ON CHIP PHOTONIC INTERCONNECTIONS: WIRED AND WIRELESS TECHNOLOGIES

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Ring-Based Networks for On Chip Optical Interconnections: from device design to fabrication and final characterization

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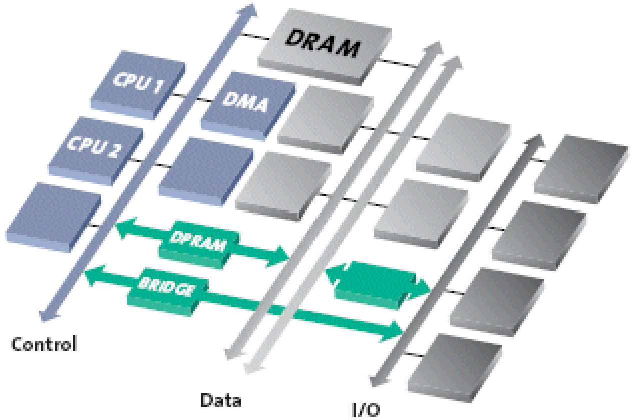

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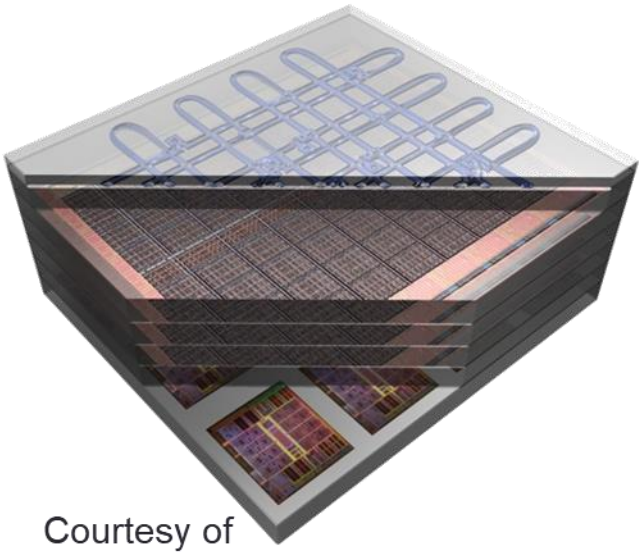

Courtesy of
Columbia University

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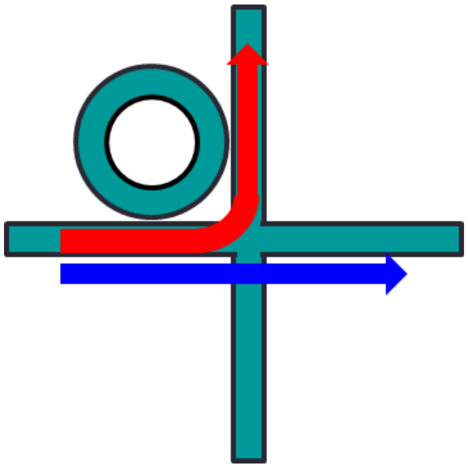

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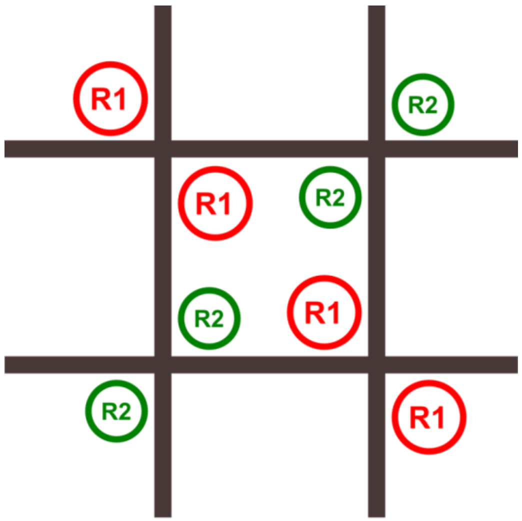

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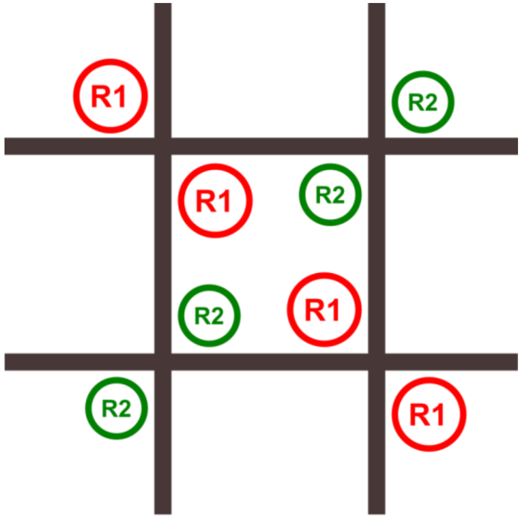

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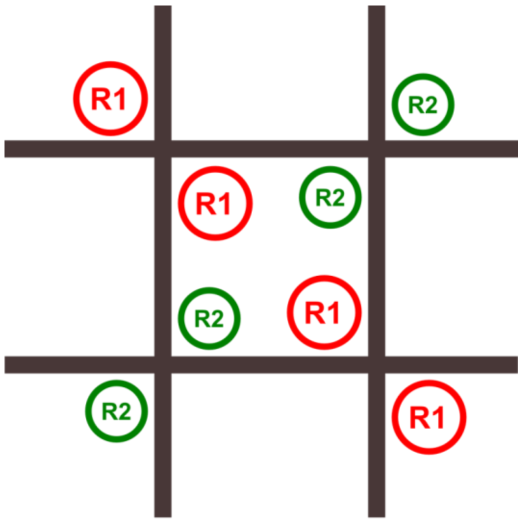
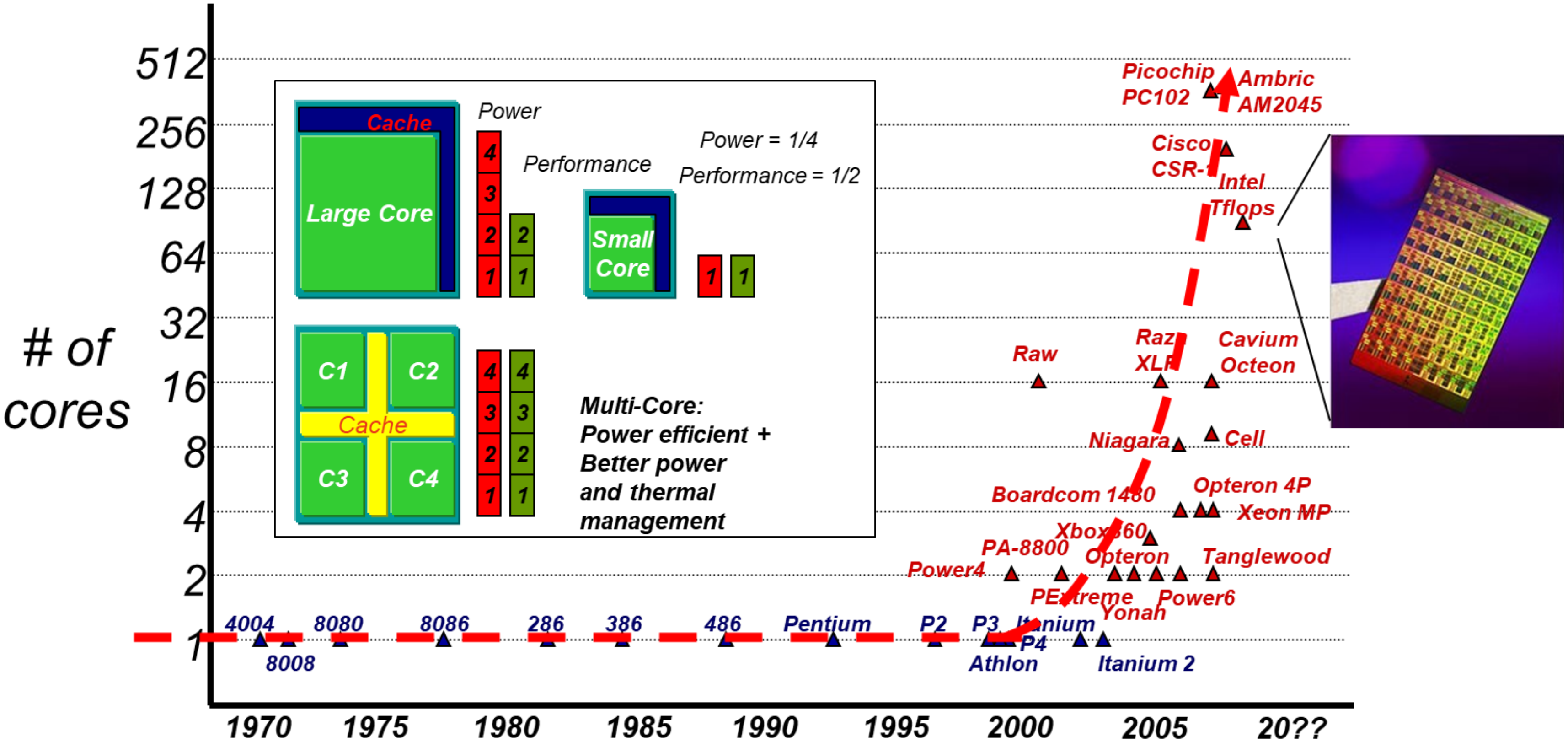
- Conclusions



IOP Lab

- Our interest in Optical Network on Chip is dated 2010



- Every commercial manufacturer of High-Performance Processors was introducing products based on Multi-Core Architectures

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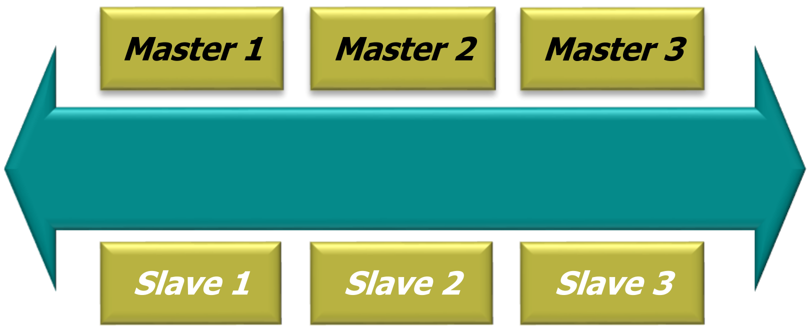
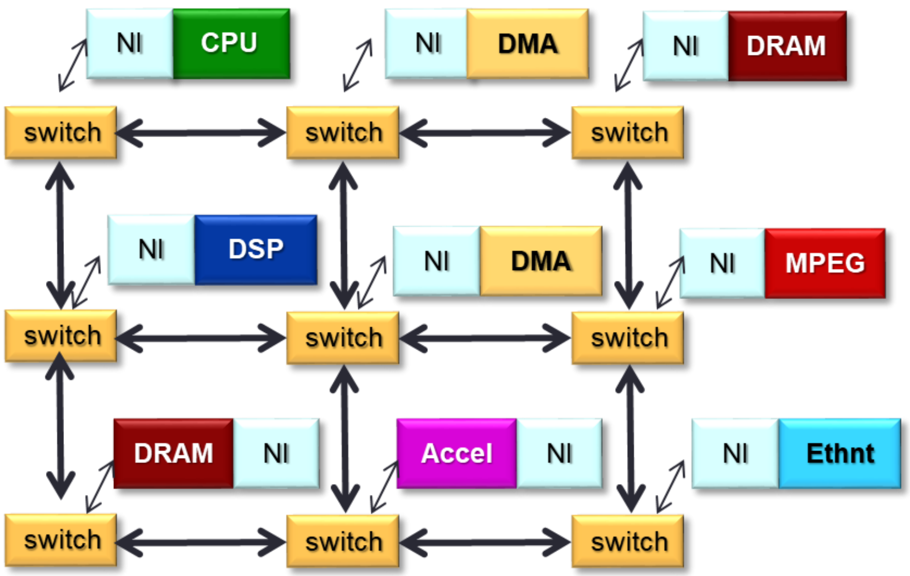
Multi-Core On-Chip Communication

- The Communication Bottleneck



- SERIALIZATION of bus access requests
- Single outstanding transaction allowed
- If wait states are needed, everybody waits

- A possible answer: Network-on-Chip (NoC)



- High heterogeneity/flexibility
  - Cores will operate at different frequencies, data widths and protocols
- High performance (bandwidth - latency)
  - Many cores will want to communicate, simultaneously
- Short and structured wiring
  - Point-to-point, predictable routing

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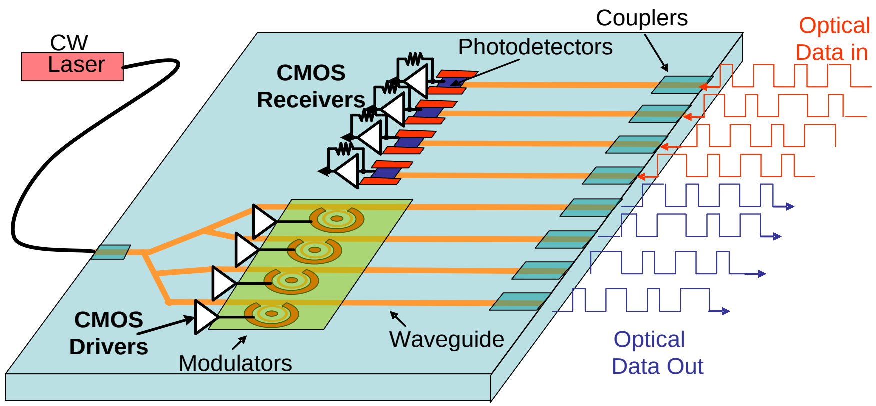
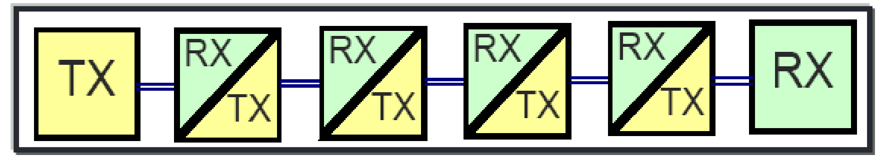
- Changing Technology? On-Chip Optical Links

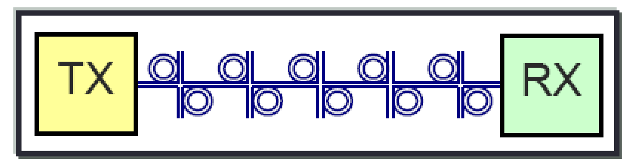


NoC

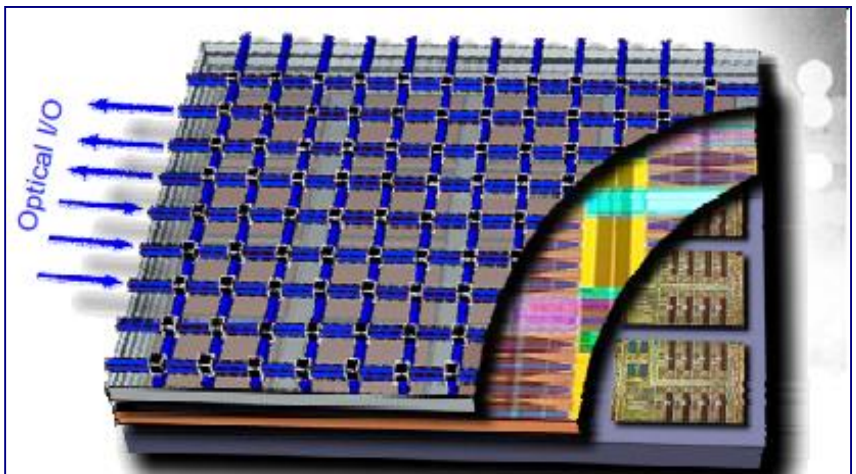


- Power is Bandwidth × Length dependent
- Buffering, Receiving and Retransmitting
- Power-hungry and BW limited by pin count

ONoC



- Power independent of Bitrate and Length
- Modulate/Receive high BW data stream once – no retransmit
- Almost seamless scaling to multi-chip systems
- Broadband switching fabric nearly free in power dissipation (scalability)



Courtesy of IBM

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- Network Proposals

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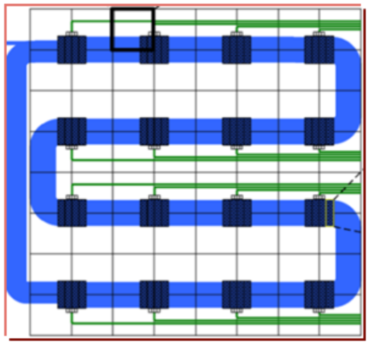
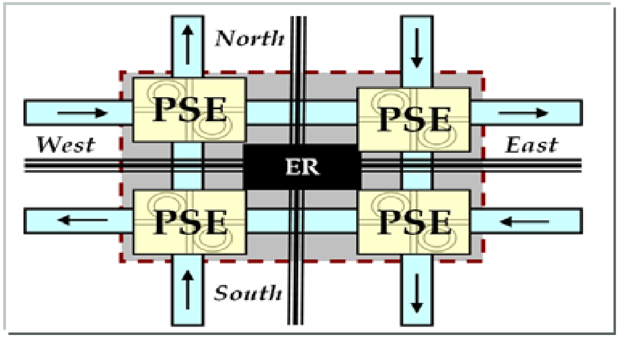
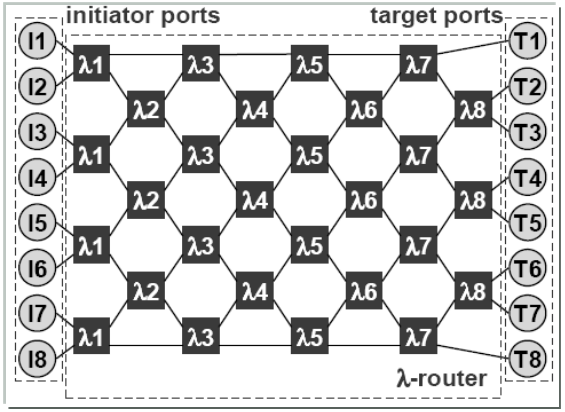
Photonic Crossbar



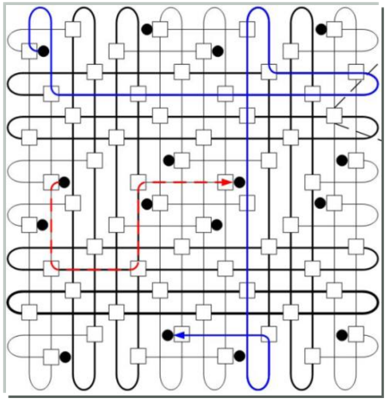
Blocking Switch



Passive Network



Folded Torus



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- Network Proposals

All based on Ring Resonators

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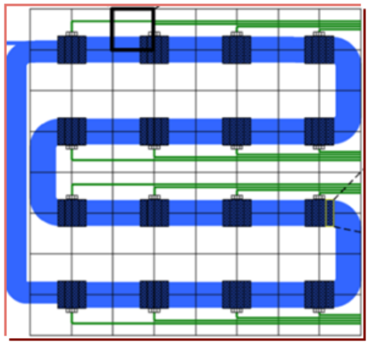

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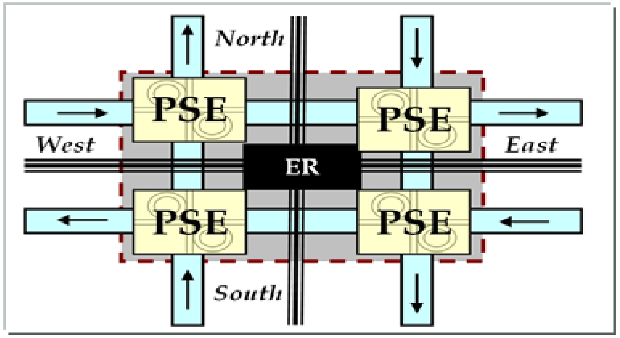

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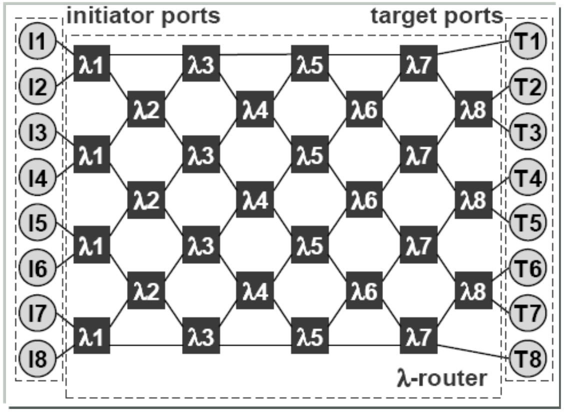

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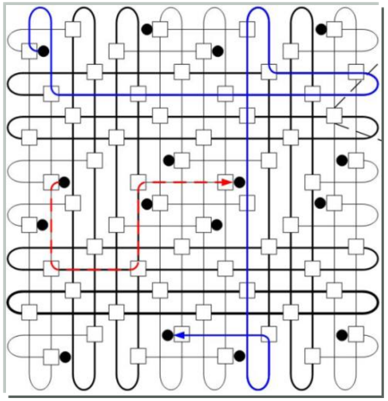

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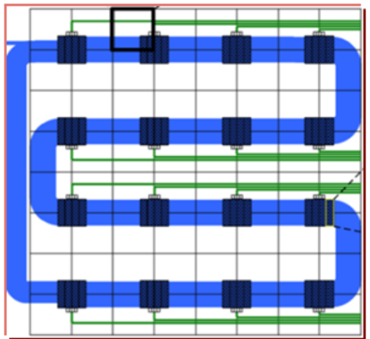

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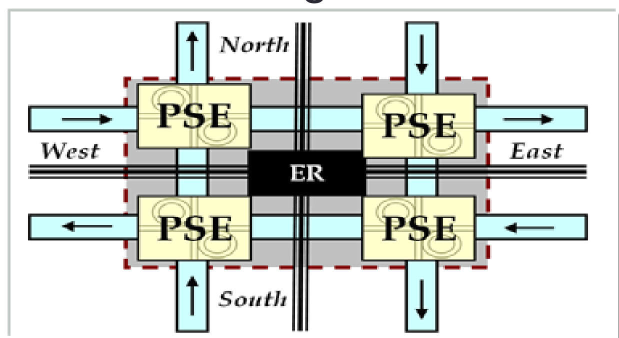

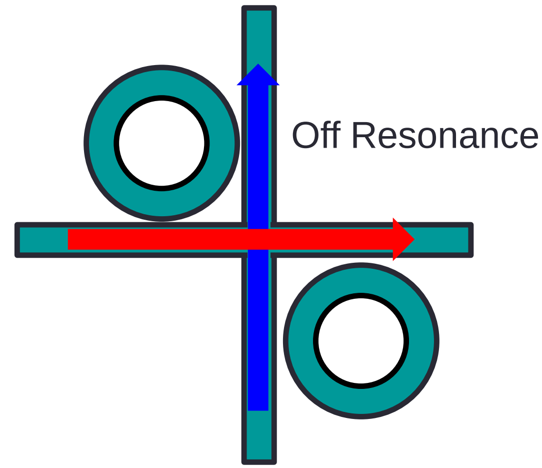

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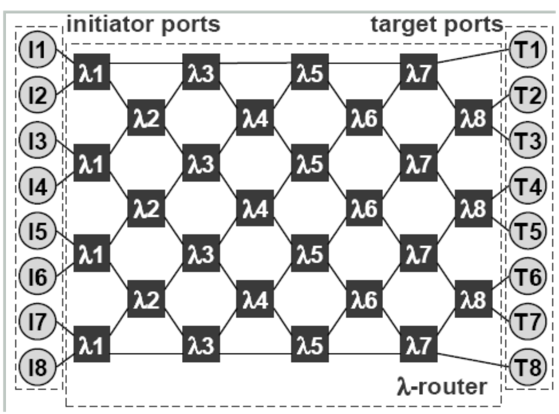

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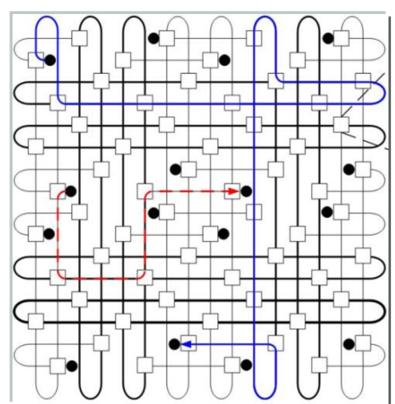

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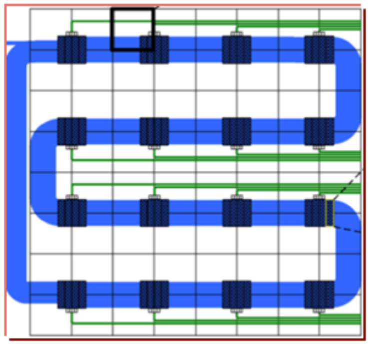

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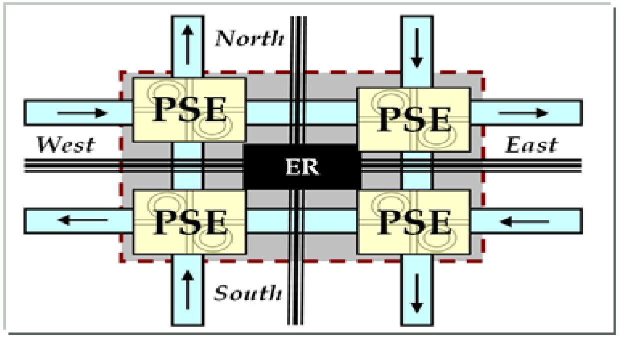

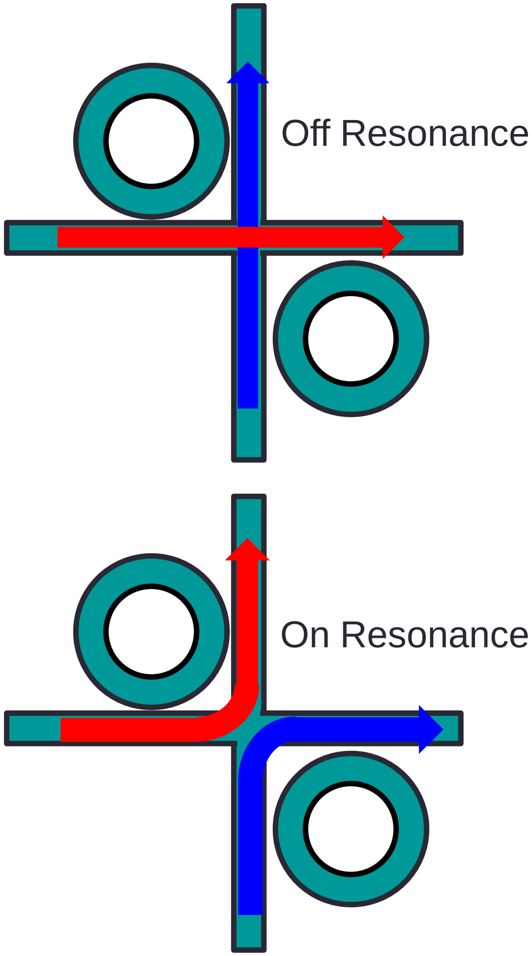

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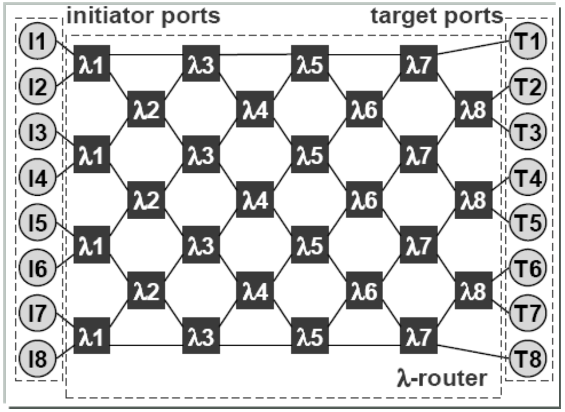

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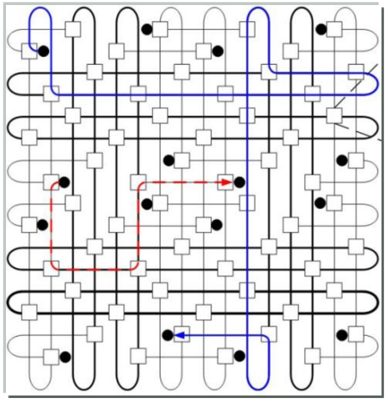

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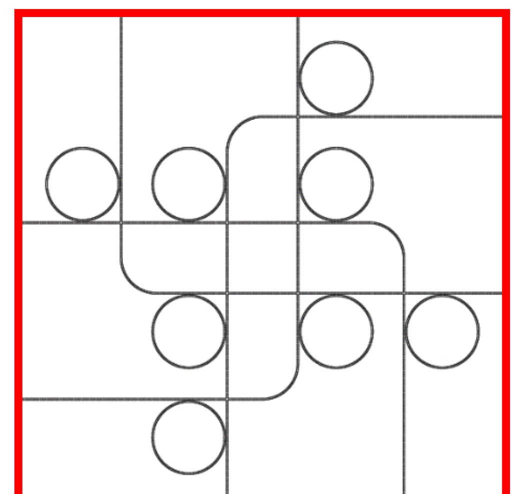

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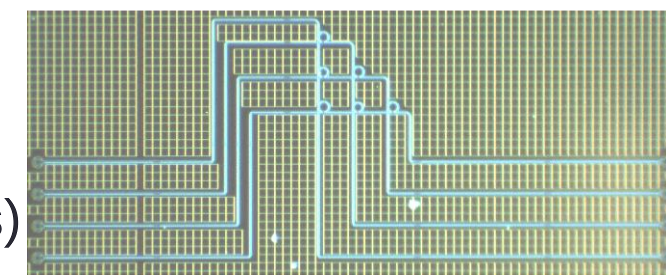

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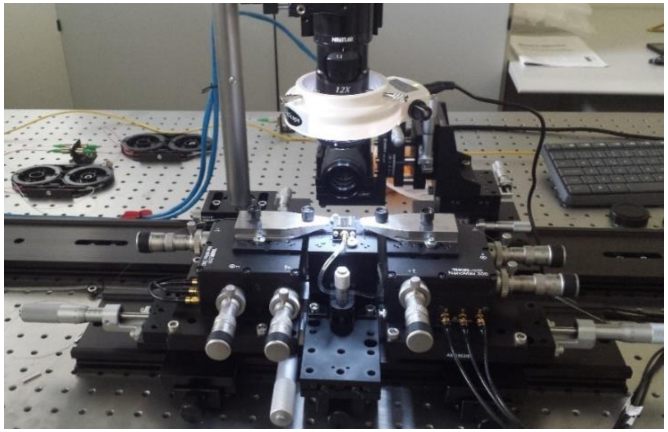
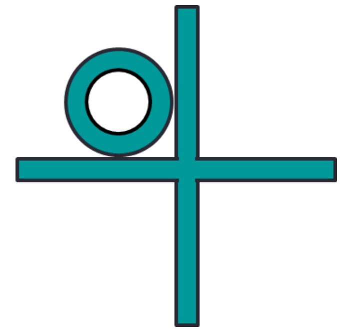
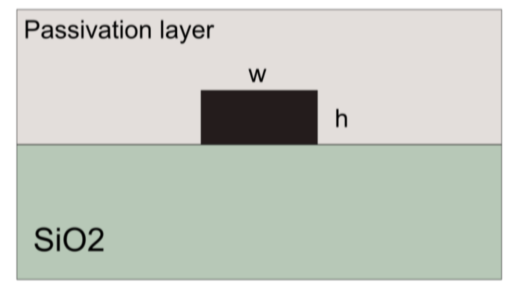
  - Characterization of the fabricated devices

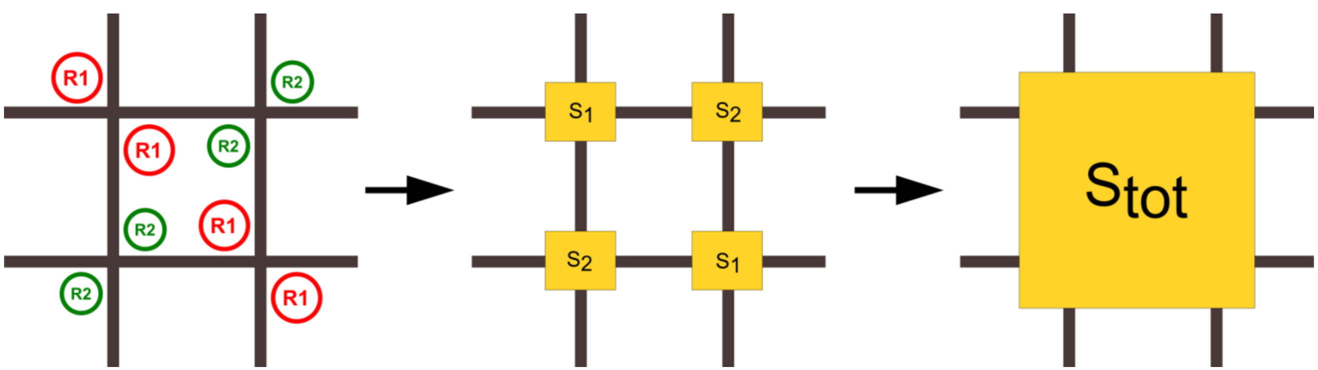


PSE for ONoC – Simulation Tools

- Photonic Switching Element based on Ring Topology
- Silicon on Insulator (SOI) Technology
  - SOI waveguides 480 × 220 nm (h × w)
  - Rings Radius = 18/20 μm
- Simulation Tools
  - FDTD for Device Analysis
  - S-Matrix for Circuit Level Modeling
    - The networks are modeled as an incremental composition of BLACK BOX described via the Scattering Matrix formalism

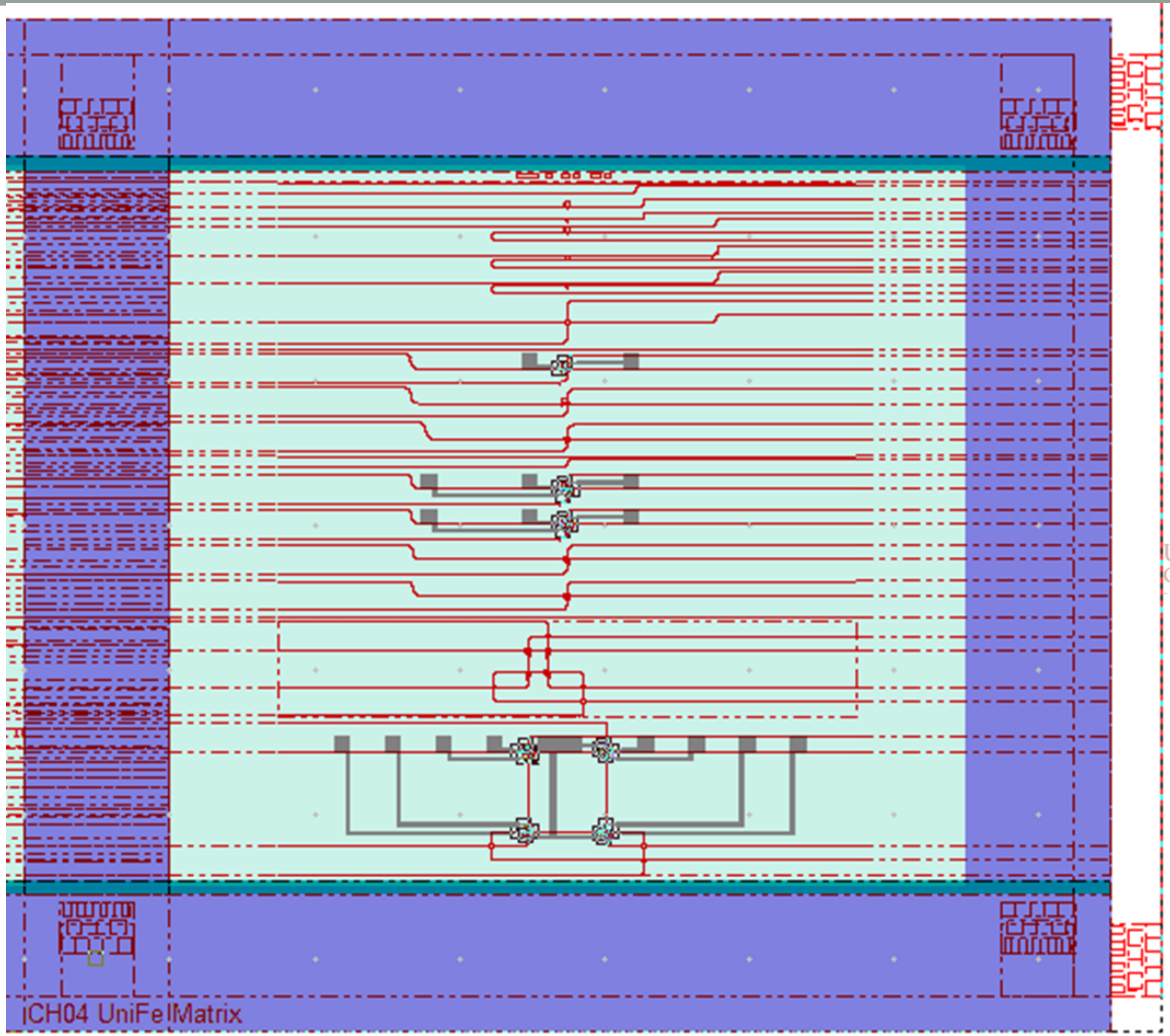






$$\begin{bmatrix} OUT_1 \\ \vdots \\ OUT_N \end{bmatrix} = [S_{tot}] \times \begin{bmatrix} IN_1 \\ \vdots \\ IN_N \end{bmatrix}$$

Fabricated SOI Chip with Micro-Ring Structures



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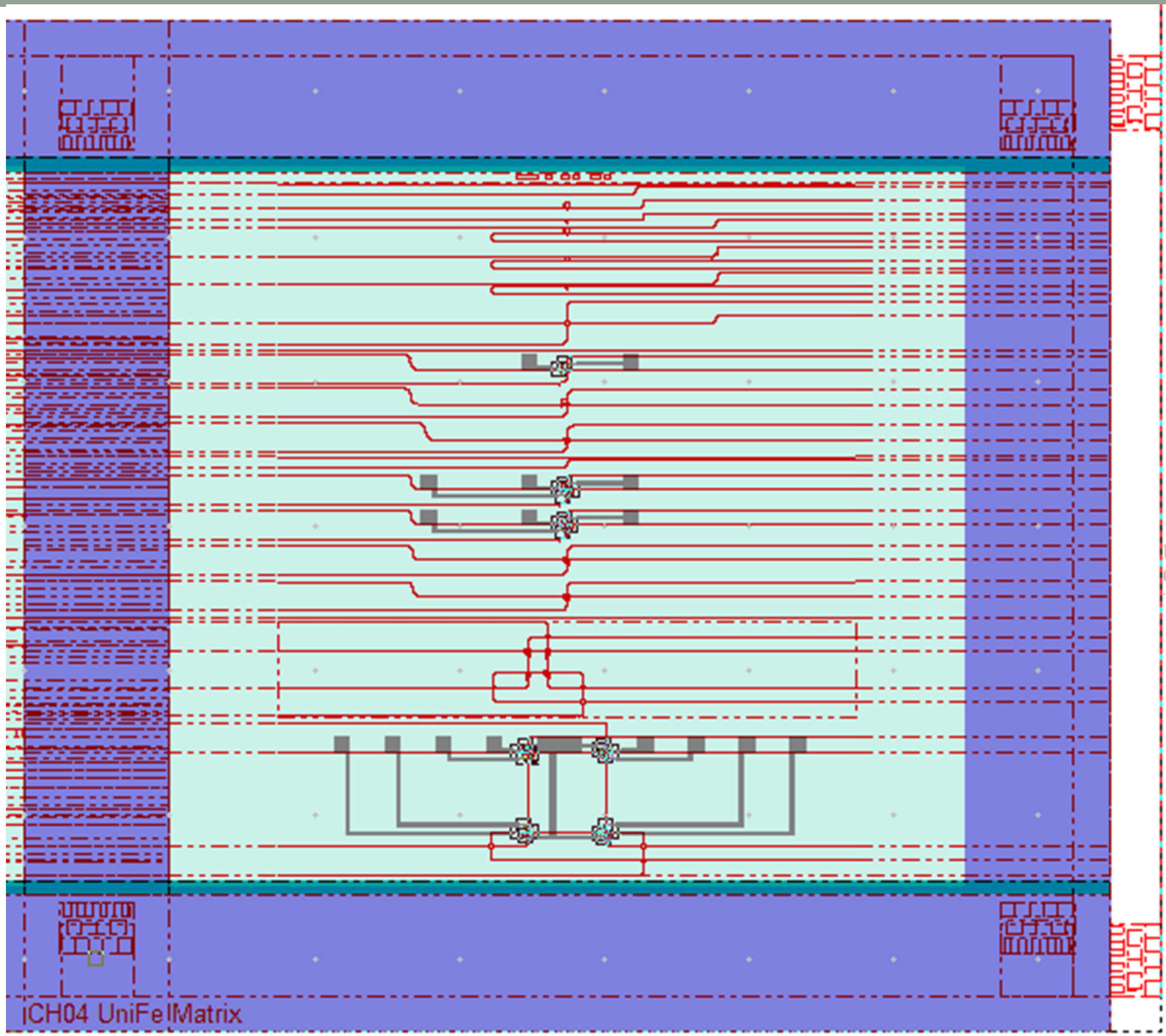
Waveguides
1 × 2 PSE



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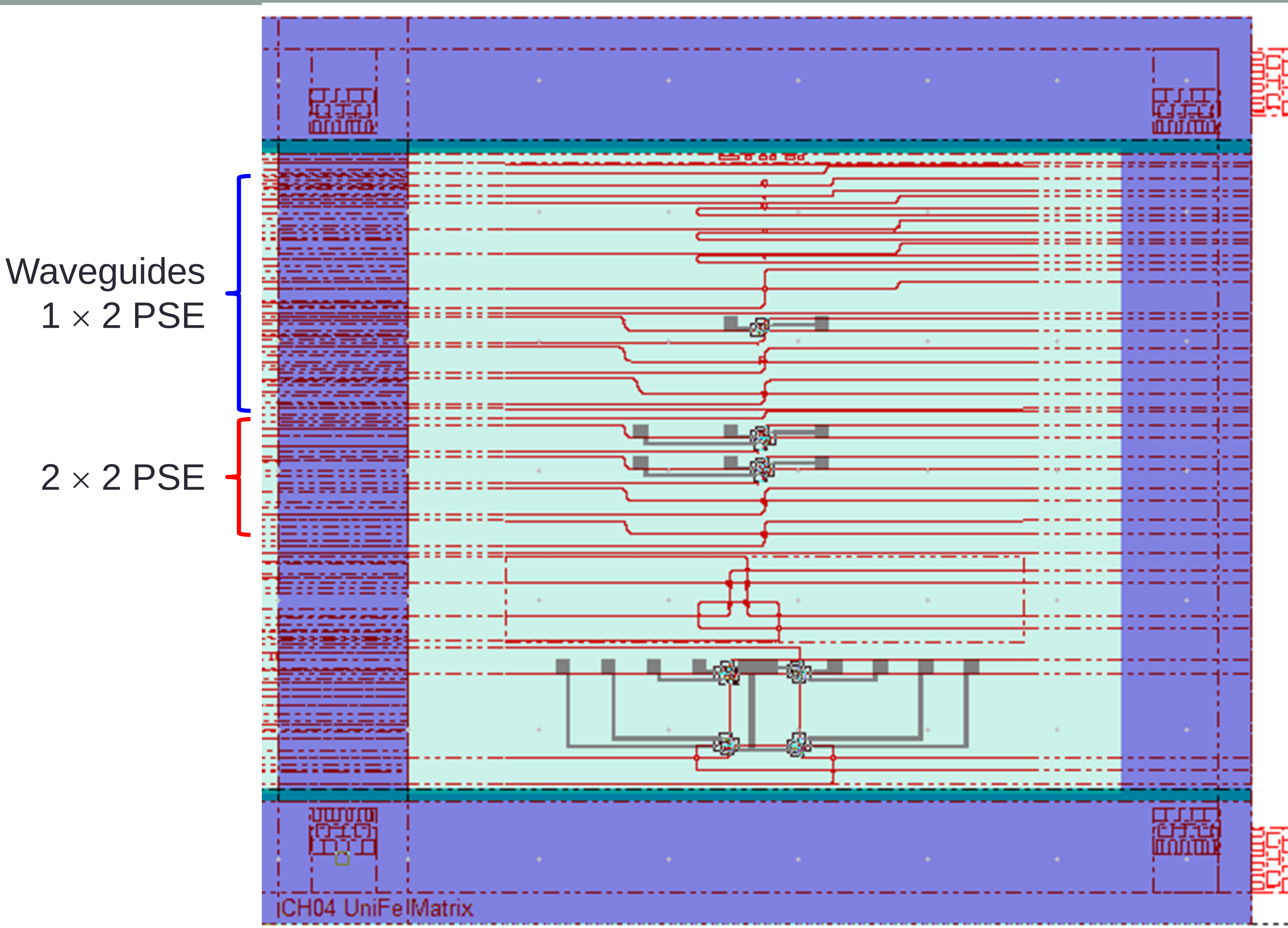

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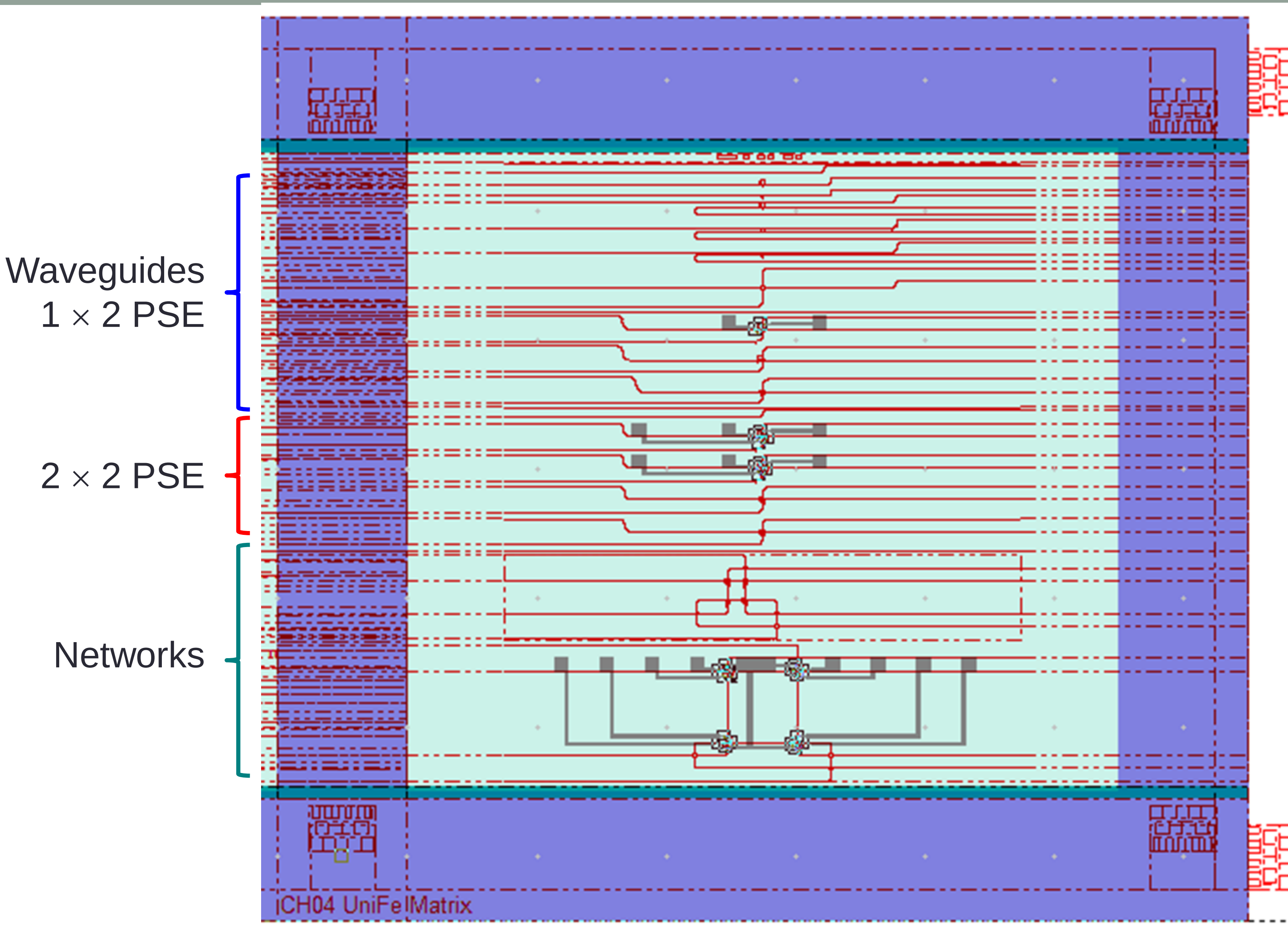

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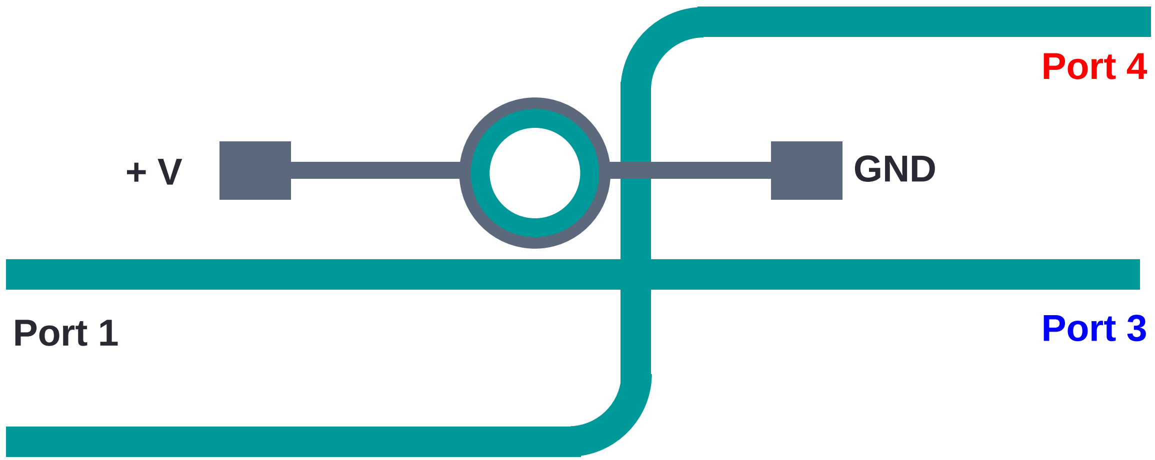
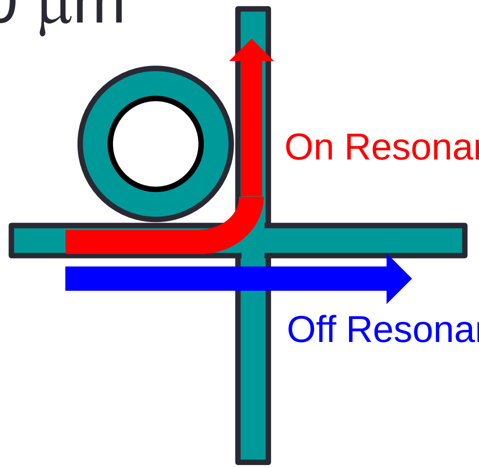
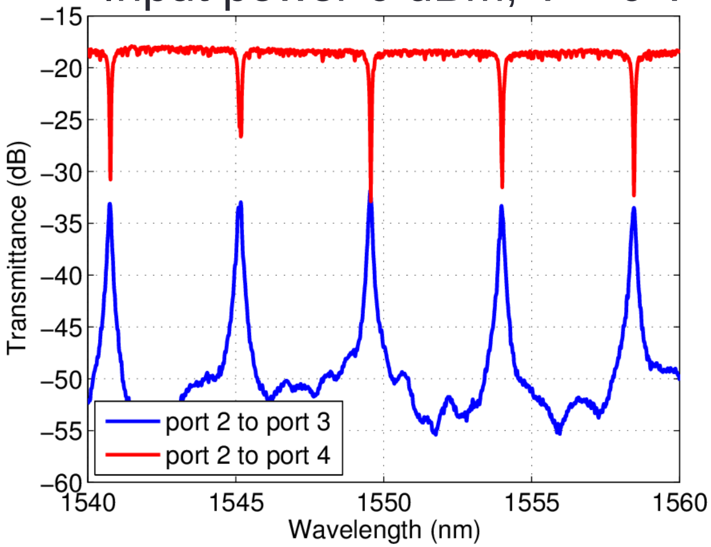
- 1 × 2 Photonic Switching Element - R = 20 μm

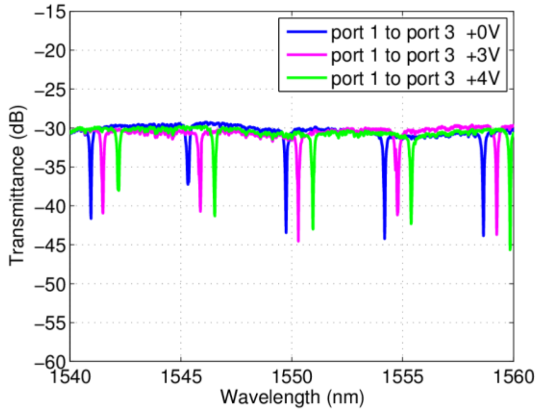


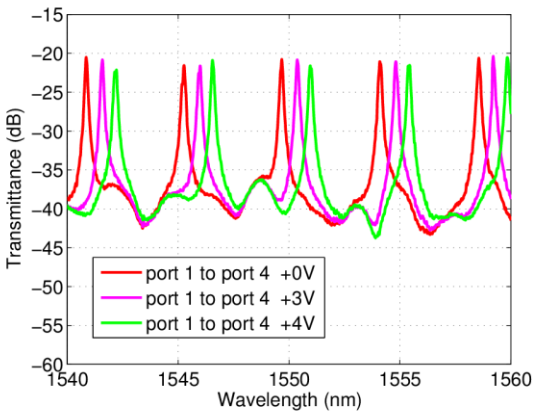


Thermal Tuning of the Ring

Input power 0 dBm; V = 0 V

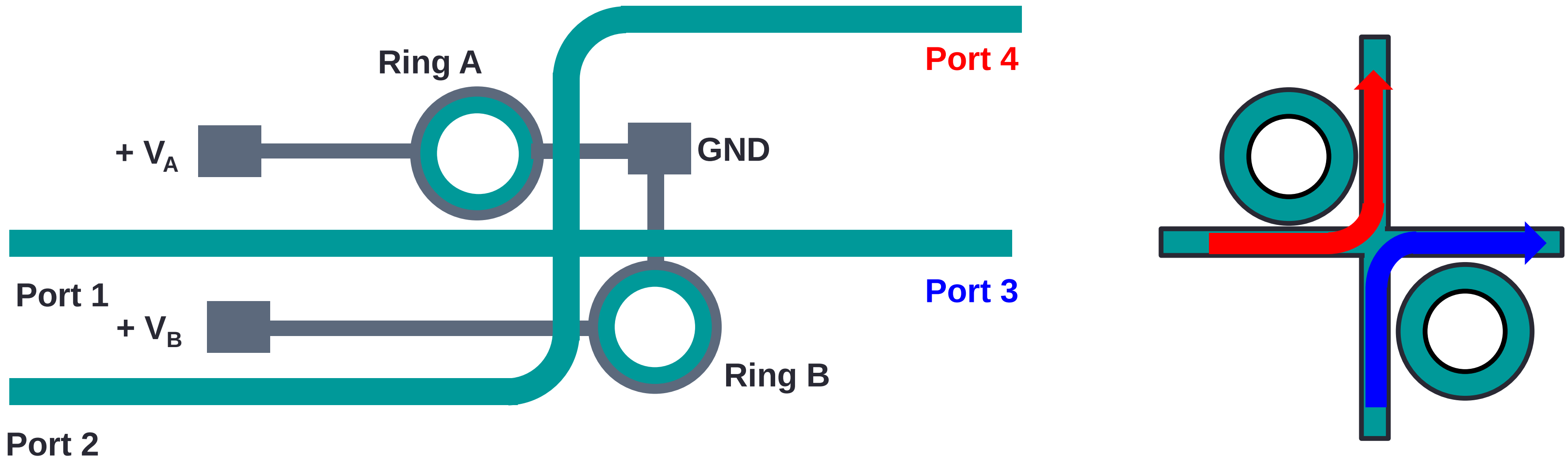


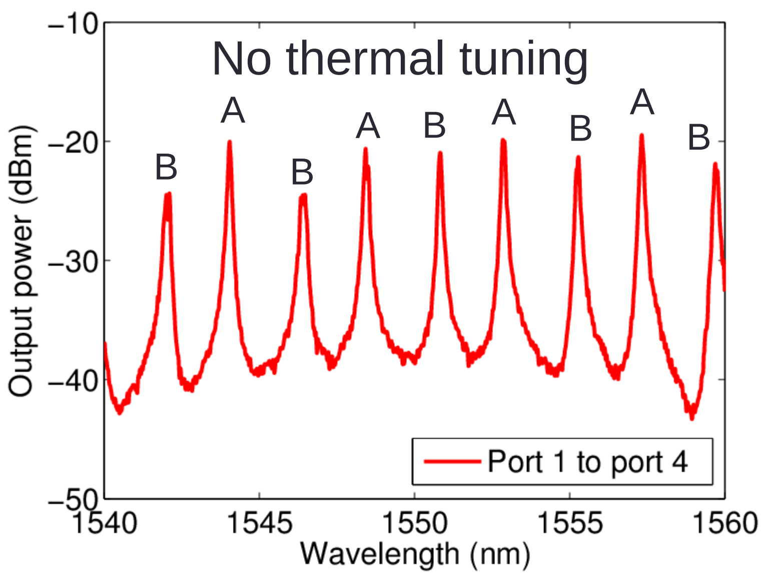


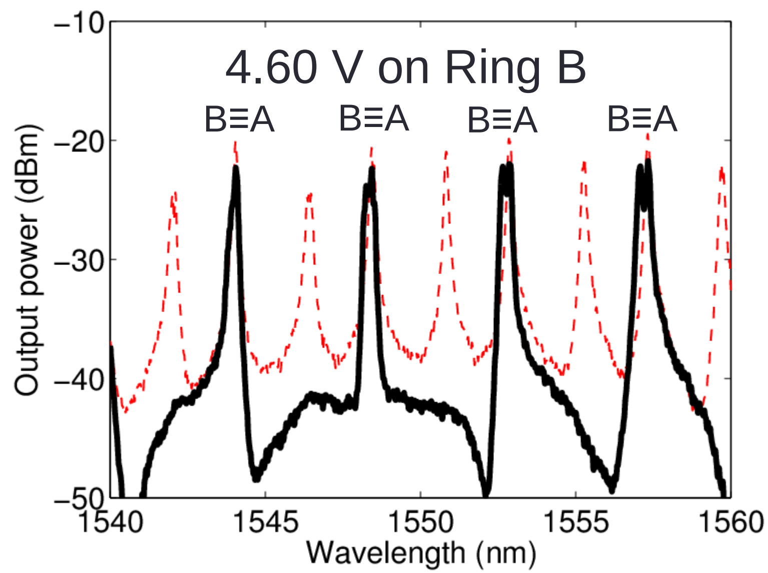


Wavelength shift to power ratio
0.16nm/mW (@1550nm)

- 2×2 Photonic Switching Element – $R_1 = R_2 = 20\ \mu m$

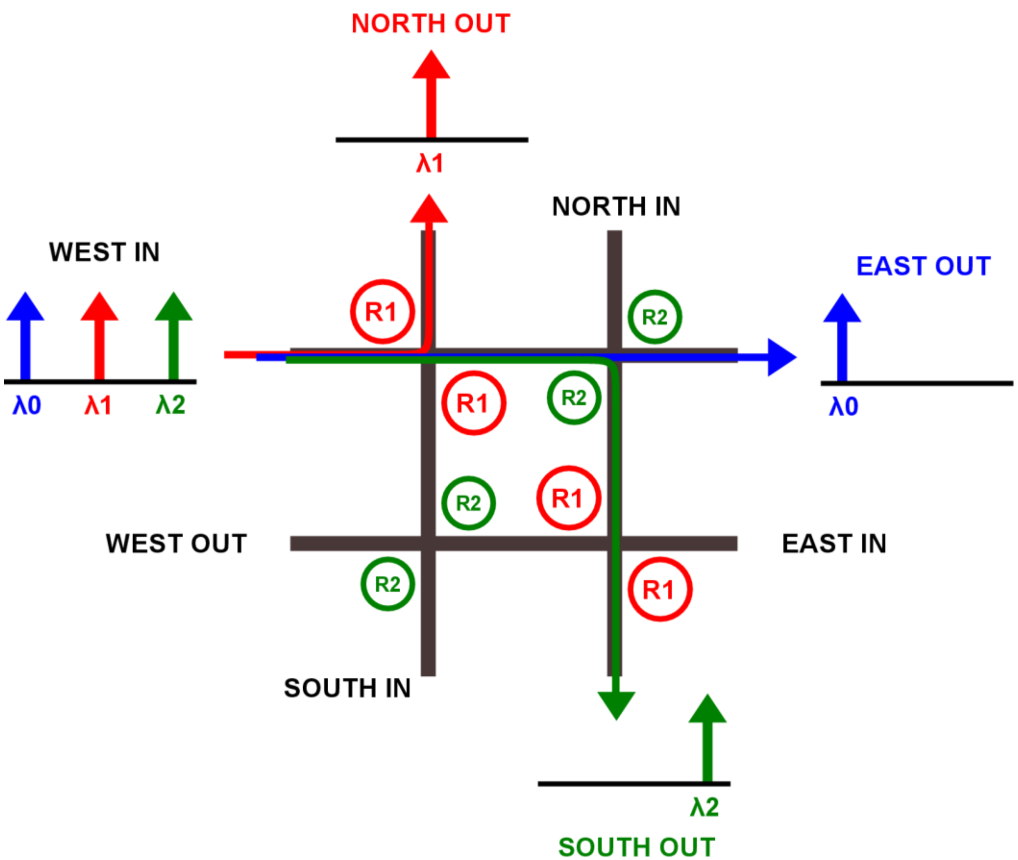






4 In – 4 Out Optical Router (GWOR)

- Router with 4 Input and 4 output ports GWOR (Generic Wavelength routed Optical Router)



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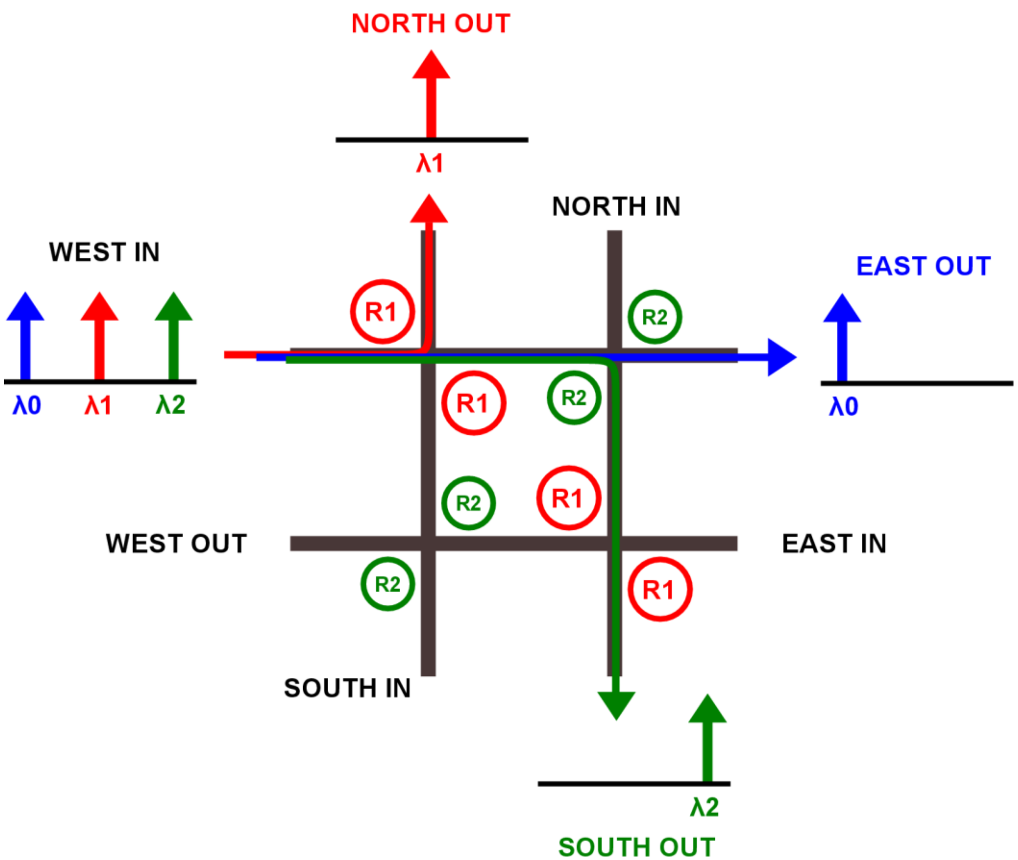

Routing Table

	NORTH OUT	EAST OUT	SOUTH OUT	WEST OUT
NORTH IN	-	λ_2		λ_1
EAST IN	λ_2	-	λ_1	
SOUTH IN	λ_0	λ_1	-	λ_2
WEST IN	λ_1	λ_0	λ_2	-

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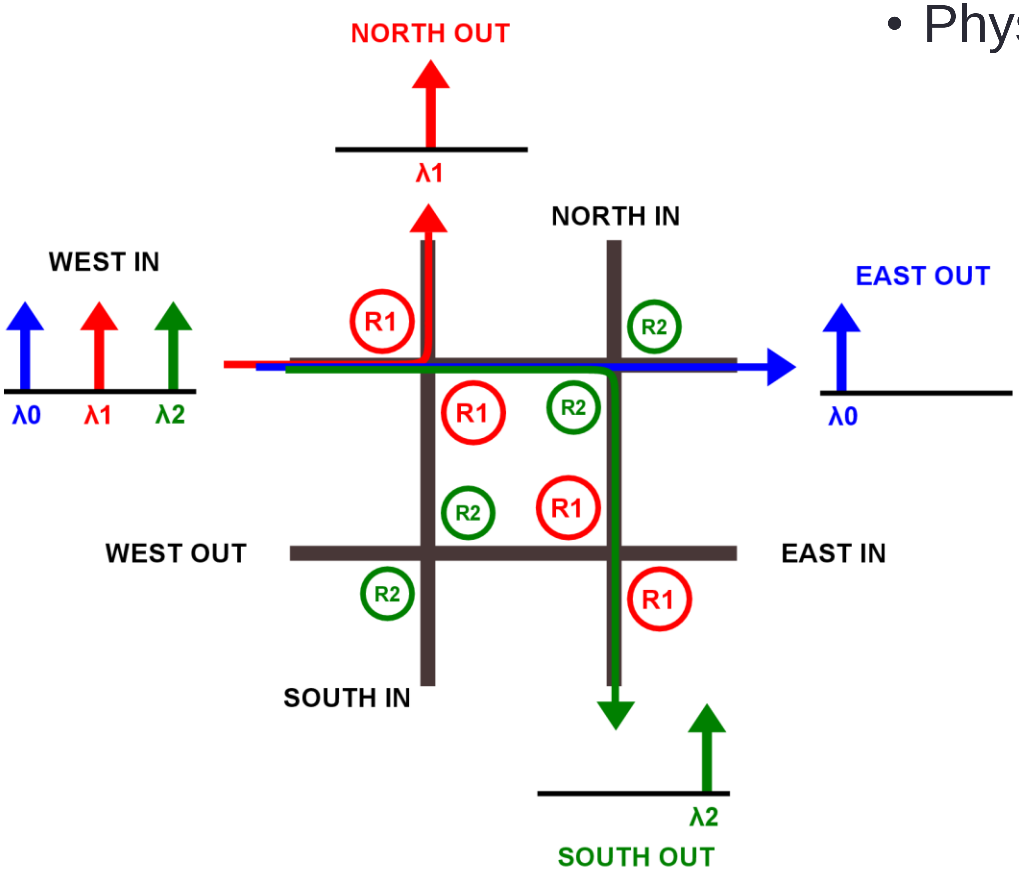

- Physical Parameters

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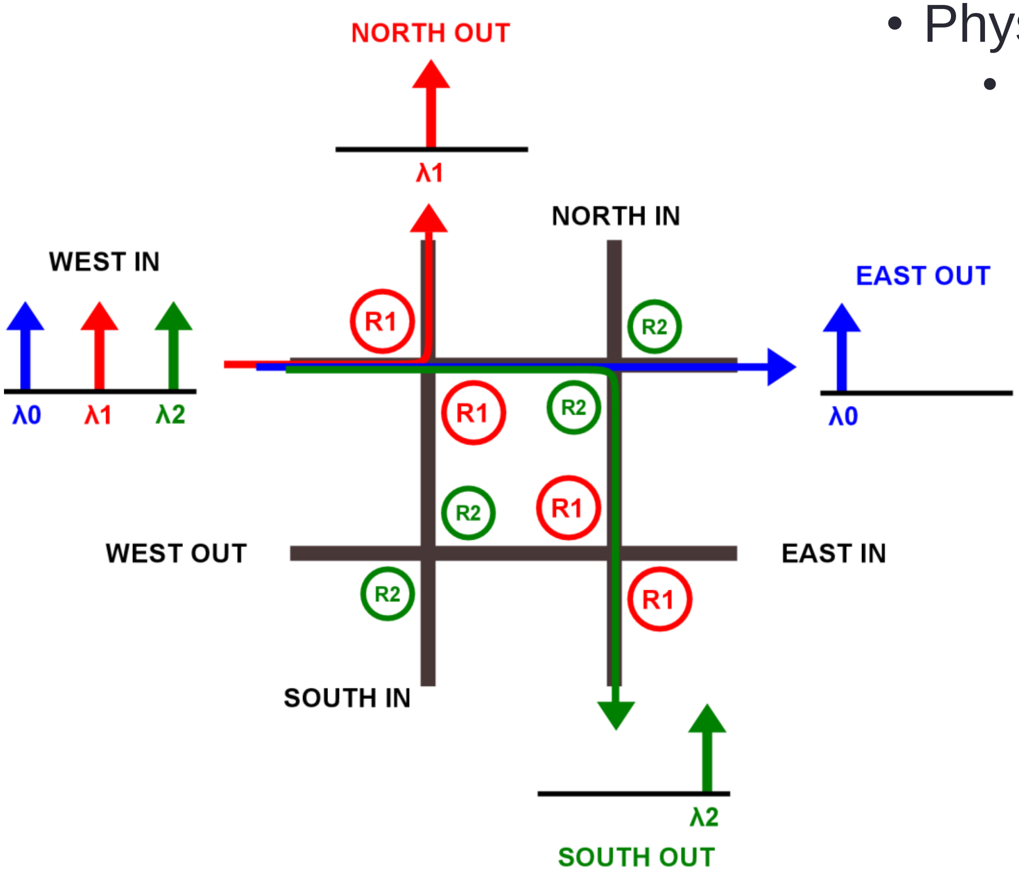
EAST IN	λ_2	-	λ_1	
SOUTH IN	λ_0	λ_1	-	λ_2
WEST IN	λ_1	λ_0	λ_2	-

- Router with 4 Input and 4 output ports GWOR (Generic Wavelength routed Optical Router)
- Wavelength dependent routing achieved through the choice of different radii for rings R1 and R2

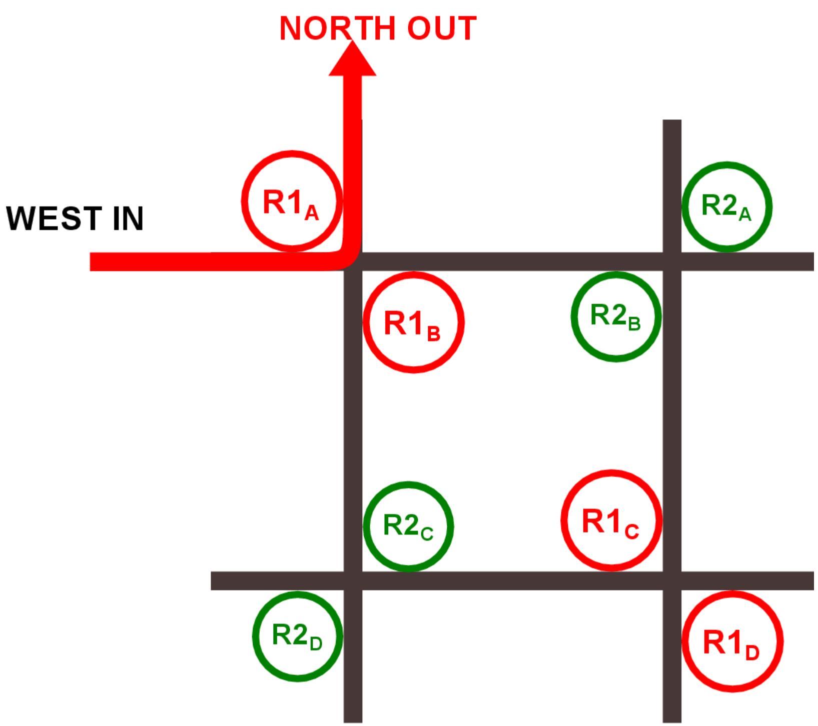


- Physical Parameters
  - Bus-to-ring gap 150 nm (power coupling K = 7.5%)
    - R1 = 20 μm Bandwidth = 15.5 GHz
    - R2 = 18 μm Bandwidth = 17.5 GHz

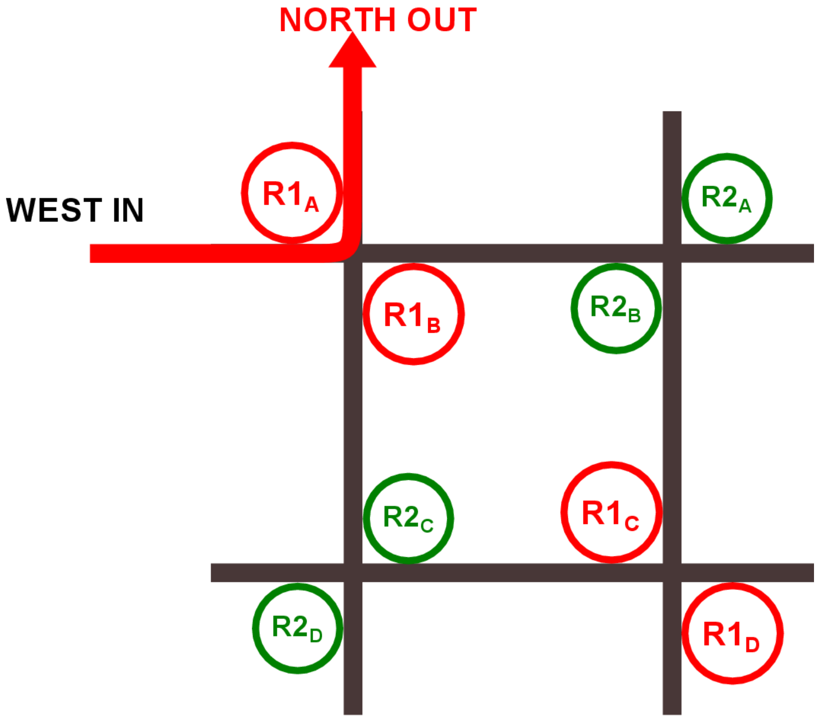
Routing Table

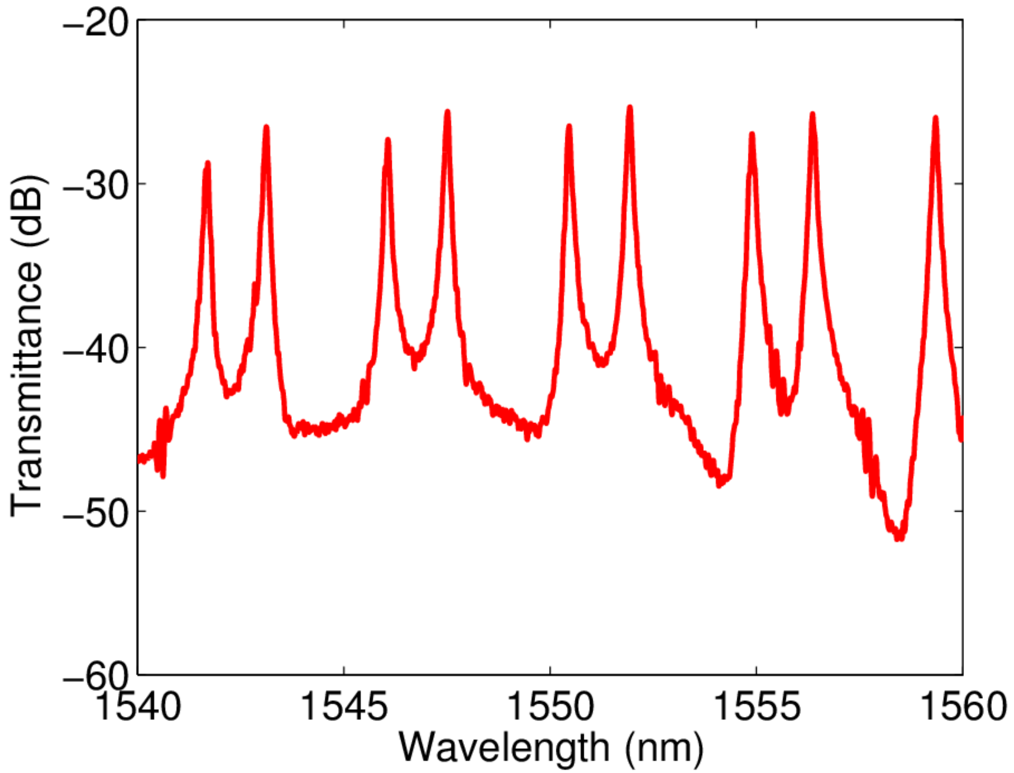
	NORTH OUT	EAST OUT	SOUTH OUT	WEST OUT
NORTH IN	-	λ_2		λ_1
EAST IN	λ_2	-	λ_1	
SOUTH IN	λ_0	λ_1	-	λ_2
WEST IN	λ_1	λ_0	λ_2	-

- Resonance Duplication due to the fabrication process
  - Misalignment in the radii of **$R1_A$** and **$R1_B$** with respect to the design value (20 μm)

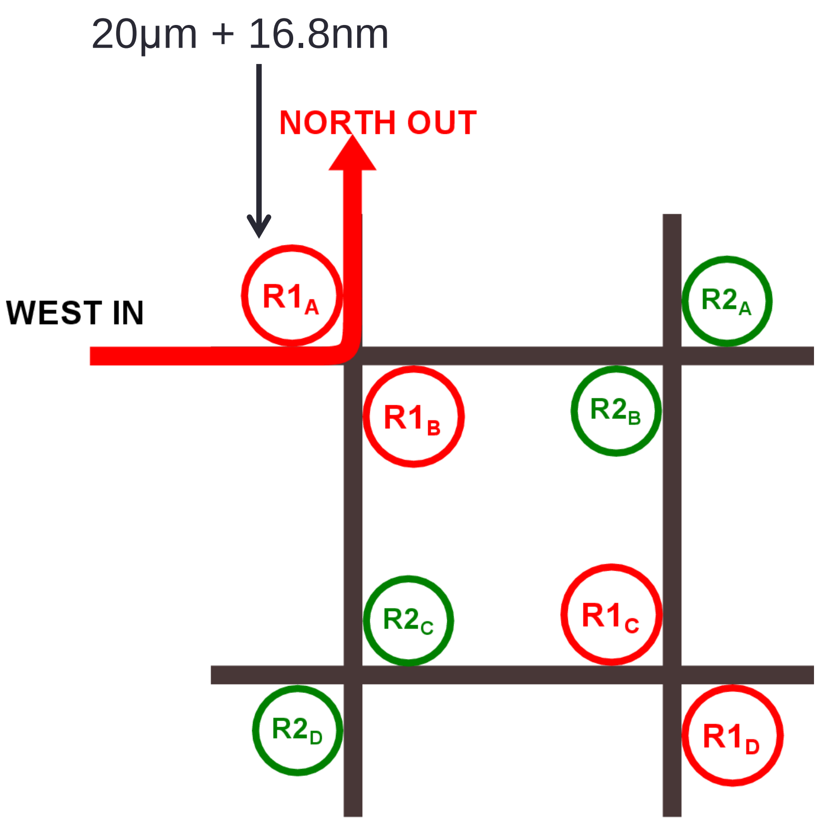


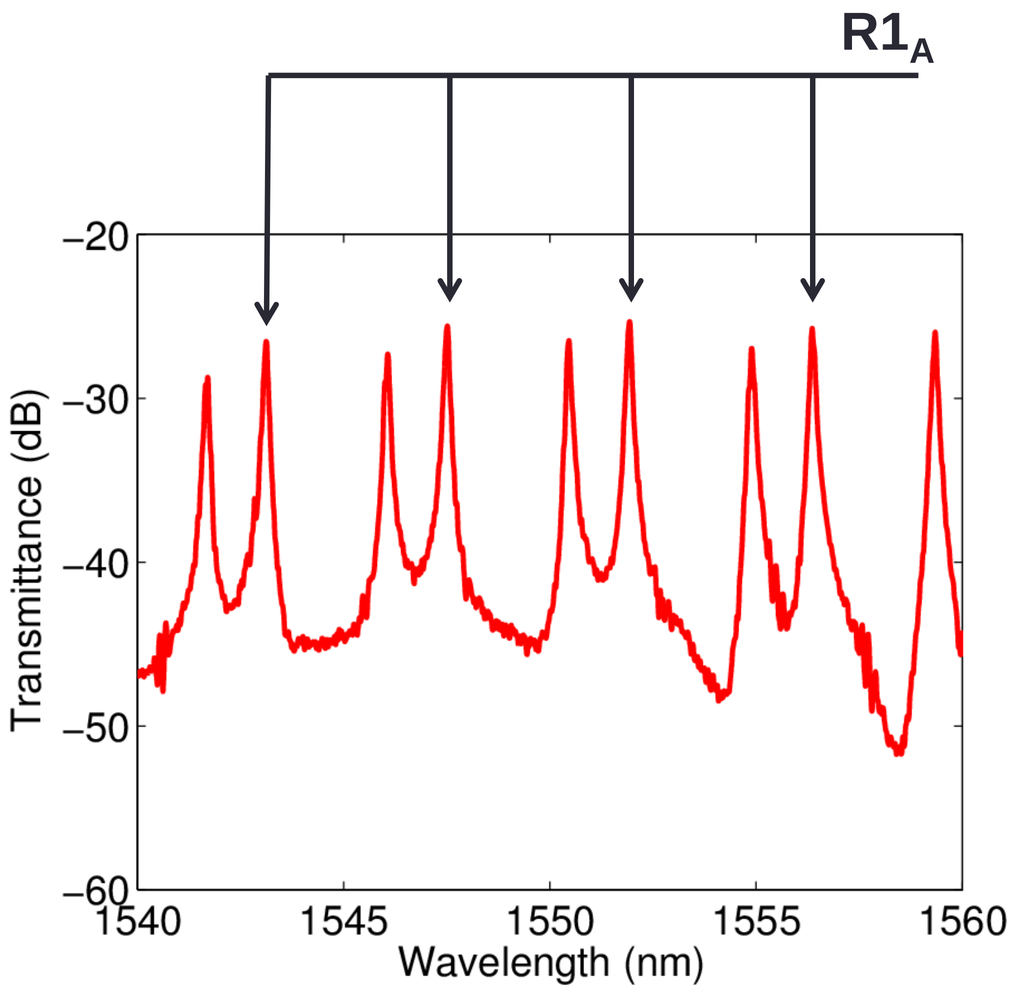
- Resonance Duplication due to the fabrication process
  - Misalignment in the radii of **$R1_A$** and **$R1_B$** with respect to the design value (20 μm)





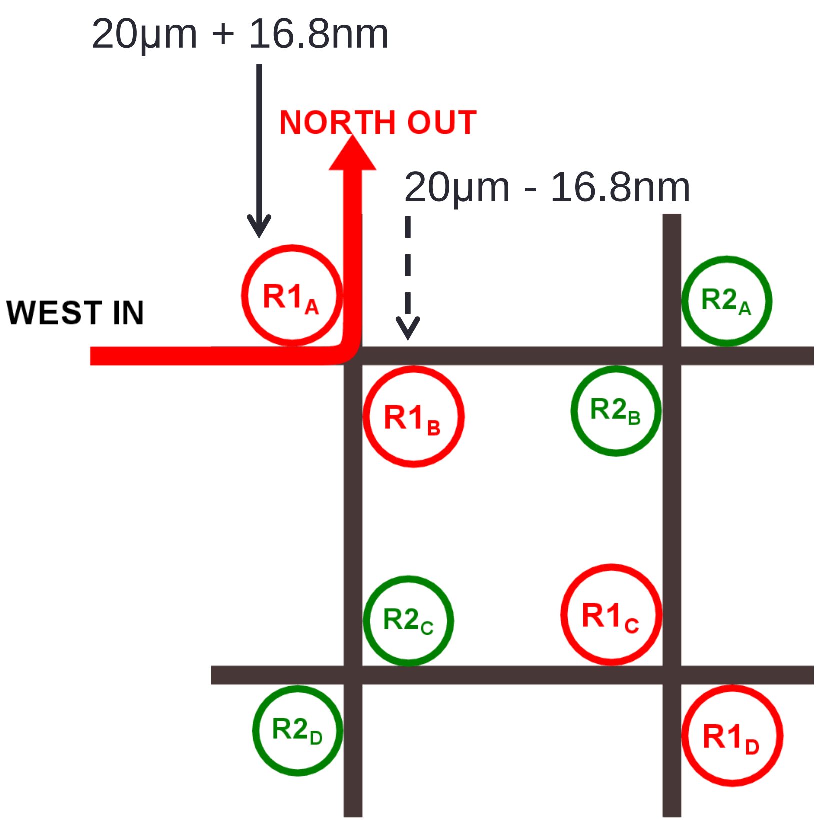
- Resonance Duplication due to the fabrication process
  - Misalignment in the radii of **$R1_A$** and **$R1_B$** with respect to the design value (20 μm)

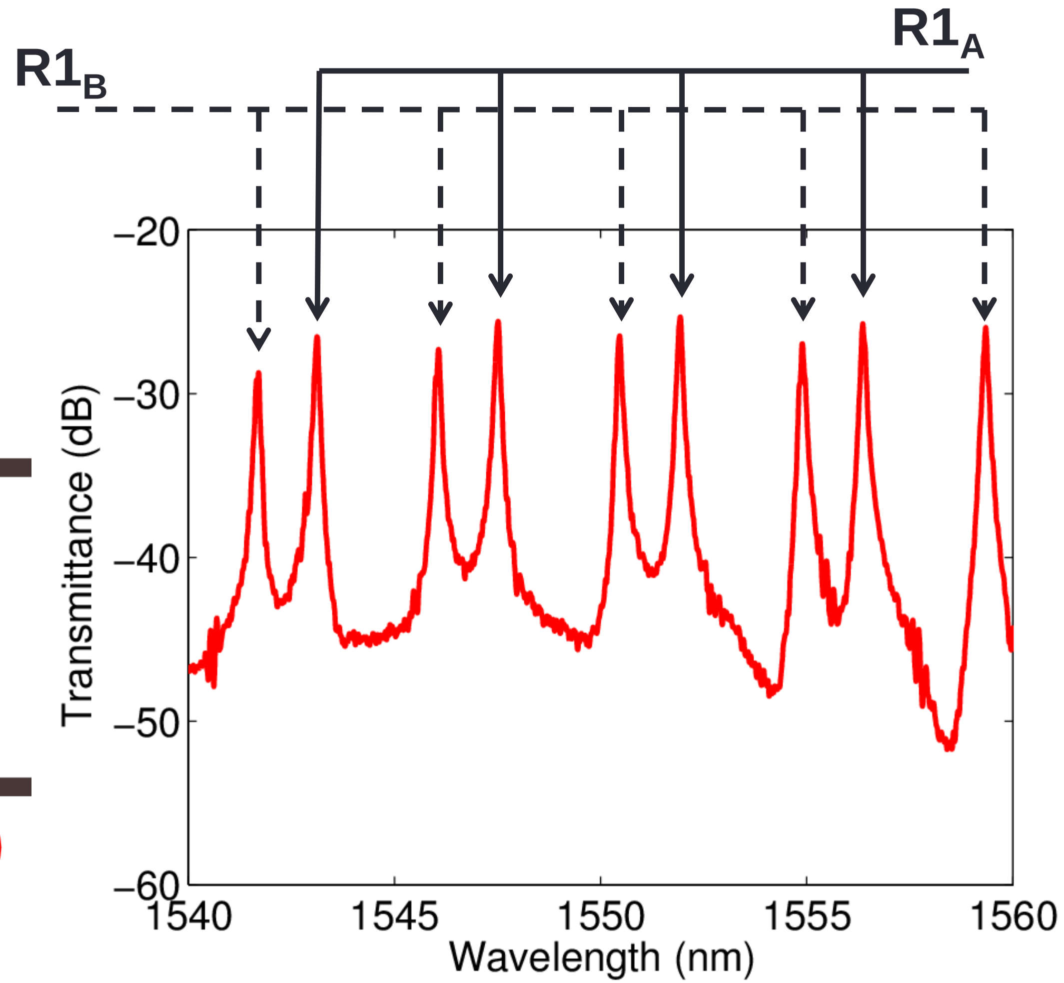




IOP Lab

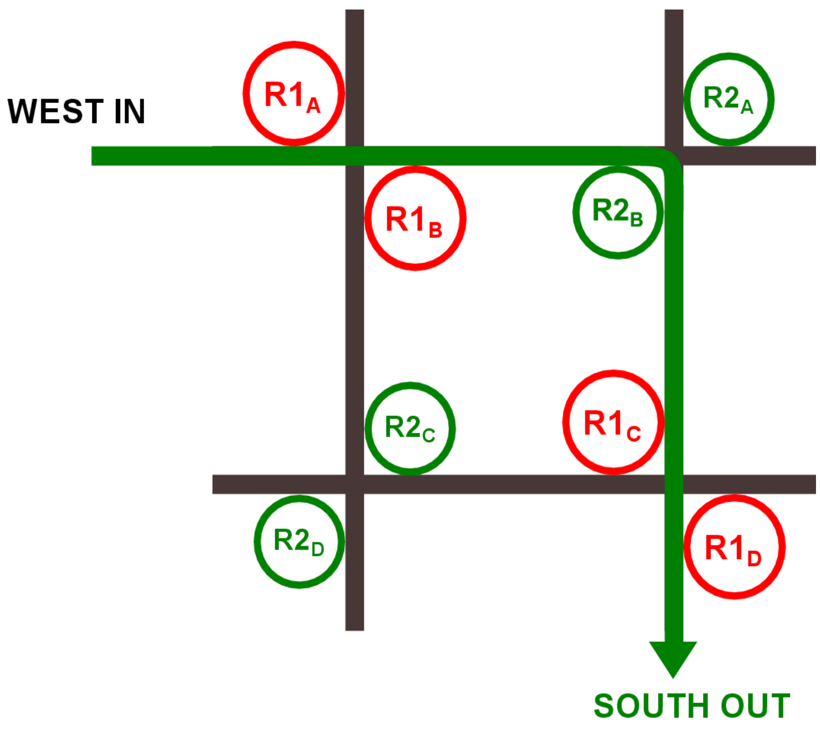
- Resonance Duplication due to the fabrication process
  - Misalignment in the radii of **R1$_A$** and **R1$_B$** with respect to the design value (20 μm)



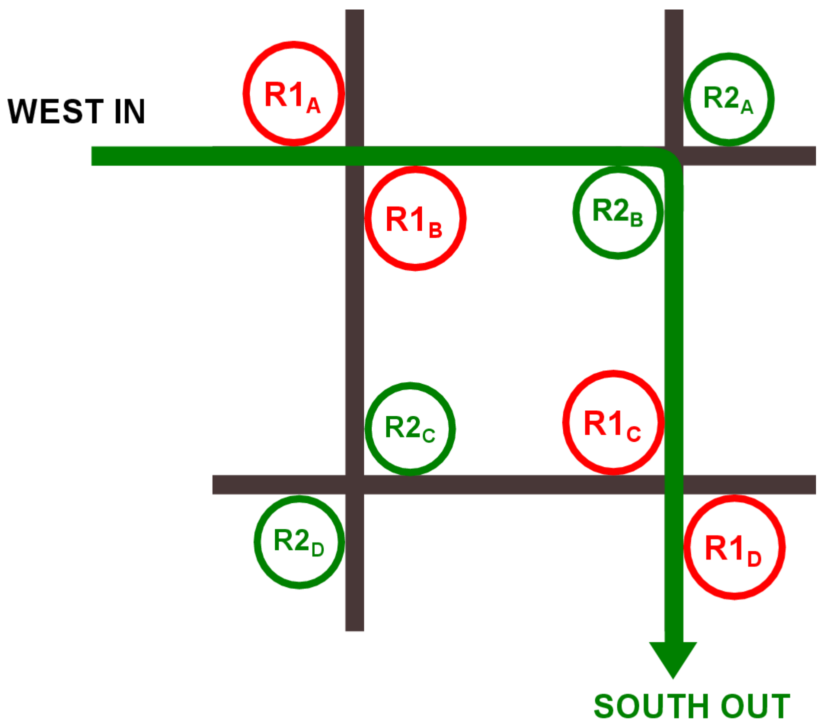


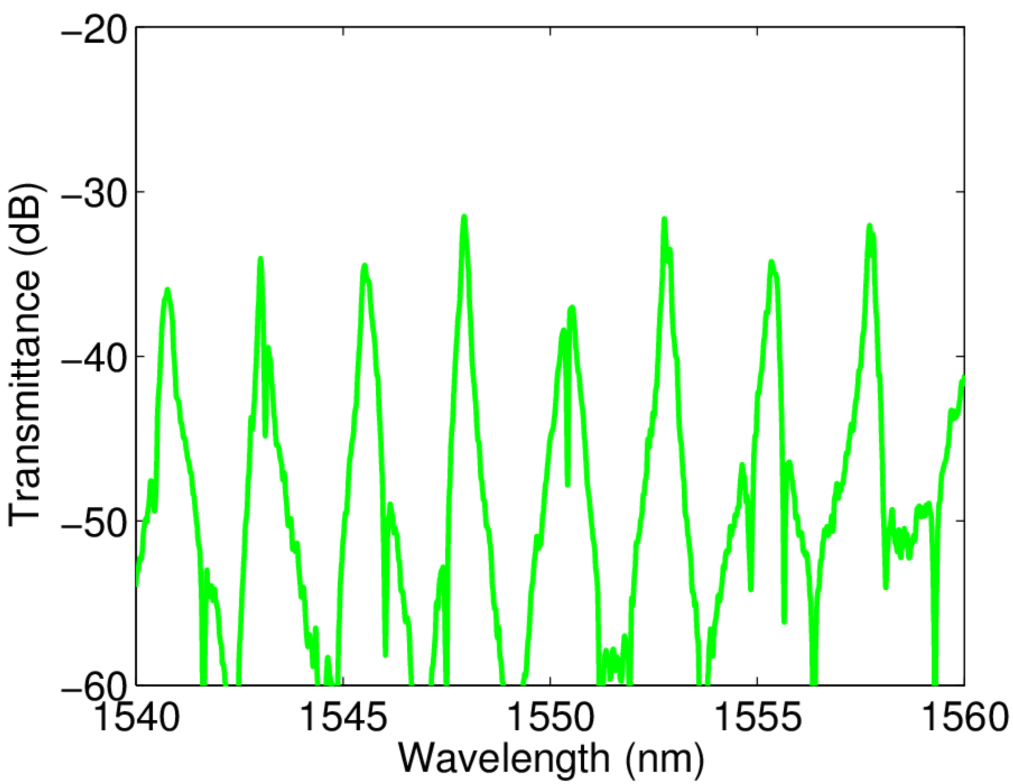
GWOR - Output Port Measurements

- Resonance Duplication due to the fabrication process
  - Misalignment in the radii of **R2$_A$** and **R2$_B$** with respect to the design value (18 μm)



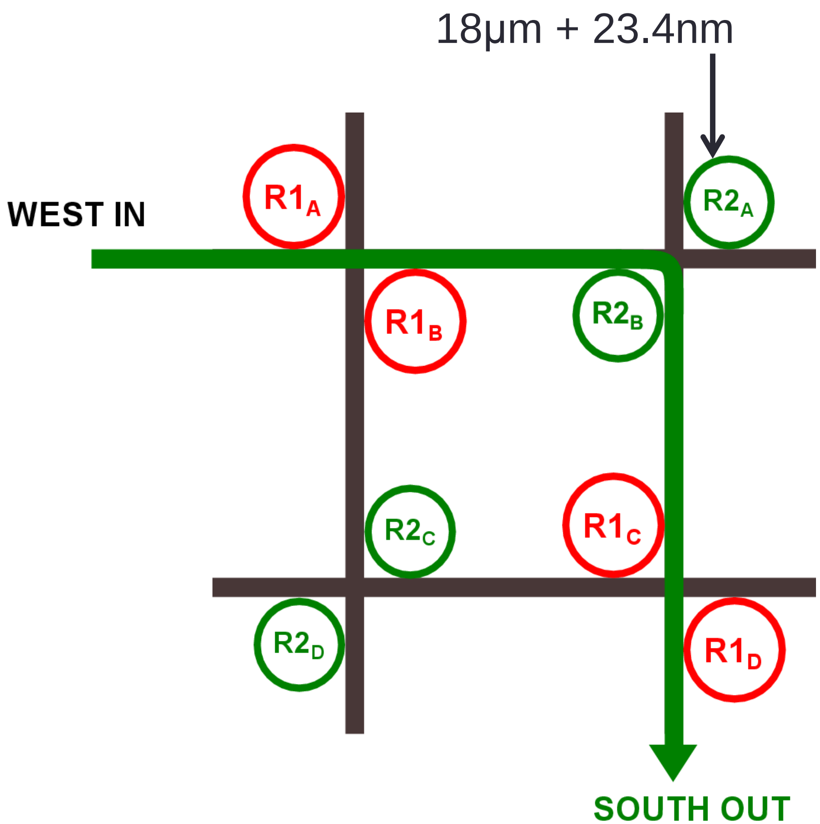
- Resonance Duplication due to the fabrication process
  - Misalignment in the radii of **$R2_A$** and **$R2_B$** with respect to the design value (18 μm)

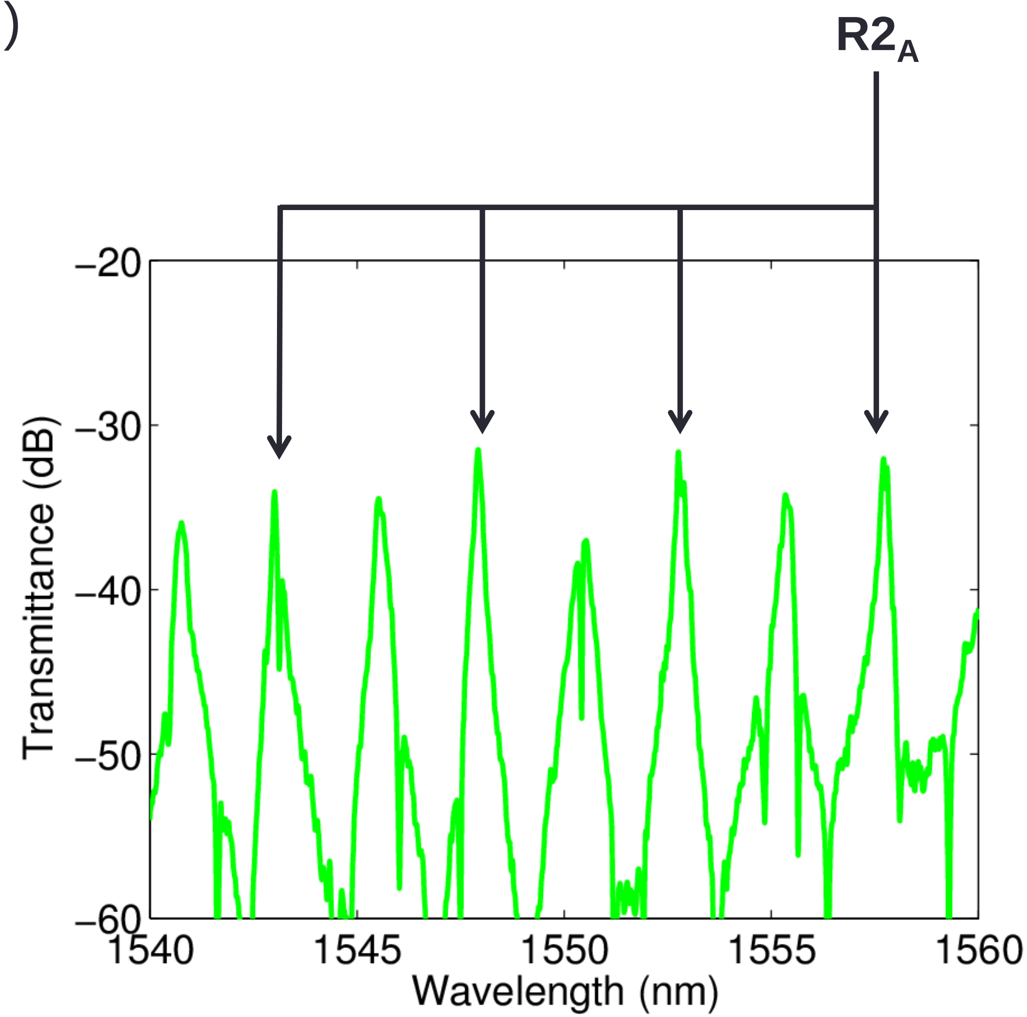




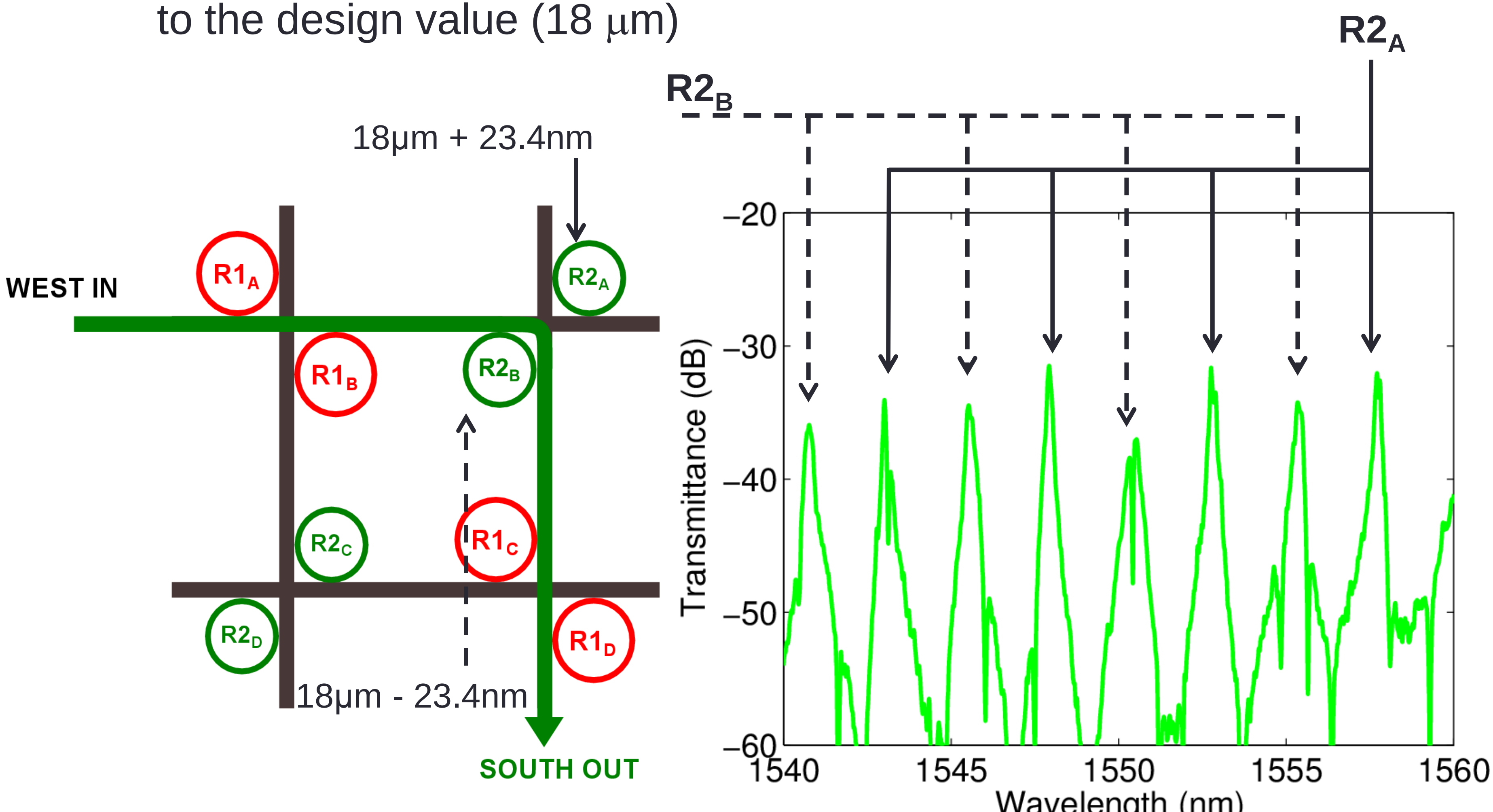
IOP Lab

- Resonance Duplication due to the fabrication process
  - Misalignment in the radii of **$R2_A$** and **$R2_B$** with respect to the design value (18 μm)

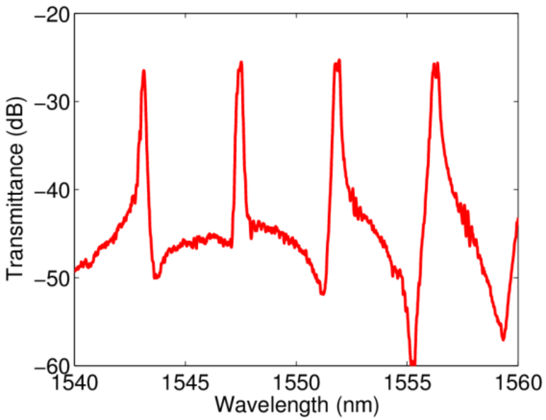


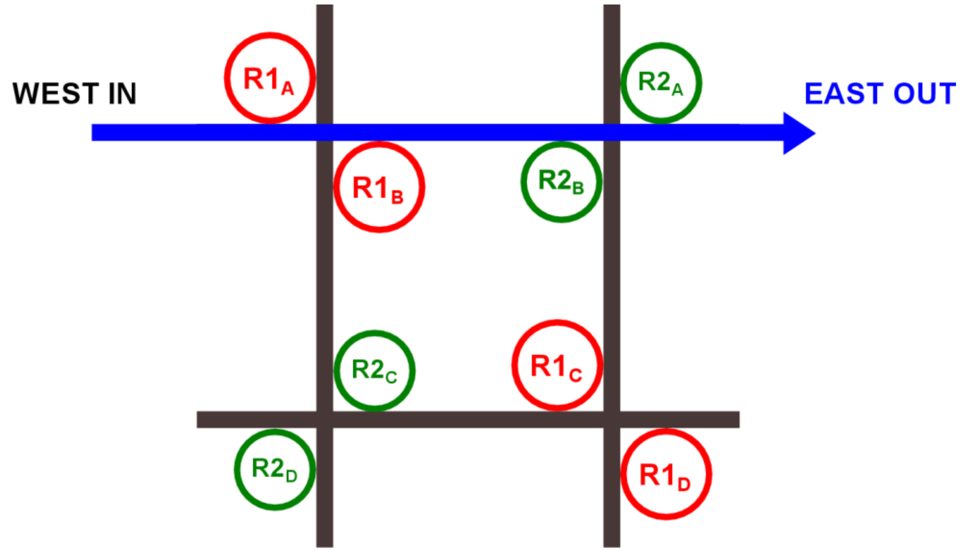


- Resonance Duplication due to the fabrication process
  - Misalignment in the radii of **$R2_A$** and **$R2_B$** with respect to the design value (18 μm)

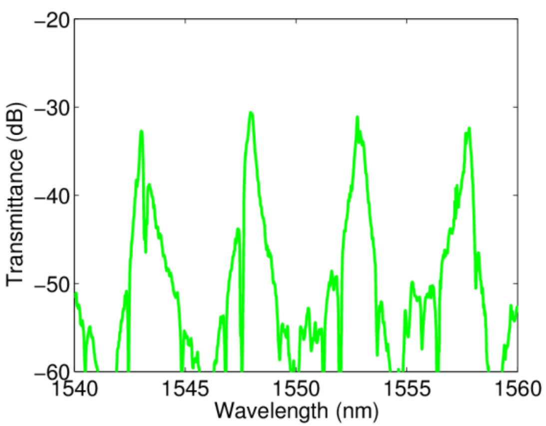


Tuning by applying 4.42 V on $R1_B$

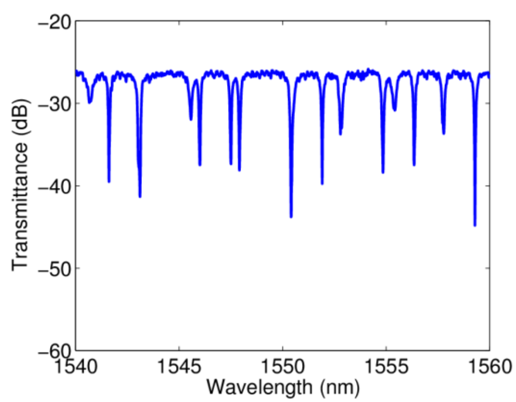




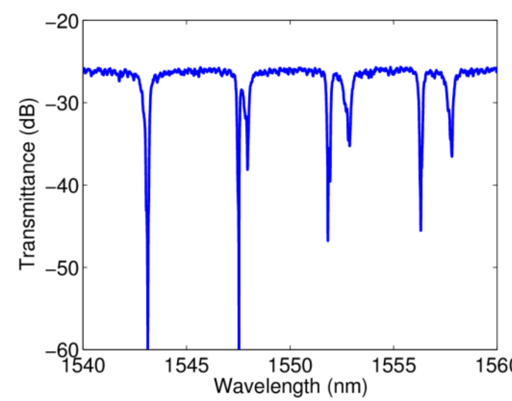
Tuning by applying 4.62 V on $R2_B$



Tuning Off

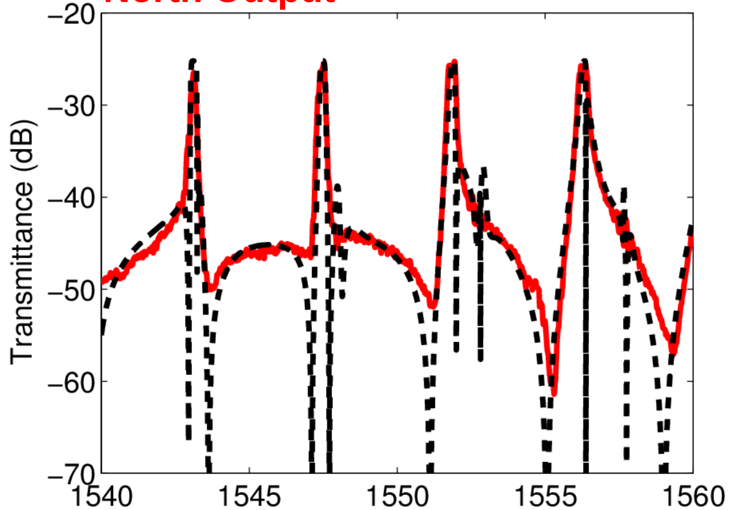


Tuning On

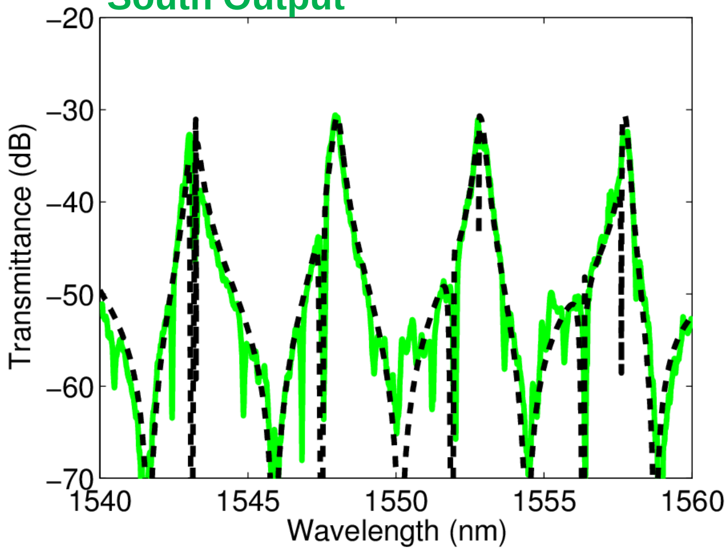


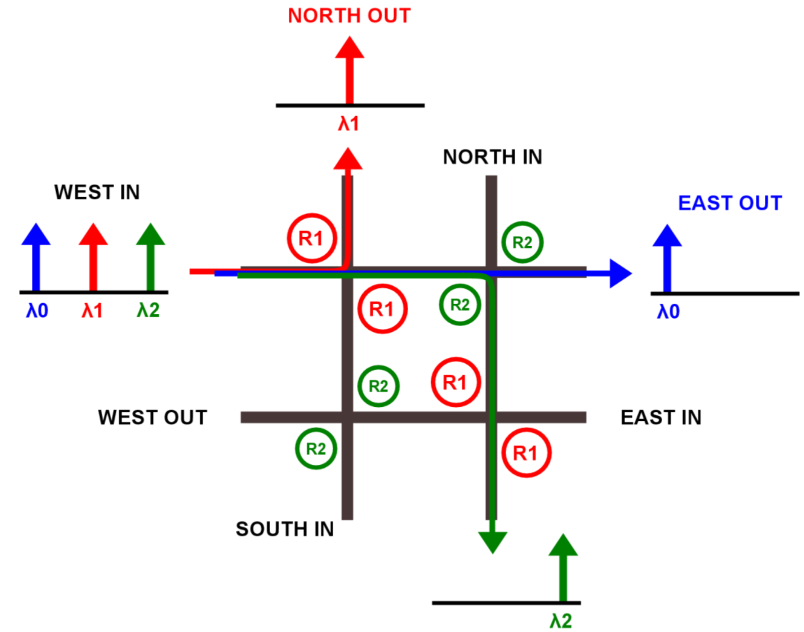
- S-Matrix vs Measurements

North Output

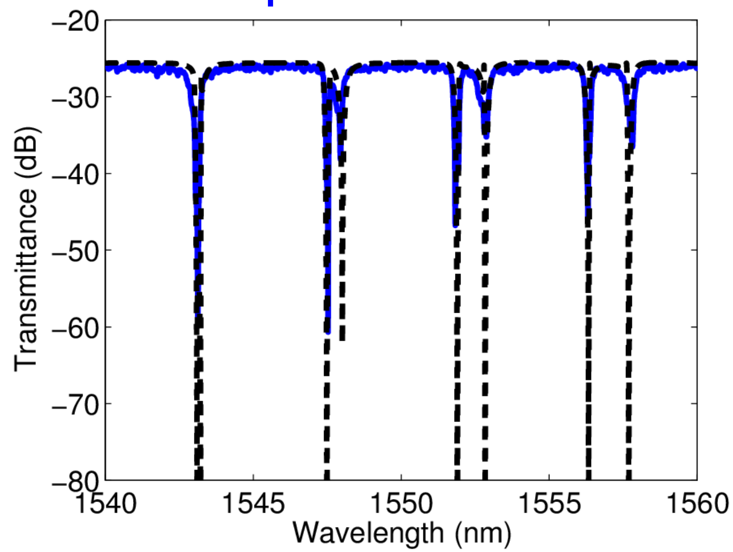


South Output

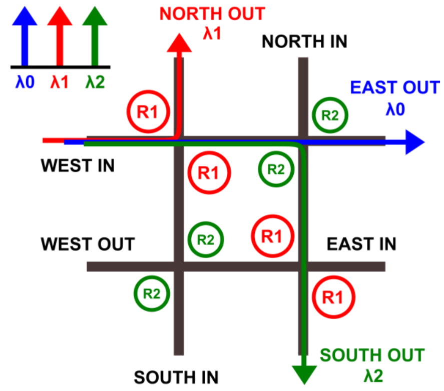


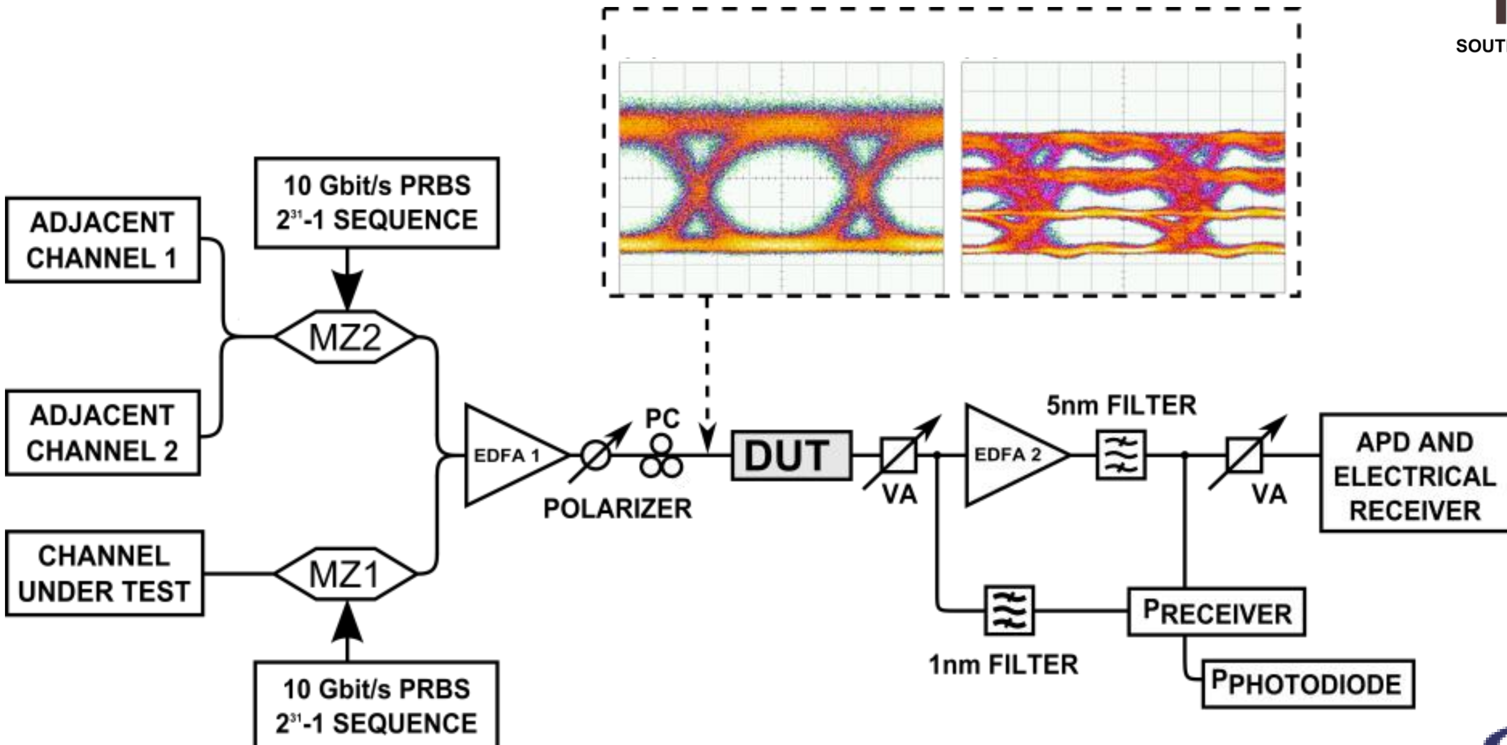


East Output

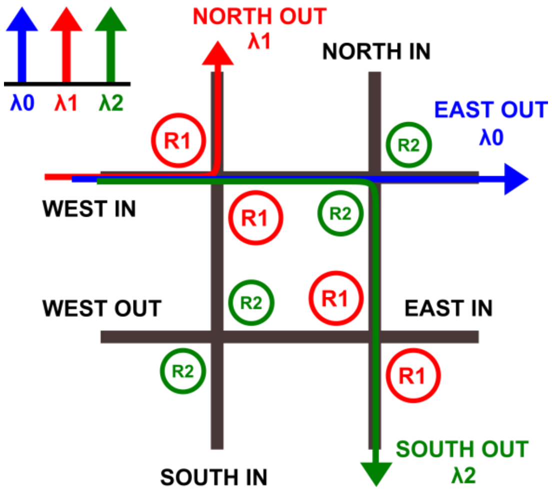


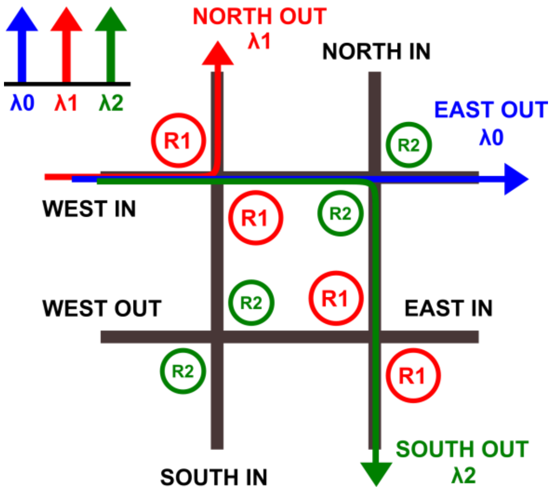
- BER Evaluation - Two dual configurations:
  - Single channel (10 Gbit/s)
  - 3-channels (3 × 10 Gbit/s) WDM

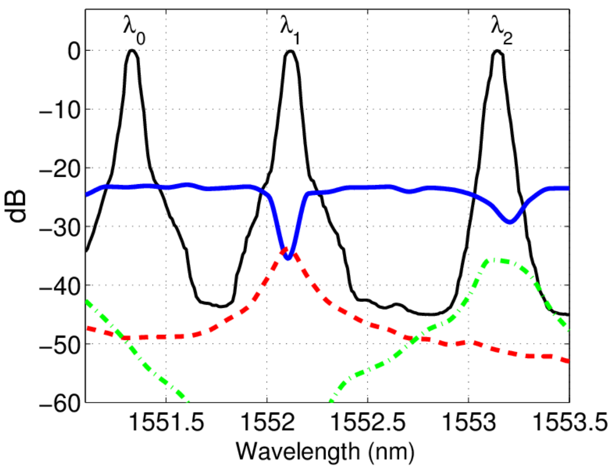


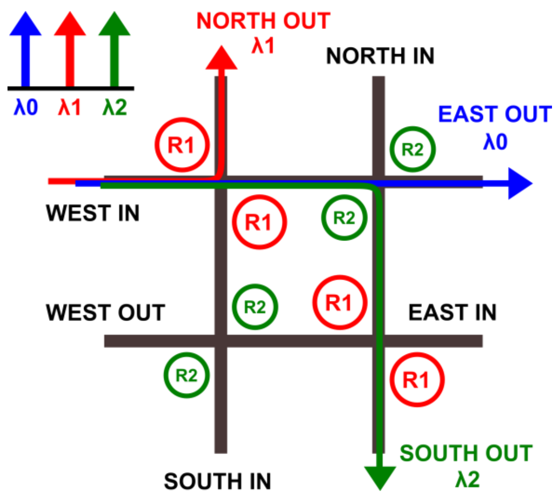


A. Parini et al., *BER evaluation of a passive SOI WDM router*, IEEE PTL 2013

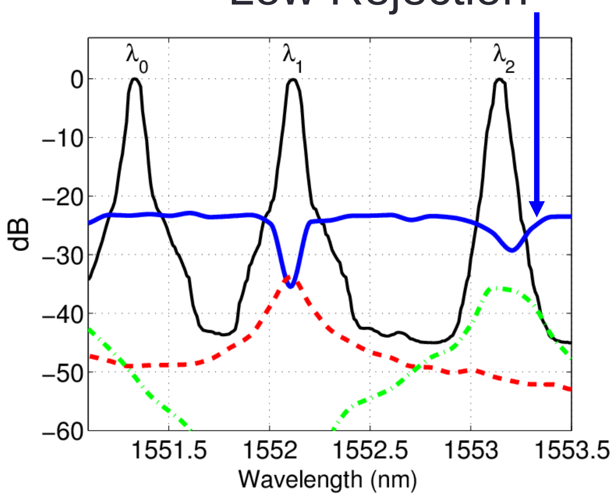

NORTH OUT
λ1
NORTH IN
EAST OUT
λ0
λ0 λ1 λ2
R1
R2
WEST IN
R1
R2
WEST OUT
R2
R1
EAST IN
R2
R1
SOUTH OUT
λ2
SOUTH IN


λ0 λ1 λ2
NORTH OUT
λ1
NORTH IN
EAST OUT
λ0
WEST IN
WEST OUT
EAST IN
SOUTH IN
SOUTH OUT
λ2
R1
R2

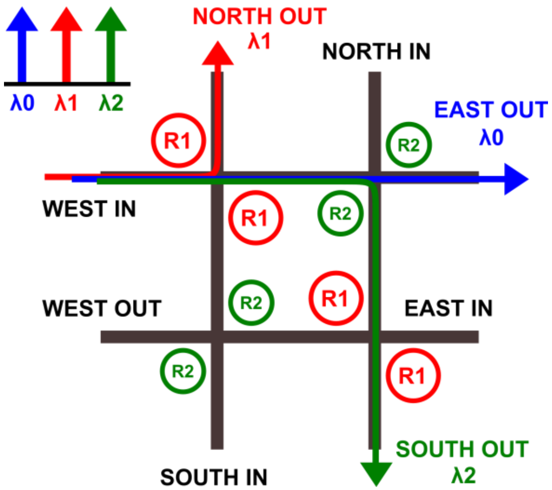

λ0
λ1
λ2
dB
0
−10
−20
−30
−40
−50
−60
1551.5
1552
1552.5
1553
1553.5
Wavelength (nm)

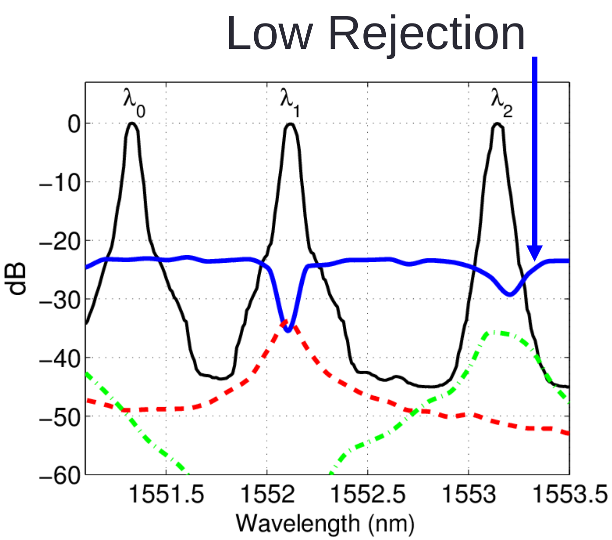


Low Rejection

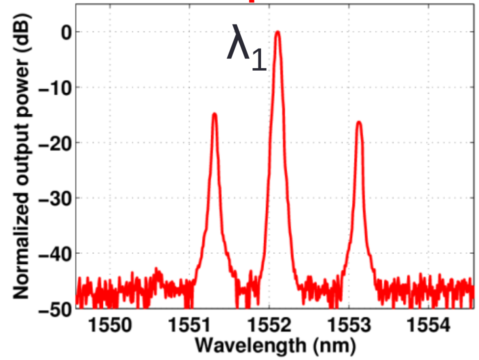


GWOR - BER Evaluation

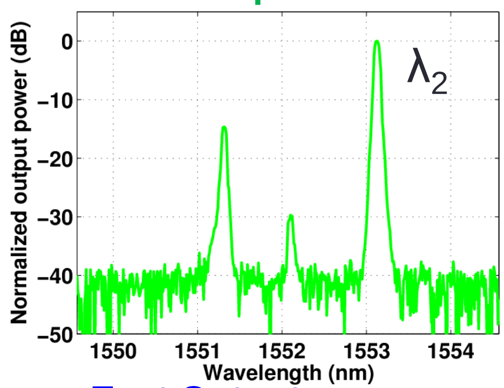




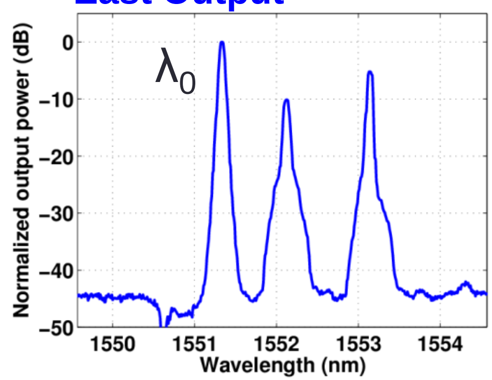
North Output



South Output

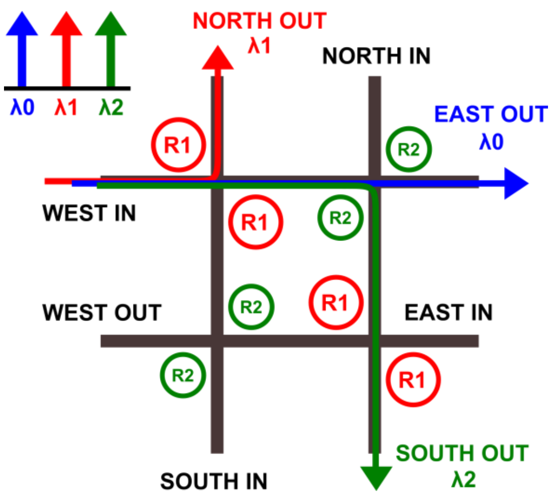


East Output

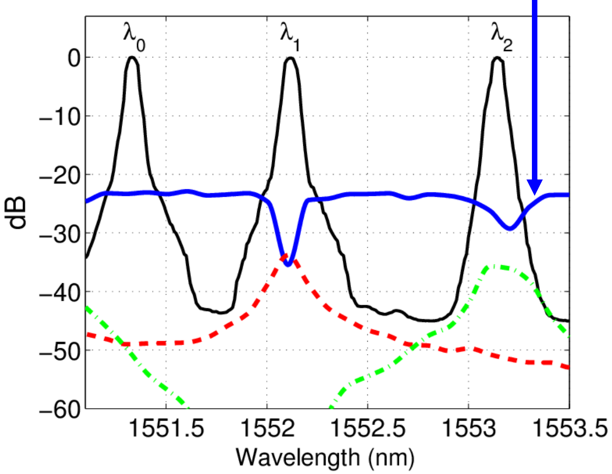


GWOR - BER Evaluation

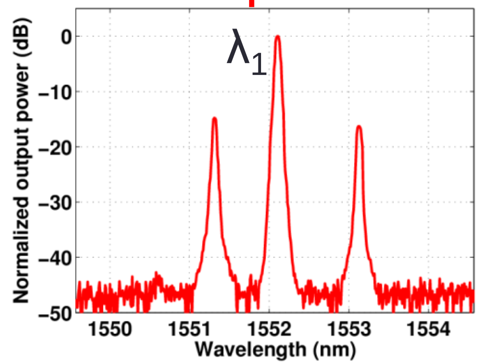
IOP Lab



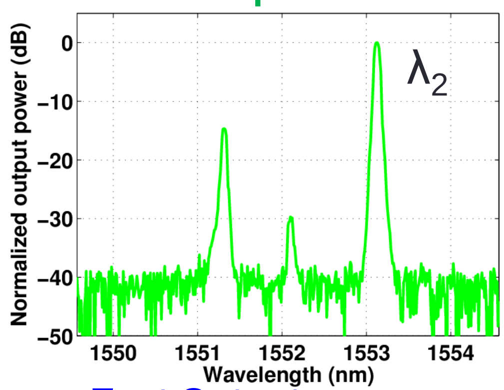
Low Rejection



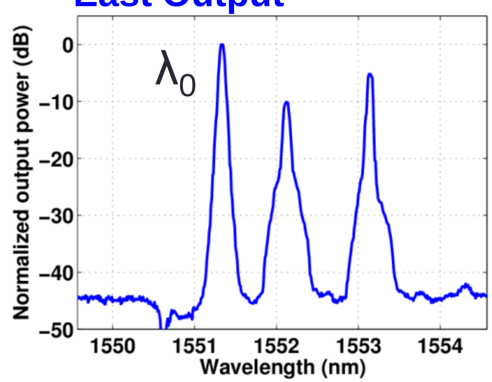
North Output

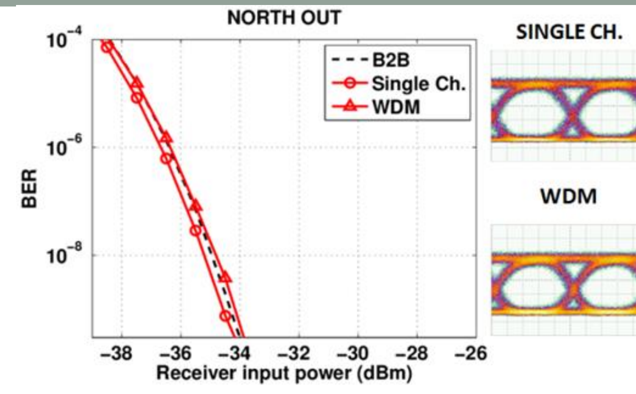


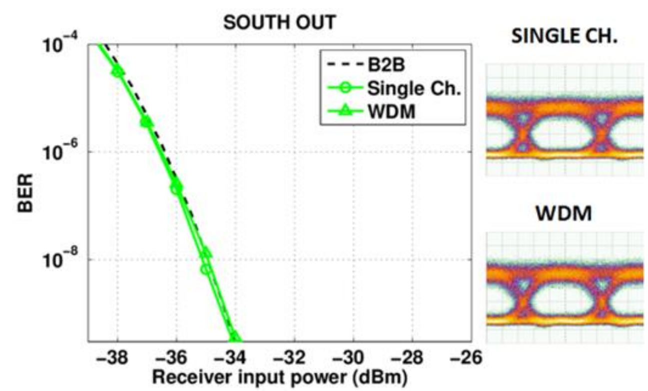
South Output

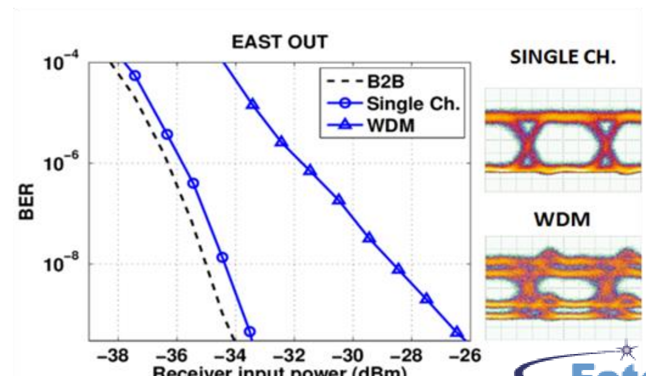


East Output



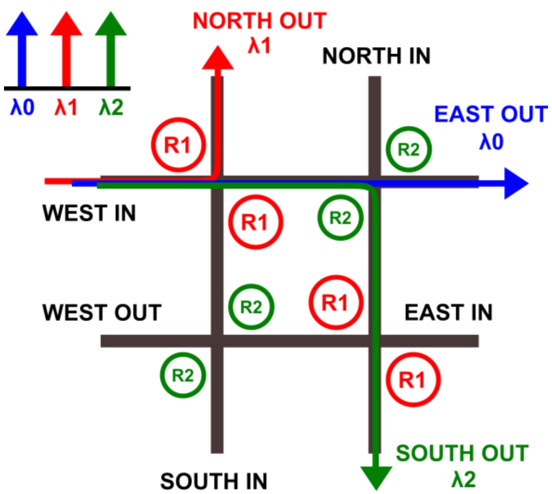




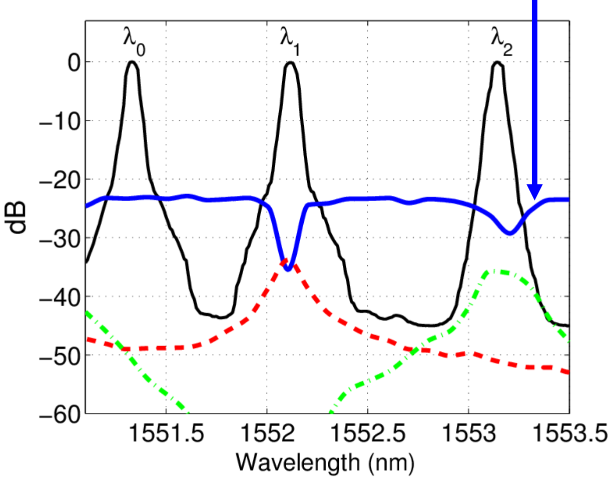


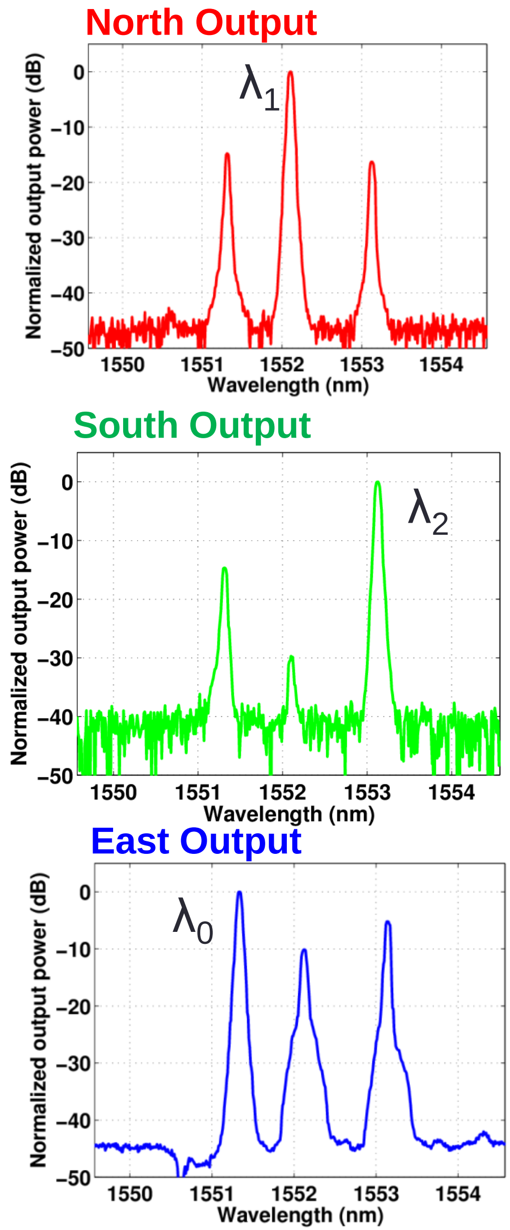
Foton

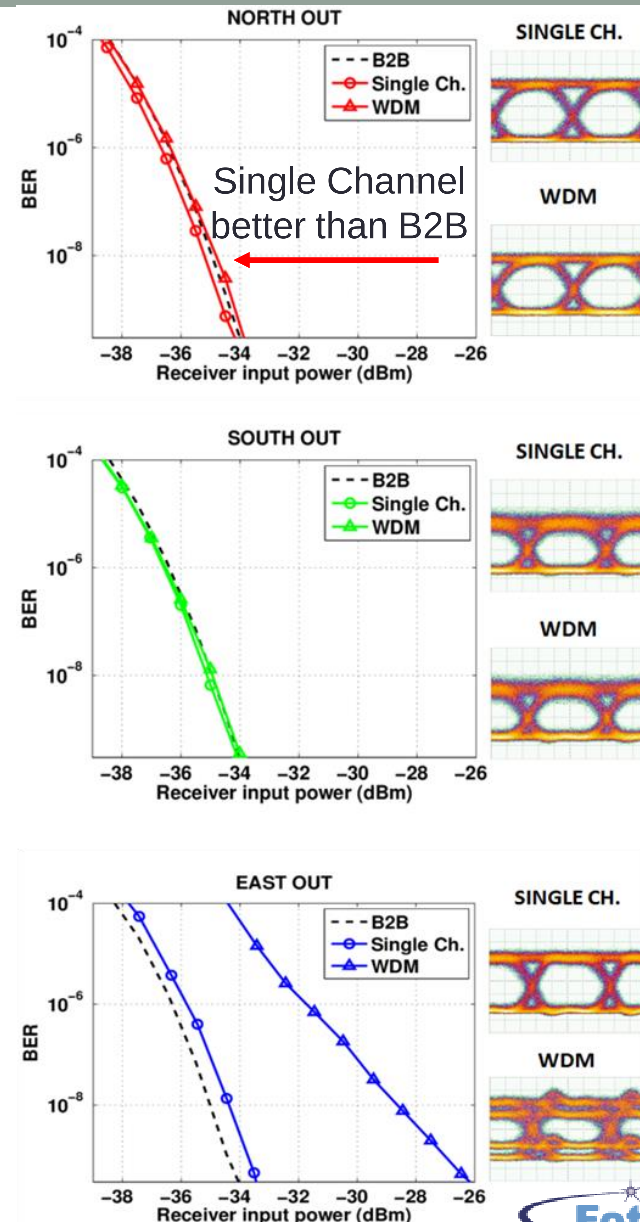
GWOR - BER Evaluation



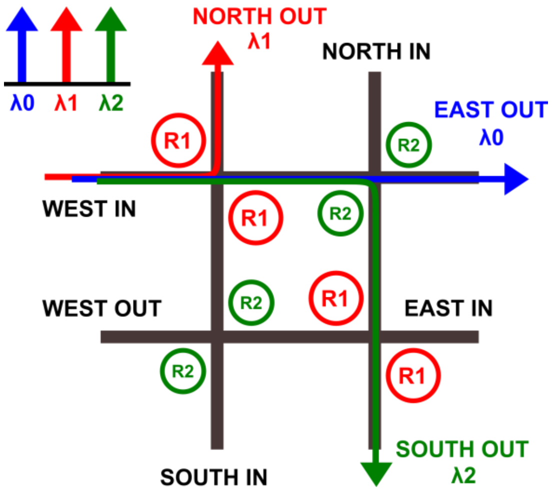
Low Rejection



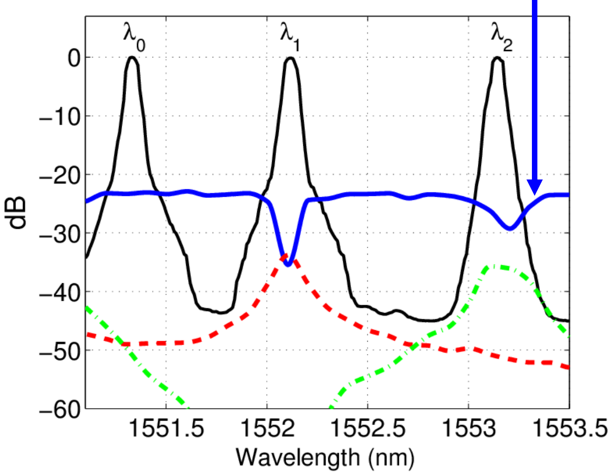




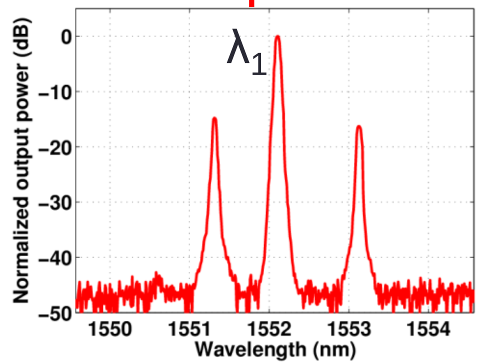
GWOR - BER Evaluation



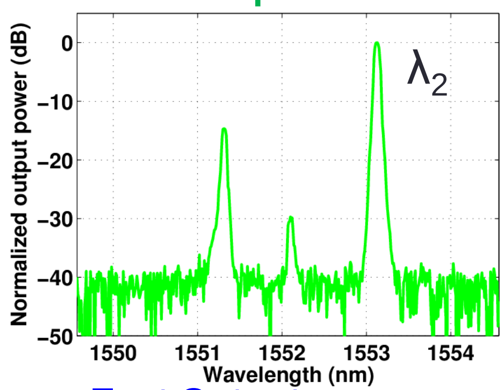
Low Rejection



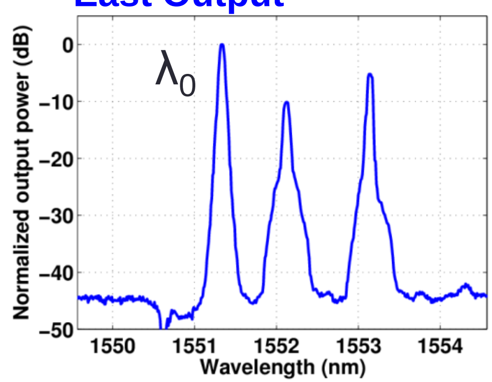
North Output

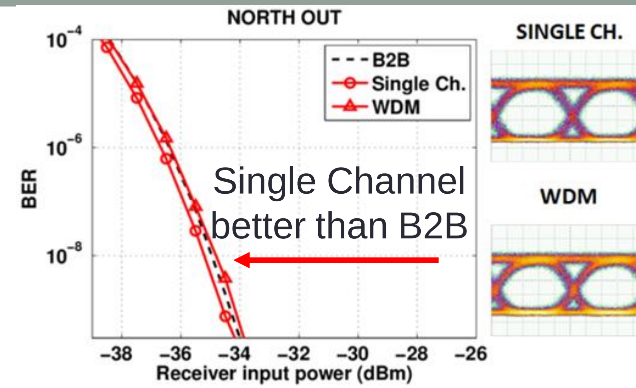


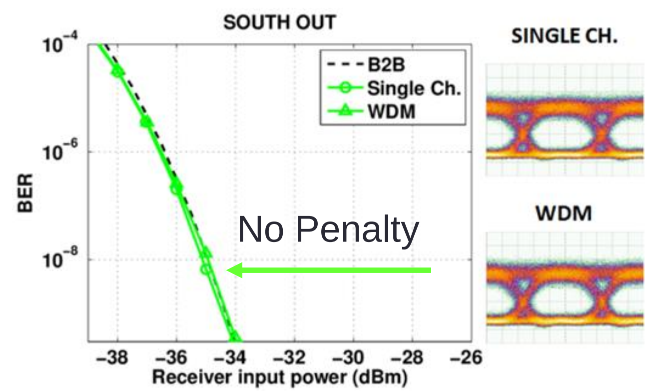
South Output

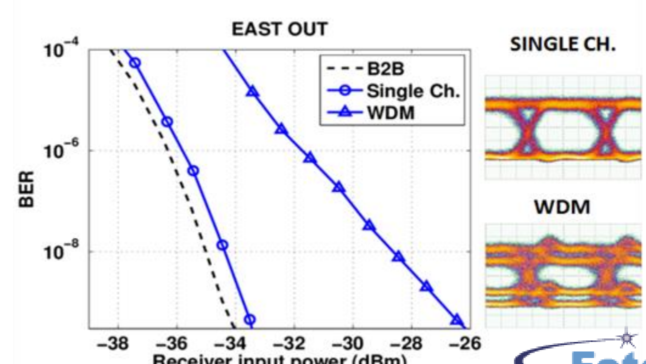


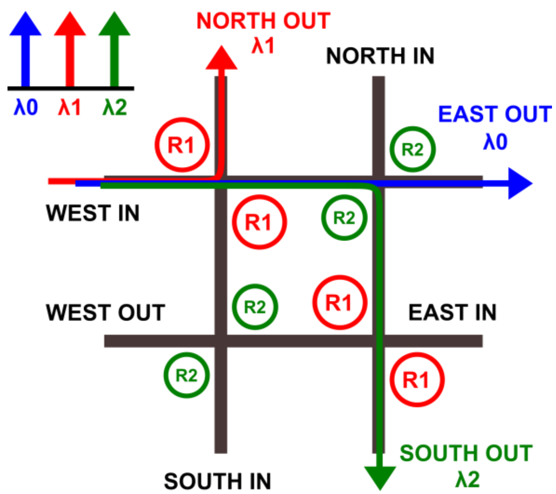
East Output

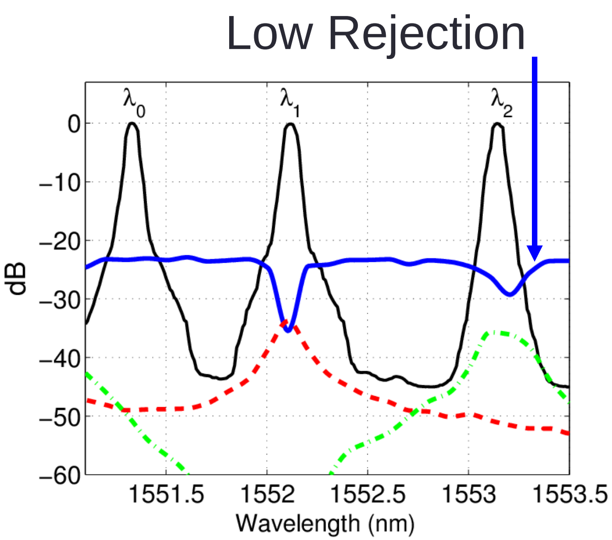




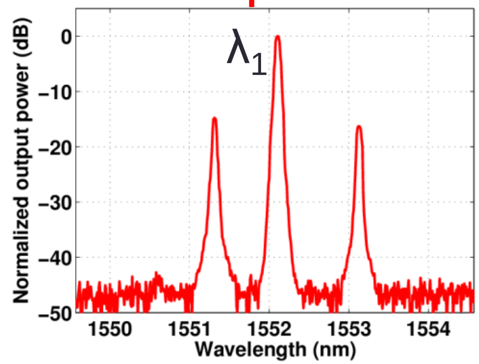




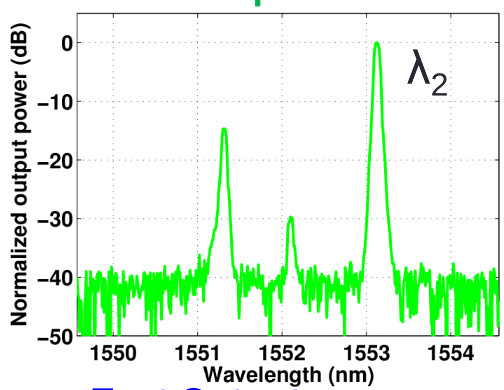




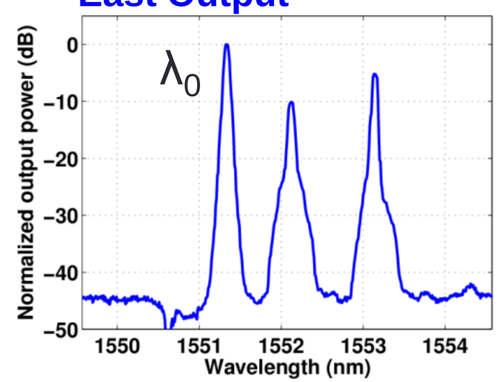
North Output

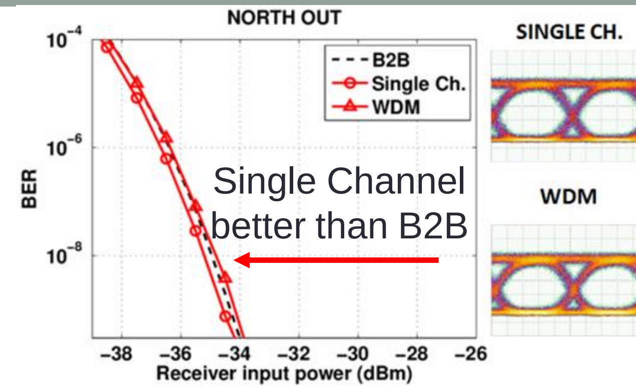


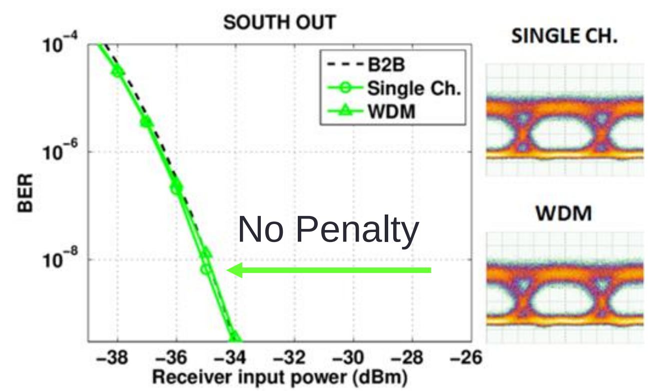
South Output

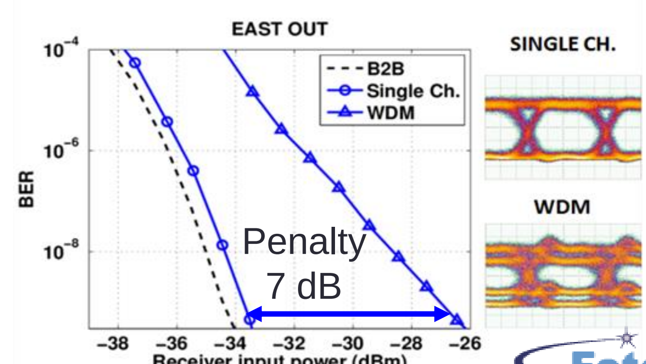


East Output

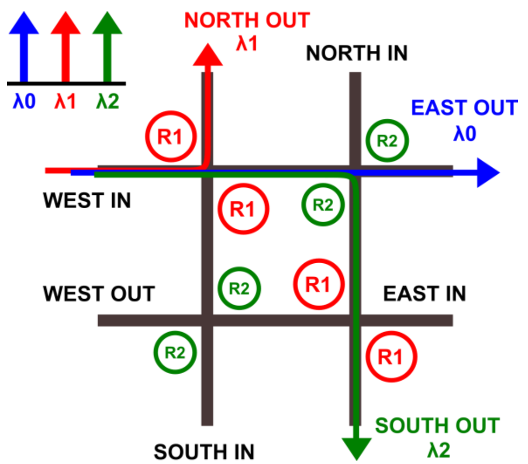








- Performance of the GWOR Router
  - Switching capabilities and robustness with respect to crosstalk demonstrated
  - BER measurements (10 Gbt/s) show
    - Fabrication issues can compromise router performances
    - 7 dB penalty on the Through Path (Low Rejection)
    - Drop-driven paths robust with respect to fabrication issues



- Sensitivity Analysis can be used to investigate the impact of technological tolerances on the performance of complex circuitry
  - The aim of Sensitivity Analysis is to assess the relations existing between a set of input factors subject to some degrees of uncertainty, and the output(s) of a model
- Elementary Effect (Morris Technique)
  - The Elementary Effect is the influence of a given input factor x_i on the output f of the system

$$EE_i(\mathbf{x}) = \frac{f(x_1, x_2, \ldots, x_i + \Delta x_i, x_{i+1} \ldots x_k) - f(x_1, x_2, \ldots, x_i, x_{i+1} \ldots x_k)}{\Delta x_i}$$

  - The statistical distribution of the elementary effects (defined as F_i) is obtained by randomly sampling N points in the space of variation of the input factors

- The Sensitivity with respect to each parameter is measured through two quantities:

- Mean Value of F_i

$$\boxed{\mu_i^* = \frac{1}{N}\sum_1^N |F_i|}$$

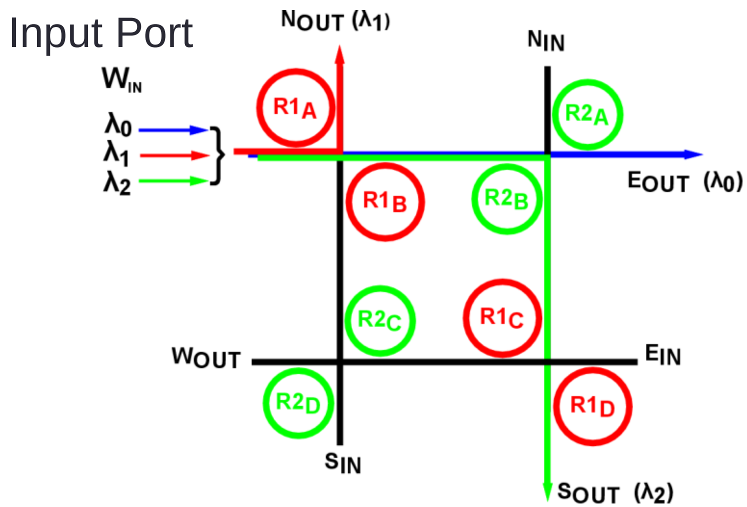
  - A high value of μ_i indicates an input variable with an important overall influence on the output

$$\boxed{\sigma_i = \sqrt{\frac{\sum_1^N \left(F_i - \mu_i^*\right)^2}{N}}}$$

- Standard Deviation of F_i

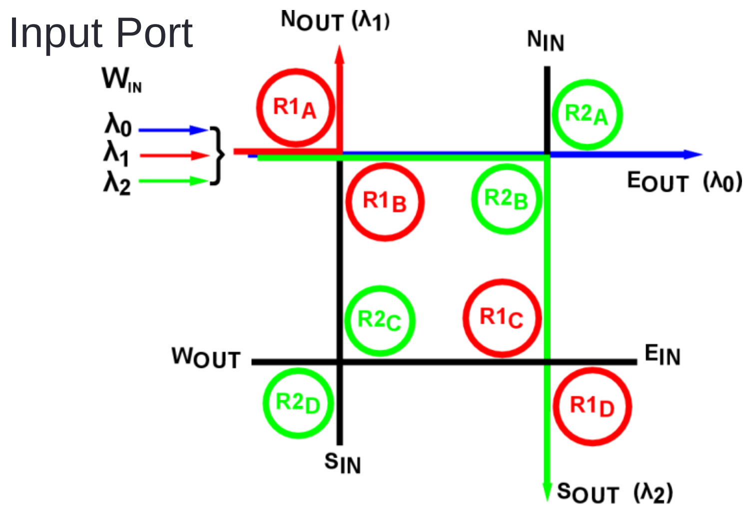
  - A high value of σ_i indicates a factor involved in interaction with other factors or whose effect is nonlinear

- Switching performance vs. variability of the rings resonances



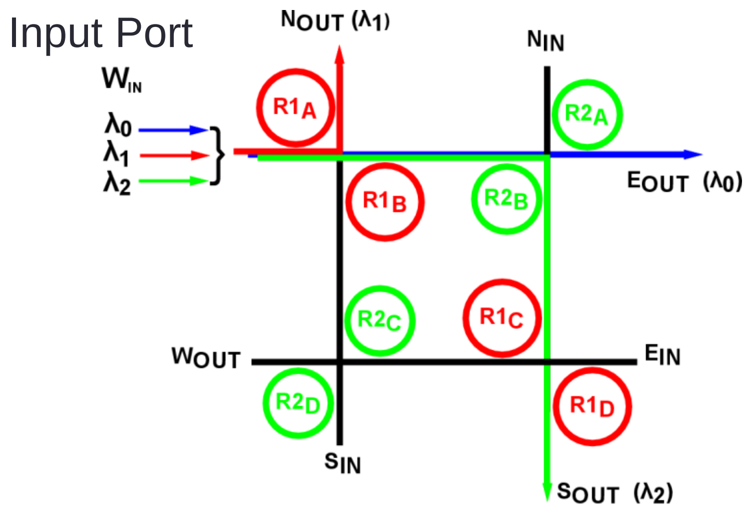
Sensitivity Analysis for the GWOR

- Switching performance vs. variability of the rings resonances



- Device behavior described through S-Parameters

- Switching performance vs. variability of the rings resonances

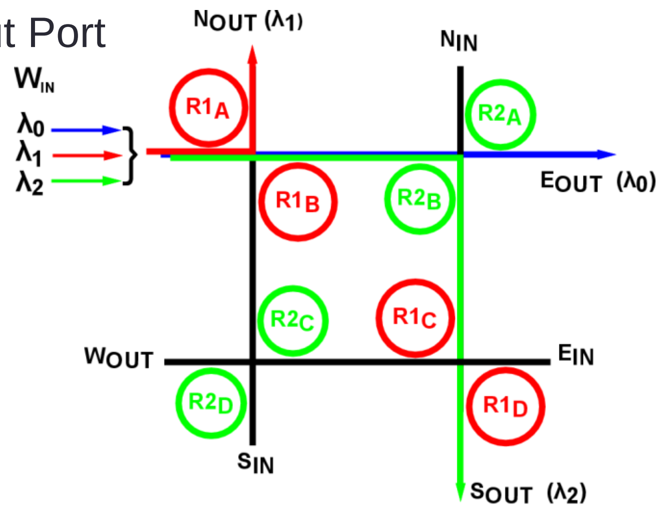


- Device behavior described through S-Parameters
- Input parameters: n_{eff} of the 8 rings

Sensitivity Analysis for the GWOR

- Switching performance vs. variability of the rings resonances

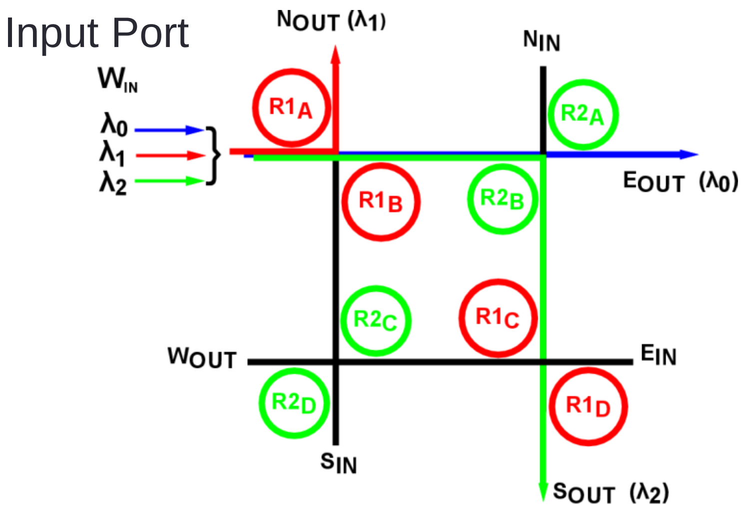
Input Port



- Device behavior described through S-Parameters
- Input parameters: n_{eff} of the 8 rings
- Output: signal vs noise (interference from other channels) at each output

IOP Lab

- Switching performance vs. variability of the rings resonances

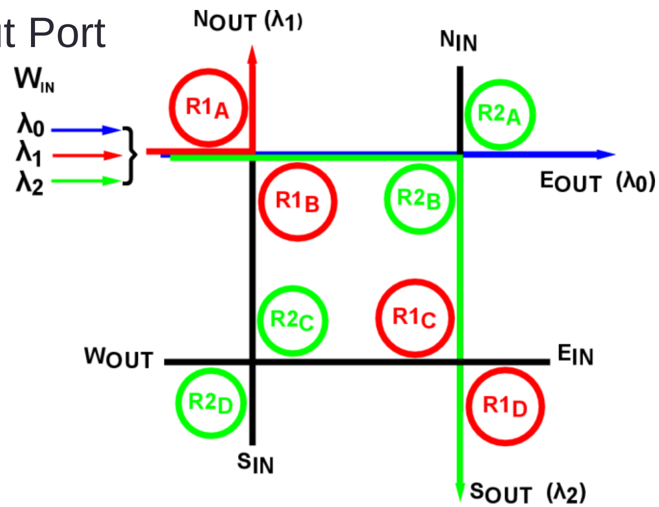


- Device behavior described through S-Parameters
- Input parameters: n_{eff} of the 8 rings
- Output: signal vs noise (interference from other channels) at each output

Channel Quality Factor (CQF) parameter

- Ratio between the power at the expected wavelength of a specific port and the power of the interfering wavelengths

- Switching performance vs. variability of the rings resonances



- Device behavior described through S-Parameters
- Input parameters: n_{eff} of the 8 rings
- Output: signal vs noise (interference from other channels) at each output

East Output

$$CQF_0 = E_{OUT}(\lambda_0)\cdot\frac{\int_{\lambda_0-3\sigma_0}^{\lambda_0+3\sigma_0} E_{OUT}(\lambda)\,d\lambda}{\int_B E_{OUT}(\lambda)\,d\lambda}$$

Channel Quality Factor (CQF) parameter

- Ratio between the power at the expected wavelength of a specific port and the power of the interfering wavelengths

North Output

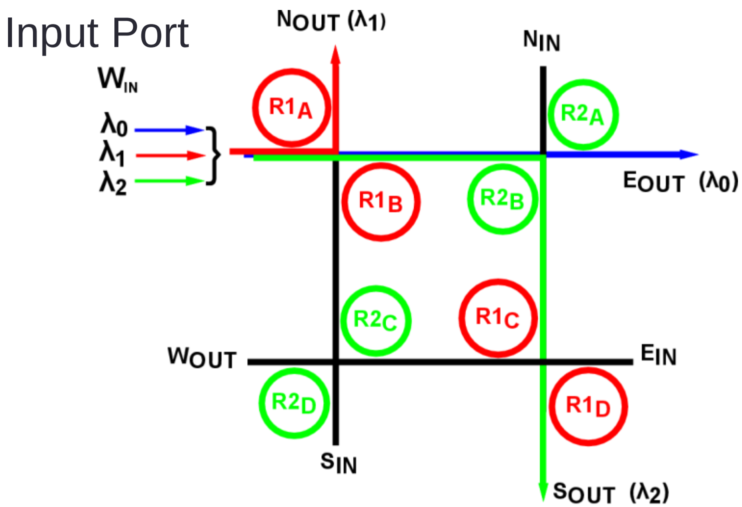
$$CQF_1 = N_{OUT}(\lambda_1)\cdot\frac{\int_{\lambda_1-3\sigma_1}^{\lambda_1+3\sigma_1} N_{OUT}(\lambda)\,d\lambda}{\int_B N_{OUT}(\lambda)\,d\lambda}$$

South Output

$$CQF_2 = S_{OUT}(\lambda_2)\cdot\frac{\int_{\lambda_2-3\sigma_2}^{\lambda_2+3\sigma_2} S_{OUT}(\lambda)\,d\lambda}{\int_B S_{OUT}(\lambda)\,d\lambda}$$

σ_i = 0.0340 μm FWHM band for each carrier wavelength

- Switching performance vs. variability of the rings resonances



- Device behavior described through S-Parameters
- Input parameters: n_{eff} of the 8 rings
- Output: signal vs noise (interference from other channels) at each output

East Output

$$CQF_0 = E_{OUT}(\lambda_0) \cdot \frac{\int_{\lambda_0-3\sigma_0}^{\lambda_0+3\sigma_0} E_{OUT}(\lambda)\, d\lambda}{\int_B E_{OUT}(\lambda)\, d\lambda}$$

North Output

$$CQF_1 = N_{OUT}(\lambda_1) \cdot \frac{\int_{\lambda_1-3\sigma_1}^{\lambda_1+3\sigma_1} N_{OUT}(\lambda)\, d\lambda}{\int_B N_{OUT}(\lambda)\, d\lambda}$$

South Output

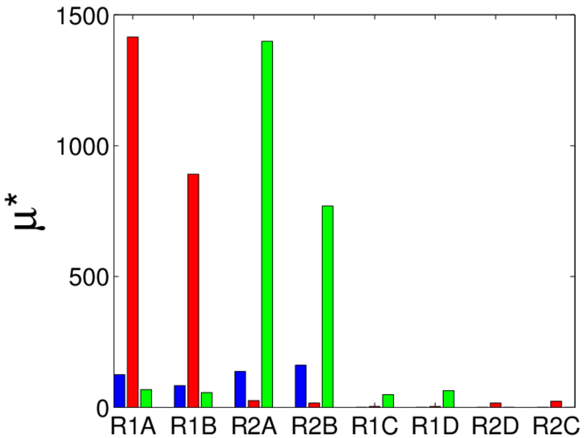
$$CQF_2 = S_{OUT}(\lambda_2) \cdot \frac{\int_{\lambda_2-3\sigma_2}^{\lambda_2+3\sigma_2} S_{OUT}(\lambda)\, d\lambda}{\int_B S_{OUT}(\lambda)\, d\lambda}$$

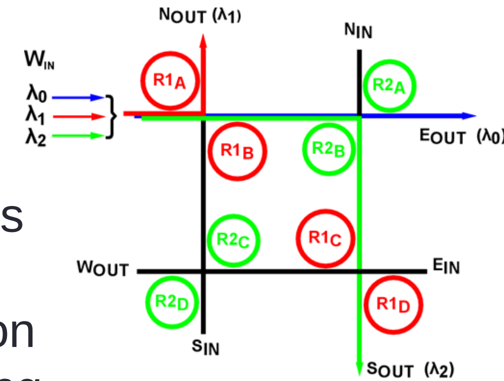
Channel Quality Factor (CQF) parameter

- Ratio between the power at the expected wavelength of a specific port and the power of the interfering wavelengths
- CQF gives an evaluation of both the finite rejection and of the detuning of the rings

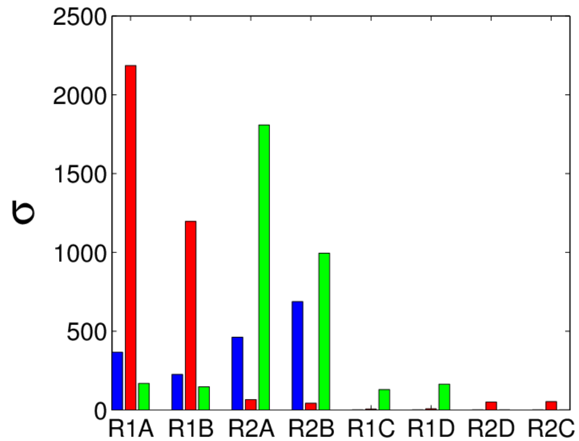
σ_i = 0.0340 μm FWHM band for each carrier wavelength

Rings' effective index normally distributed (mean value = nominal value) with **variance 10^{-3}**





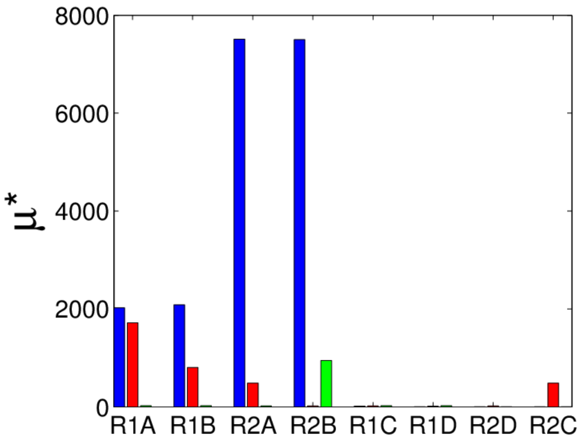
- R1A and R1B crucial rings for the North-Out port (red bars)
- R2A and R2B have similar effects for the South-Out (green bars)
- East-Out port less influenced (non resonant path). Effects of detuning overwhelmed by those on North and South ports

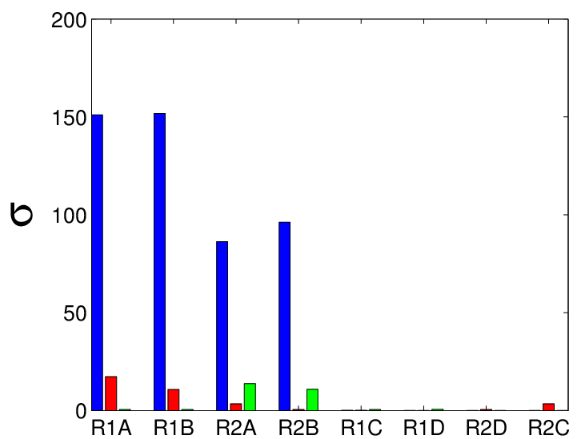


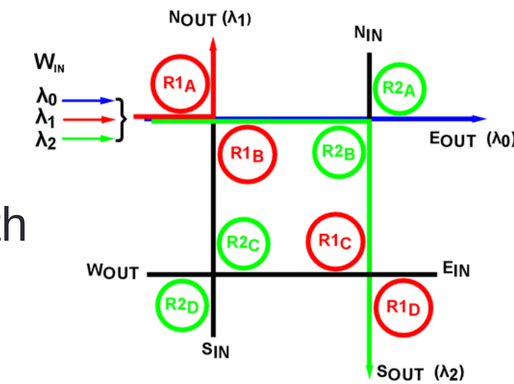
- The effects of R1A and R1B is strong on the North-Out port
- The same happens for R2A and R2B for what concerns the South-Out port
- All of these rings influence also the quality of the East-Out port

A. Parini, G. Bellanca, Quant Electron (2015) 47: 3145. https://doi.org/10.1007/s11082-015-0168-4

Rings' effective index normally distributed (mean value = nominal value) with **variance 10^{-6}**







- The most affected output is now the East-Port
- The rings on the West to East path have the greatest impact
- R1A, R1B and R2A, R2B all have a small impact (in relative terms) on the drop paths
  - The functionalities of the ports driven by the drop paths are less affected by the randomness of ring parameters
- The West-In to East-Out path is compromised
- Ring parameters variability strongly influence the switching efficiency

A. Parini, G. Bellanca, Quant Electron (2015) 47: 3145. https://doi.org/10.1007/s11082-015-0168-4

Conclusions

- Optical Network for On-Chip Optical Interconnections
  - Motivations for using ONoC
  - Basic Switching elements (1 $\times$ 2 PSE and 2 $\times$ 2 PSE)
  - 4 In - 4 Out Optical Network - GWOR
  - Problems related to fabrication tolerances
  - Performance Evaluation
  - Sensitivity Analysis as effective tool to investigate critical parameters

Conclusions

- Optical Network for On-Chip Optical Interconnections
  - Motivations for using ONoC
  - Basic Switching elements (1 × 2 PSE and 2 × 2 PSE)
  - 4 In - 4 Out Optical Network - GWOR
  - Problems related to fabrication tolerances
  - Performance Evaluation
  - Sensitivity Analysis as effective tool to investigate critical parameters

Now … Going wireless

… Optically …

ON CHIP PHOTONIC INTERCONNECTIONS: WIRED AND WIRELESS TECHNOLOGIES

Prof. Giovanna Calò, Politecnico di Bari

Prof. Gaetano Bellanca, University of Ferrara

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OUTLINES

- Introduction
- Design of on-chip integrated antennas
  - Plasmonic antennas
  - Antenna arrays
- Wireless link performance
  - Finite Difference Time domain simulations
  - Ray tracing simulations
  - Bit Error Probability

The WiNOT Project

- **W**i**reless** **N**etworks through on-chip **O**ptical **T**echnology
- Italian National Project
- Starting date: December 2017
- 3 Universities Involved
  - **Politecnico di Bari** (Coordinator): design of optical antennas
  - **University of Bologna**: development of a ray-tracing tool to investigate the optical propagation inside the chip
  - **University of Ferrara**: network analysis and optimization. Measurements on fabricated devices
- Technological Partner
  - IIT - Center for Biomolecular Nanotechnologies

Politecnico di Bari

University of Ferrara
- Ex Labore Fructus -

The WiNOT Project

Design of Optical Antennas for Wireless Optical Connections

- Antenna Design
- Fabrication
- Integration with the Optical Layer
- Antenna Array
- Measurements

Development of a Ray-Tracing Simulator to investigate propagation in Complex Environments

- Long - Distance FDTD Simulations
- Ray – Tracing Simulator

Network Analysis Optimization

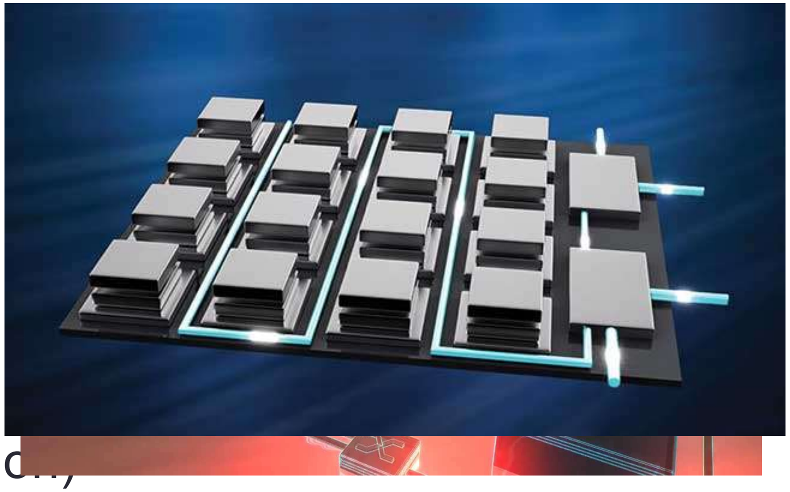
- Network performance with a single link
- Network performance with multiple links
- Performance evaluation and Optimization

Politecnico di Bari

University of Ferrara
- EX LABORE FRUCTUS -

Introduction

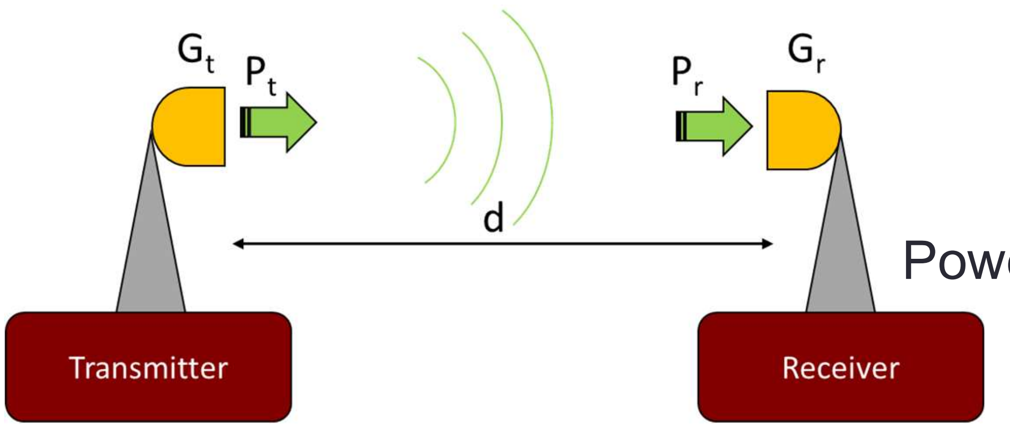
- Optical Interconnections on-chip proposed to have efficient communication between processors on the same die (ONoC)
  - Problems: footprint, layout complexity, signal loss and crosstalk due to multiple waveguide crossing
- RF Wireless Connections (WiNoC) investigated, to avoid multiple waveguide crossing
- Optical Wireless NoC (OWiNoC)
- All-Optical solution(Wired + Wireless) presenting some advantages
  - No transceivers
  - No latency (for optical-to-electrical conversion)
  - Bit transparency
  - Reduced power consumption



https://www.photonics.com/a61635/
https://lightwave.ee.columbia.edu

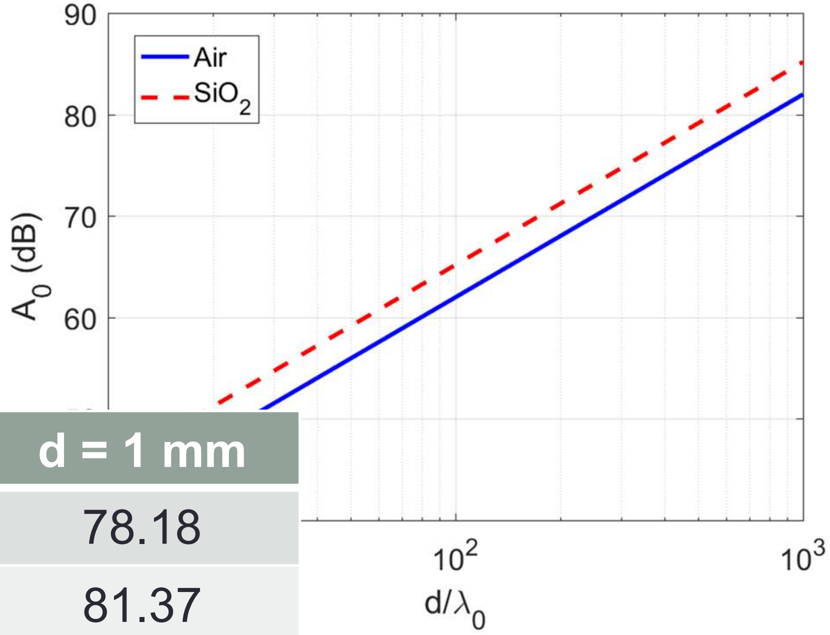
Wireless Optical Network on Chip

- Propagation in homogeneous medium: the Friis formula



$$A_0 = -20\log_{10}\left(\frac{\lambda_0/n}{4\pi d}\right)$$

Power decay for free-space propagation



$$P_r = P_t + G_r + G_t + 20\log_{10}\left(\frac{\lambda_0/n}{4\pi d}\right)$$

P_r: received power (dBm)

λ_0 = 1.55 μm	d = 50 μm	d = 100 μm	d = 1 mm
A_0 - Air	52.16	58.18	78.18
A_0 - SiO_2	55.35	61.37	81.37

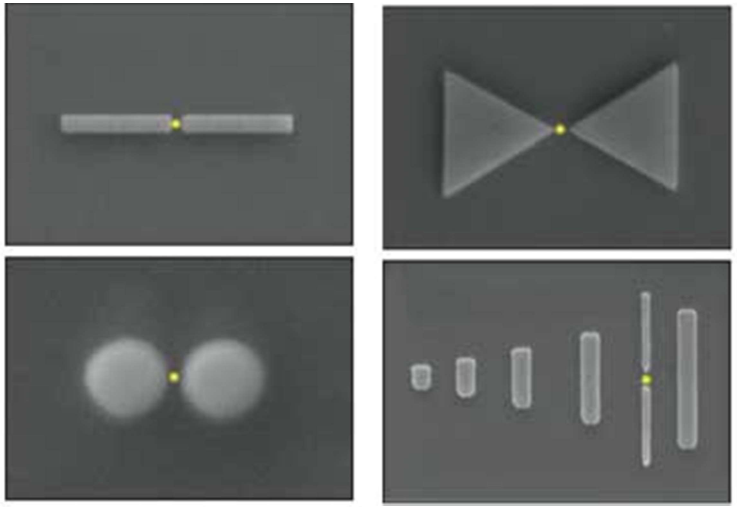
λ_0: wavelength
n: refractive index
d: distance of the link

P_t = 0 dBm (1mW), P_r = -20 dBm, $A_0 \cong$ 82 dB ⇨

⇨ OWiNoC applications need antennas with high gain

Antennas for Optical Wireless Network on Chip

- Plasmonic Optical Antennas



- Problems
  - Directivity is not very high
  - Resonant antennas ⇨
    ⇨ Small bandwidth
  - Excitation through silicon optical waveguides challenging

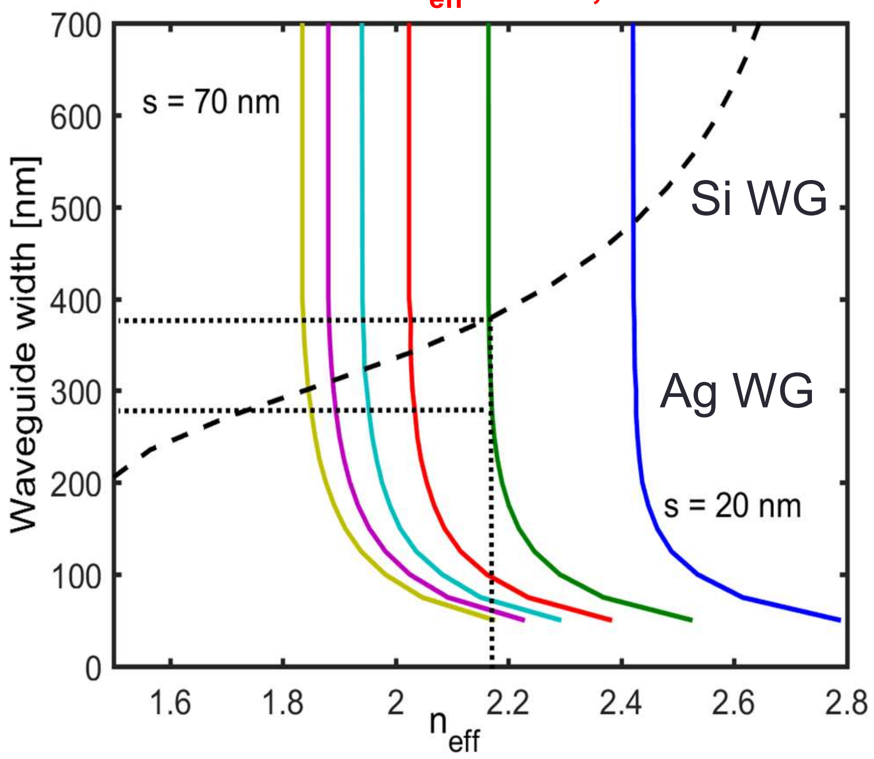
https://www.photonics.ethz.ch/en/general-information/research/optical-antennas.html

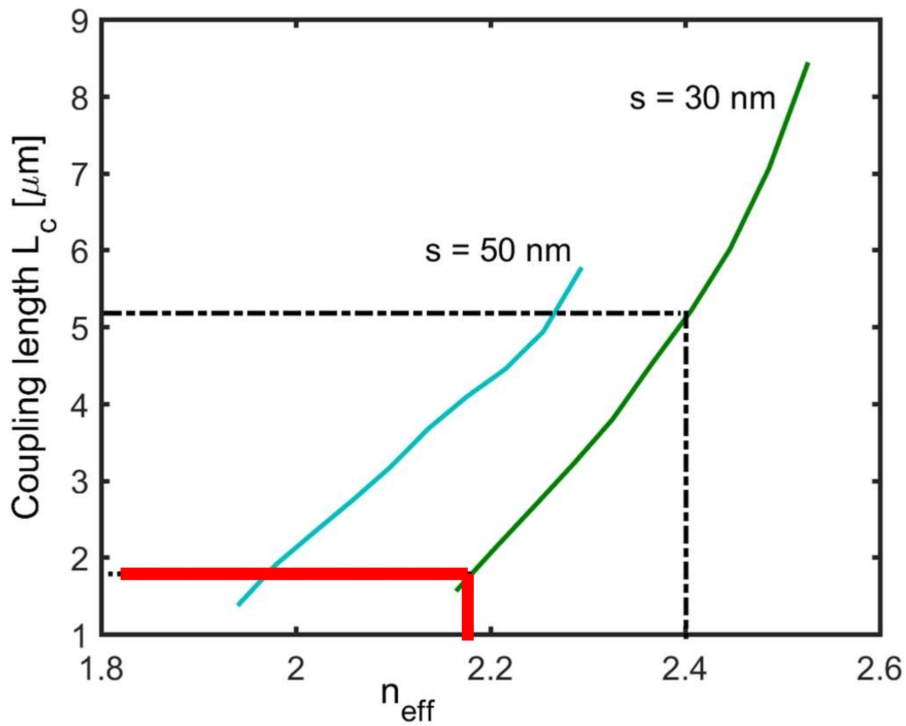
- Vivaldi Antenna
  - Used in the microwave range
  - High gain and large bandwidth

- Design of a Vivaldi Antenna for Optical Wavelengths

Vivaldi plasmonic antenna

n_{eff} = 2.17, s = 30 nm





Coupled Mode Theory

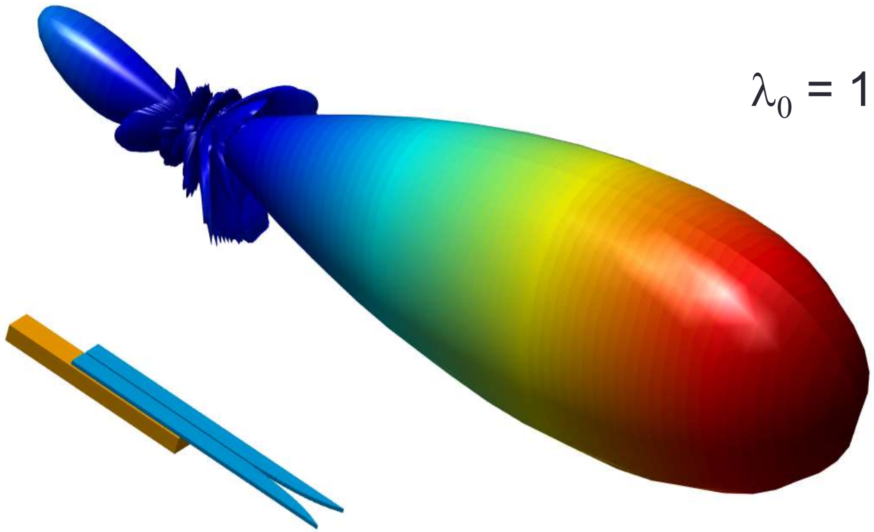
Efficient coupling: Silicon and Plasmonic waveguides with same n_{eff} for their fundamental (TE) modes

$$L_c = \frac{\lambda_0}{2|n_e - n_o|}$$

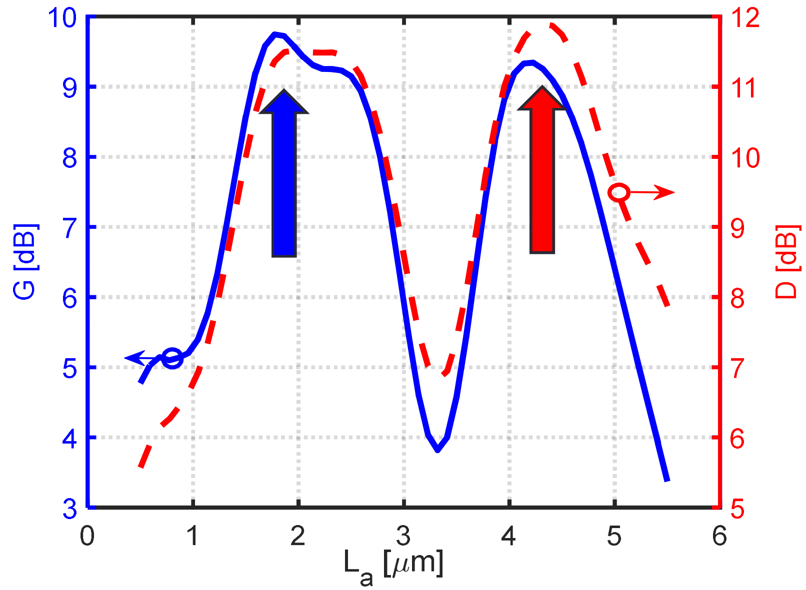
s = 30 nm, **n_{eff} = 2.17**, w = 380 nm, p = 270 nm , **L_c = 1.63 μm**

[1] G. Bellanca et al., Optics Express (2017)

Vivaldi plasmonic antenna



$\lambda_0 = 1.55$ μm

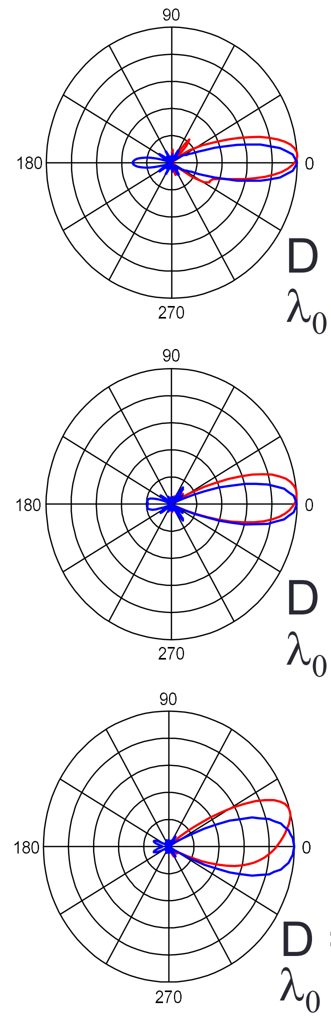


Optimized Geometry: $L_a = 1.75$ μm

Directivity

E Plane (Hor.)

H Plane (Vert.)



D = 9.1 dB
$\lambda_0 = 1.50$ μm

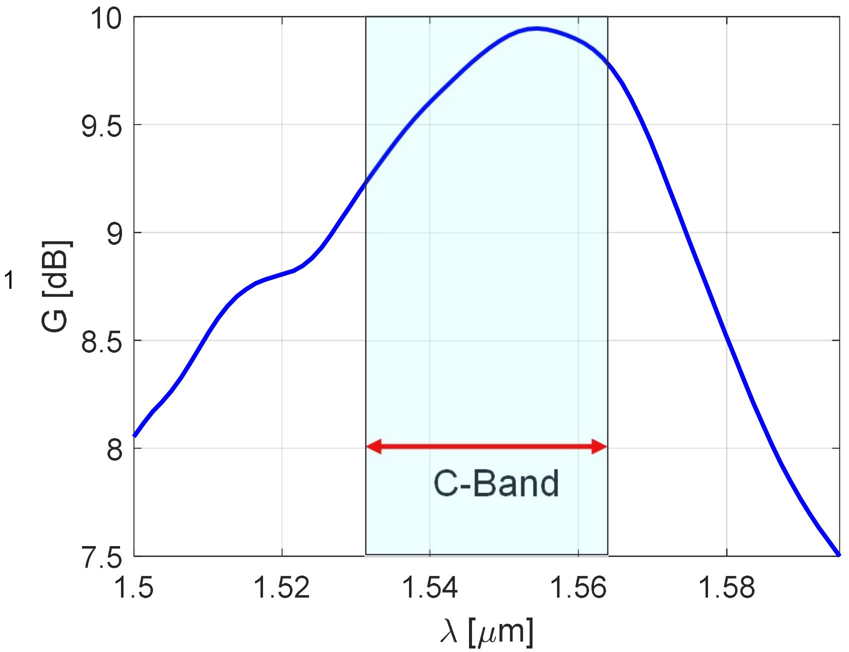
D = 11.1 dB
$\lambda_0 = 1.55$ μm

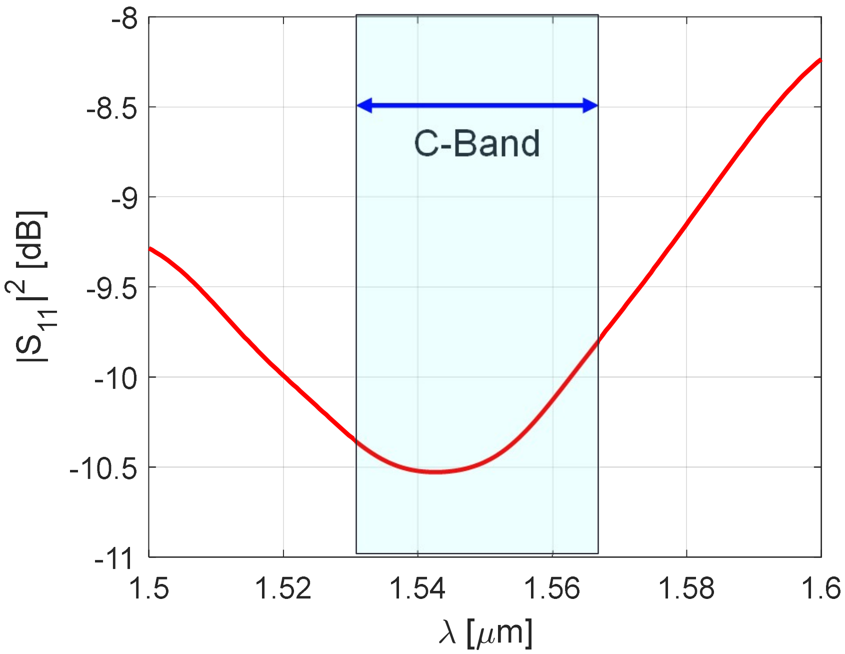
D = 9.6 dB
$\lambda_0 = 1.60$ μm

Optimized Optical Vivaldi Antenna

- Coupler length L_c, Antenna length L_a and Antenna shape have been optimized to maximize Gain and Bandwidth
- The Vivaldi antenna performs well for all the wavelengths in the C Band (1530 ÷ 1565 nm)
  - Radiation patterns have regular shapes
  - Gain always above 9 dB
  - Impedance Matching is good ($|S_{11}|^2 < -9.5$ dB)

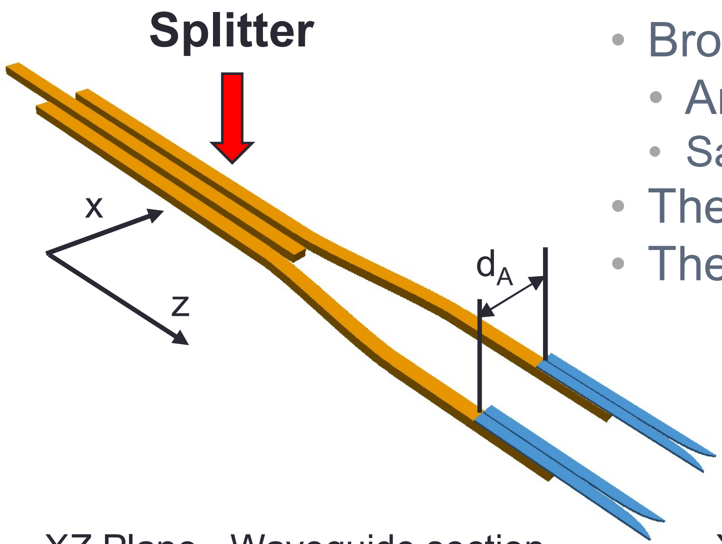
E Plane (H)
H Plane (V)





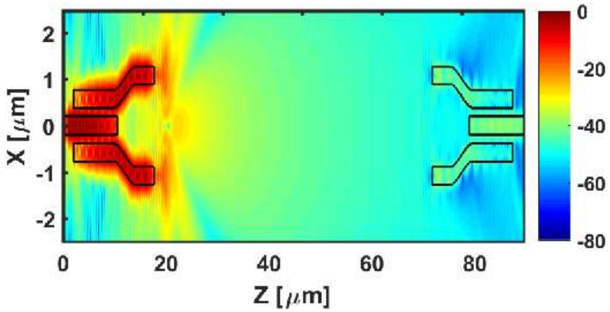
Broadside array of two Vivaldi radiators

- Antenna Arrays are compositions of Antennas suitably positioned and properly excited (playing with both amplitude and phase)
  - Directivity increase
  - Beam-Steering (changing the direction of the main lobe)

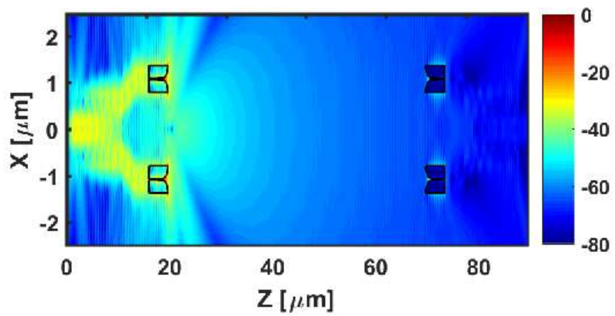


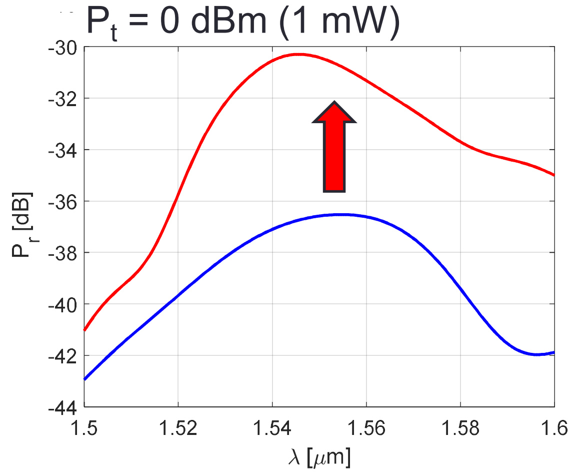
- Broadside Array of Vivaldi Antennas
  - Antennas aligned along the *x* axis
  - Same Amplitudes and Phases of the Excitations
- The Gain increases of about 3 dB
- The Received Power increases of about 6 dB

XZ Plane - Waveguide section



XZ Plane - Antenna section

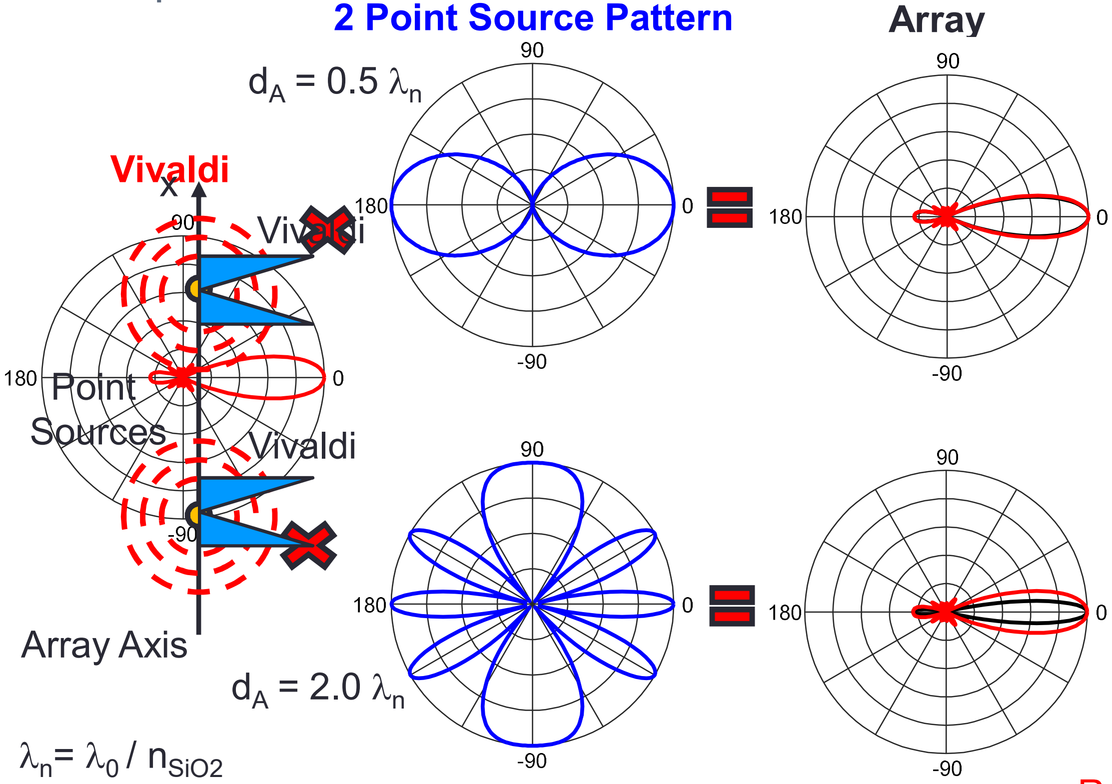




[2] G. Calò et al., Optical and Quantum Electronics (2017)

Broadside array of two Vivaldi radiators

- Radiation Pattern of the Array obtained through pattern multiplication theorem
  - Pattern of elementary (point) sources
  - Pattern of the Vivaldi Antenna
  - With the proposed configuration, only radiation patterns on the Horizontal (E) plane can be modified



No Grating Lobes on the Radiation Pattern of the 2 Point Source
Radiation Patterns of Array and Vivaldi almost indistinguishable
No increase in the directivity

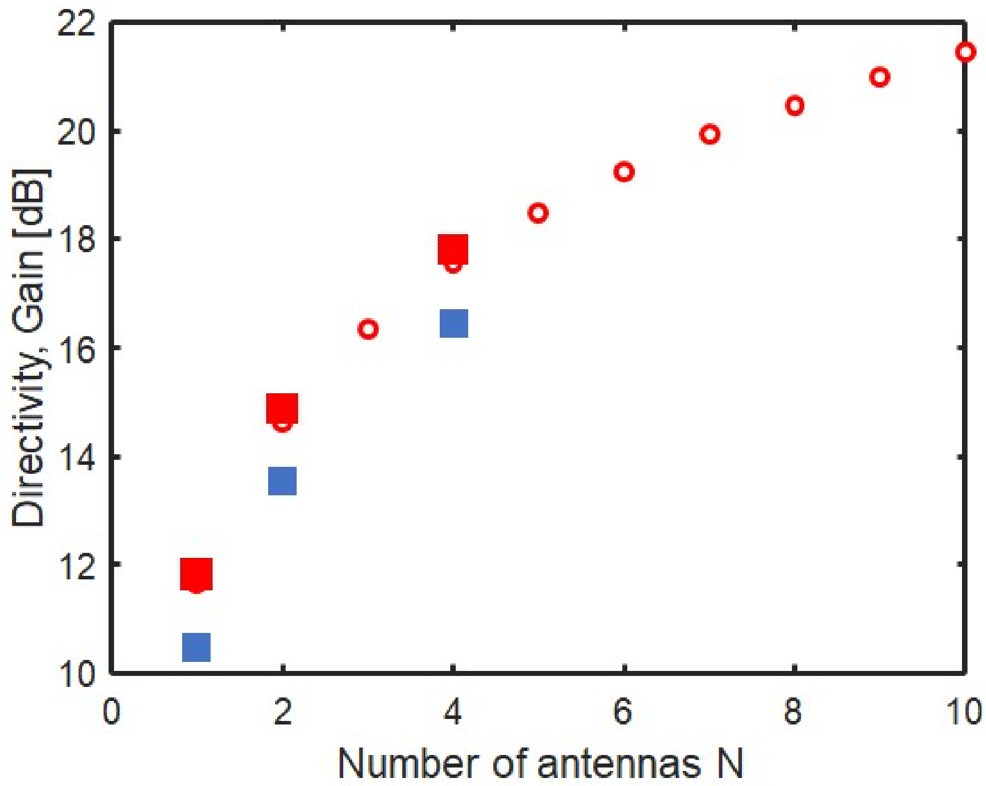
Grating Lobes on the Radiation Pattern of the 2 Point Source
Narrower Radiation Pattern for the Array
⇨Increase in the directivity (D = 16.7 dB)

$\lambda_n = \lambda_0 / n_{SiO2}$

Radiation Patterns on the Horizontal Plane

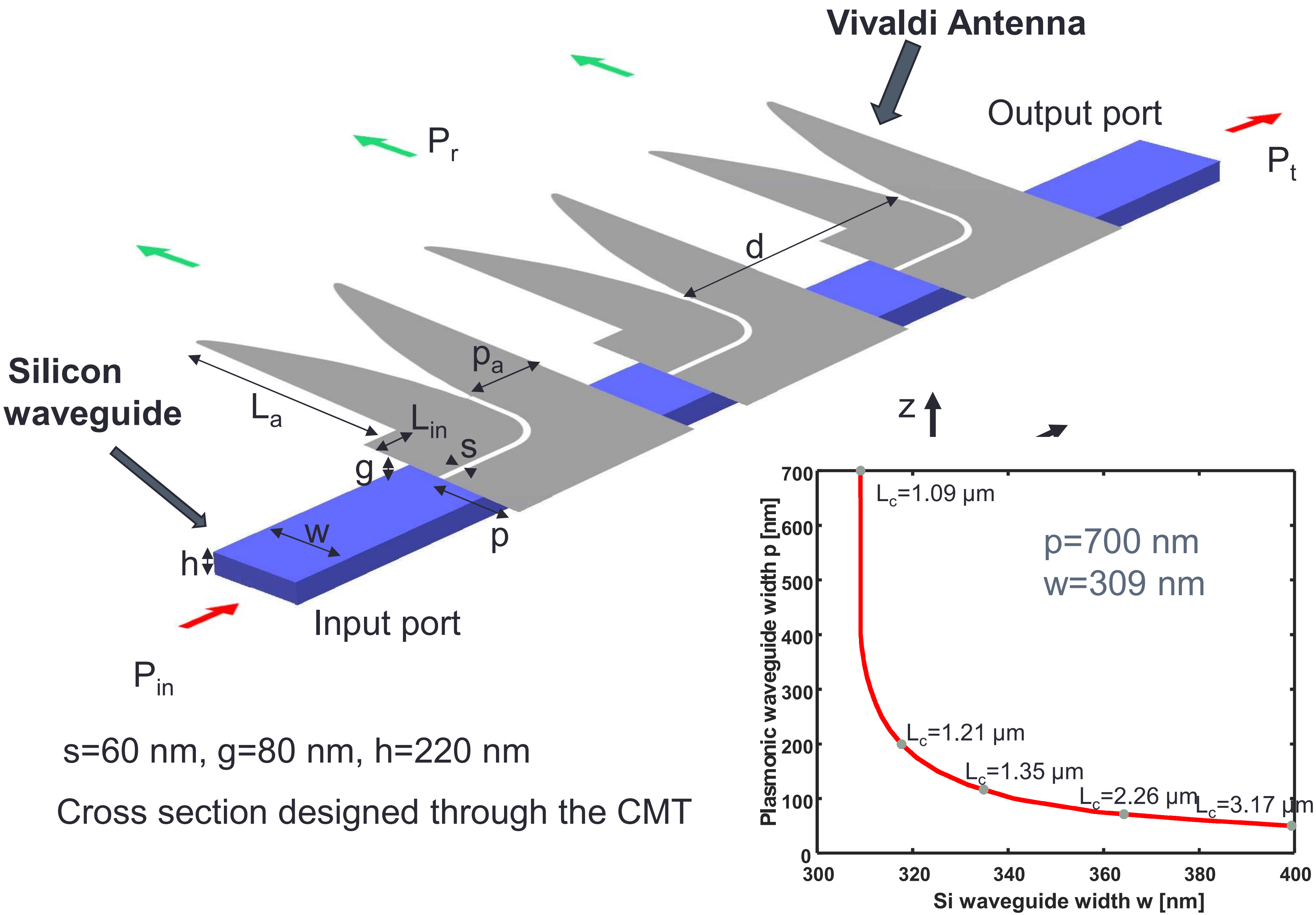
Radiation Pattern Vivaldi Antenna
Radiation Pattern Array of Vivaldi Antennas

Broadside array of N Vivaldi radiators



- Array directivity (red squares) and gain (blue squares) as a function of the number of antenna N (N=1, 2, and 4) by FDTD. The red circles report the array directivity calculated according to antenna theory
- In all the considered cases, the radiation efficiency is η= G/D = 0.7
- Large footprint of the overall array owing to the feeding network.

Travelling wave Vivaldi antenna array

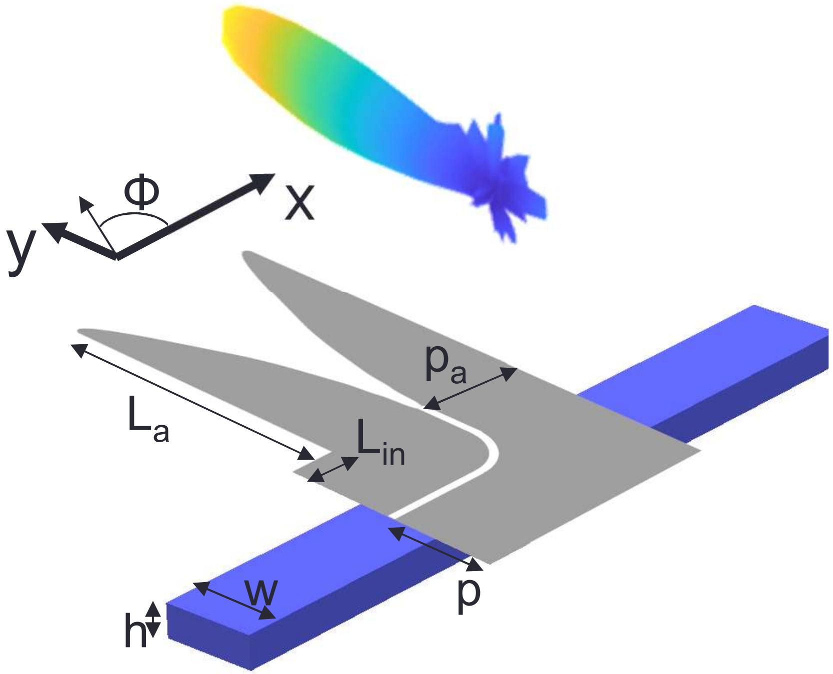


$s=60$ nm, $g=80$ nm, $h=220$ nm

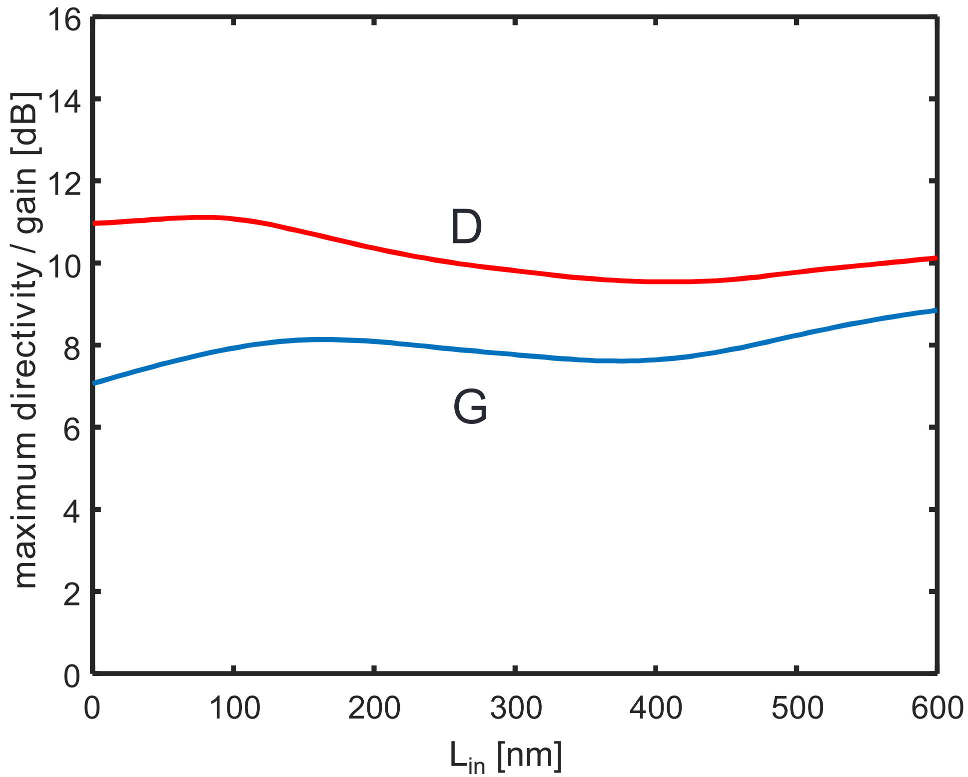
Cross section designed through the CMT

Design of the tilted Vivaldi antenna

- Design requirements for the single antenna: partial power transfer from the Si to the plasmonic slot waveguide, as well as good antenna directivity



Length of the input straight region L_{in}
(antenna length L_a=1500 nm, arbitrarily chosen)

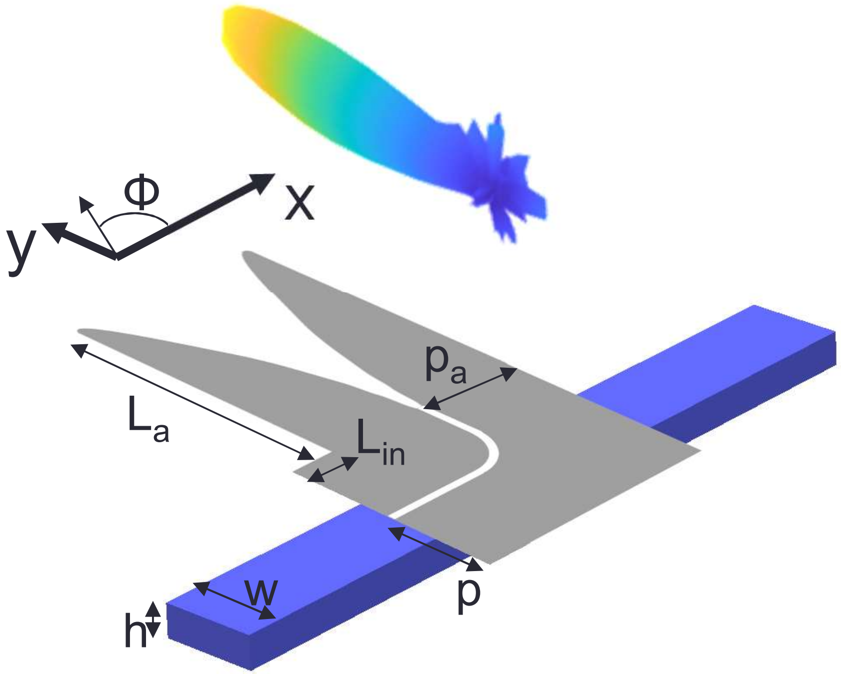


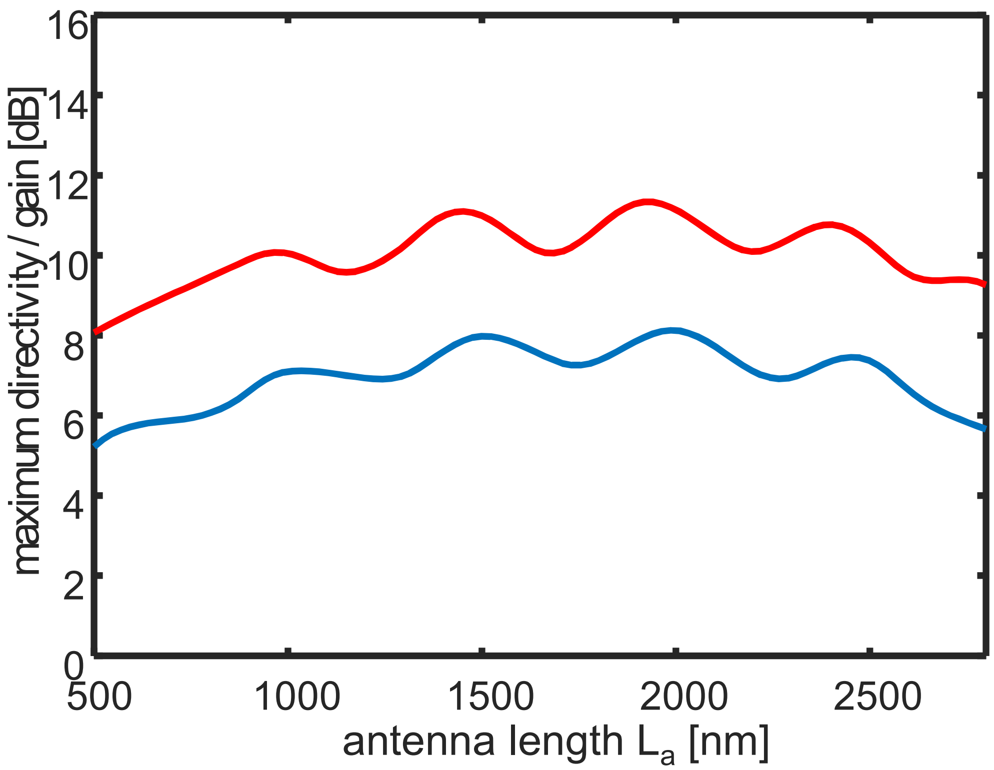
L_{in}=100 nm, maximum directivity D=11.1 dB and enough power left in the Si waveguide to feed the following antennas

Design of the tilted Vivaldi antenna

- Design requirements for the single antenna: partial power transfer from the Si to the plasmonic slot waveguide, as well as good antenna directivity

Antenna length L_a

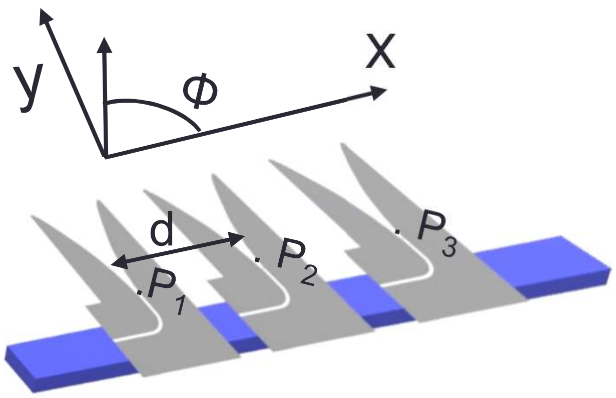


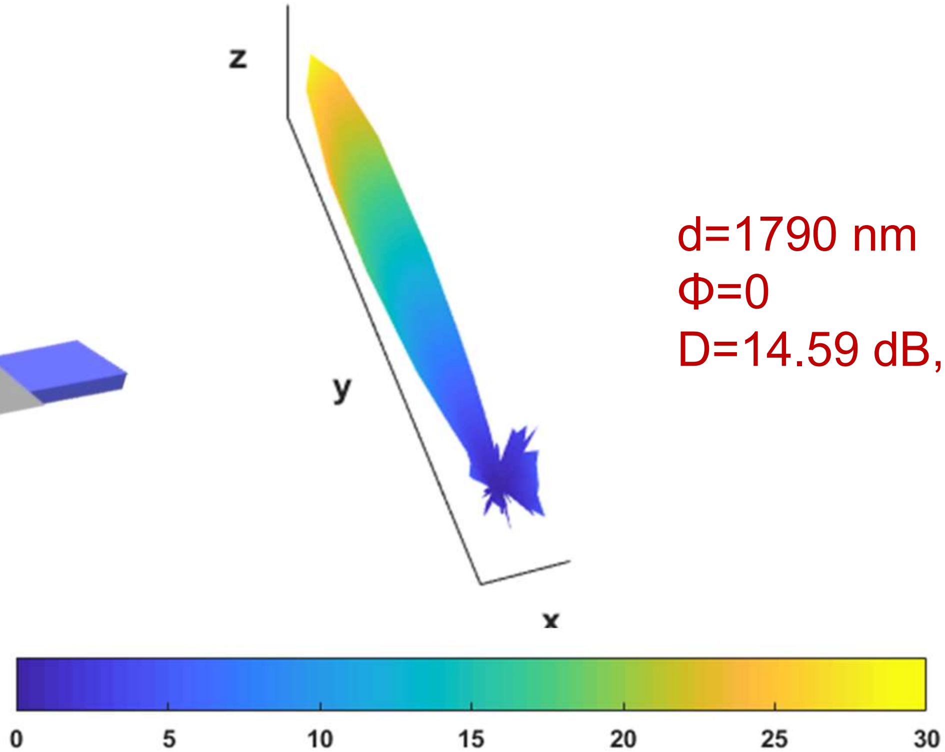


L_a=2000 nm, maximum directivity D=11.4 dB

Tilted Vivaldi antenna ARRAY (N=3)

- The variation of the distance between the antennas induces a phase shift between the antennas





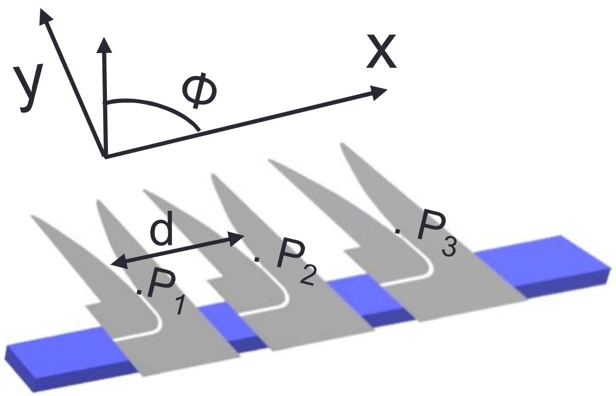
d=1790 nm
Φ=0
D=14.59 dB, G=13.47 dB

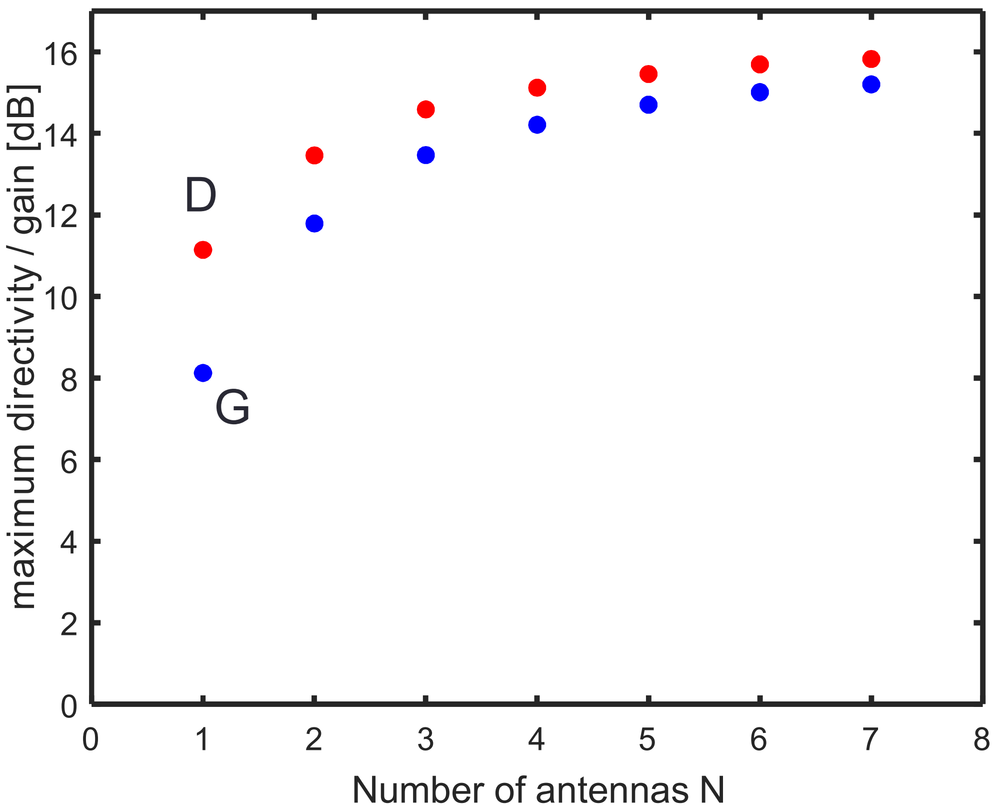
variation of the directivity and of the gain with d

variation of the tilt angle Φ of the beam with d

Tilted Vivaldi antenna ARRAY

- Gain and directivity increase with the number of antennas

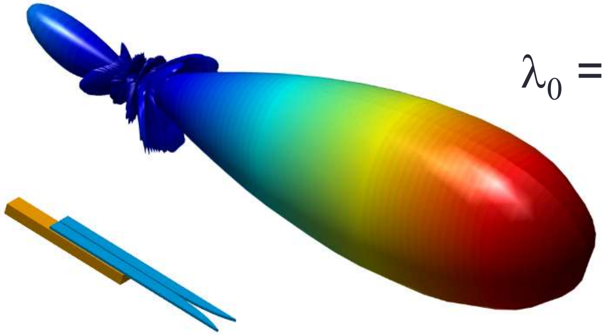




N=5, d=1790 nm, Φ=0
D=15.46 dB, G=14.70 dB

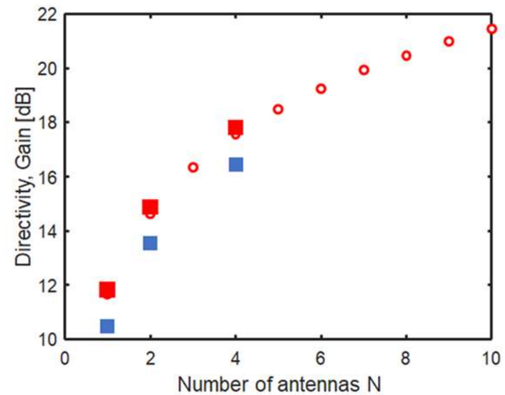
Conclusions

- On-Chip Optical Wireless Connections: High Gain antennas are needed to cope with free space attenuation

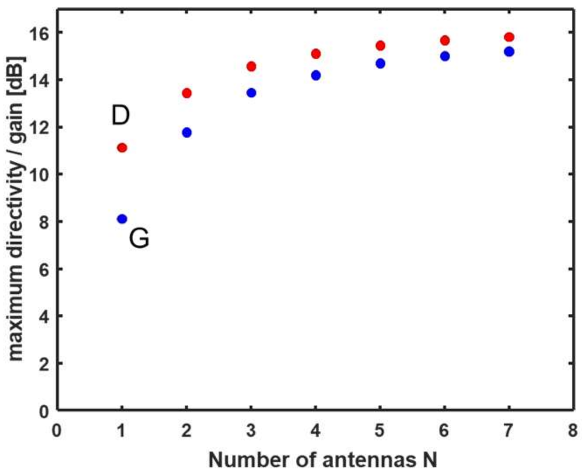


λ_0 = 1.55 μm

- Vivaldi Antenna:
  Coupling with SOI waveguides
  9.9 dB Gain – Full C Band coverage



❖ Broad-side antenna arrays:
High directivity (N=5, D=18 dB)
large footprint (tens of μm)



❖ Travelling wave antenna arrays:
lower directivity (N=5, D=15 dB)
small footprint (3.5 μm x 8.7 μm)