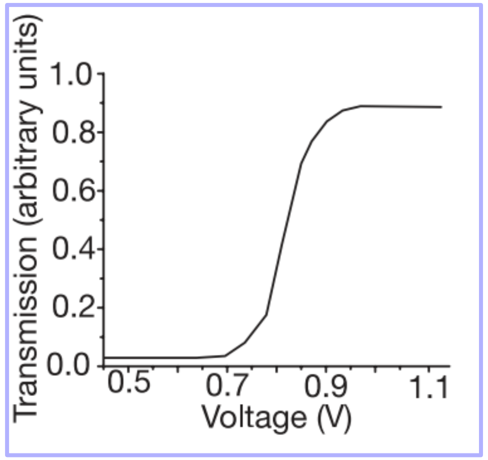
Ring resonator

APPLICATIONS

- Modulator / switch
  - A change of effective refractive index is induced by an external signal (electrical, thermal, optical)





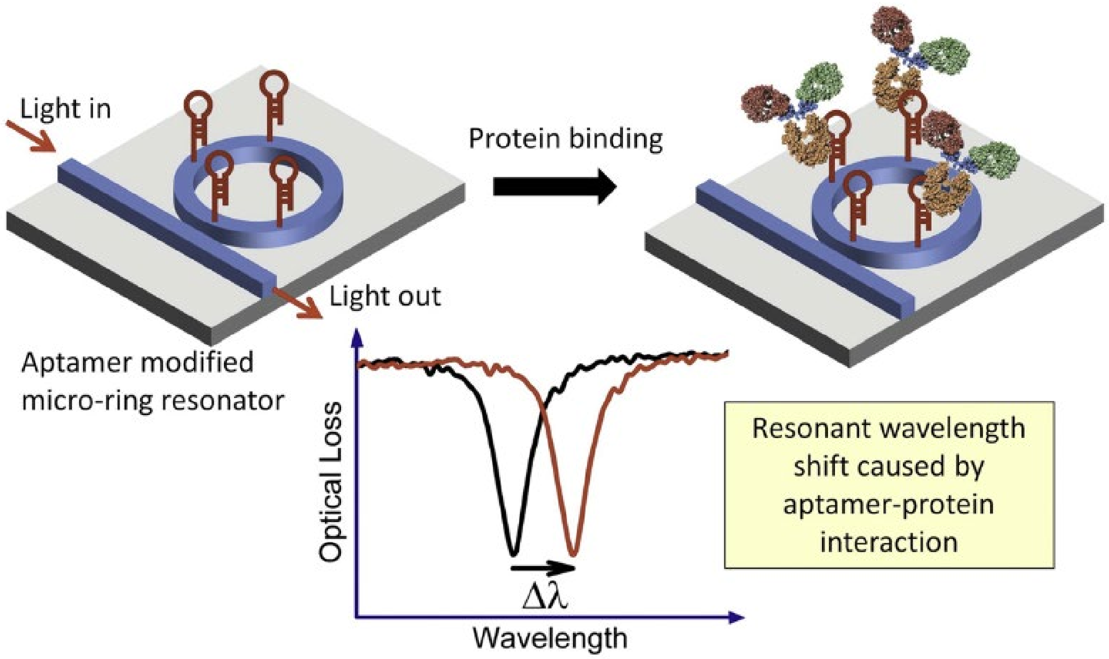


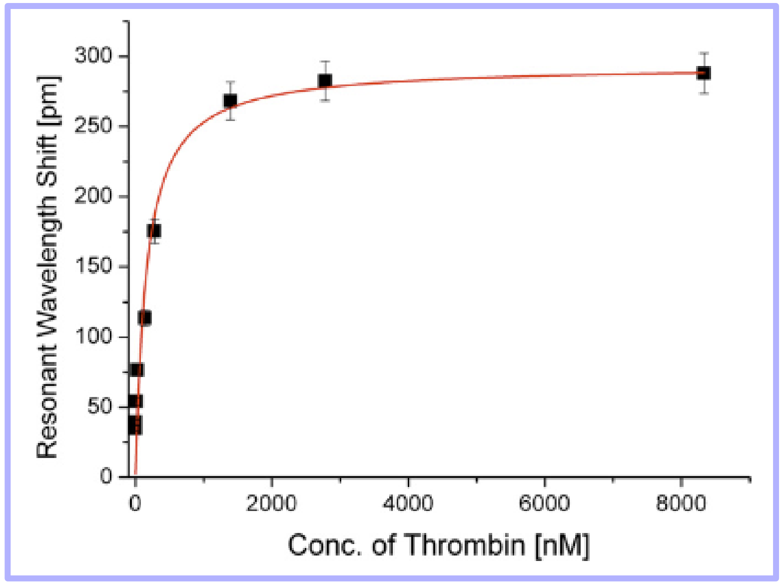
Q. Xu, B. Shcmidt, S. Pradhan, and M. Lipson, “Micrometer-scale silicon electro-optic modulator,” Nature, no. 435, pp. 325–327, May 2005.

Ring resonator

APPLICATIONS

- (Bio) sensing
  - The change of effective refractive index is induced by the substance to be detected
  - A higher sensing sensitivity can be achieved





M.K. Park, et al., “Label-free aptamer sensor based on silicon microring resonators”, Sensors and Actuators B: Chemical, vol. 176, 2013.

Homework #4-Part 2

- Design a multi-channel notch filter by using a single ring resonator. The goal is that wavelengths at ring resonances (ϕ=0) are suppressed with maximum extinction ratio while wavelengths out-of-resonance (ϕ=π) are passed with minimum insertion losses.
    1. Determine the transmission coefficient for working at critical coupling if power losses in the ring are 1.2dB.
    2. Taking into account the transmission coefficient calculated before, how does affect to the filter performance if losses increase to 3dB?
    3. If now losses increase up to 10 dB. Explain how would you design the transmission coefficient to keep the extinction ratio higher than 6dB and minimize the insertion losses out of the resonance.
- Now, let us consider that the single ring resonator is replaced by an add-drop ring resonator to extract the filtered wavelengths. The power losses in the ring are 1.2dB. Explain how would you design the transmission coefficients of the through and drop ports to have insertion losses below 3 dB and an extinction ratio above 10 dB at both output ports.
- Use the virtual laboratories "Performance of a single ring resonator for photonic applications" (https://laboratoriosvirtuales.upv.es/eslabon/ringresonator) and "Performance of an add-drop ring resonator for photonic applications" (https://laboratoriosvirtuales.upv.es/eslabon/adddropring) to obtain and justify the results

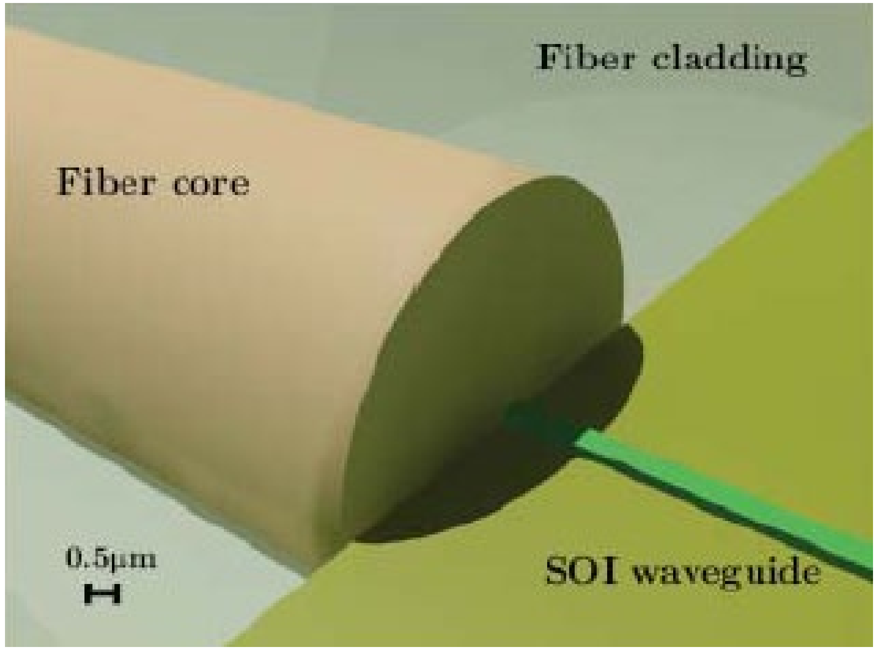
Single PDF file for Part 1 and Part 2 with 4 pages maximum. Include key plots from virtual laboratory

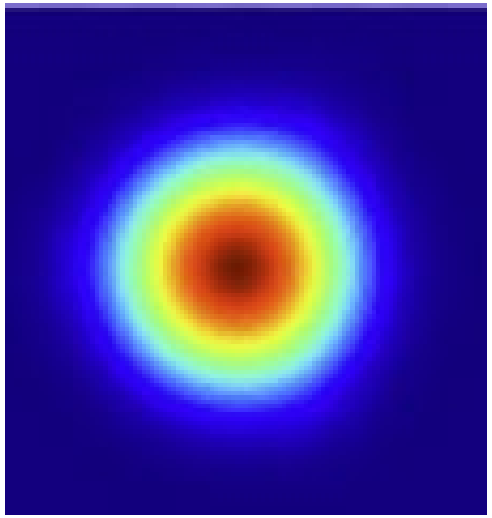
Outline

- Waveguide bend
- Y-junction
- Directional coupler
- Multimode interference coupler
- Mach-Zehnder interferometer
- Ring resonator
- Fiber coupling structures

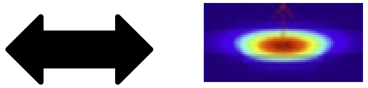
Fiber coupling structures

- High coupling losses (>15dB) between the optical fiber and a nanophotonic optical waveguide mainly occur due to the large size mismatch → mandatory use of coupling structure





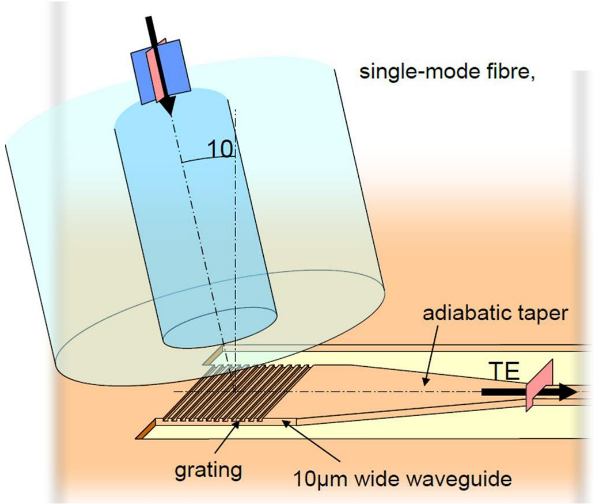
Mode profile of optical fiber



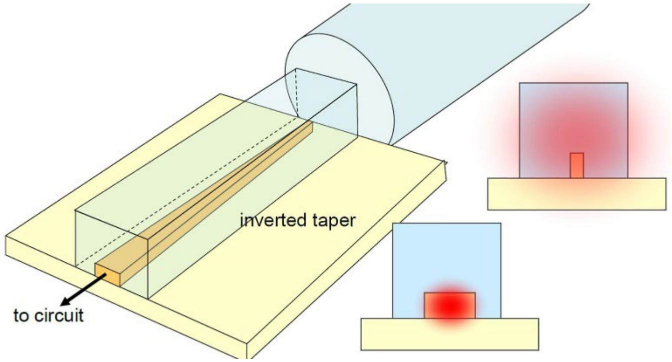
Mode profile of photonic waveguide

Fiber coupling structures

GRATING COUPLER



INVERTED TAPER



Coupling technique	Inverted taper	Grating coupler
Wafer-level testing capability	Low (Horizontal coupling)	High (Vertical coupling)
Footprint	~ 100µm	~ 10µm
Coupling losses	~ 1dB	> 3 dB (can be improved with more complex designs)
Optical bandwidth	>100nm	~ 40nm
Polarization	Insensitive (can work for both polarizations)	Sensitive (usually works only for one polarization)

W. Bogaerts, "Coupling light to silicon photonic circuits“, Silicon photonics course from HELIOS project

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Questions to review

- What is the effect of waveguide losses on the extinction ratio of an asymmetric MZI?
- Which state, bar or cross, is less wavelength dependent and more tolerant to process variations when the 2x2 MZI is used as a switch?
- How can we achieve narrow resonances in a ring resonator?
- If we want to implement an intensity modulator with a ring resonator, what will be the best coupling regime? Why?
- What coupling technique, inverted taper coupler or grating coupler, is preferable in terms of insertion loss? and in terms of the manufacturing process testing?