Parametric exploration of vertical tapered couplers for 3D optical interconnection

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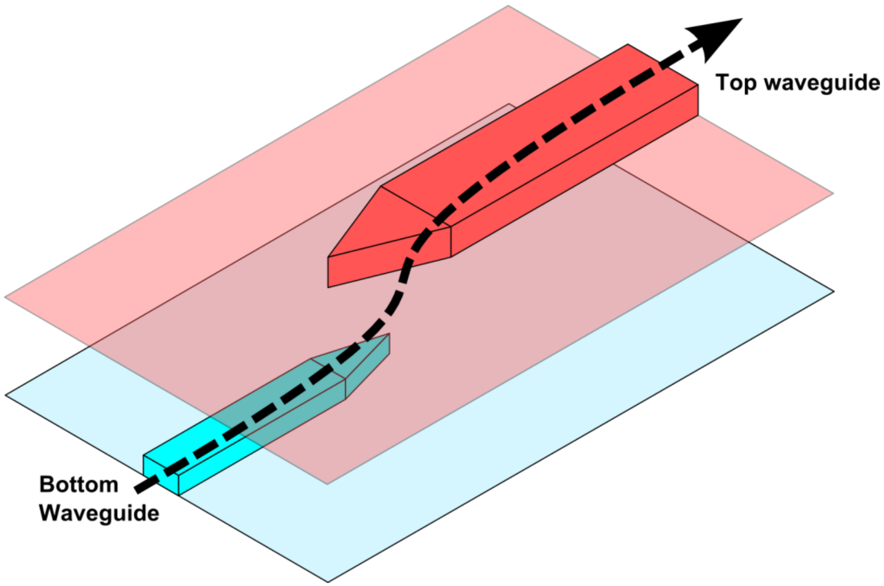
Aim and Outline of this Work

- **AIM OF THE WORK**
  - Numerically investigate the design space of tapered couplers for vertical interconnections
  - Optimization of insertion losses via longitudinal shift

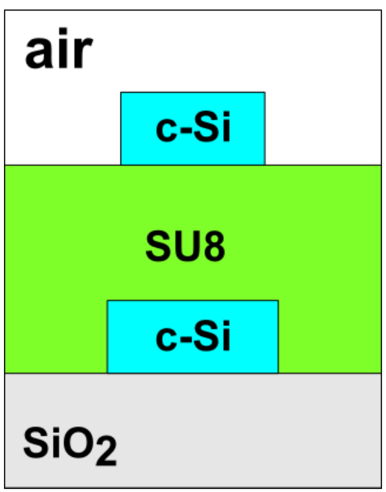


- **OUTLINE**
  - 3D technological platforms: configurations and parameters
  - Performance evaluation of vertical tapers
  - Planar crossings versus “bridge” solution
  - Appendix: tapers / two levels ring resonators
  - Summary

3D Technological Platforms : Configurations

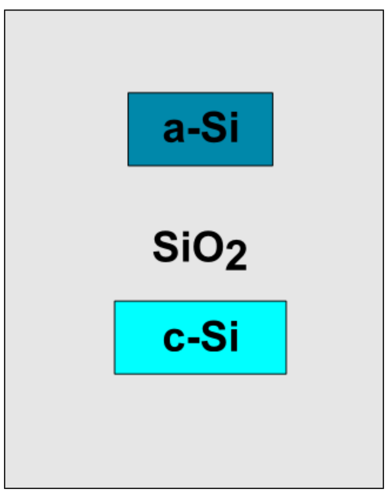
- **3D Vertical stacking proposed in Optical Networks on Chip to overcome limits induced by the increase in device density**
  - Avoiding crossings
  - Introducing a secondary level for optical integration
- **Technological platforms for 3D Stacking explored in this work:**

(A) Crystalline Silicon over Crystalline Silicon



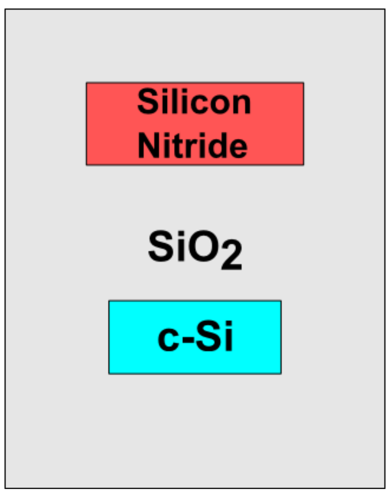
Y. Zhang, et al. "0.88 THz Skew-free 1-to-32 Optical Clock Distribution on Adhesively Bonded Silicon Nanomembrane", IEEE PTL (2014)

(B) Amorphous Silicon over Crystalline Silicon



R. Sung et al., "Impedance matching vertical optical waveguide couplers for dense high index contrast circuits“, Optics Express (2008).

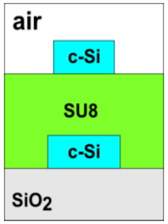
(C) Silicon Nitride over Crystalline Silicon



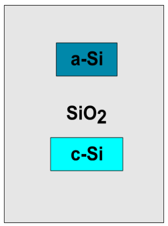
A.M. Jones, et al., "Ultra-low crosstalk, CMOS compatible waveguide crossings for densely integrated photonic interconnection networks“, Optics Express (2013)

3D Technological Platforms : Optical Parameters

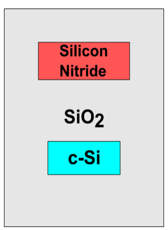
- **Technologies for 3D Stacking : Optical Parameters**



- **(A) Crystalline Silicon waveguide over Crystalline Silicon waveguide**
  - n_{Si} = 3.45, n_{SiO2} = 1.45, n_{SU8} = 1.575
  - Propagation loss values: 2.5÷3 dB/cm (bottom layer), 4.3 dB/cm (top layer)



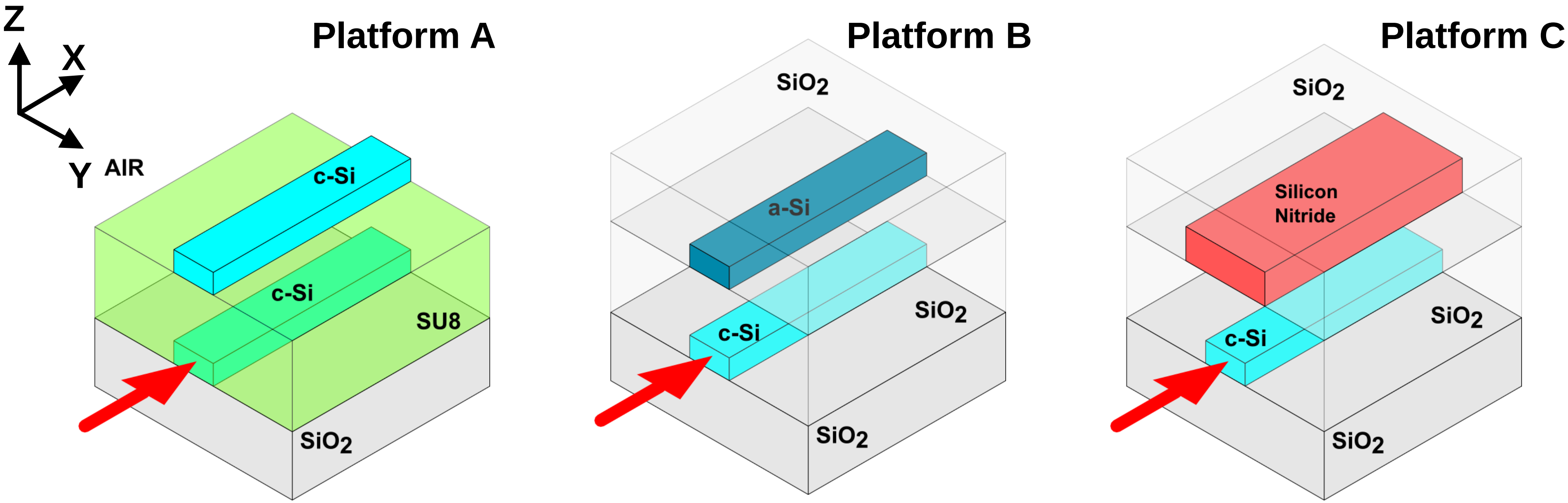
- **(B) Amorphous Silicon waveguide over Crystalline Silicon waveguide**
  - n_{Si} (bottom) = 3.45, n_{Si} (top) = 3. 77, n_{SiO2} = 1.45
  - Propagation loss values: 2.5÷3 dB/cm (bottom), > 3 dB/cm (top)



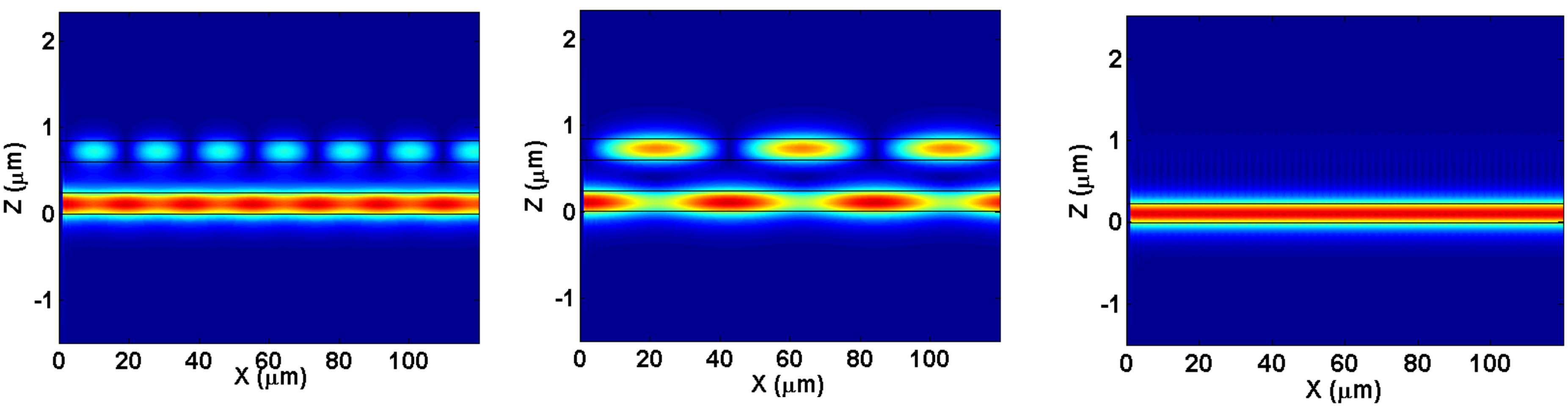
- **(C) Silicon Nitride waveguide over Crystalline Silicon waveguide**
  - n_{Si} = 3.45, n_{Si3N4} (TOP) = 2, n_{SiO2} = 1.45
  - Propagation loss values: 2.5÷3 dB/cm (bottom), 1 dB/cm (top)

Waveguide Core Material	Waveguide properties		
	Waveguide width (nm)	Waveguide height (nm)	Effective Index fundamental mode @ 1550nm
c-Si n_{SI} = 3.45	480	220	2.389
a-Si n_{SI} = 3.77	480	220	2.736
Si_3N_4 n_{Si3N4} = 2.0	**1000**	**400**	1.642

Parallel Waveguides : Field Evolution



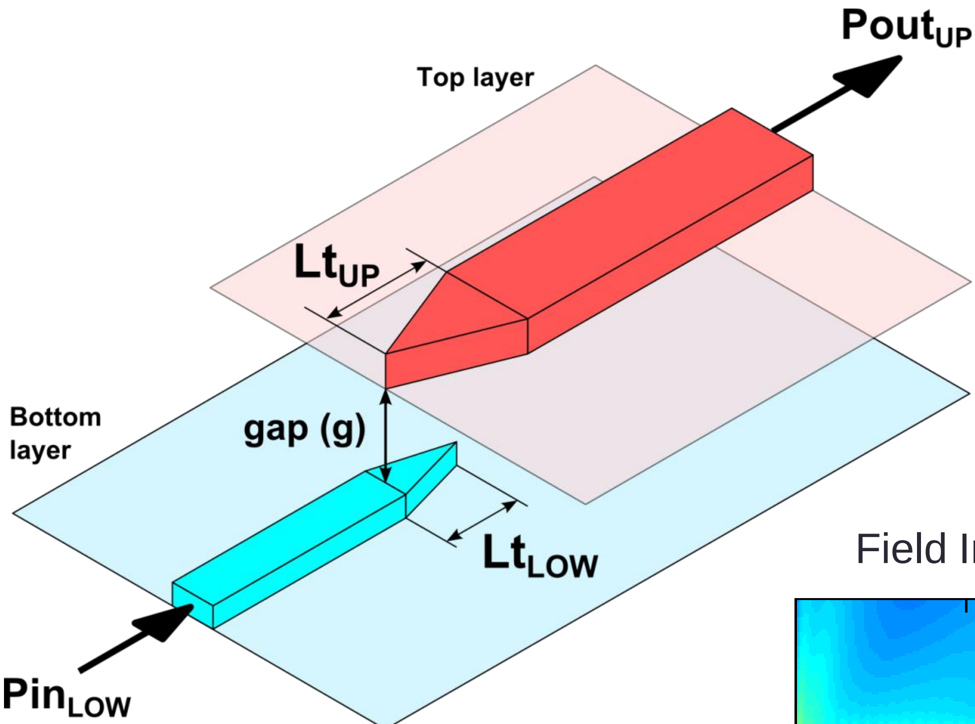
Lateral view (X-Z section) of the field propagation



- On platform C, due to mismatch between waveguides, very low coupling is observed
- Good for mutual isolation, but bad if we want to switch level

Inverse Taper Couplers

- **Vertical coupling based on Inverse Tapers**

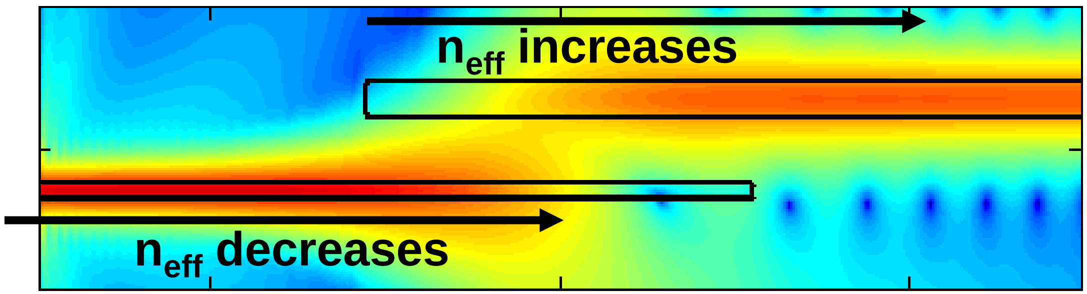


Main properties

- **High coupling efficiency**
- **Simple design and fabrication**
- **Robustness**
- **Large footprint ☹**

$$IL_{LINK} = -10 \cdot \log_{10}\left(\frac{Pout_{UP}}{Pin_{DOWN}}\right)$$

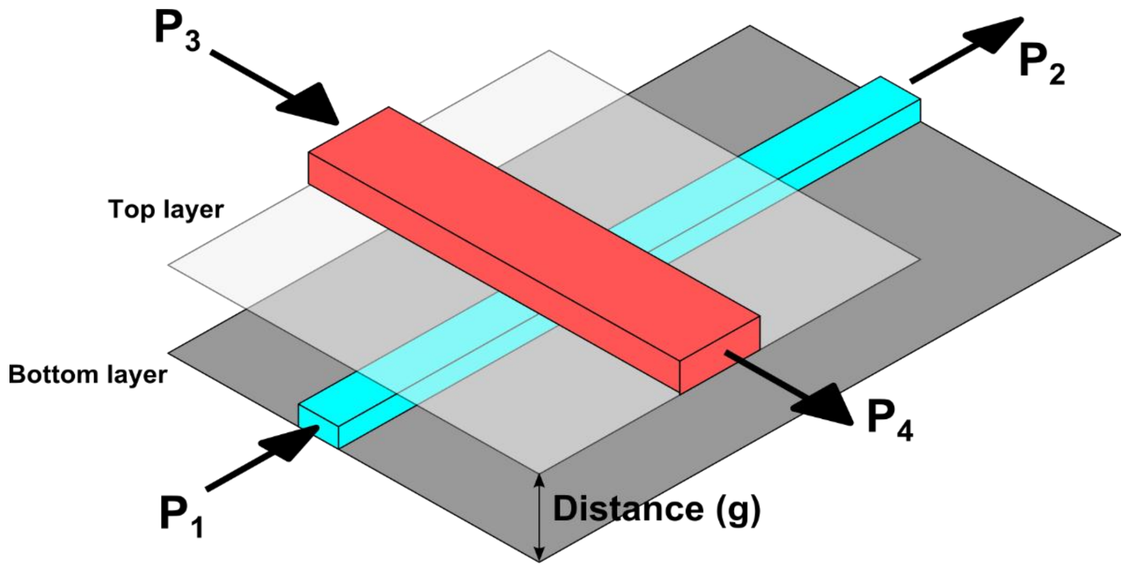
Field Intensity evolution @ 1550nm (FDTD sim.)



- Effective index of bottom waveguide decreases as the top one increases
- Coupling takes place when waveguides effective indices are equal/similar
- Efficient coupling if mode profiles have good superimposition

Vertical distance between layers

- **3D stacking design – minimum vertical distance**
  - Determination of the **gap g** between the two optical layers
    - **Small gap: easier coupling, but crosstalk between the two layers**
  - Once the gap has been determined, a vertical coupler can be designed (length of the inverse tapers)



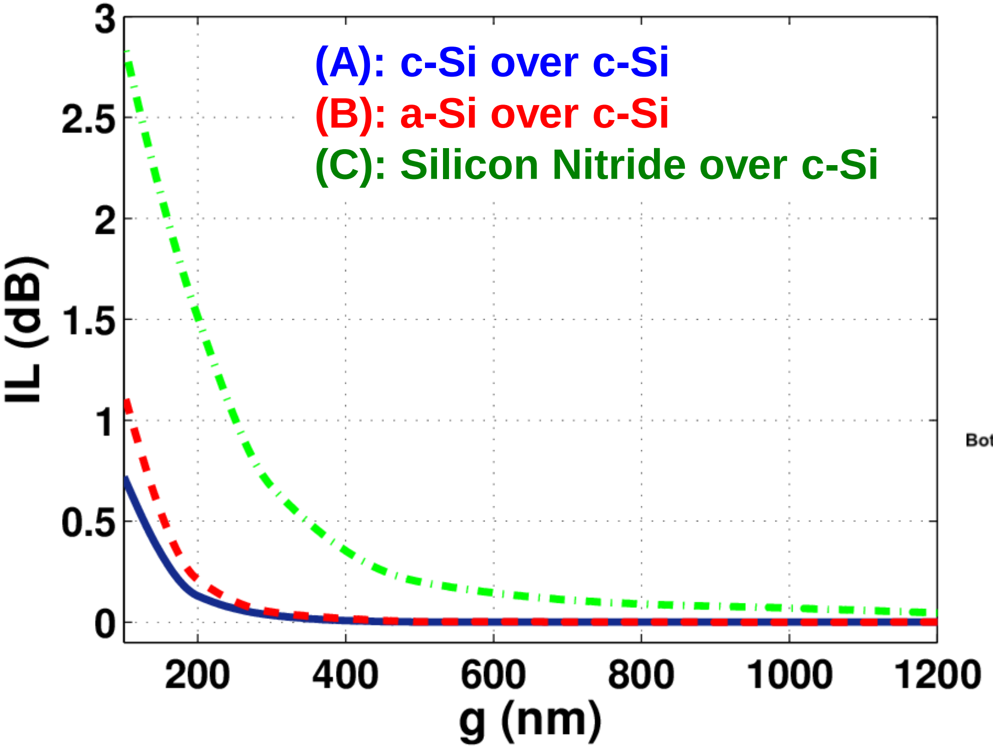
$$IL_{LOW} = -10 \cdot \log_{10}\left(\frac{P_2}{P_1}\right)$$

$$IL_{UP} = -10 \cdot \log_{10}\left(\frac{P_4}{P_3}\right)$$

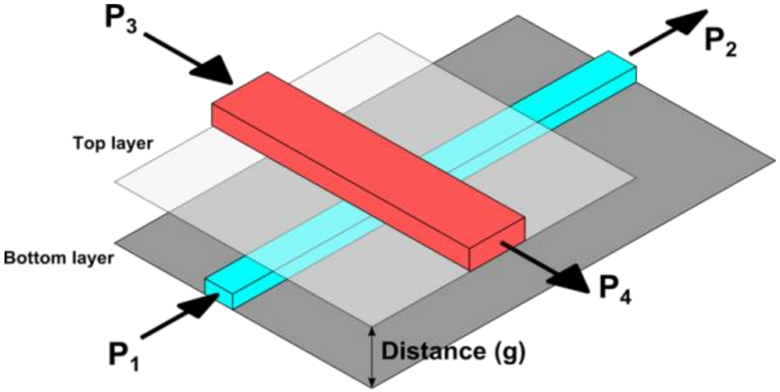
- Insertion loss caused by waveguide interactions
- Crosstalk is very low due to mode mismatch (-40 dB)

Two levels crossing : Insertion Losses

- **90° Crossing between waveguides on different layers**



Insertion loss evaluated in the worst case scenario (propagation in the waveguide with weaker confinement)



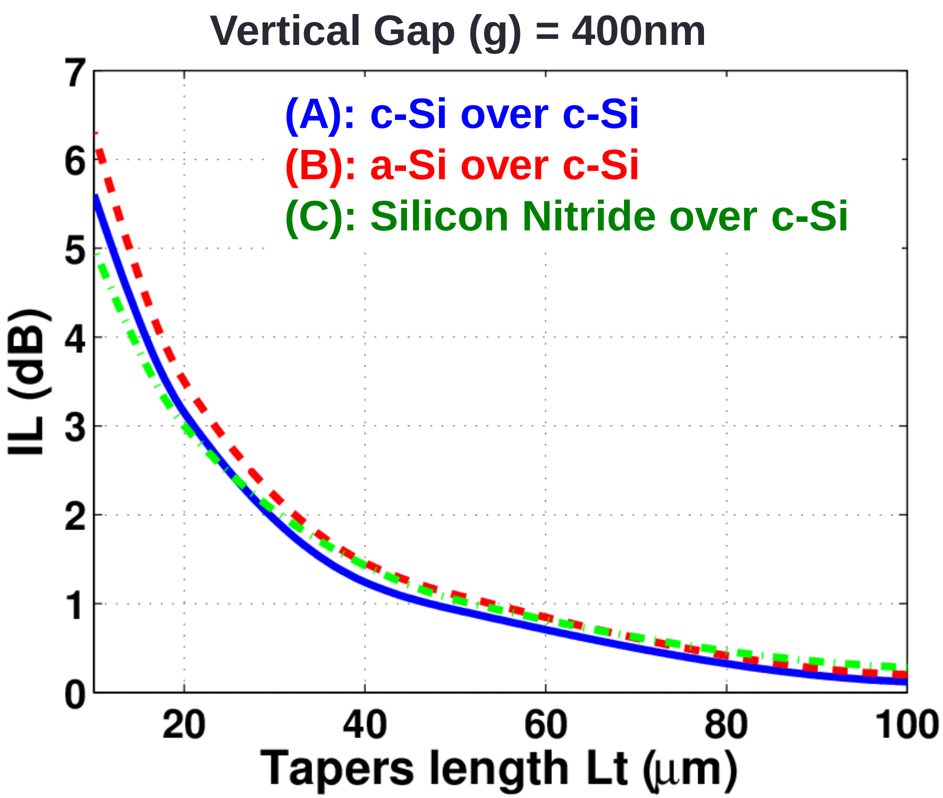
$$IL_{LOW} = -10 \cdot \log_{10}\left(\frac{P_2}{P_1}\right)$$

$$IL_{UP} = -10 \cdot \log_{10}\left(\frac{P_4}{P_3}\right)$$

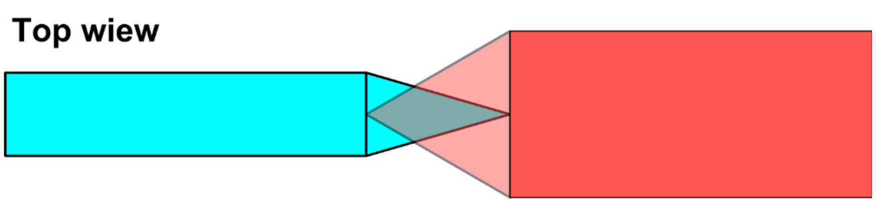
- For g = 400 nm, IL is limited to 0.05 dB for A and B platforms
- For g = 400 nm, IL is of about ≈0.2 dB, for C platform
  - **NOTE: for an optimized 90° <u>planar</u> (on a single level) crossing: IL = 0.2dB**

Vertical coupler : Insertion Losses

- **Performance evaluation as a function of tapers length**



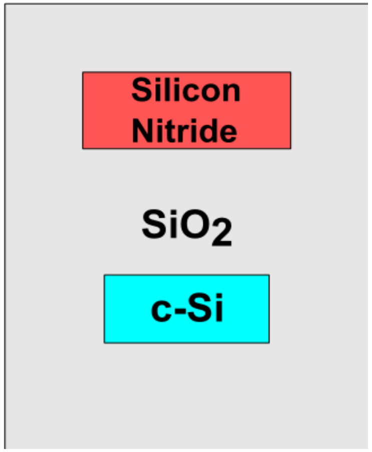
NO relative shift between tapers: the top tip begins to widen as the bottom tip begins to shrink



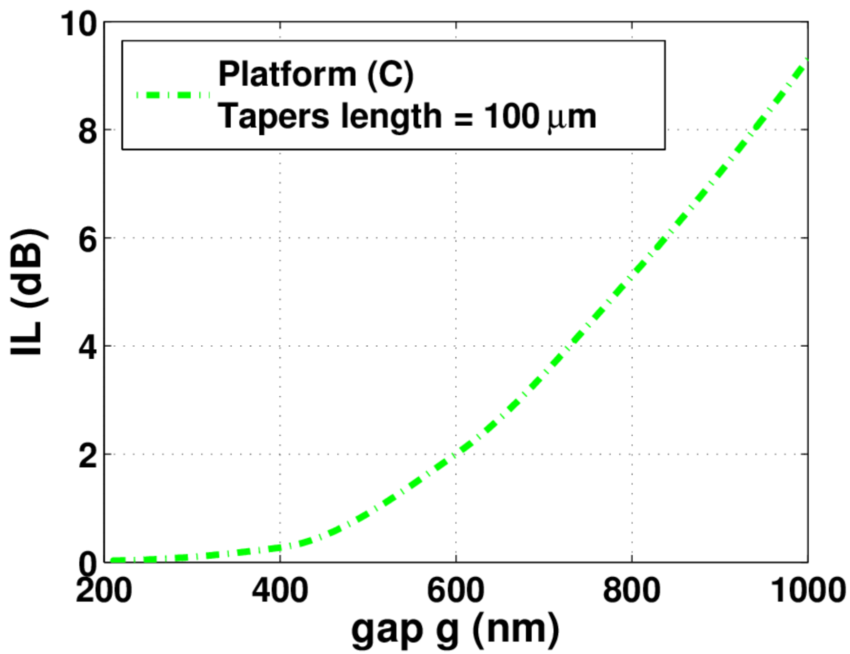
$$IL_{LINK} = -10 \cdot \log_{10}\left(Pout_{UP} / Pin_{LOW}\right)$$

- With taper lengths of **100 µm, IL is < 0.05 dB for all the platforms**
- However, for the Platform C when g = 400nm, ≈ 0.2dB of IL for each crossing between waveguides on different layers are expected

Considerations on Platform C



- On platform C, a coupler designed with two tapers of length 100 µm can assure IL < 0.05 dB when the vertical distance between the layers is 400 nm
- But, on platform C, 400 nm between the layers is not enough to avoid mutual crosstalk when two waveguides on superposed levels intersect
- To operate on platform C, we need to increase the vertical distance between the layers.

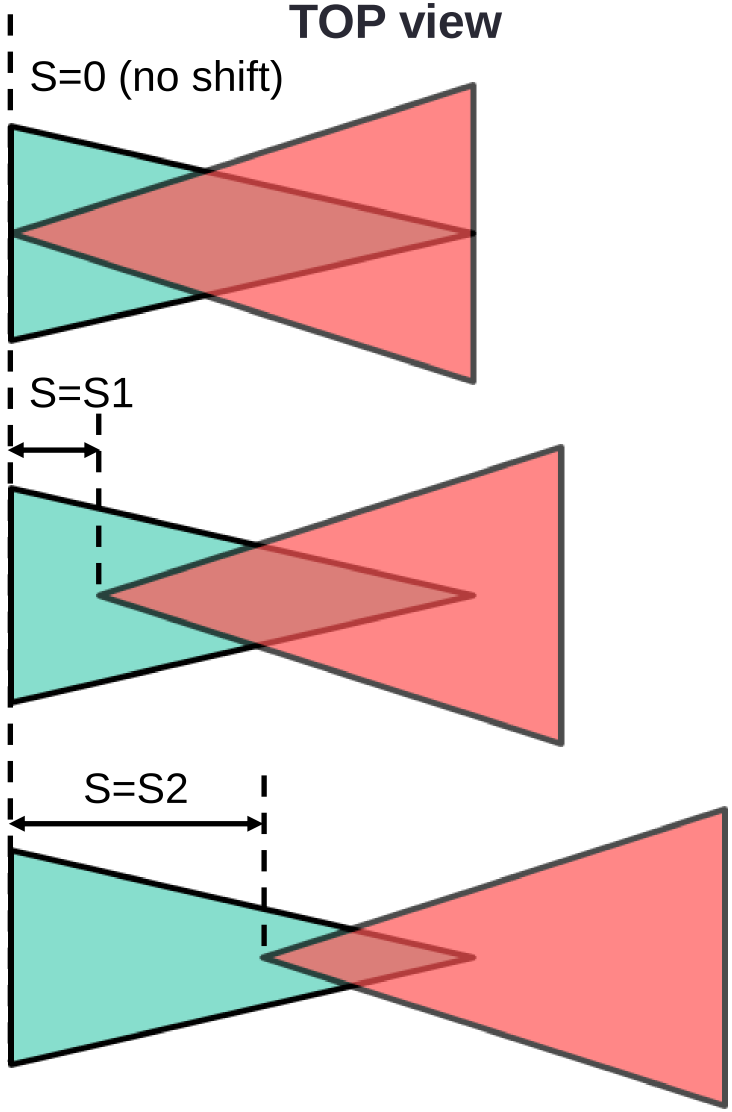


With a vertical gap g = 1000 nm, crosstalk between levels is low, but a coupler with tapers of 100 µm is too lossy for a practical use (IL = 9 dB)

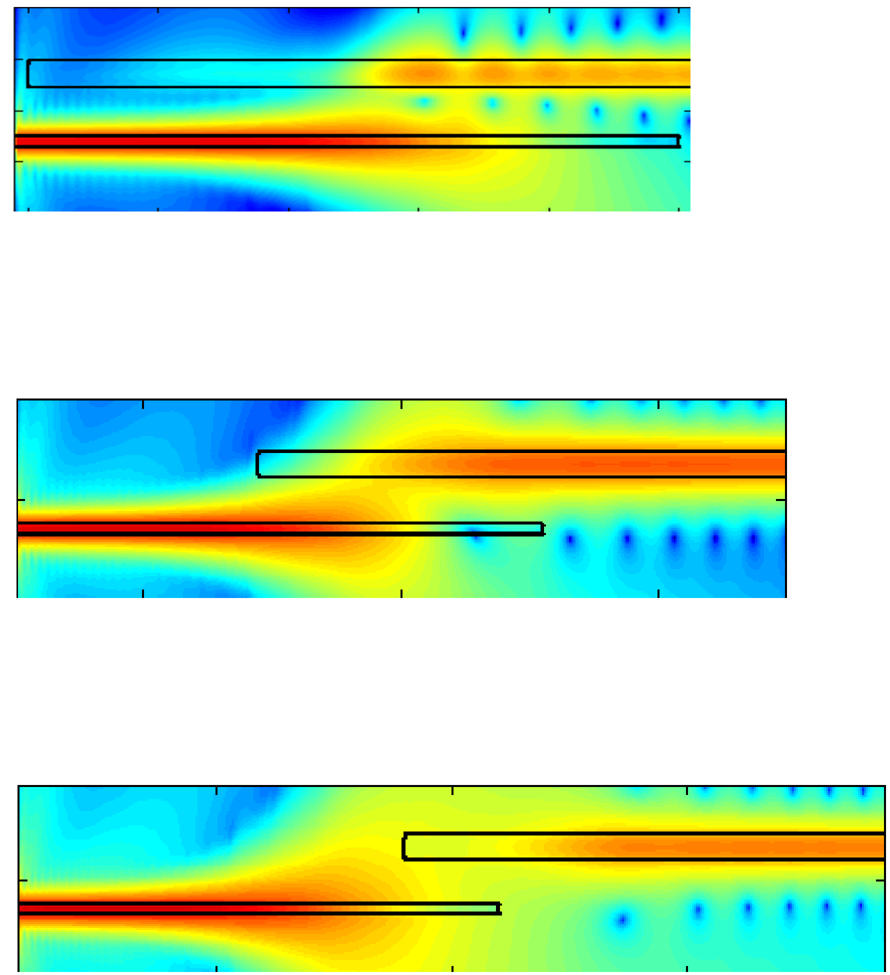
Coupler optimization

- **Optimization via relative longitudinal shift (S) of the tapers**

TOP view

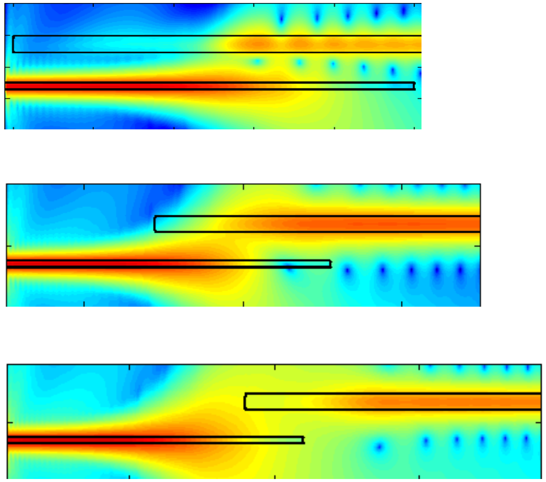


Field evolution (lateral view)



Coupler optimization on Platform C

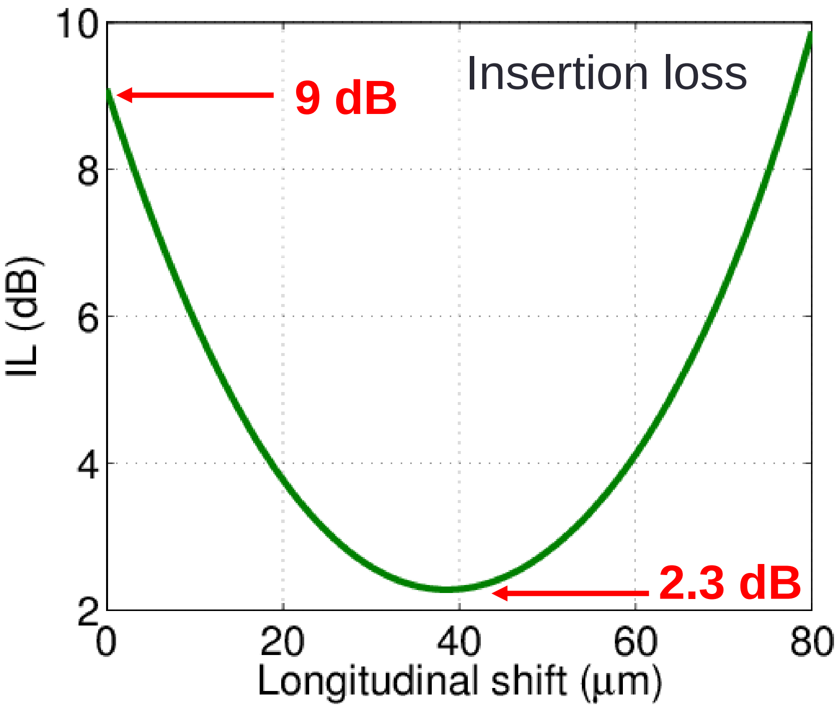
- Performance evaluation as a function of the relative **longitudinal shift (S)** between tapers
- Tapers length 100 µm
  Vertical gap = 1000 nm
  Shift (**S**) from 0 to +80 microns

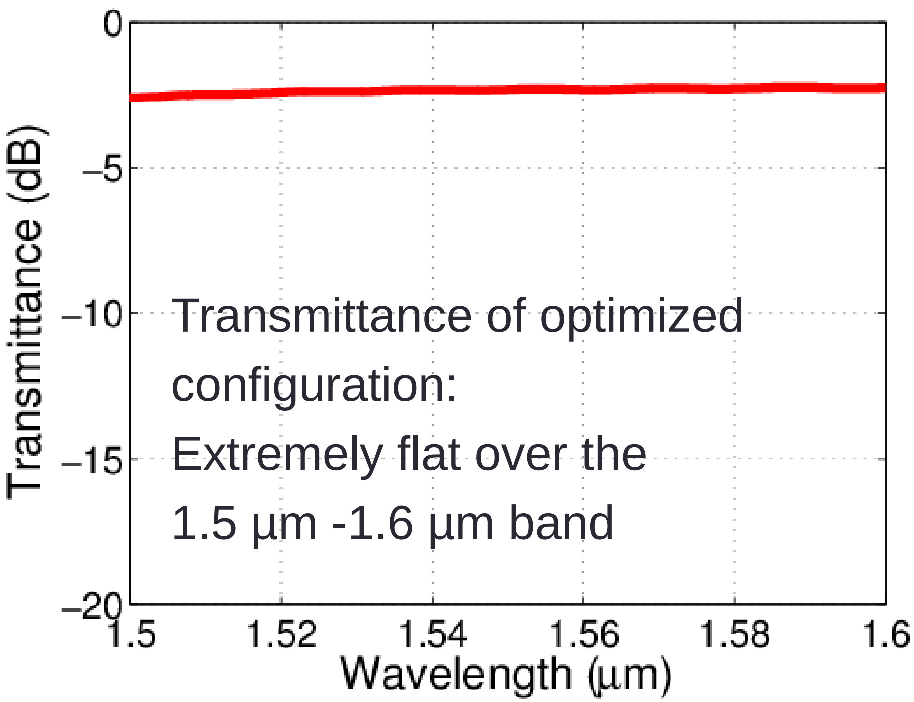


s = 0 µm

s = 40 µm

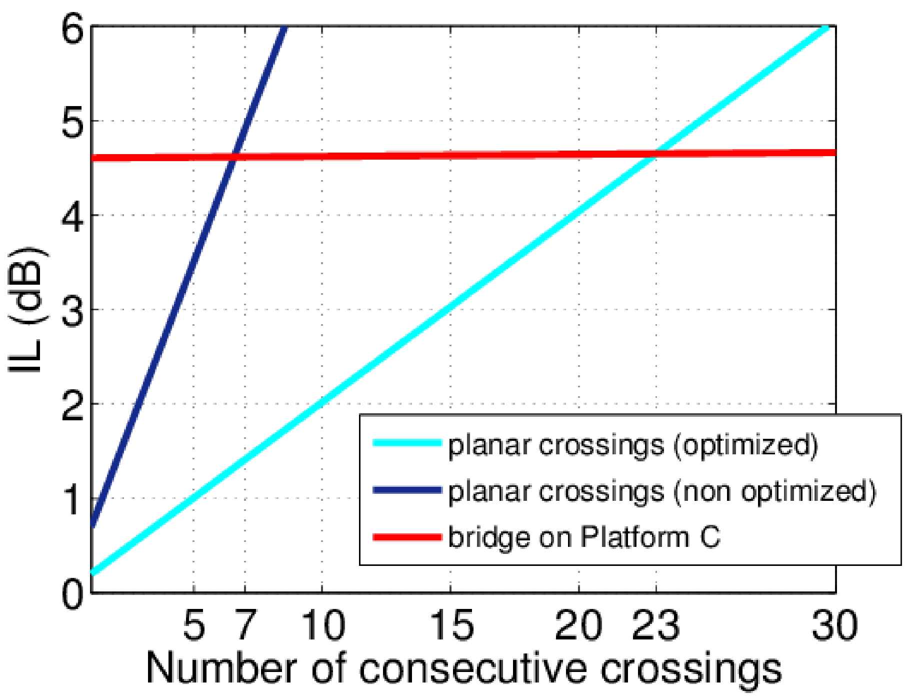
s = 80 µm

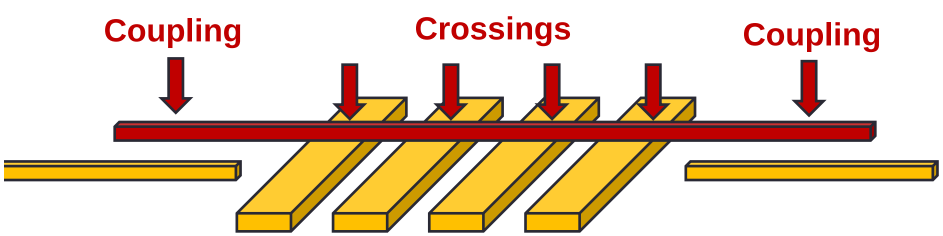




Comparison : planar crossings – vertical links

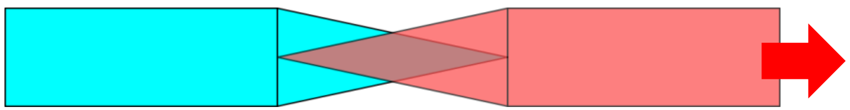
- **“Bridge” on platform C**
  - By considering optimized planar crossings (IL = 0.2dB), the use of 3D stacking is convenient when removing more than 23 crossings
  - With non-optimized crossings (IL = 0.7dB), 3D stacking is convenient when removing more than 7 crossing



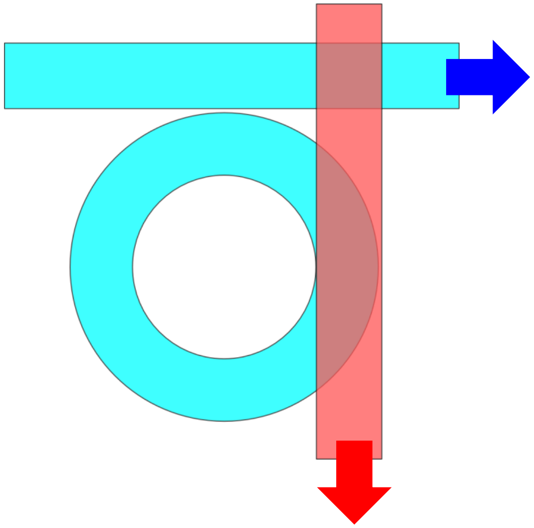


- 20 µm × 20 µm optimized crossings (IL = 0.2 dB)
- Waveguide losses for nitrure are considered (1 dB/cm)

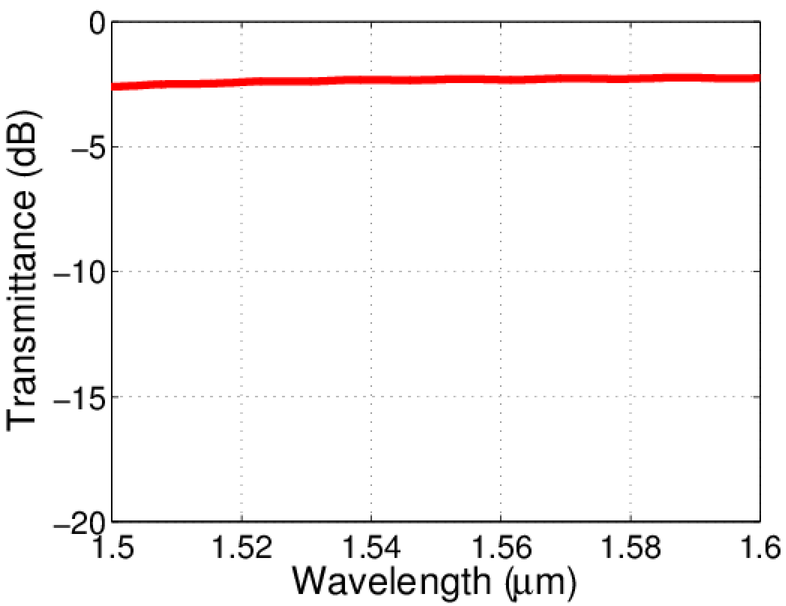
Tapers / Ring structures

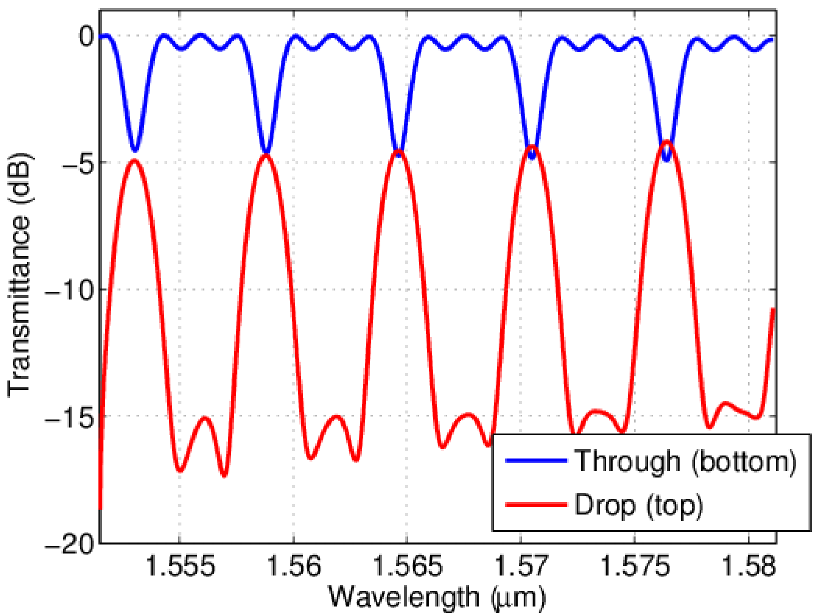


NON wavelength selective object



INTRINSICALLY wavelength selective





To summarize :

- Tapered couplers can be used to link heterogeneous optical layers
- Trade off among tapers length, distance between layers and transmission efficiency
- Relative shift of the tapers can be exploited to increase efficiency
- Open issues : tapers shape, asymmetrical tapers….