Università degli Studi di Ferrara

Department of Engineering Ferrara

INTEGRATED OPTICS & PHOTONICS LABORATORY UNIVERSITY OF FERRARA

ON-CHIP WIRELESS OPTICAL INTERCONNECTS: RESULTS AND PERSPECTIVES

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Giovanni Serafino, Stefano Soresi, Scuola Sant'Anna, Pisa, Italy

Politecnico di Bari

Sant'Anna Scuola Universitaria Superiore Pisa

Aim of the Presentation

To show the results obtained in the last years
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Presentation Outline

- Introduction
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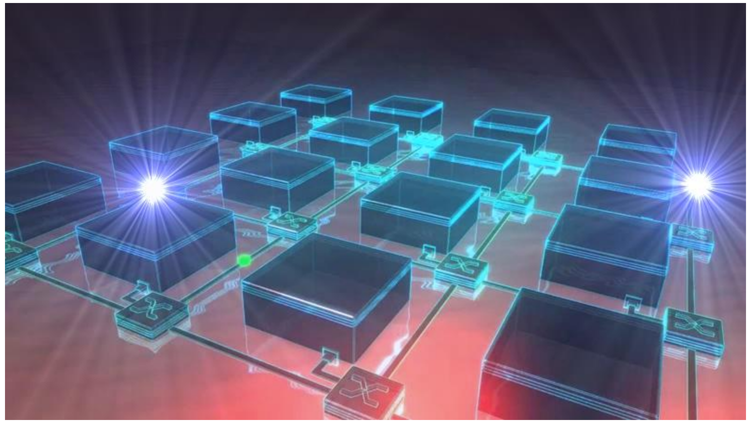

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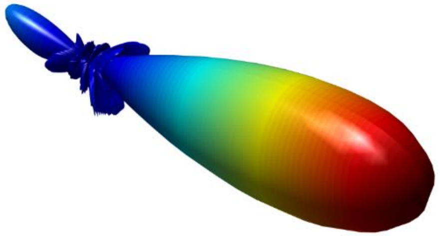

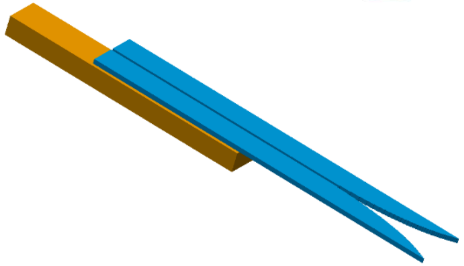

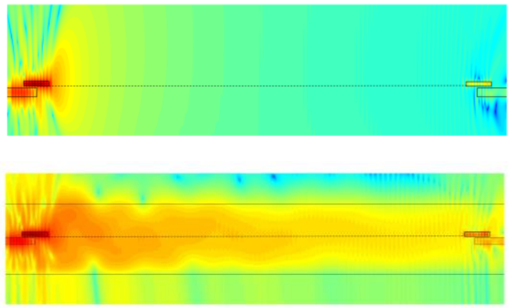

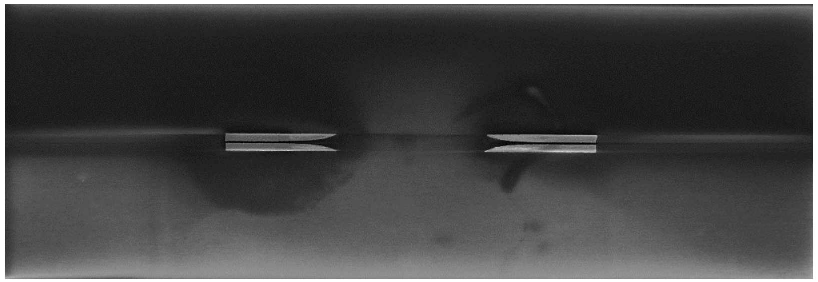

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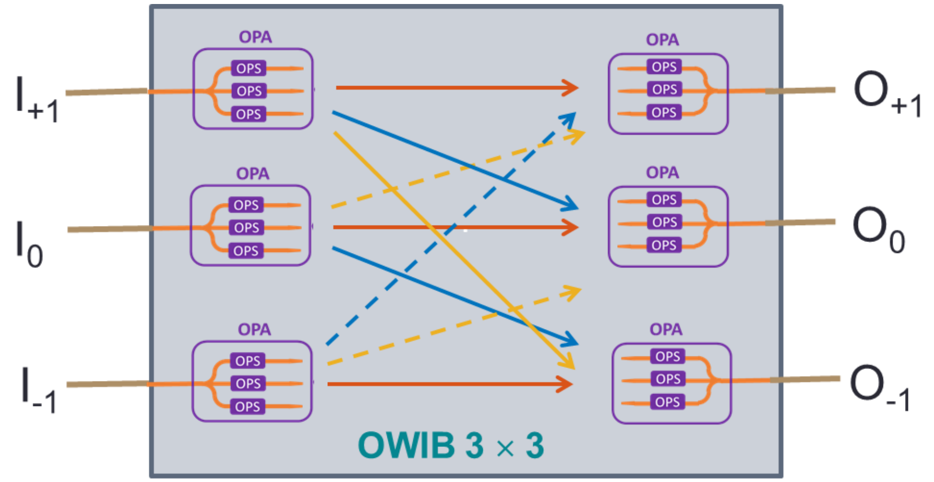

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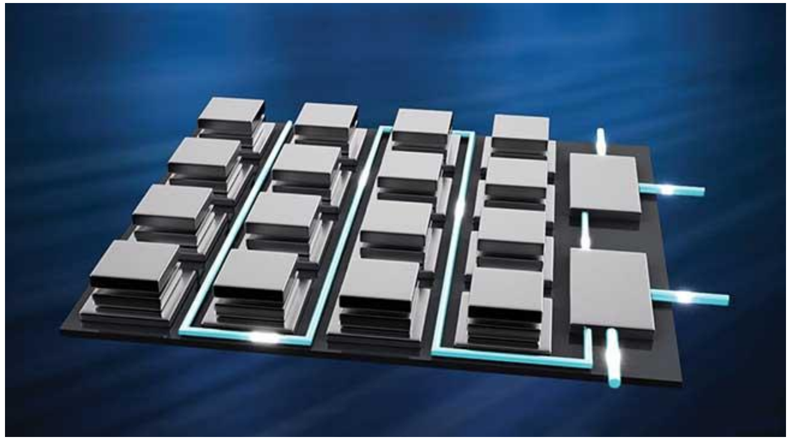

https://www.photonics.com/a61635/

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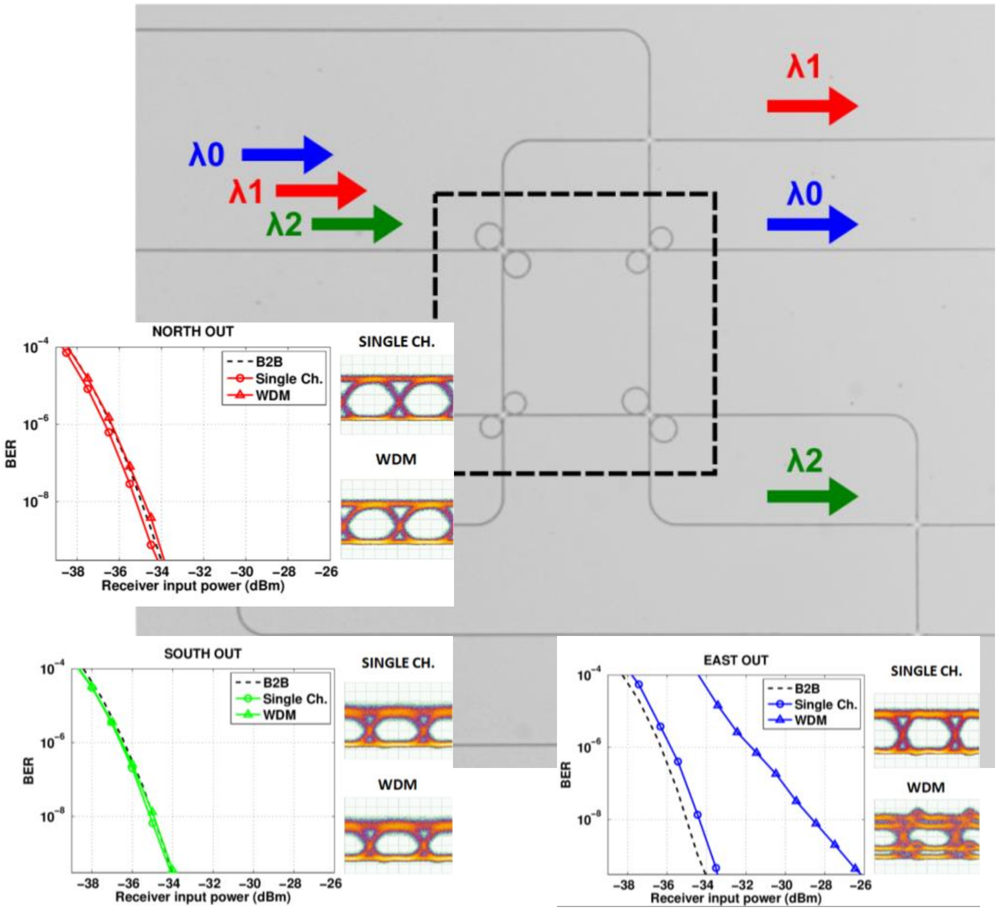

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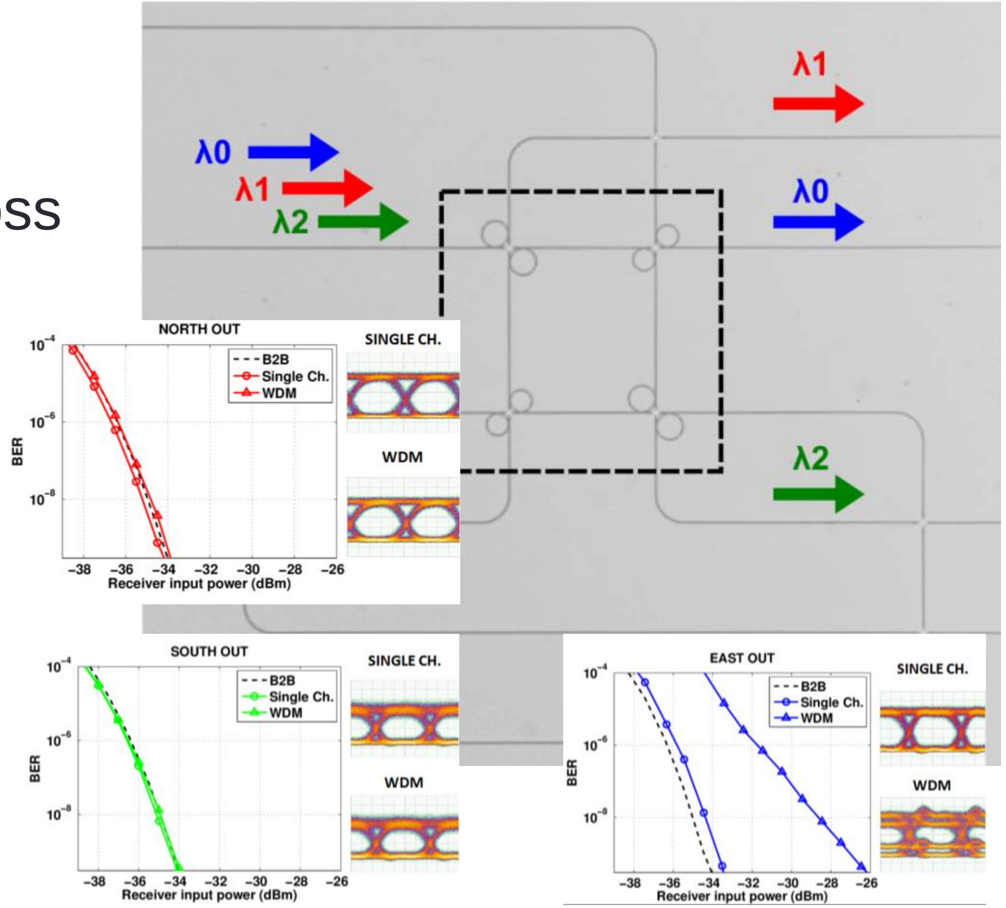

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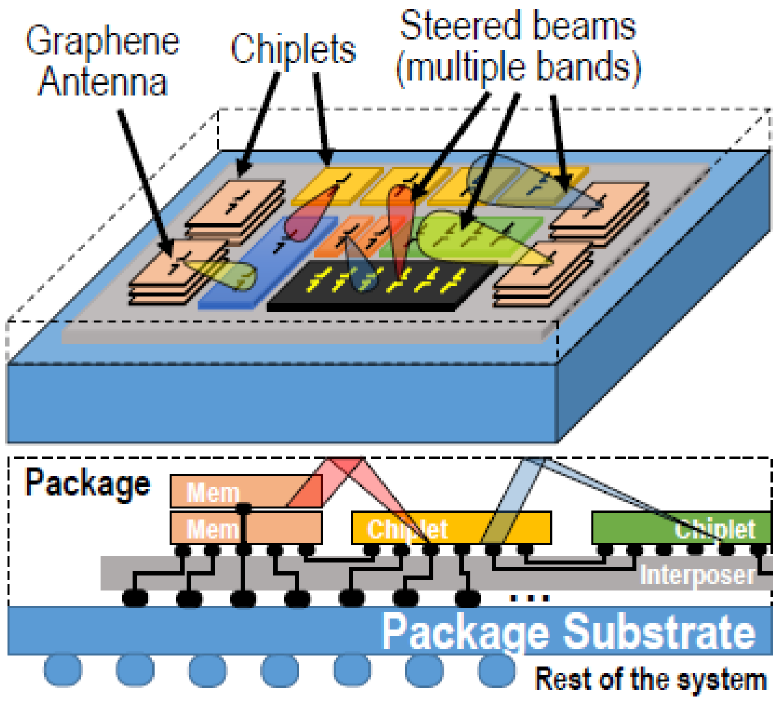

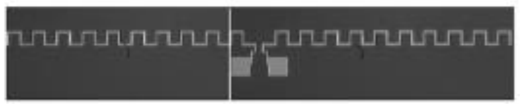

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S. Abadal et Al. “Graphene-based Wireless Agile Interconnects for Massive Heterogeneous Multi-chip Processors”, https://arxiv.org/abs/2011.04107v1

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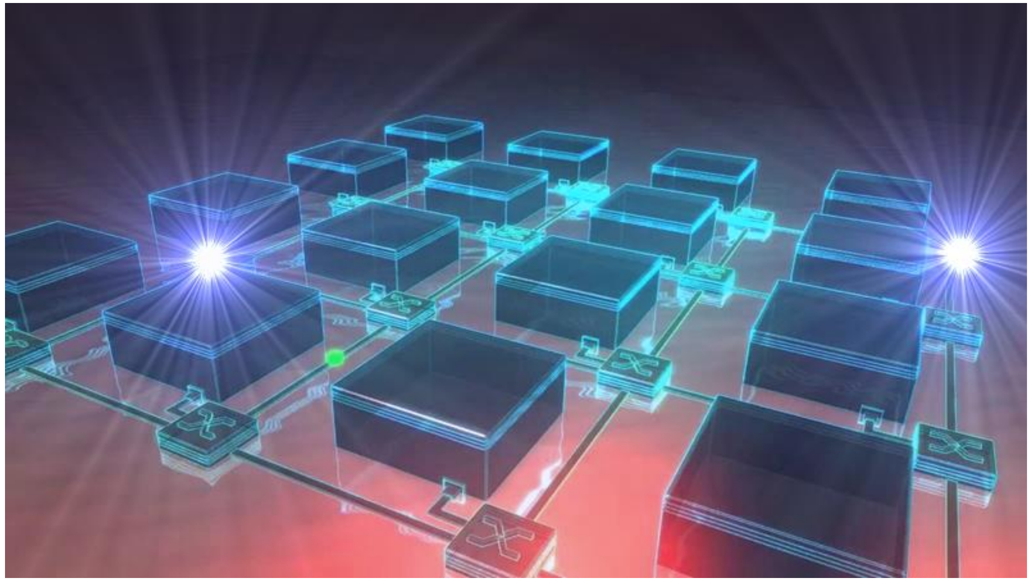

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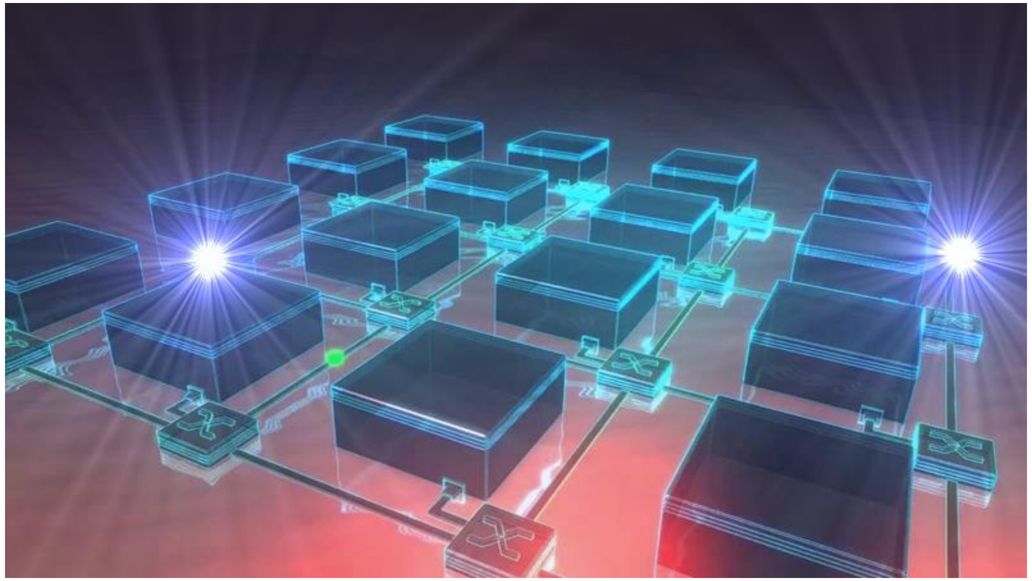

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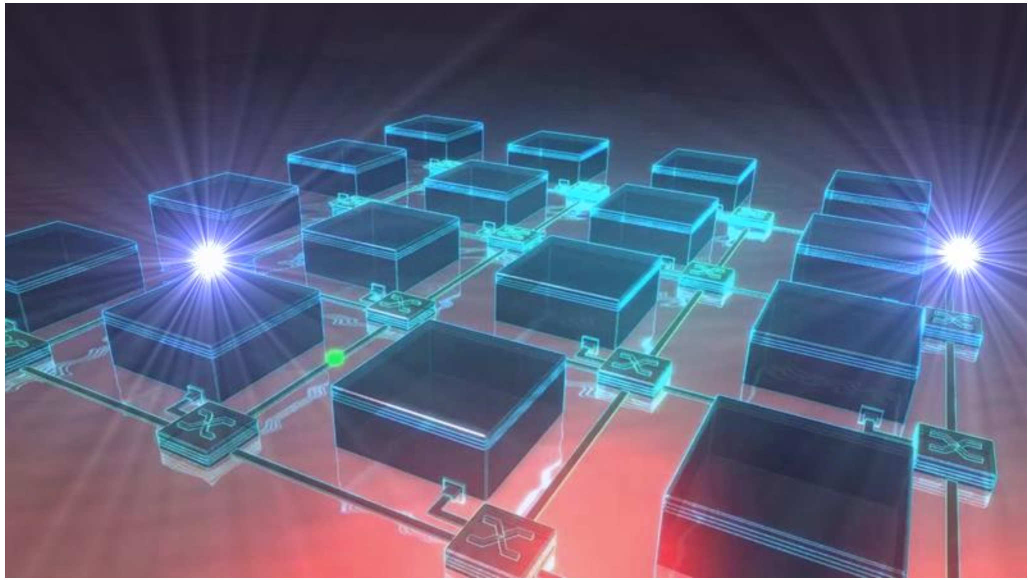

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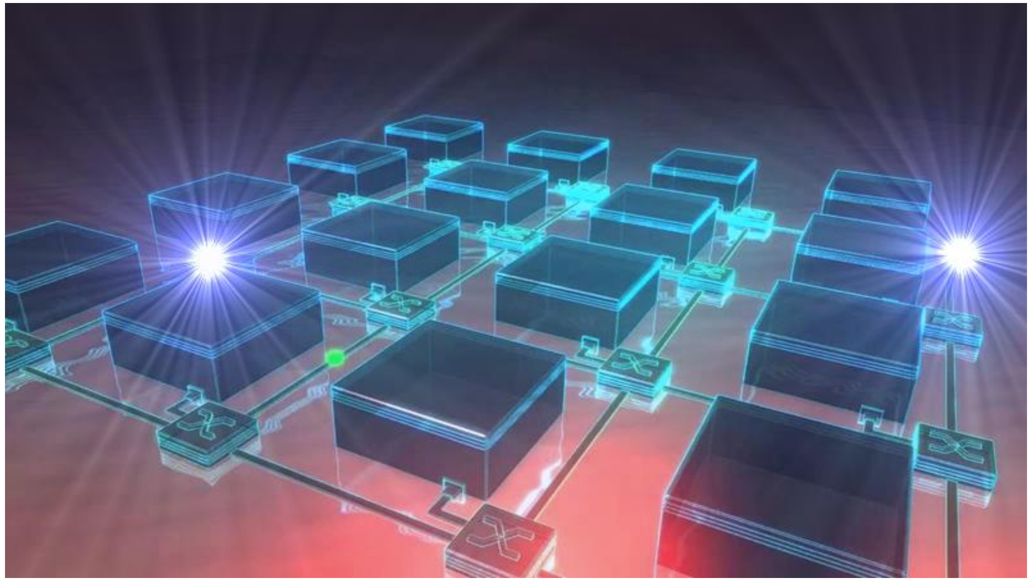

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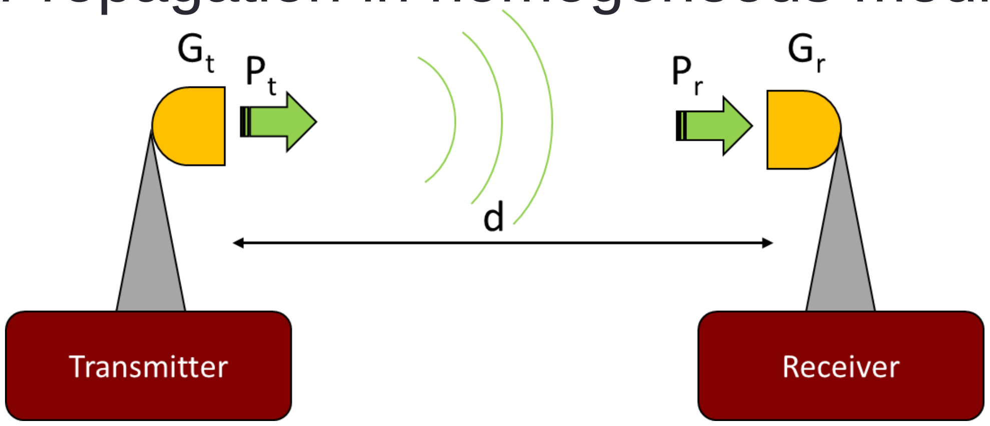

$$P_r = P_t + G_r + G_t + 20\log_{10}\left(\frac{\lambda_0 / n}{4\pi d}\right)$$

P_r: received power (dBm)
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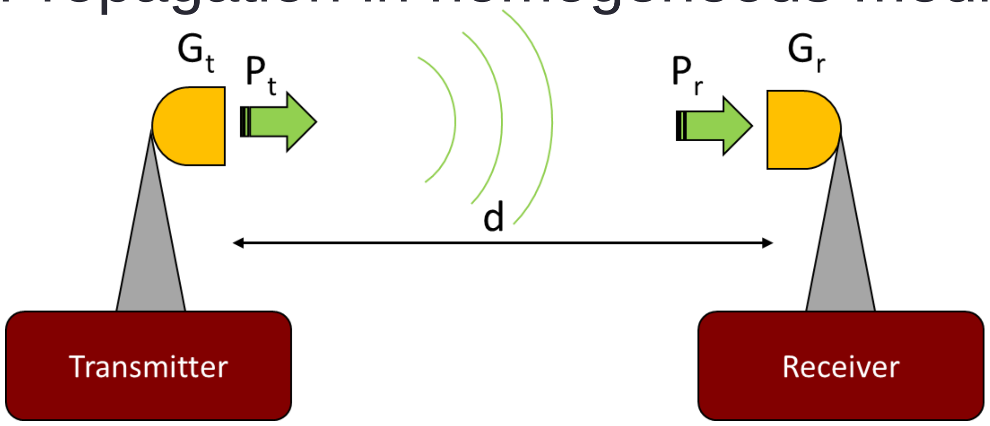

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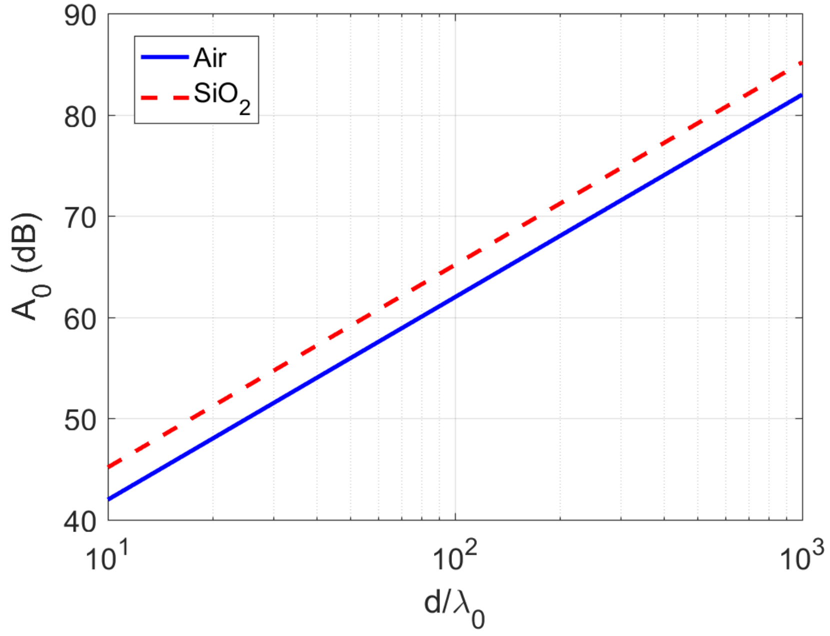
λ_0 = 1.55 μm	d = 50 μm	d = 100 μm	d = 1 mm
A_0 – Air (dB)	52.16	58.18	78.18
A_0 - SiO_2 (dB)	55.35	61.37	81.37



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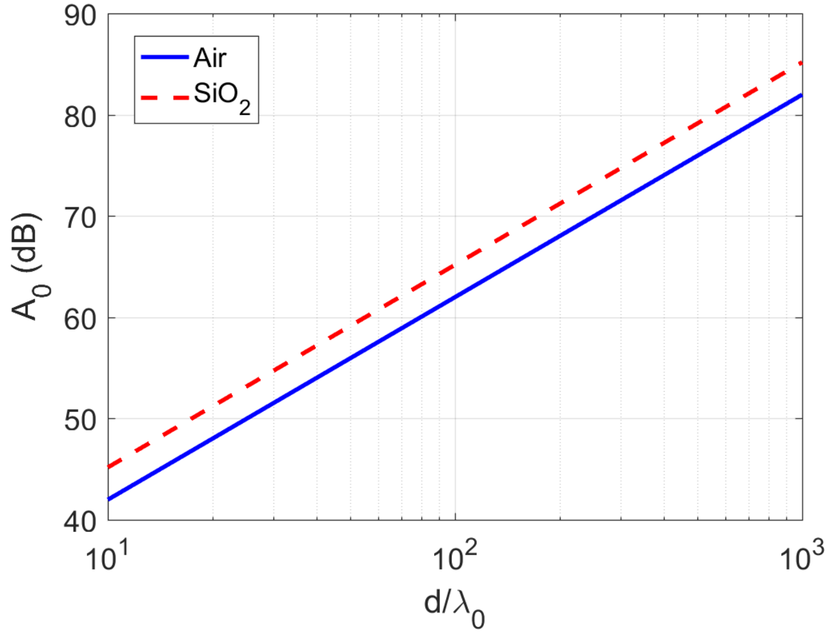

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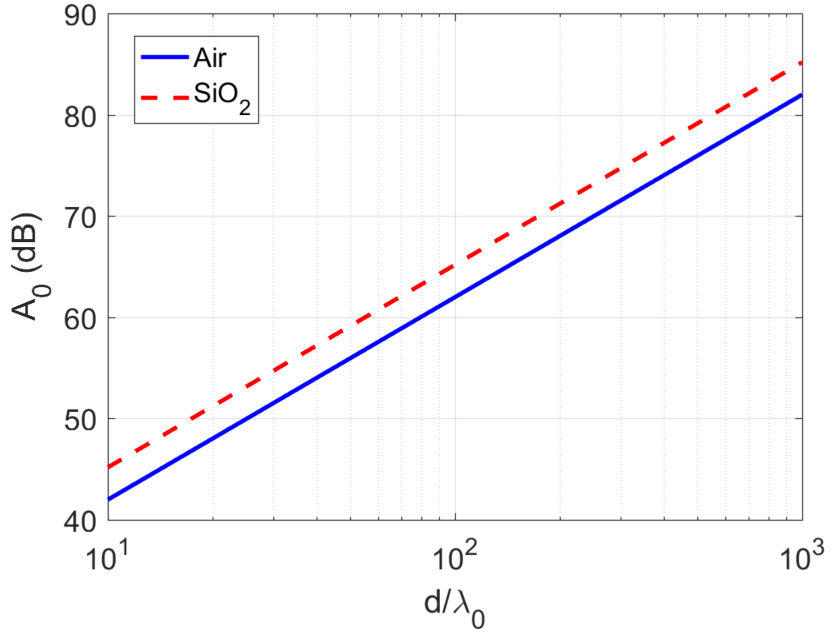

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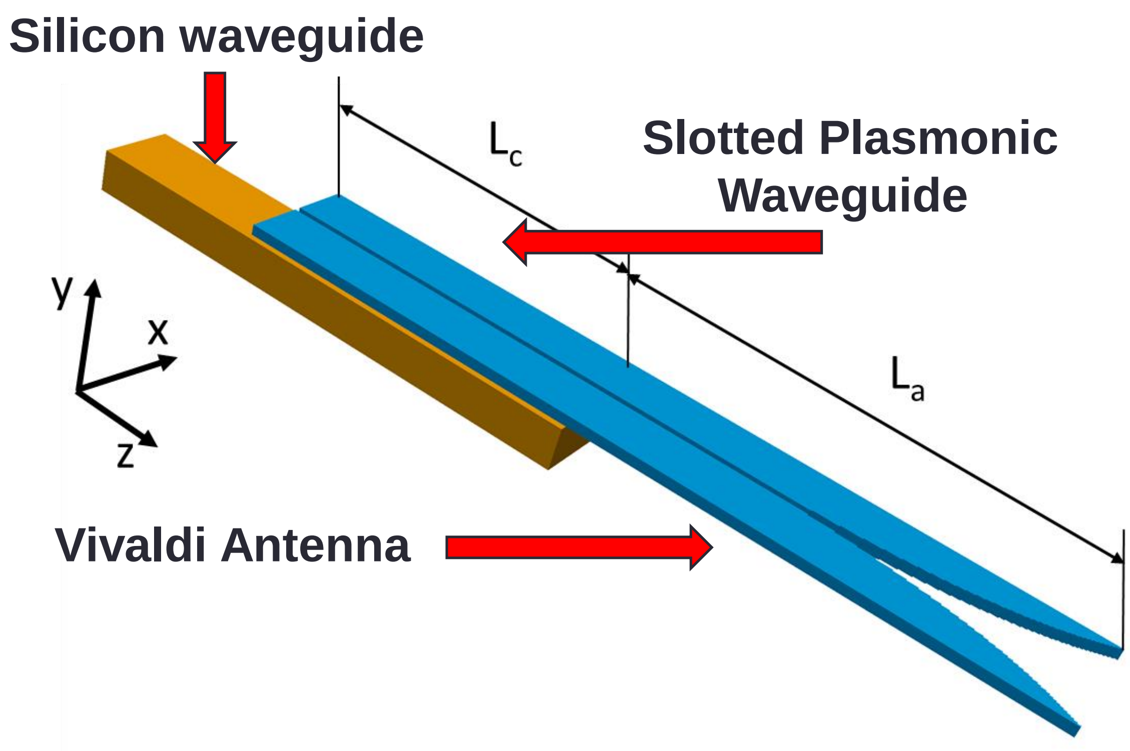
⇨ OWiNoC applications need antennas with high gain

Plasmonic Vivaldi Antenna

- Plasmonic Antenna excited through a Silicon waveguide



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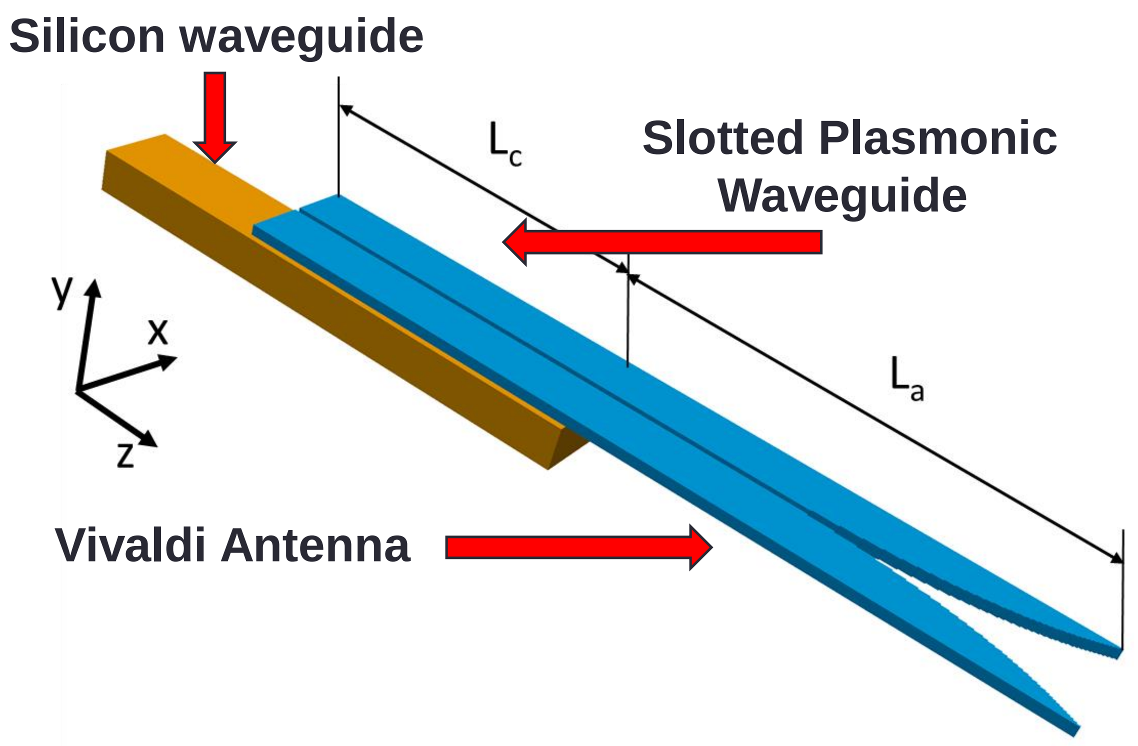
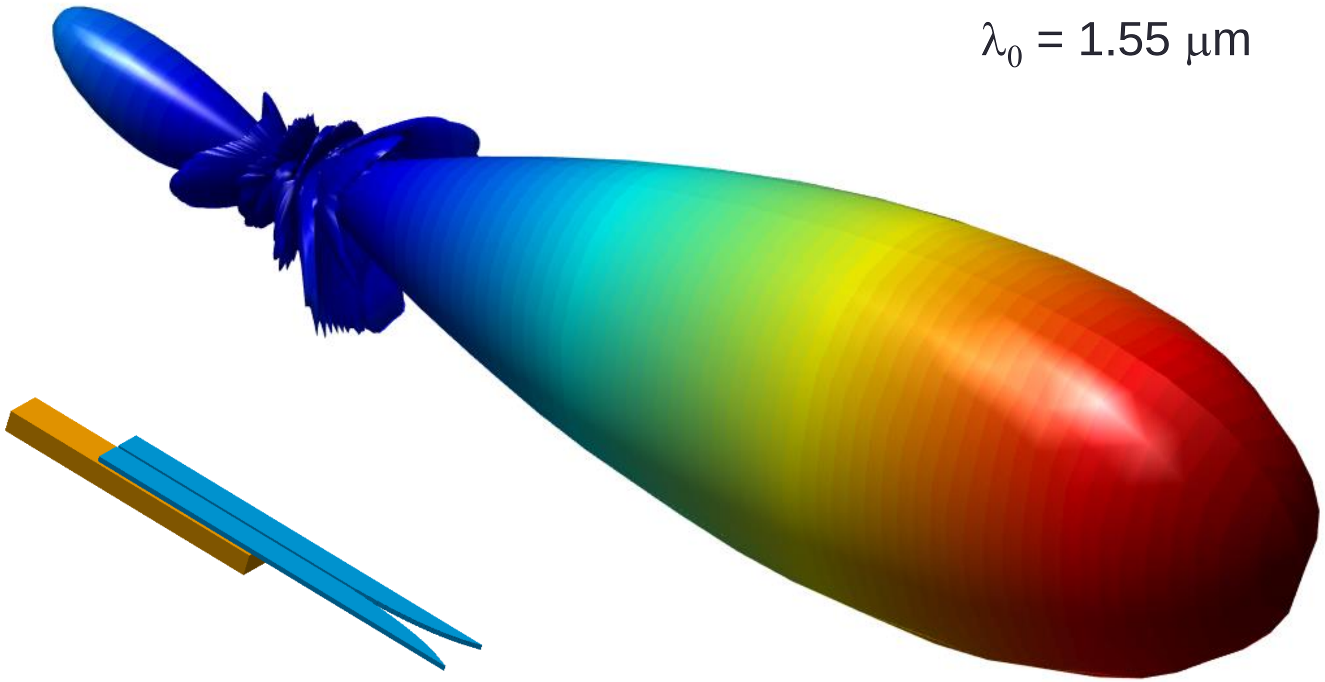


Plasmonic Vivaldi Antenna

- Plasmonic Antenna excited through a Silicon waveguide
- Compatible with CMOS Technology
- On-Plane Radiation + Wide Band Communication

λ_0 = 1.55 μm



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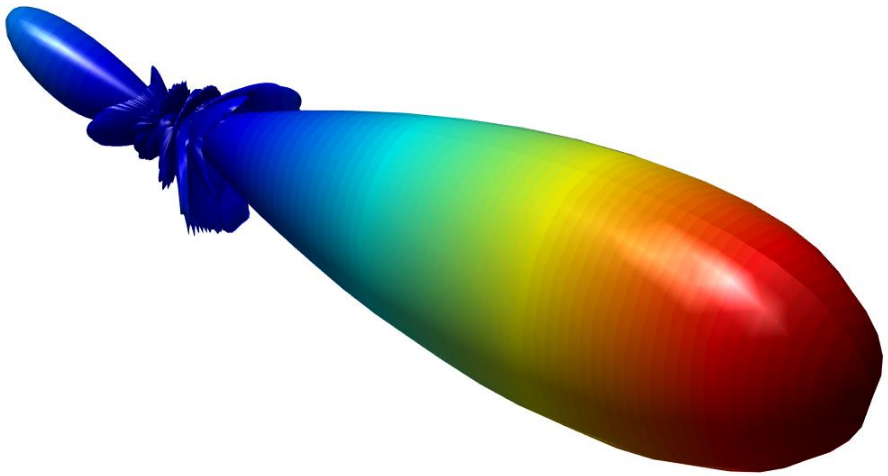

- Antenna performance evaluated by FDTD (Lumerical®) through Near Field to Far Field Transformation

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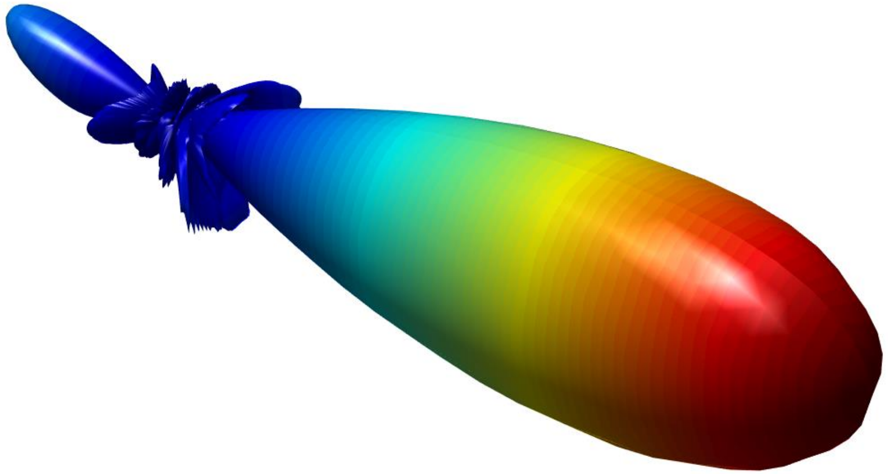

$$D = \frac{P(\vartheta_M, \varphi_M)}{P_{Tot}/4\pi}$$

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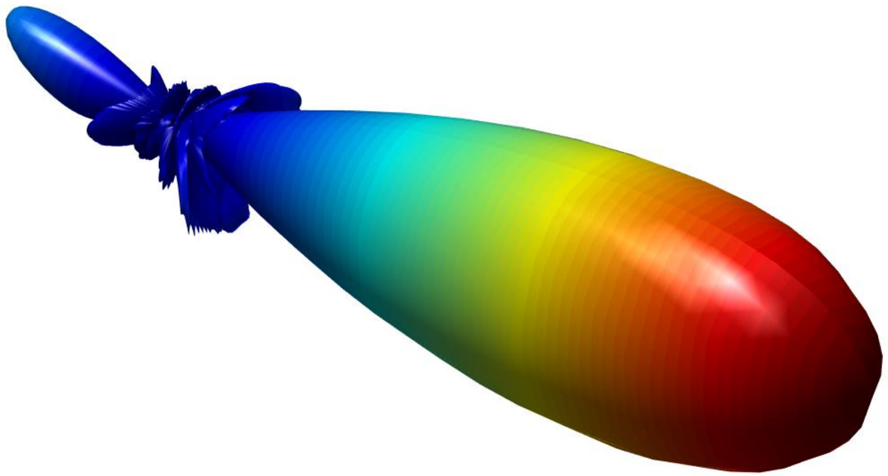

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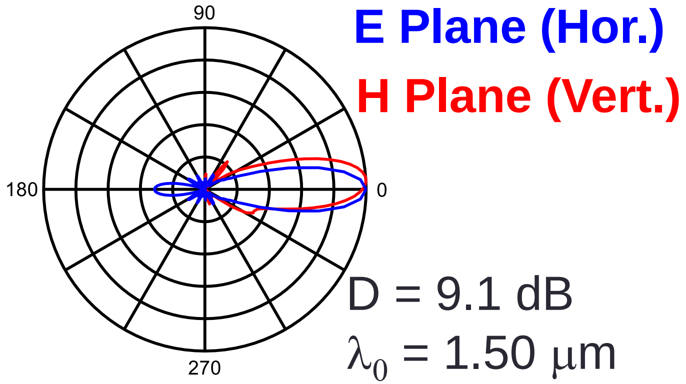
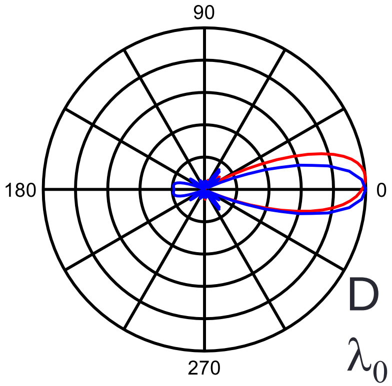
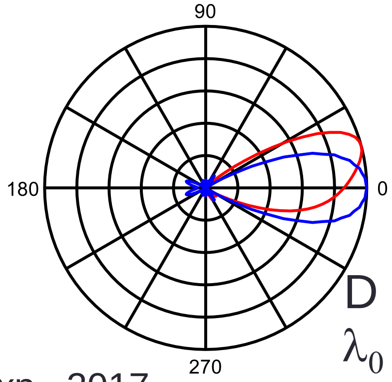


D = 9.1 dB
λ_0 = 1.50 μm



D = 11.1 dB
λ_0 = 1.55 μm



D = 9.6 dB
λ_0 = 1.60 μm

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G. Bellanca et al., "Integrated Vivaldi plasmonic antenna for wireless on-chip optical communications", Opt. Exp., 2017

Plasmonic Vivaldi Antenna

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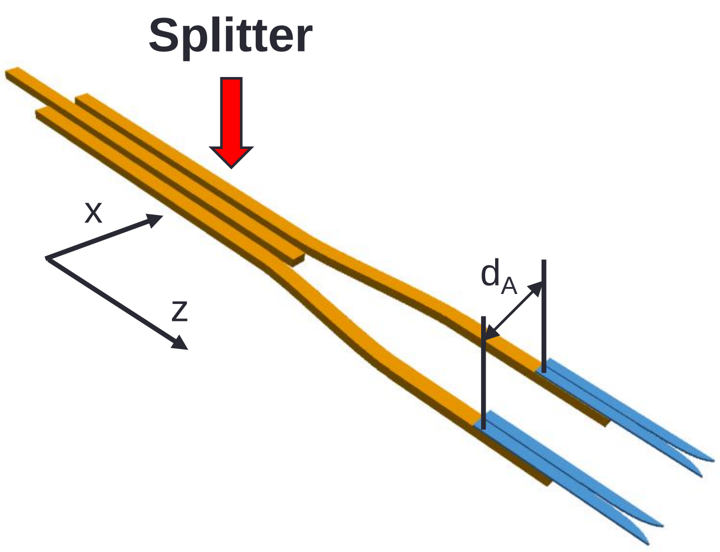
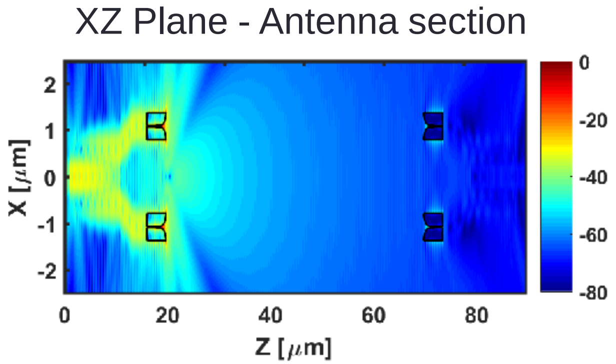
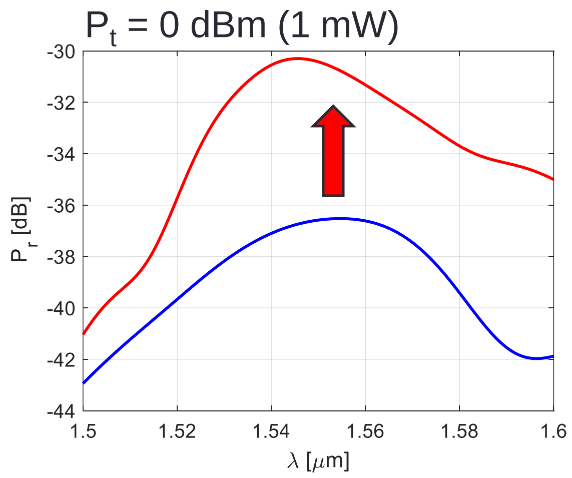
- Compatible with CMOS Technology
- On-Plane Radiation + Wide Band Communication
- Antenna array allows increasing antenna gain







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On-Chip Optical Propagation

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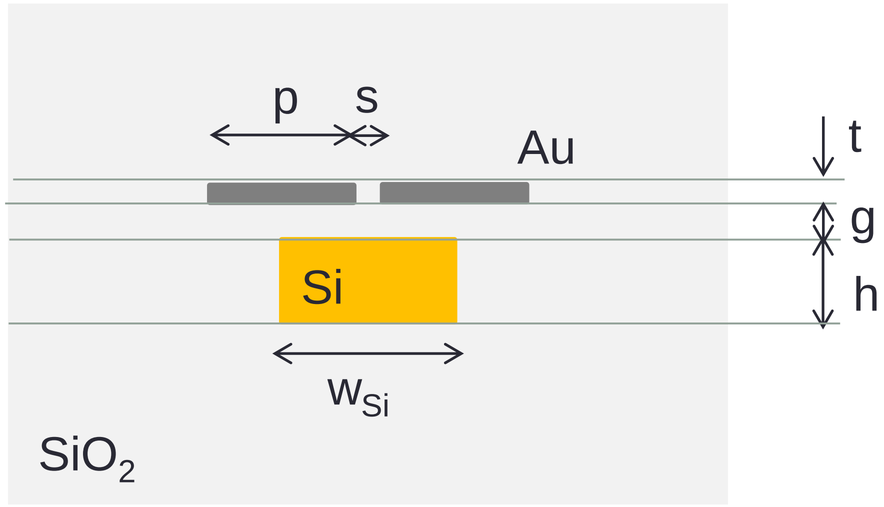

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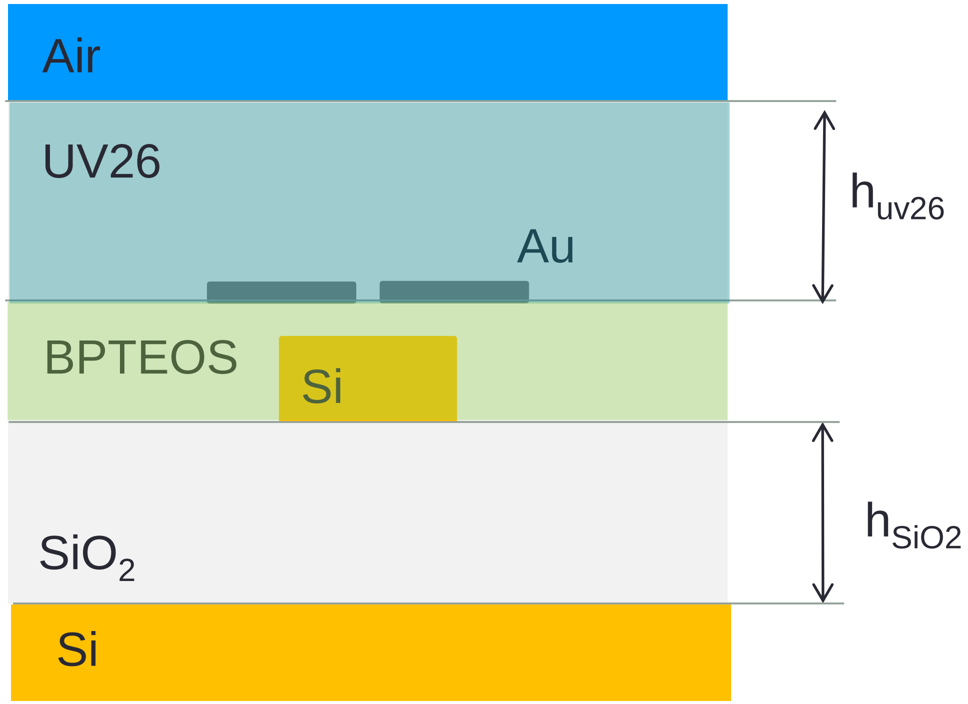
- … but also a realistic scenario must be considered (Multilayer Stack)



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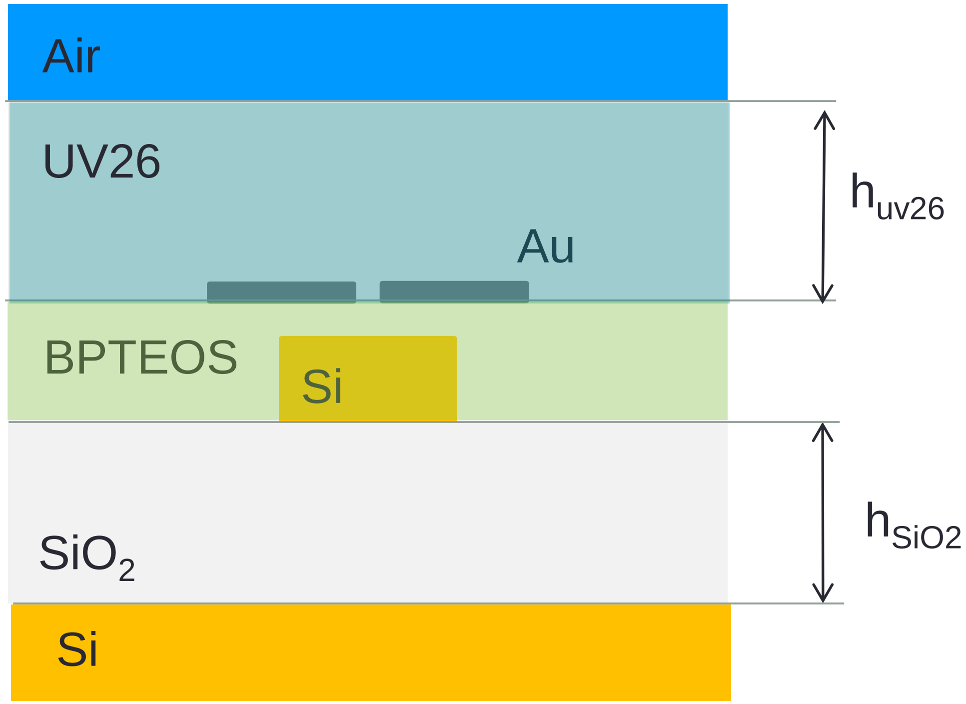

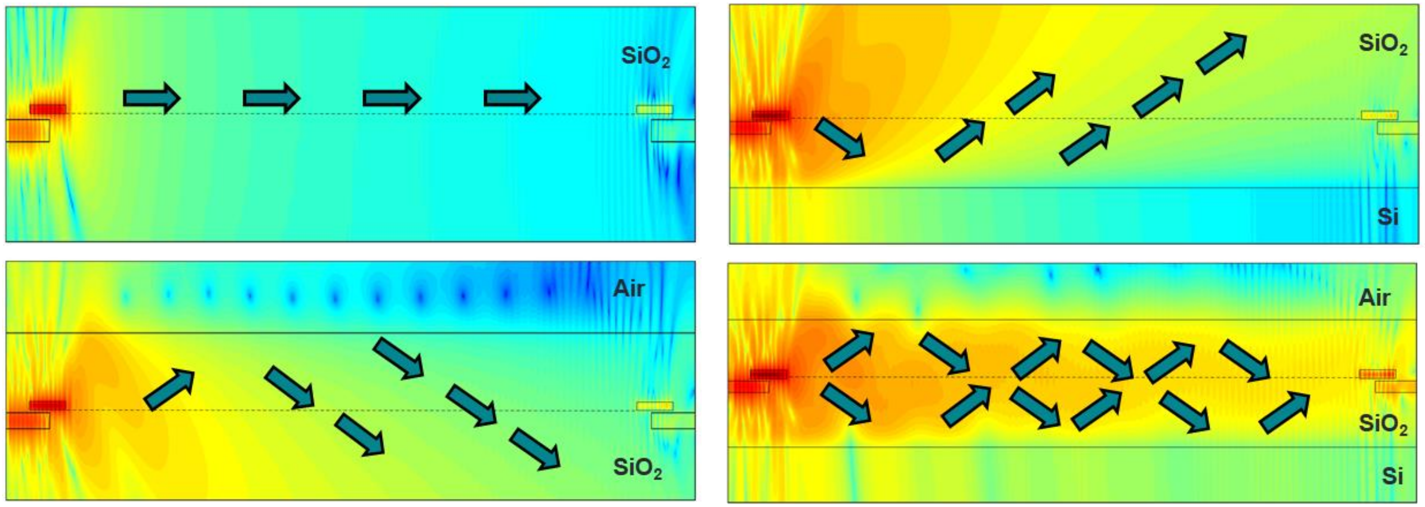

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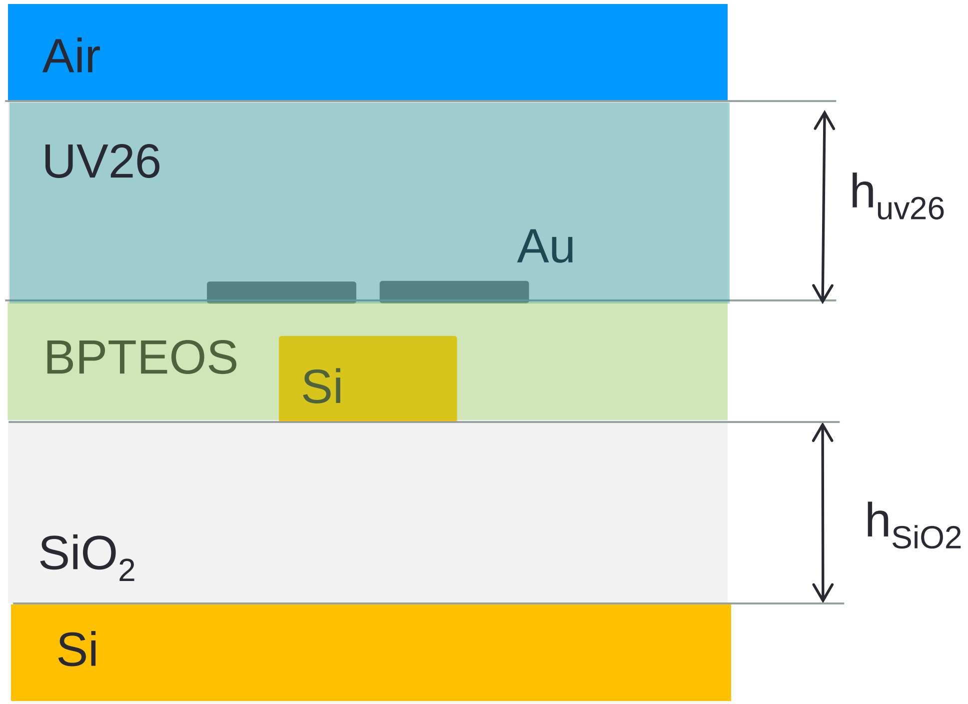

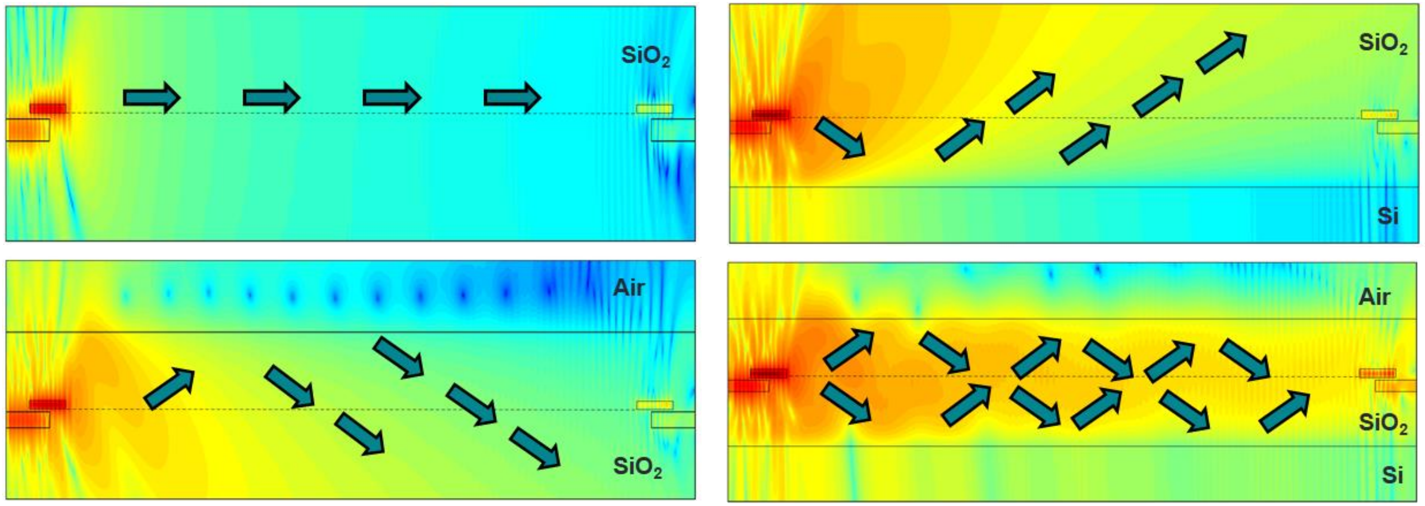

FDTD Simulation – λ_0 = 1.55 μm

Medium	P_r (dBm)
Homogeneous	- 36.50
Air on top	- 42.48
Si on bottom	- 48.21
Both interfaces	- 28.06

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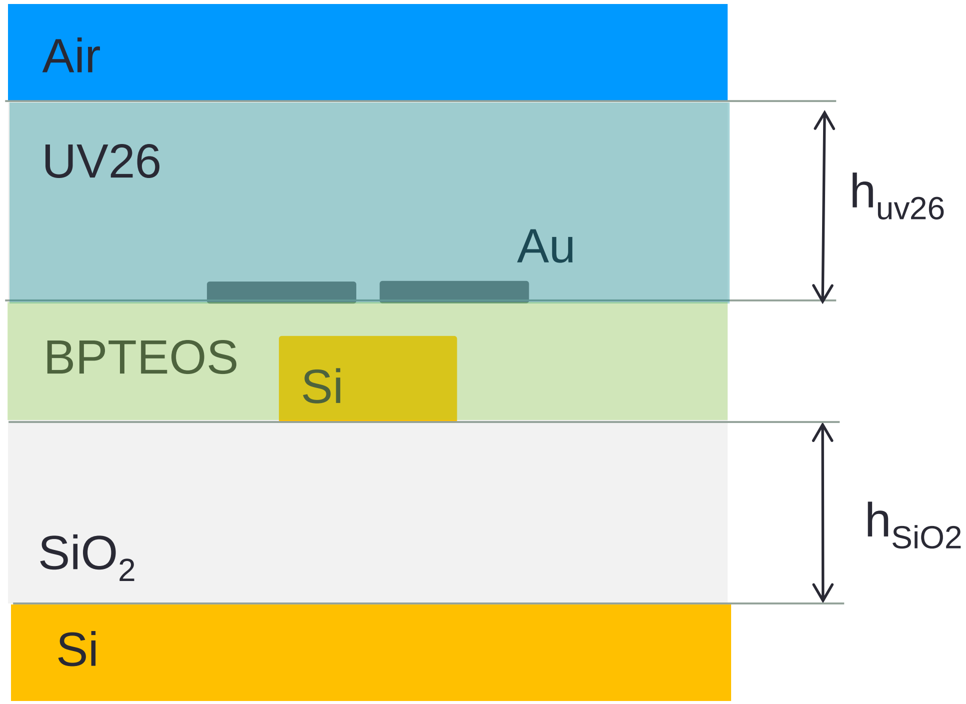

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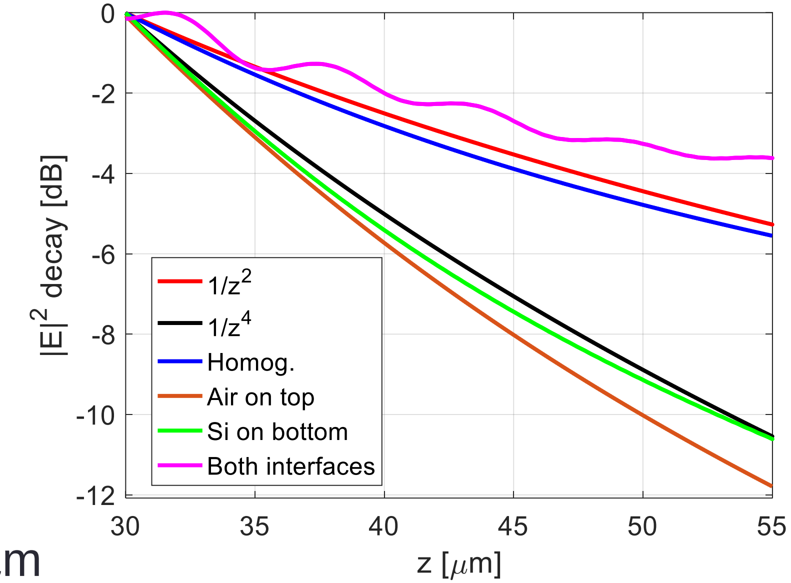

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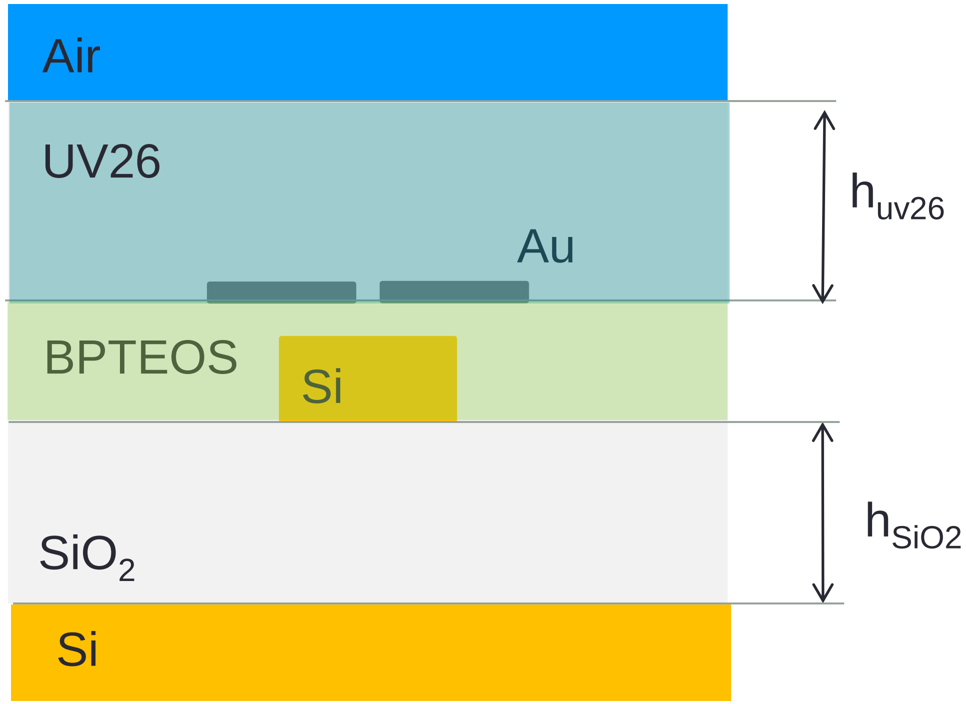

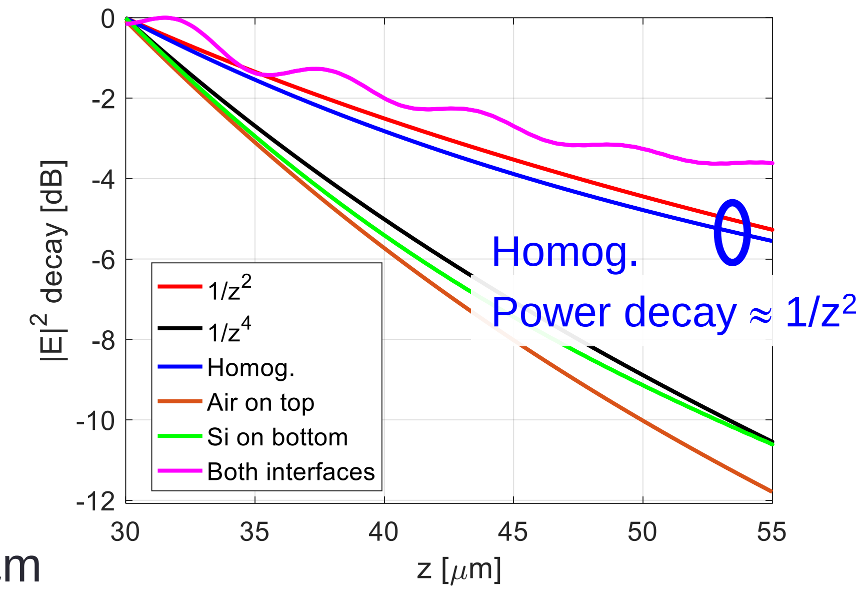

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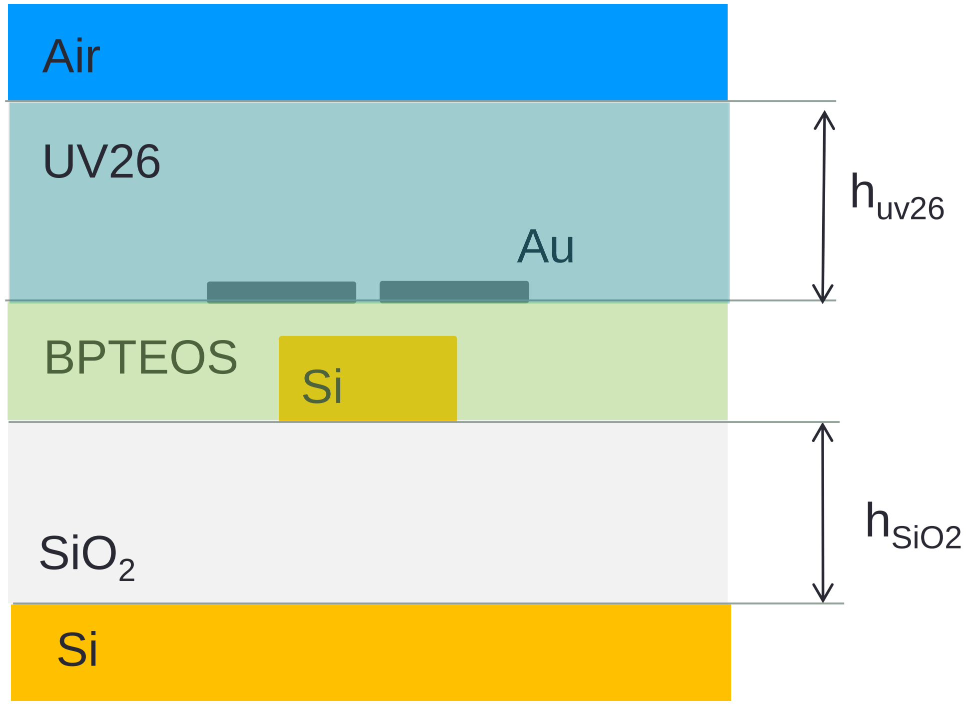

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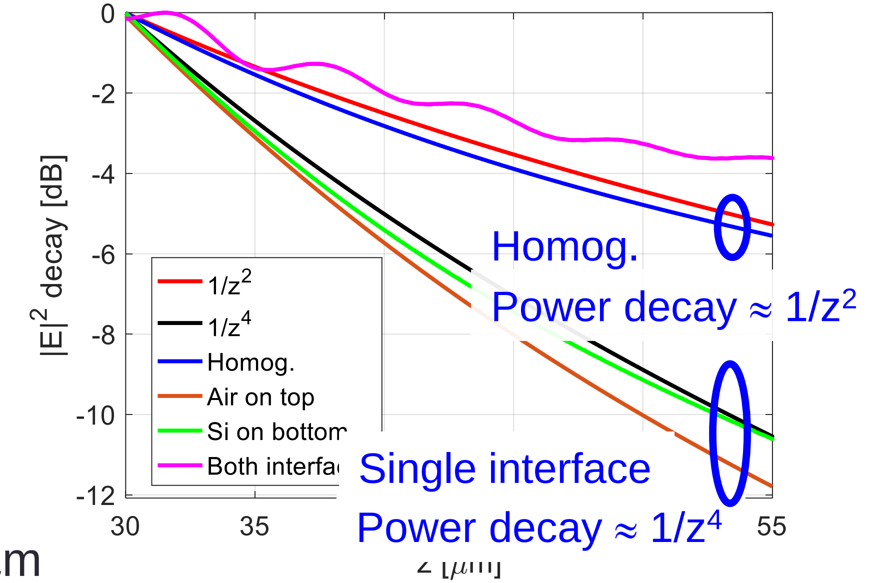
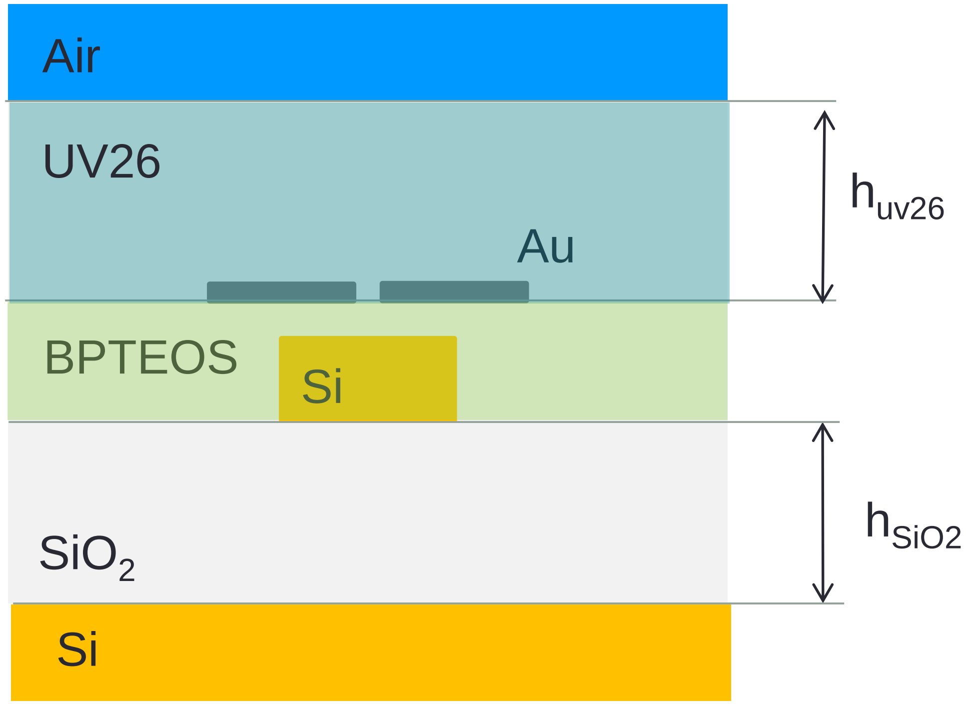


RX antenna removed from the scenario

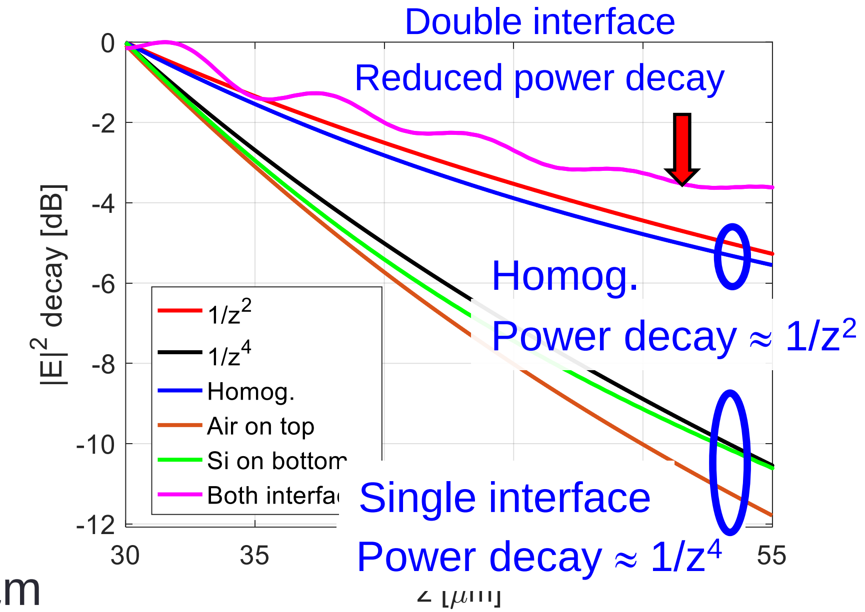
d_{link} = 50 μm
$G_r = G_t \approx 10$ dB
P_t = 0 dBm

- Antenna's geometry needs optimization …
- … but also a realistic scenario must be considered (Multilayer Stack)



FDTD Simulation – λ_0 = 1.55 μm

Medium	P_r (dBm)
Homogeneous	- 36.50
Air on top	- 42.48
Si on bottom	- 48.21
Both interfaces	- 28.06



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On-Chip Optical Propagation

- Antenna's geometry needs optimization …
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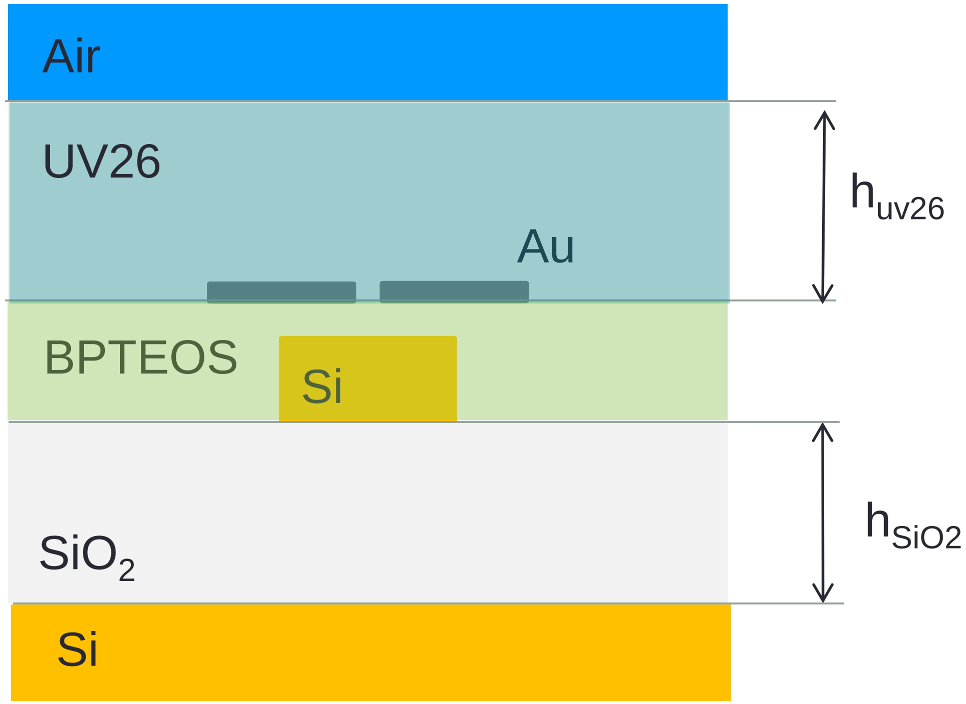
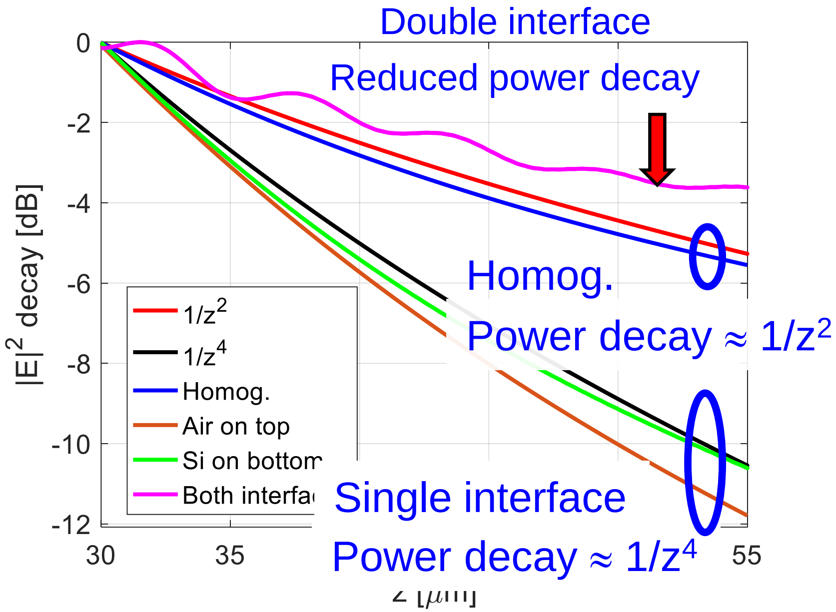


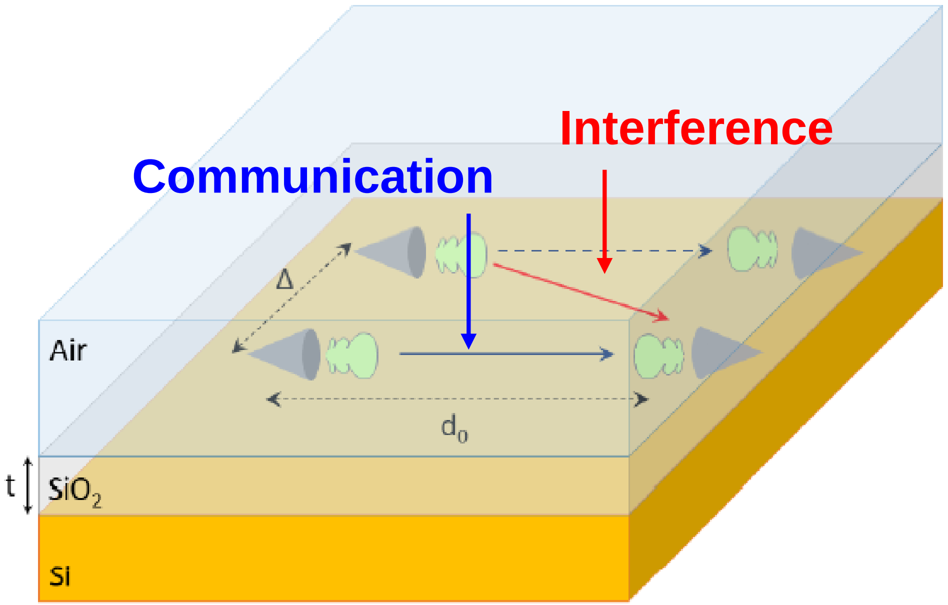


RX antenna removed from the scenario

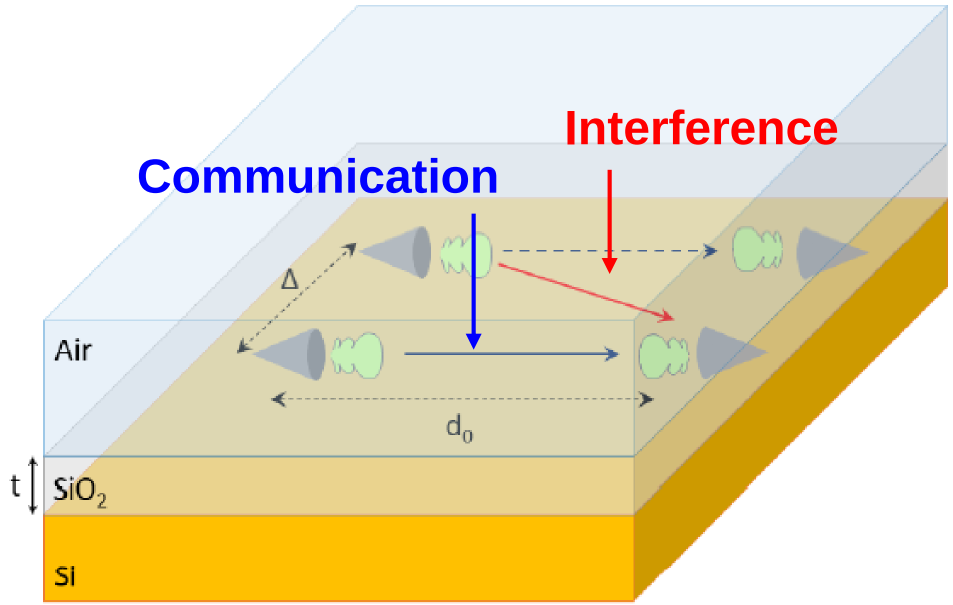
- Optimization of the different layer thicknesses plays a role

On-Chip Optical Propagation

- Influence of the thickness of the cladding layer on the System Performance



- Influence of the thickness of the cladding layer on the System Performance
  - Optical Wireless Channel (Multilayer) simulated through Ray Tracing (long links)



On-Chip Optical Propagation

- Influence of the thickness of the cladding layer on the System Performance
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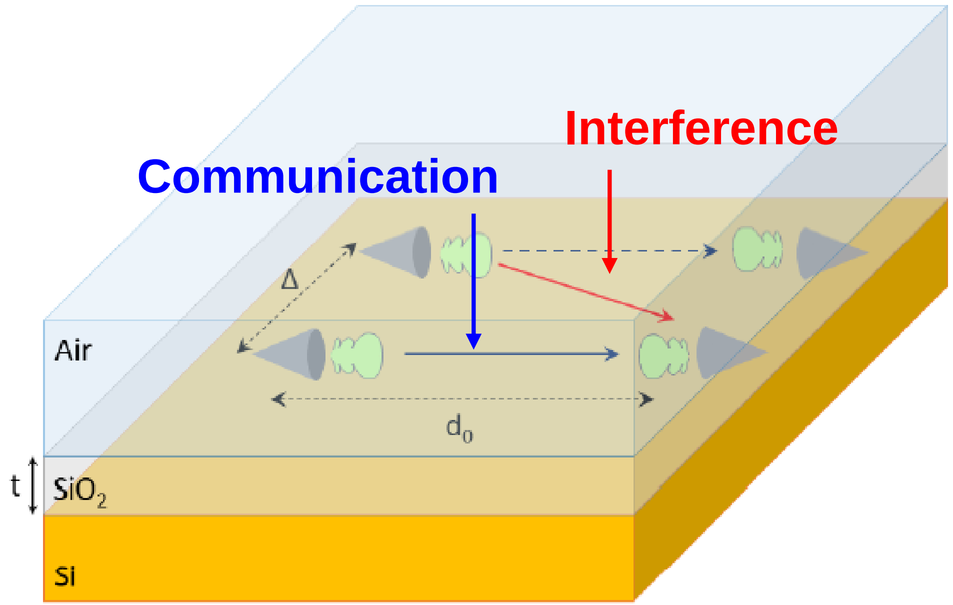
  - System performance evaluation through Bit Error Probability (BEP)



Noise (Gaussian)
Interference power
} BEP evaluation

Fuschini et al., "Ray Tracing Modeling of Electromagnetic Propagation for On-Chip Wireless Optical Communications", J. Low Power Electron. App., 2018

On-Chip Optical Propagation

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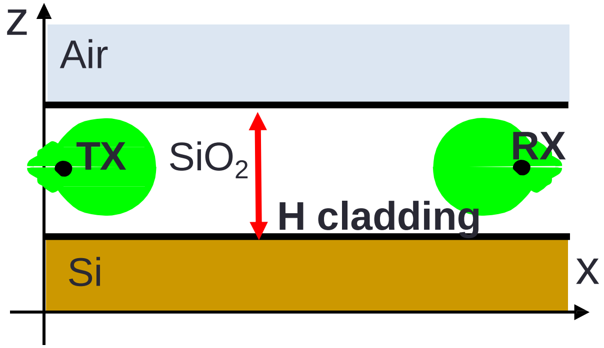
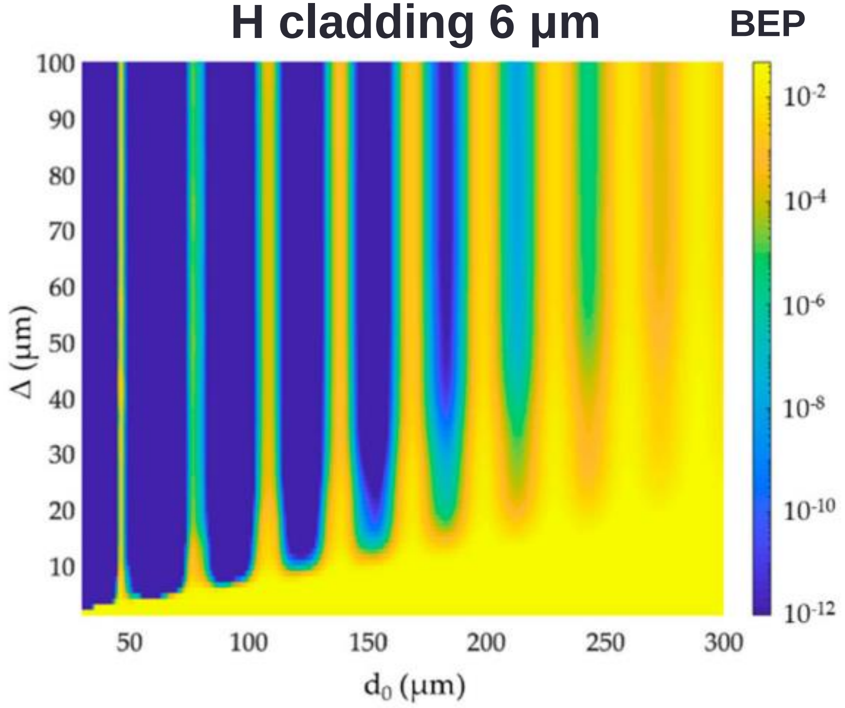
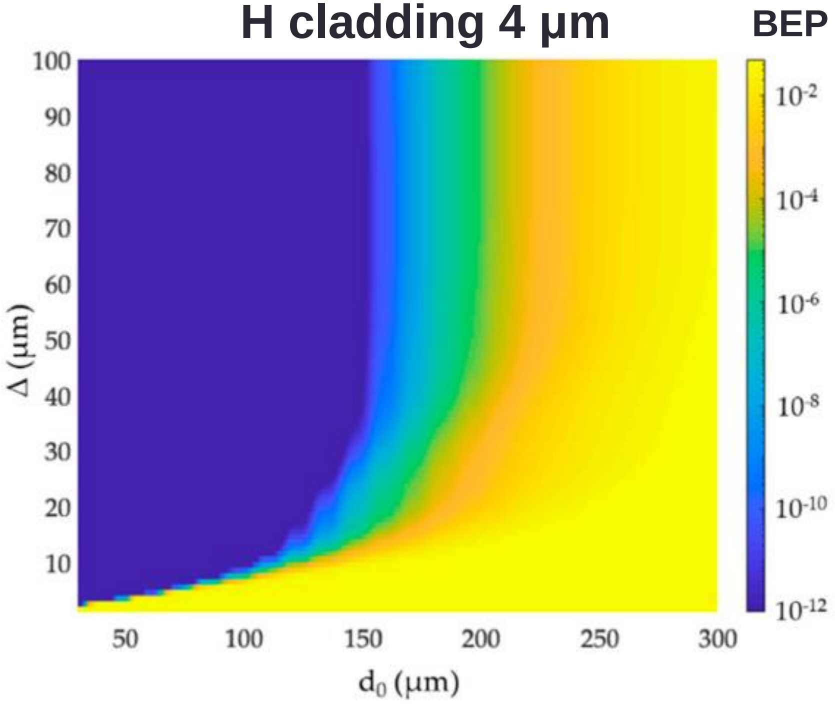


H cladding 6 µm



H cladding 4 µm



On-Chip Optical Propagation

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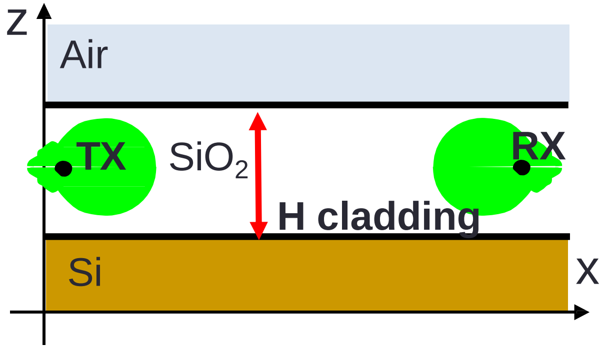
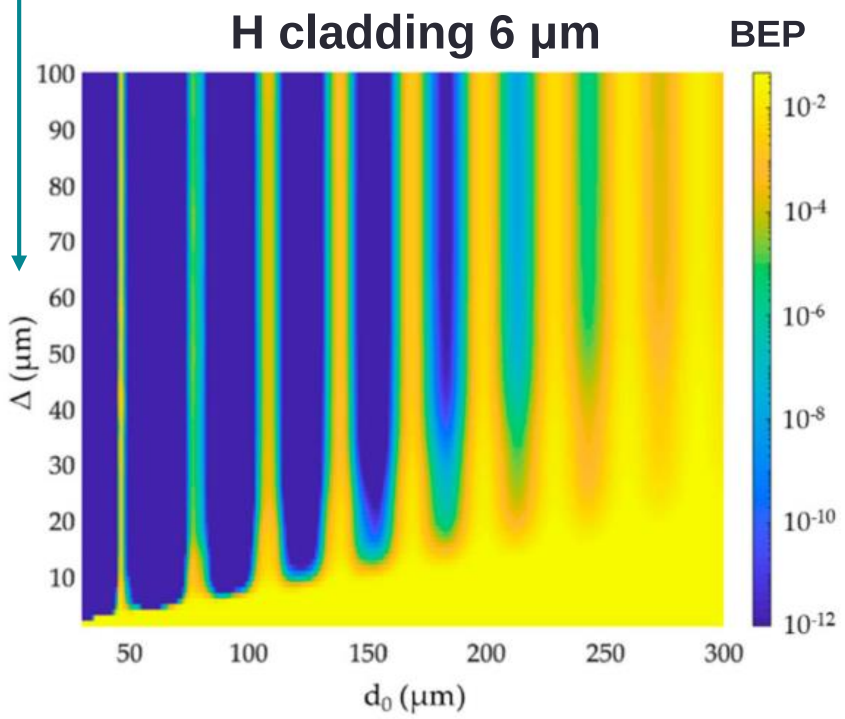
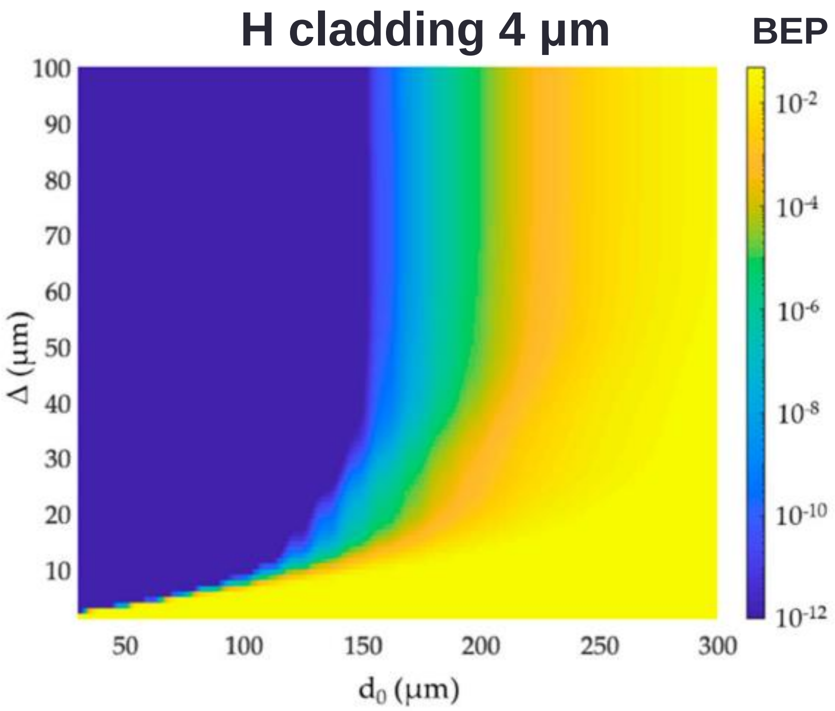


Lateral distance between the transmitting and the interfering antennas





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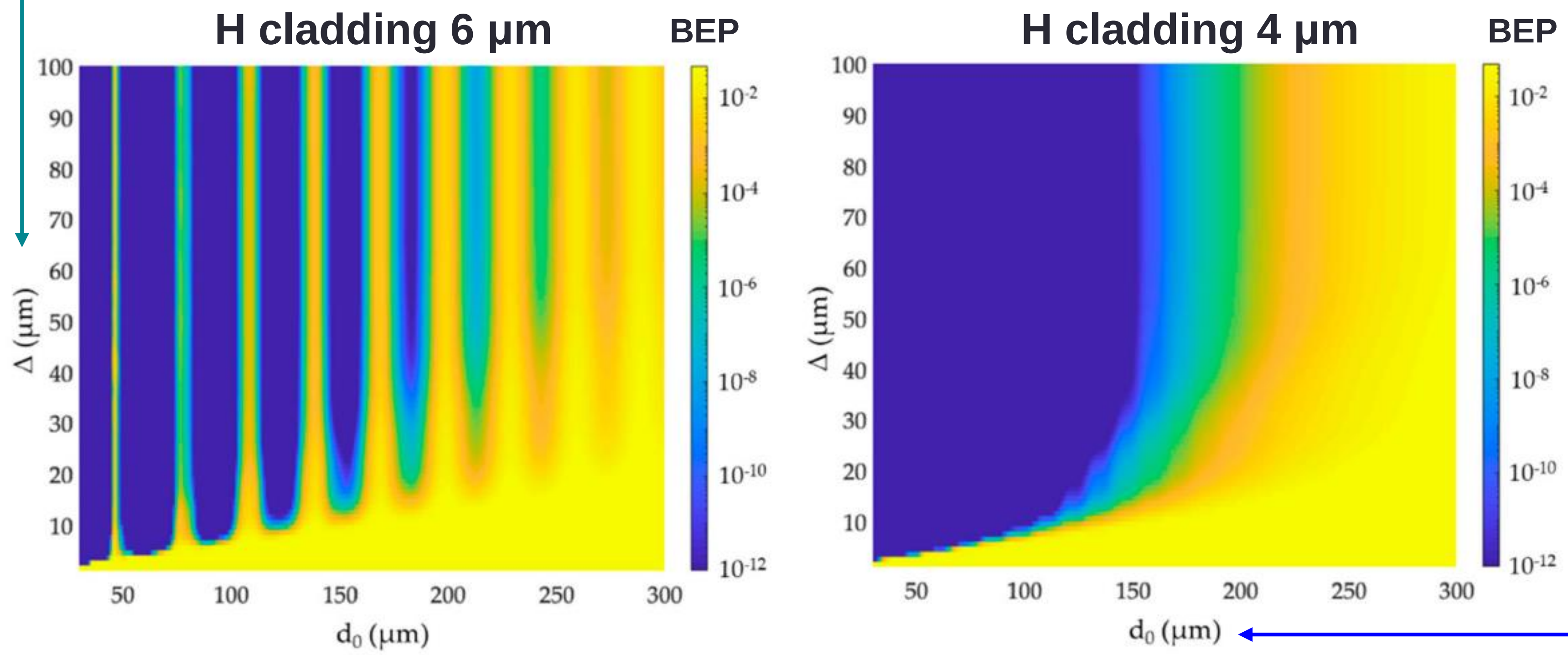

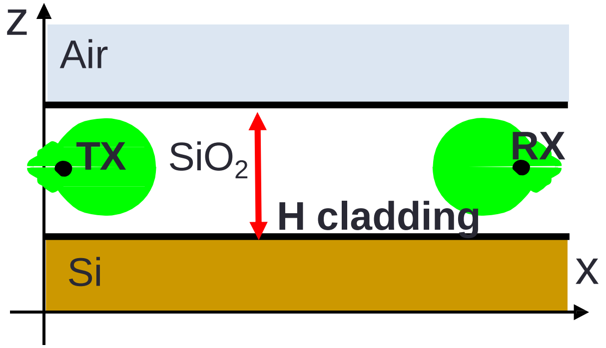

Link distance

On-Chip Optical Propagation

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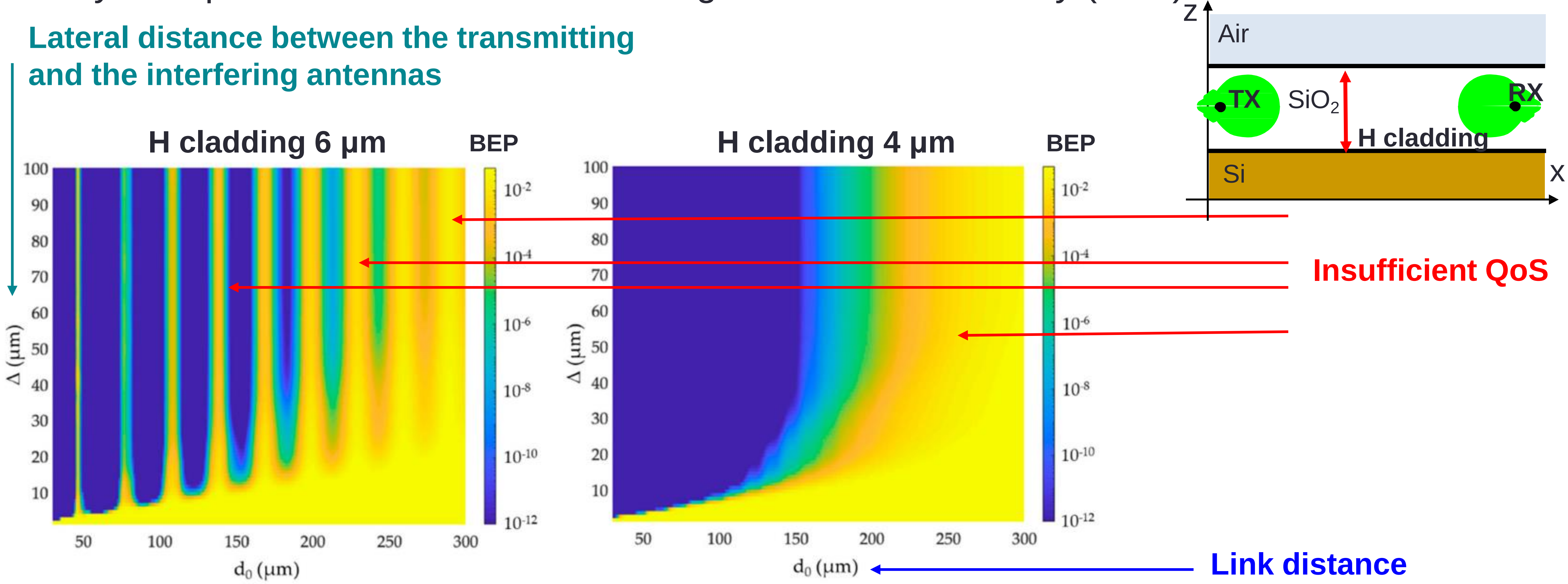
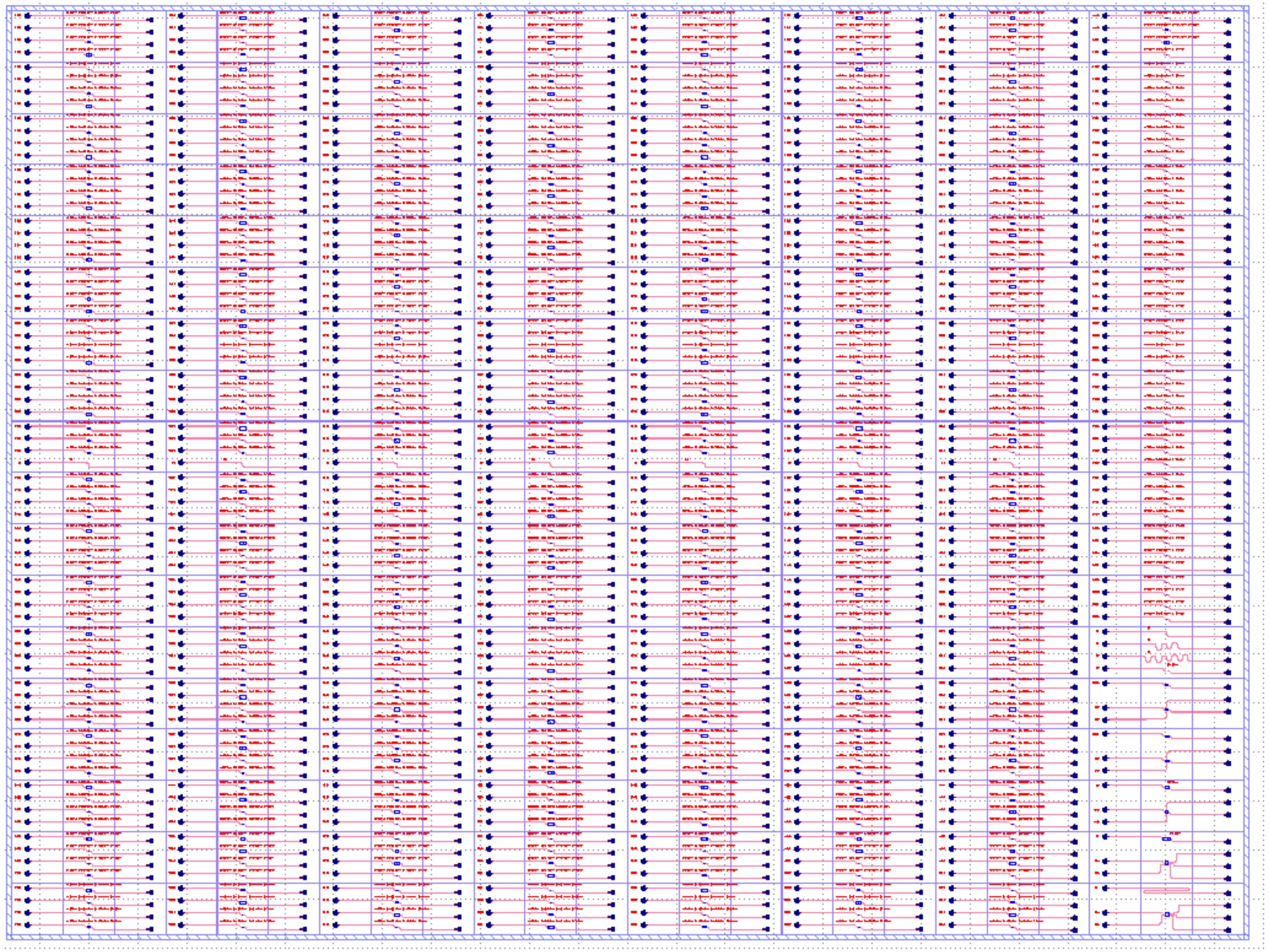
Lateral distance between the transmitting and the interfering antennas



F. Fuschini, M. Barbiroli, G. Calò, et Al., “Multi-Level Analysis of On-Chip Optical Wireless Links”, Appl. Sci. 2020

Fabrication – Plasmonic and Dielectric Antennas

- Plasmonic Vivaldi Antenna



Fabrication – Plasmonic and Dielectric Antennas

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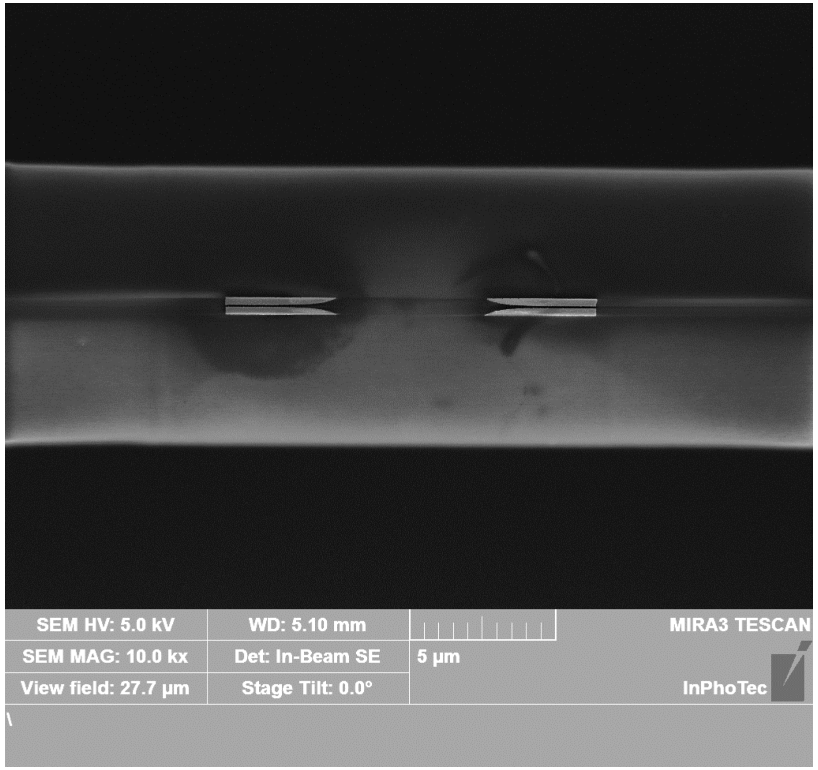

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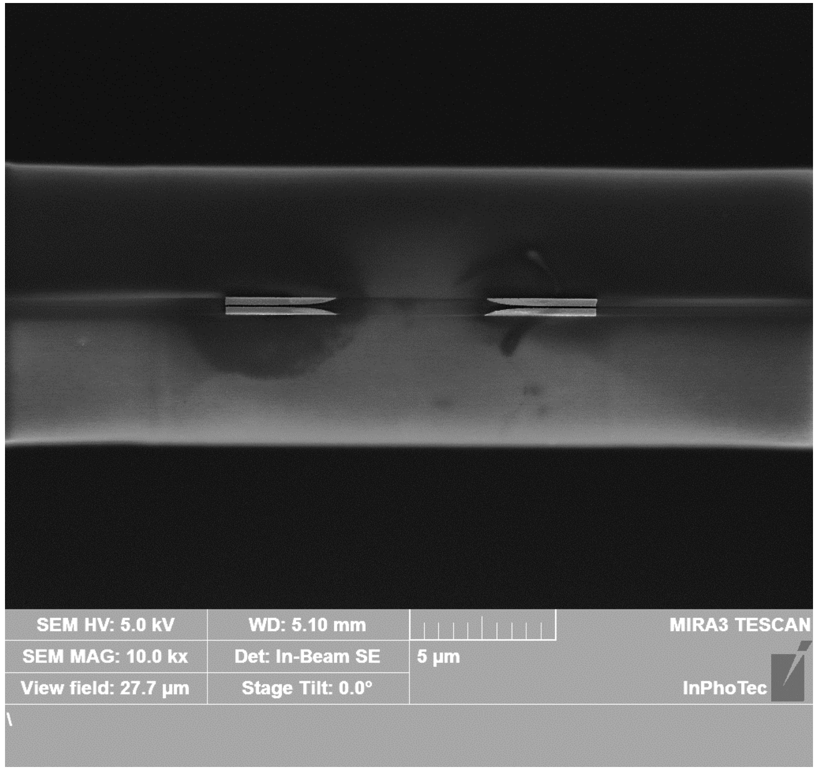
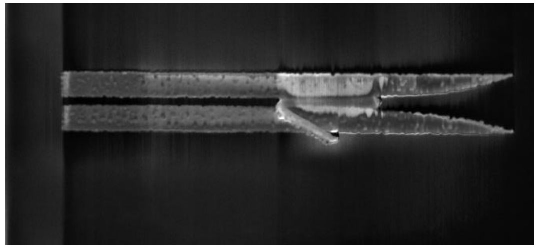
- Plasmonic Vivaldi Antenna



Lift-off problems



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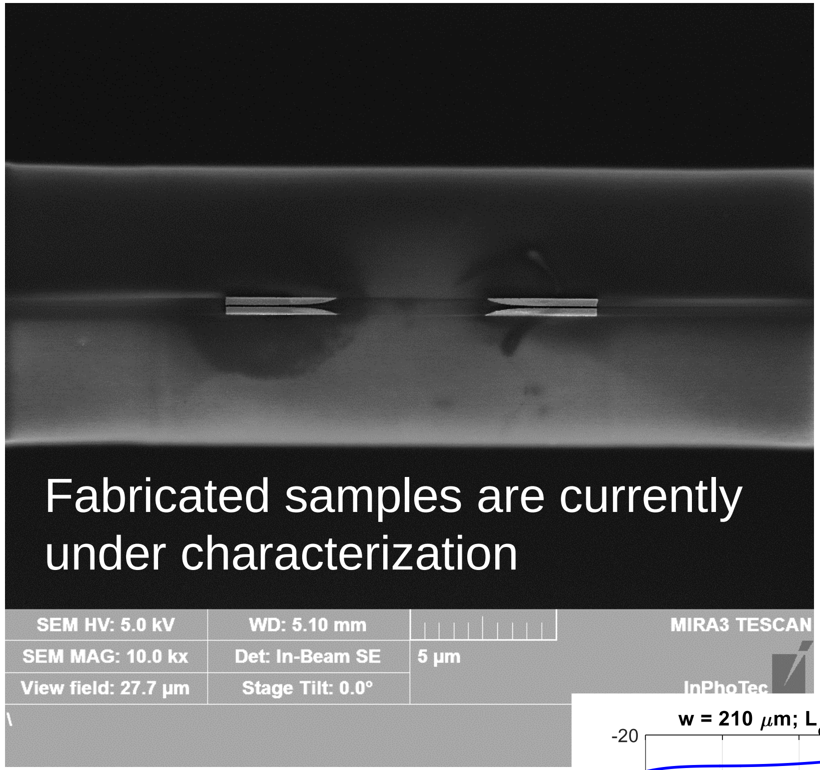

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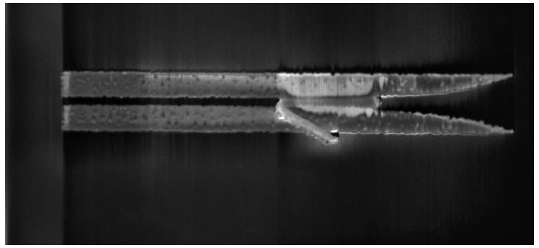

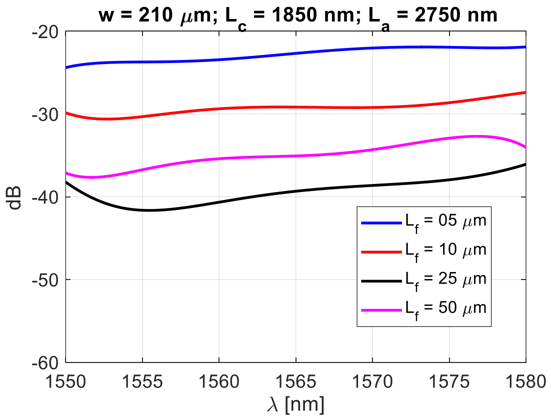

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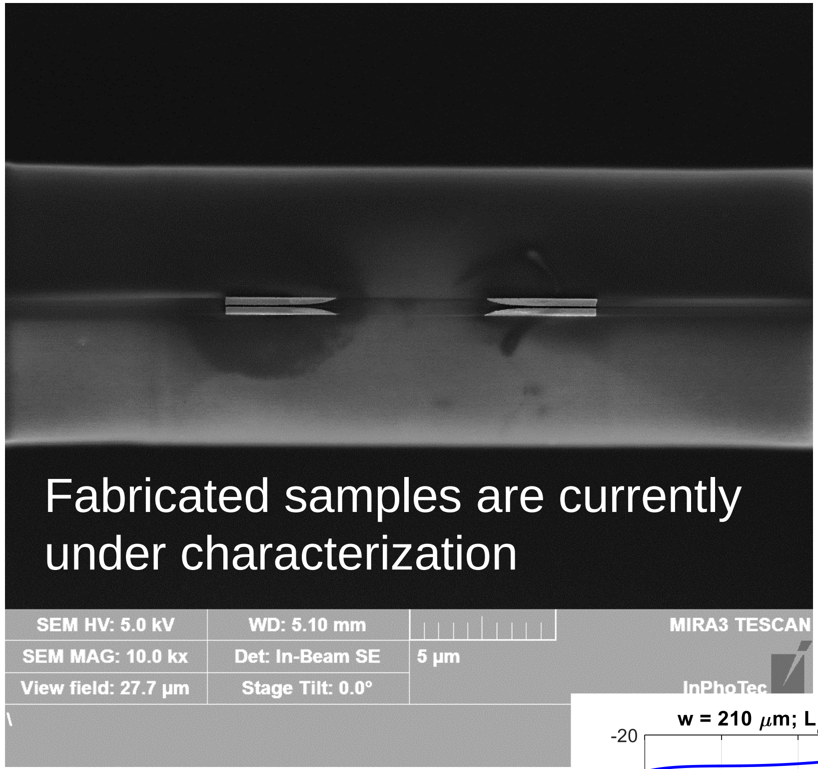

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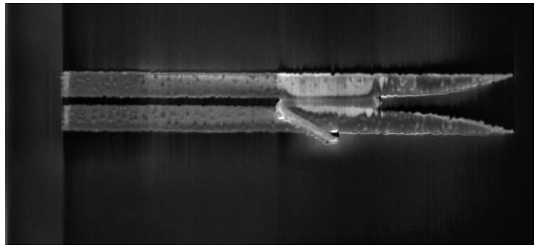
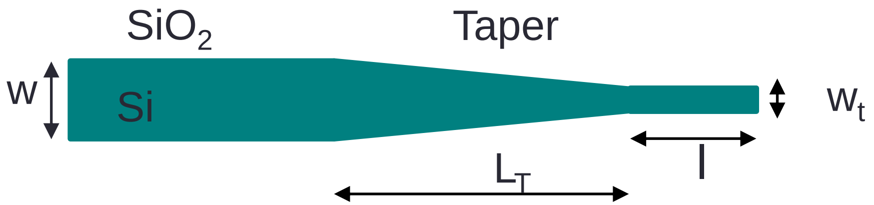
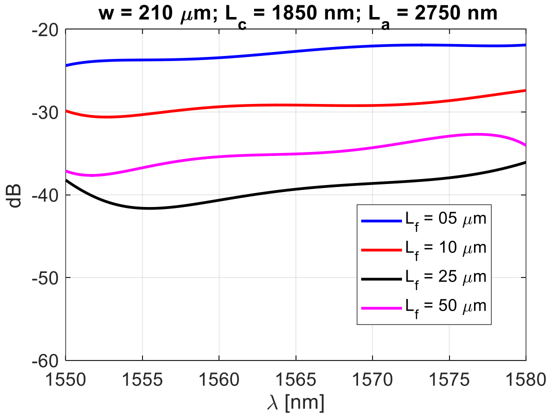


- Dielectric Taper Antenna





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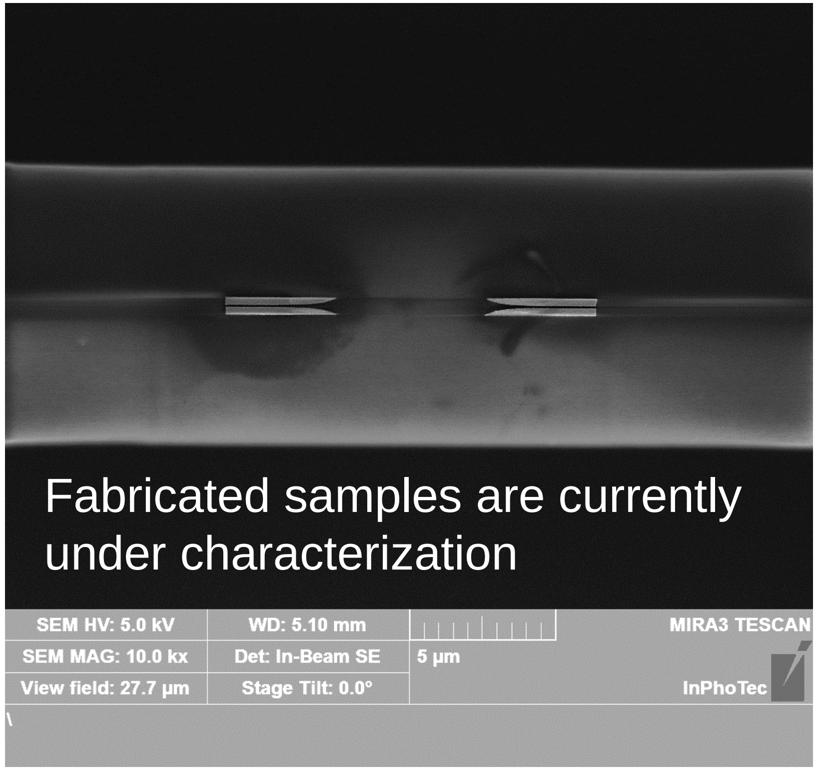
- Plasmonic Vivaldi Antenna



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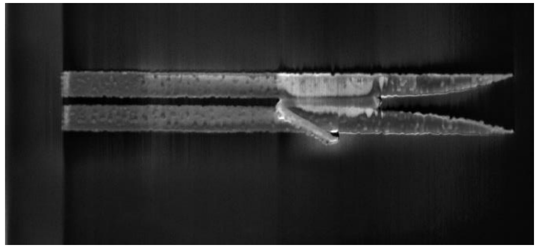

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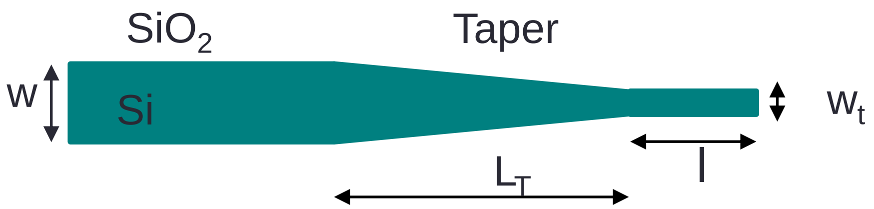
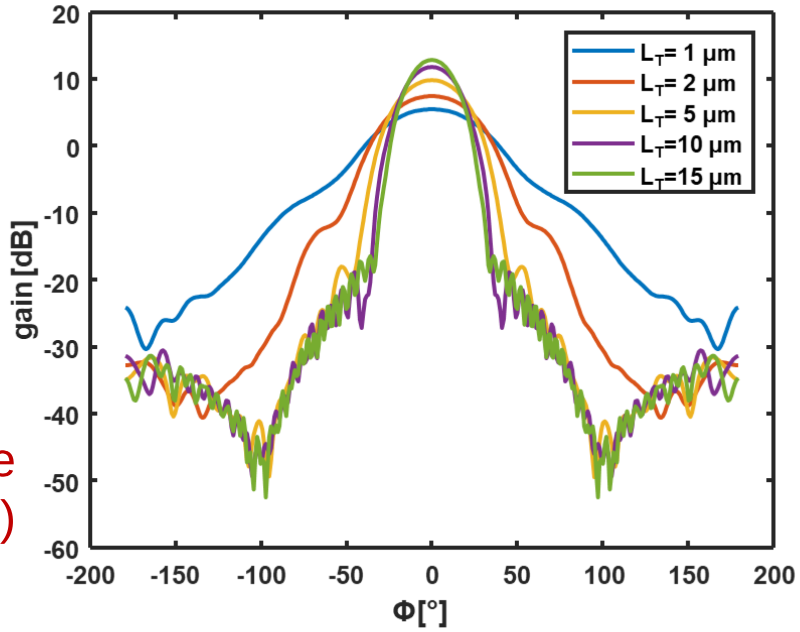


- Simple to design and fabricate
- Maximum gain 5 dB ÷ 12 dB according to the taper length
- Flat response in the C band (1530 nm ÷ 1565 nm)

Horizontal plane (E-plane)



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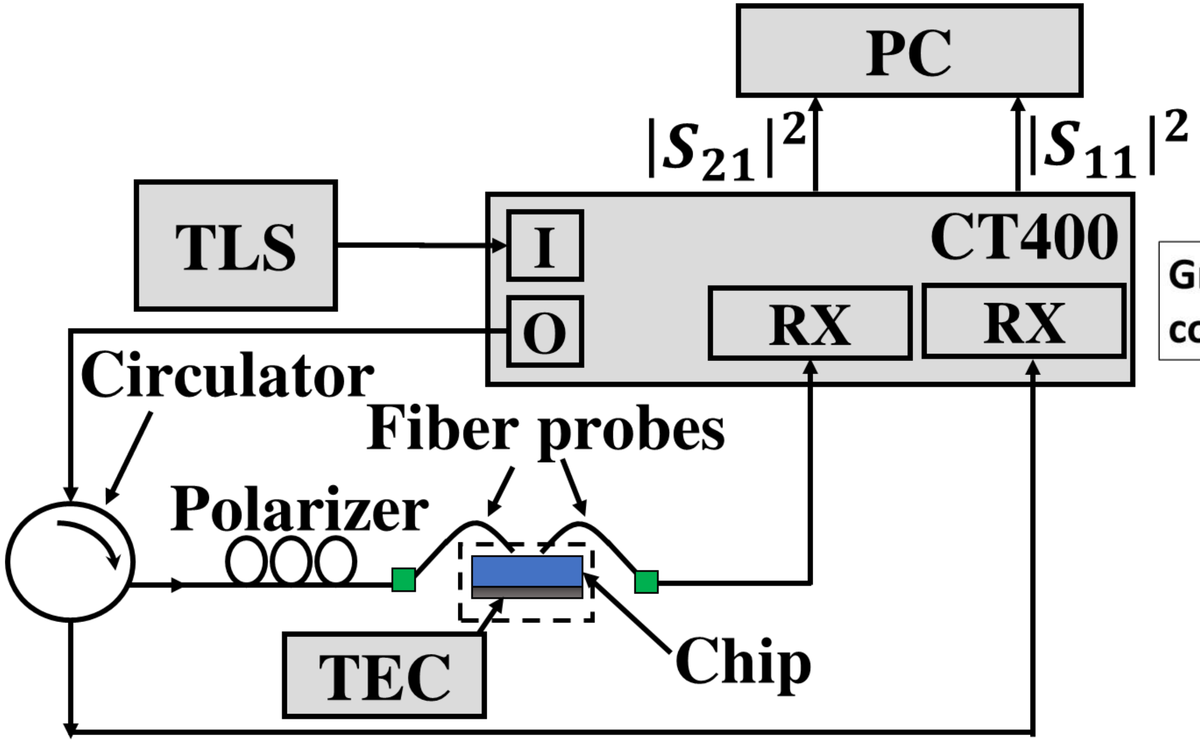
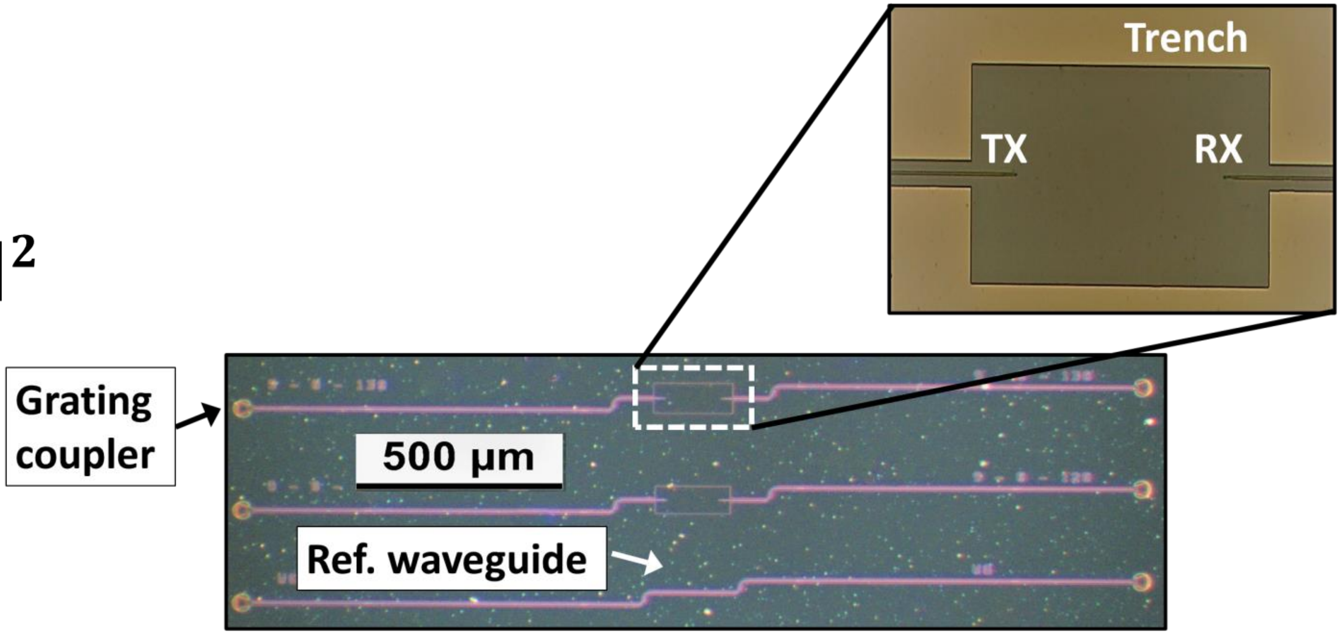
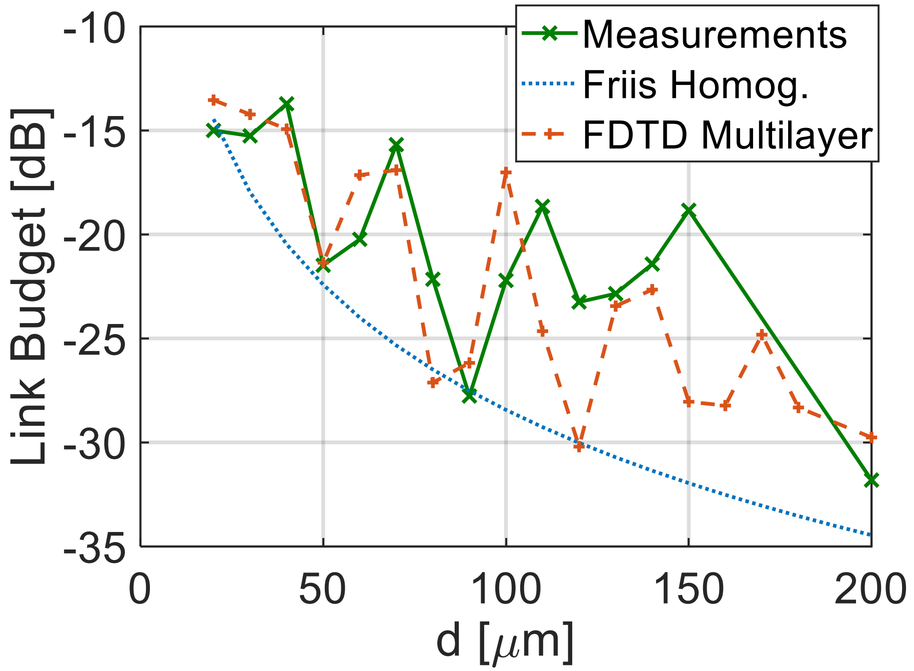
- Link budget evaluated by normalizing the measured received power of each link with the one of a straight reference waveguide





On-Chip Optical Wireless Communication

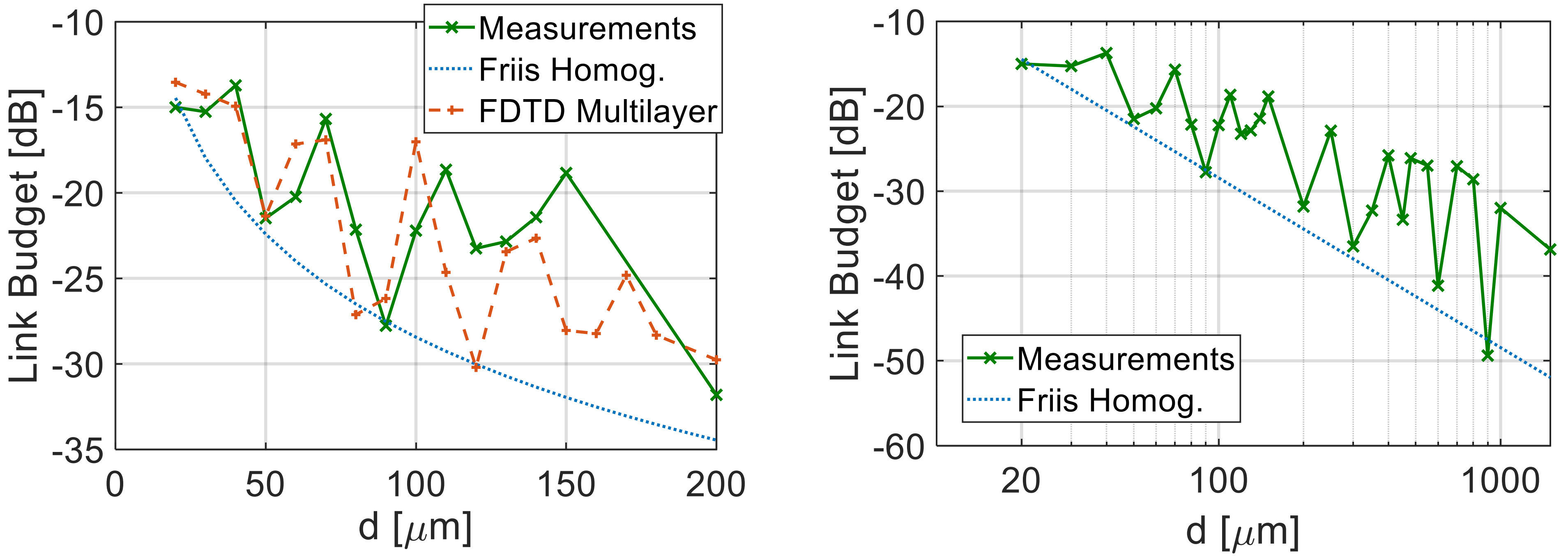
- Link budget evaluated by normalizing the measured received power of each link with the one of a straight reference waveguide
- Experimental results confirmed:
  - The behavior predicted by the FDTD for the propagation on a Multilayer Stack



J. Nanni et Al., “Multi-path propagation in on-chip optical wireless links”, IEEE PTL, 2020

On-Chip Optical Wireless Communication

- Link budget evaluated by normalizing the measured received power of each link with the one of a straight reference waveguide
- Experimental results confirmed:
  - The behavior predicted by the FDTD for the propagation on a Multilayer Stack
  - The higher average link budget on a Multilayer Stack with respect to the propagation on a homogeneous environment



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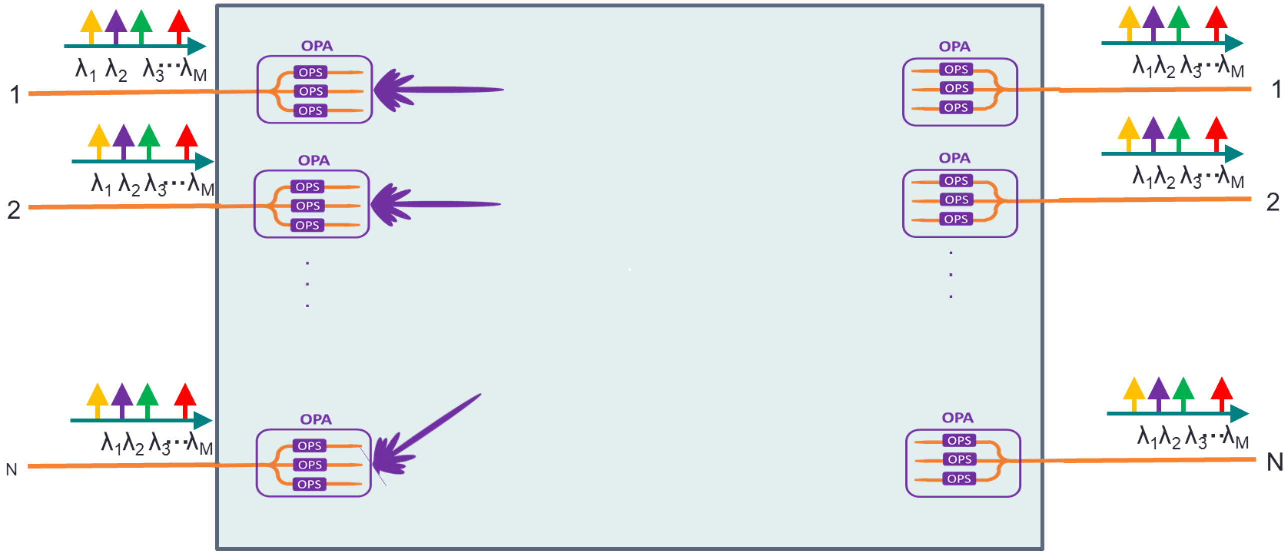
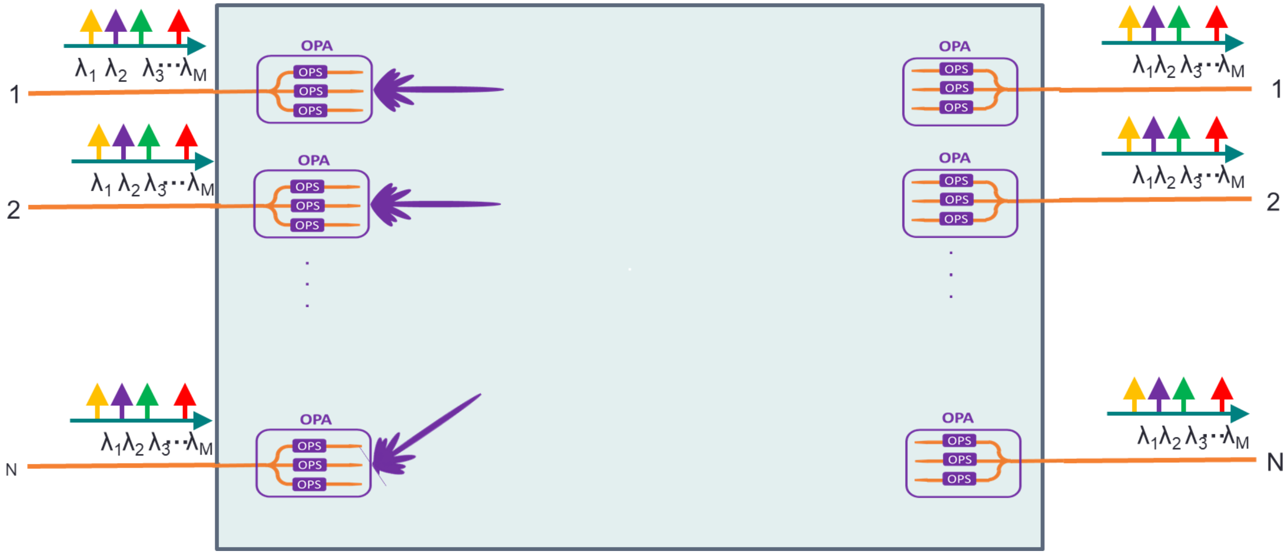
- Wireless Optical Interconnection can be exploited for the realization of a Wide Band Optical Wireless Switch



Wireless Optical Interconnection

- Wireless Optical Interconnection can be exploited for the realization of a Wide Band Optical Wireless Switch

- Wireless N × N interconnection fabric using Optical Phased Arrays (OPAs)



Wireless Optical Interconnection

- Wireless Optical Interconnection can be exploited for the realization of a Wide Band Optical Wireless Switch

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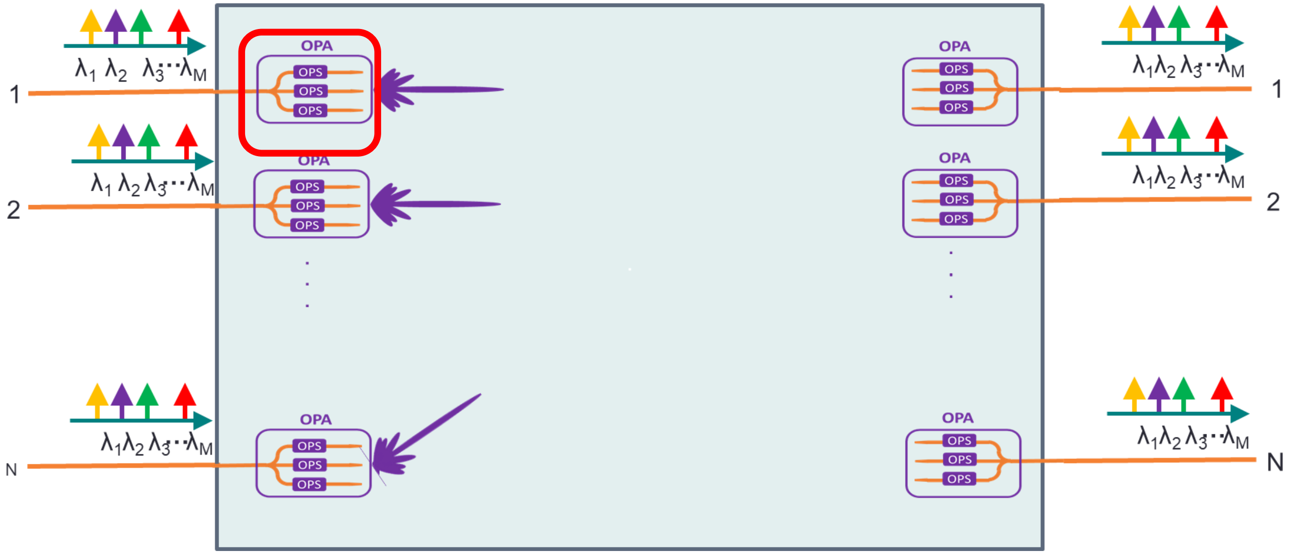
  - Optical Antenna Array with Phase Controlled Excitation of each element, to allow steering of the Radiation Pattern



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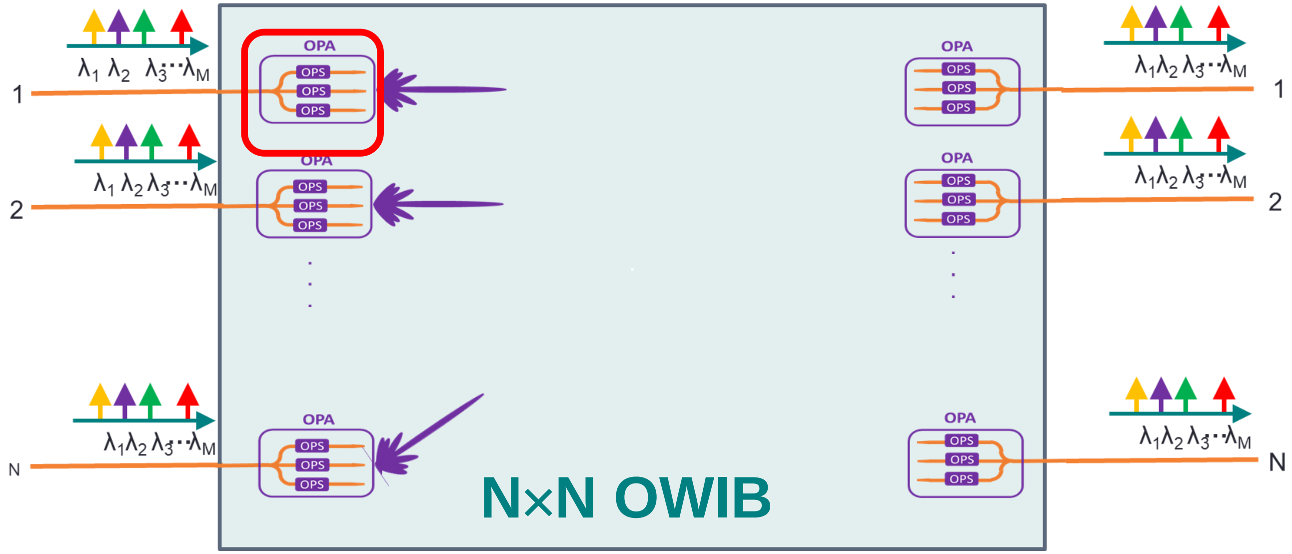

- N × N Wide-Band Optical Wireless Interconnection Block (OWIB)

Wireless Optical Interconnection

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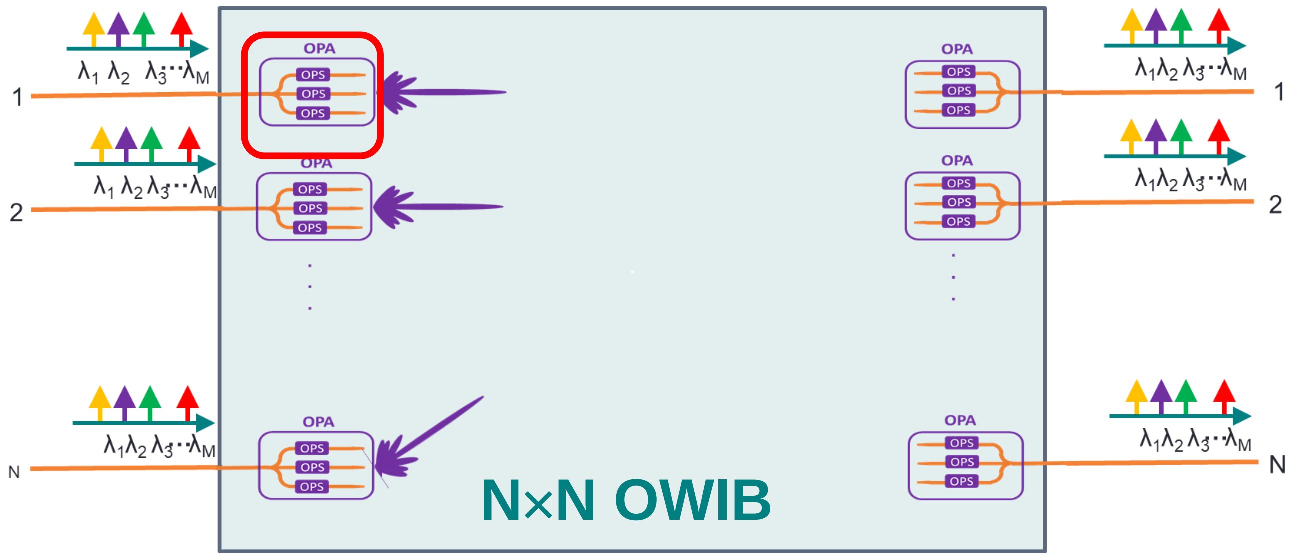
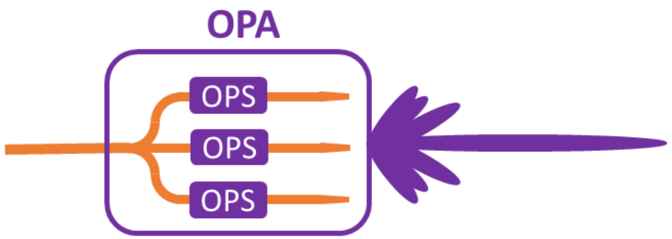


- N × N Wide-Band Optical Wireless Interconnection Block (OWIB)
    - Reconfigurable interconnection through Optical Phased Arrays (OPAs)



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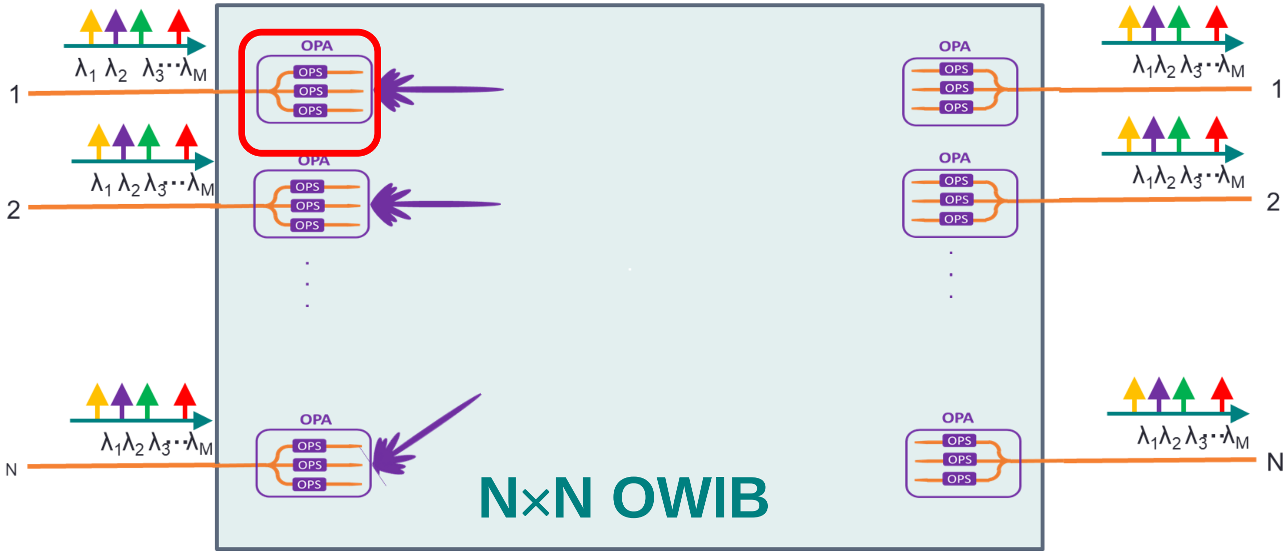

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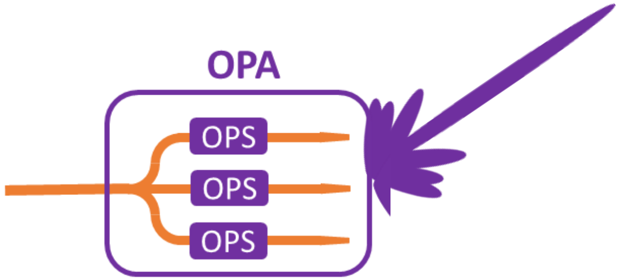

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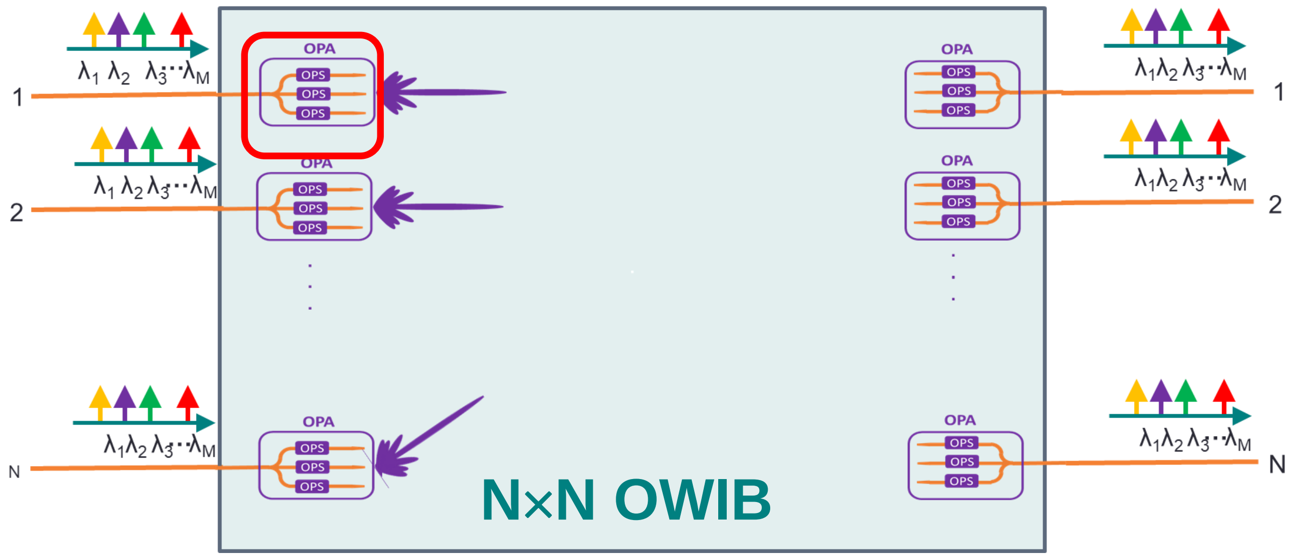

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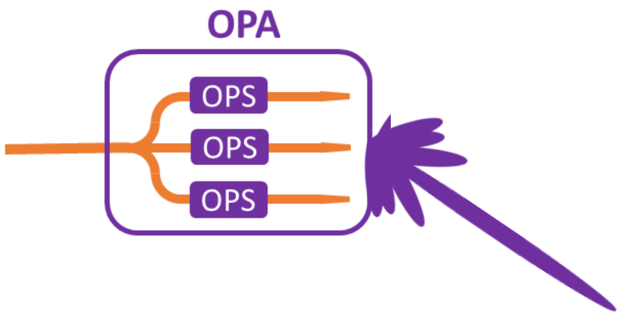

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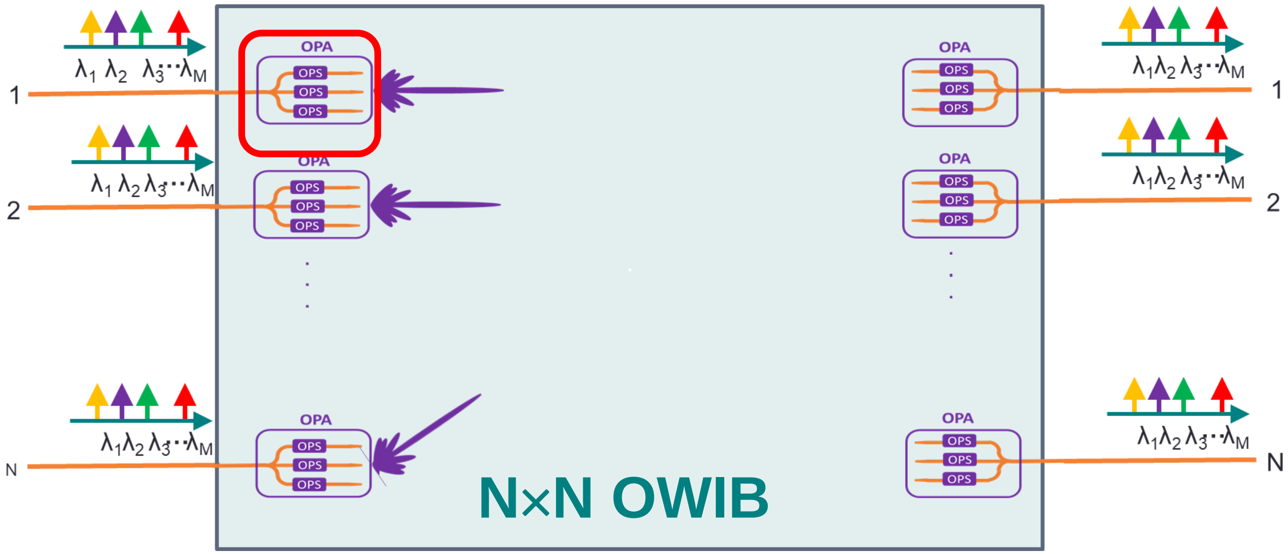
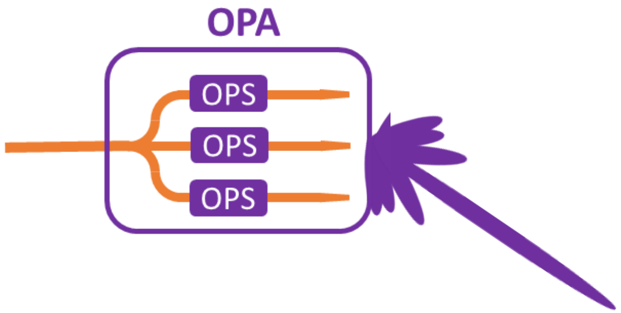
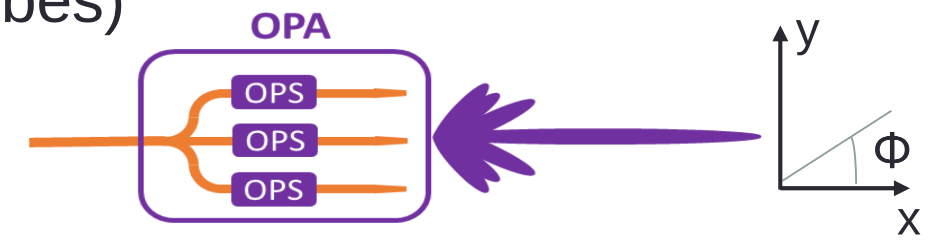


- N × N Wide-Band Optical Wireless Interconnection Block (OWIB)
  - Reconfigurable interconnection through Optical Phased Arrays (OPAs)
    - Optical Phase Shifters (OPSs) can be realized exploiting thermo-optic or plasma-optic effect



Design of a 1 × 3 Optical Phased Array

- Antenna Distance $d_{ant} < \lambda/n_{SiO2}$ (No Grating Lobes)



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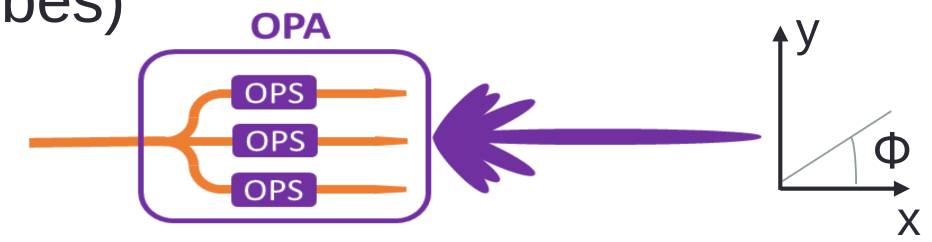

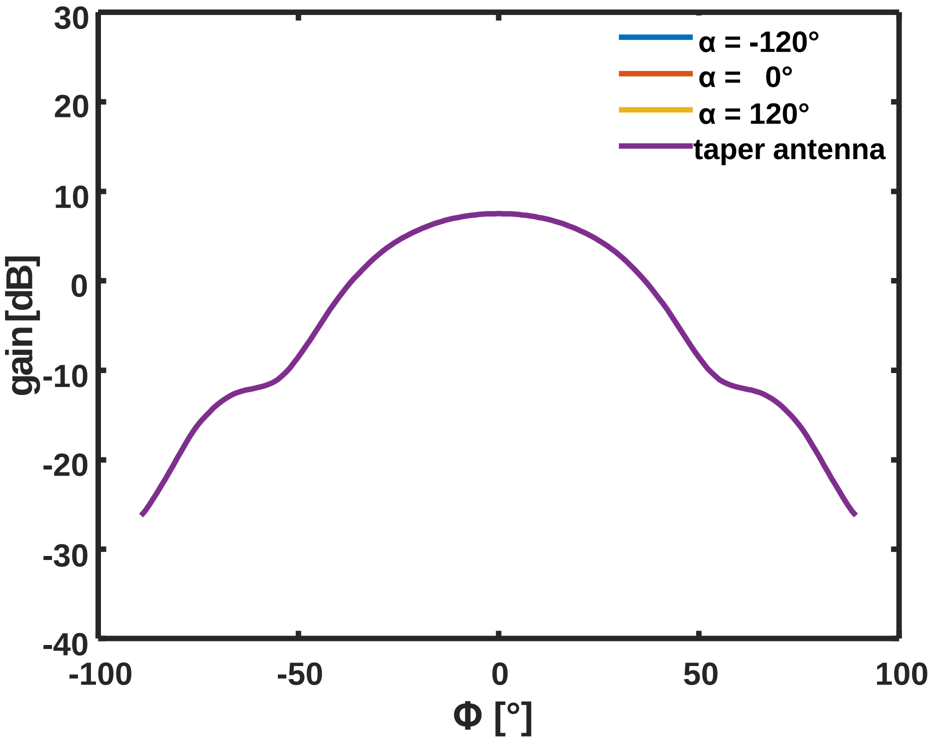

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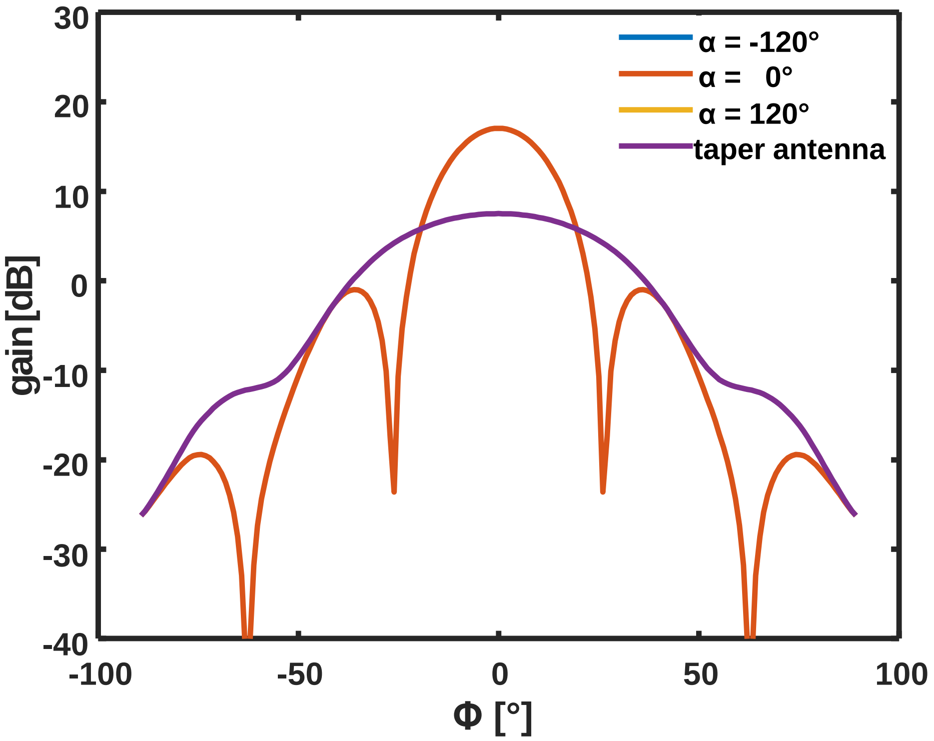

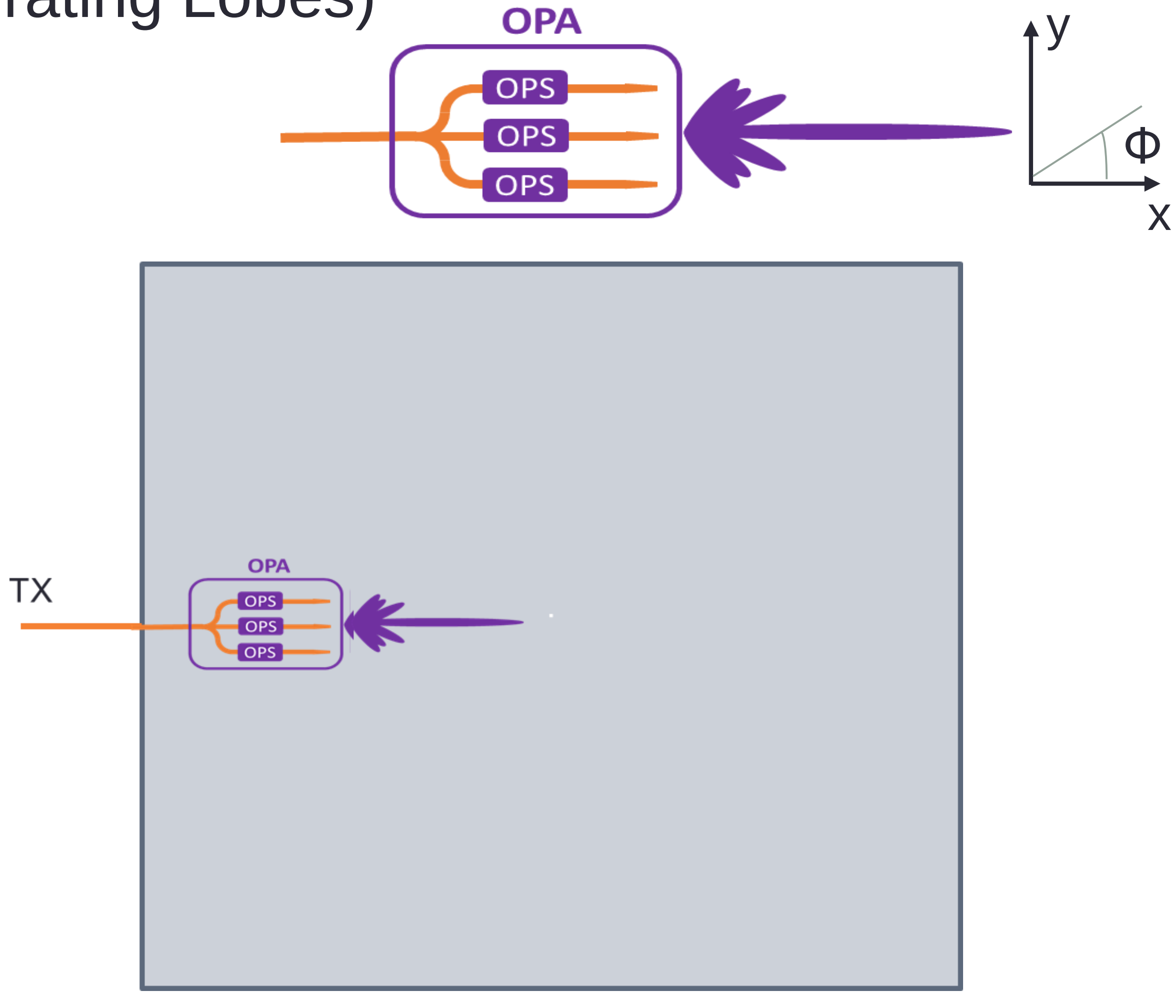

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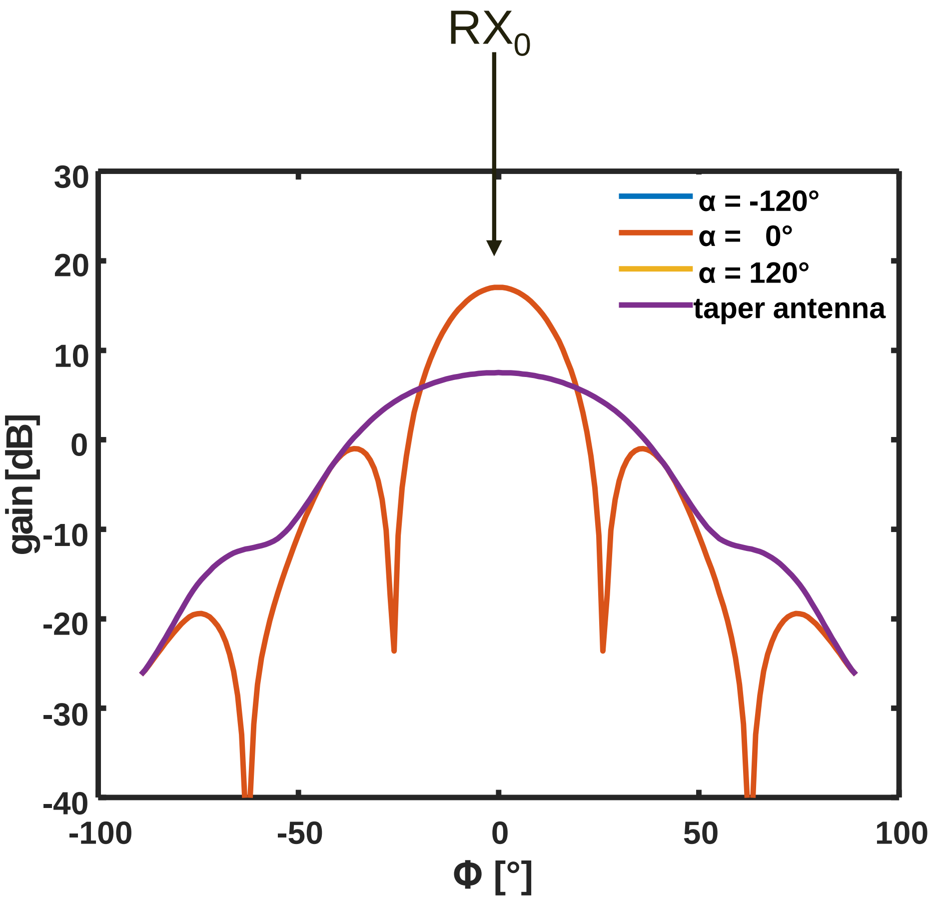

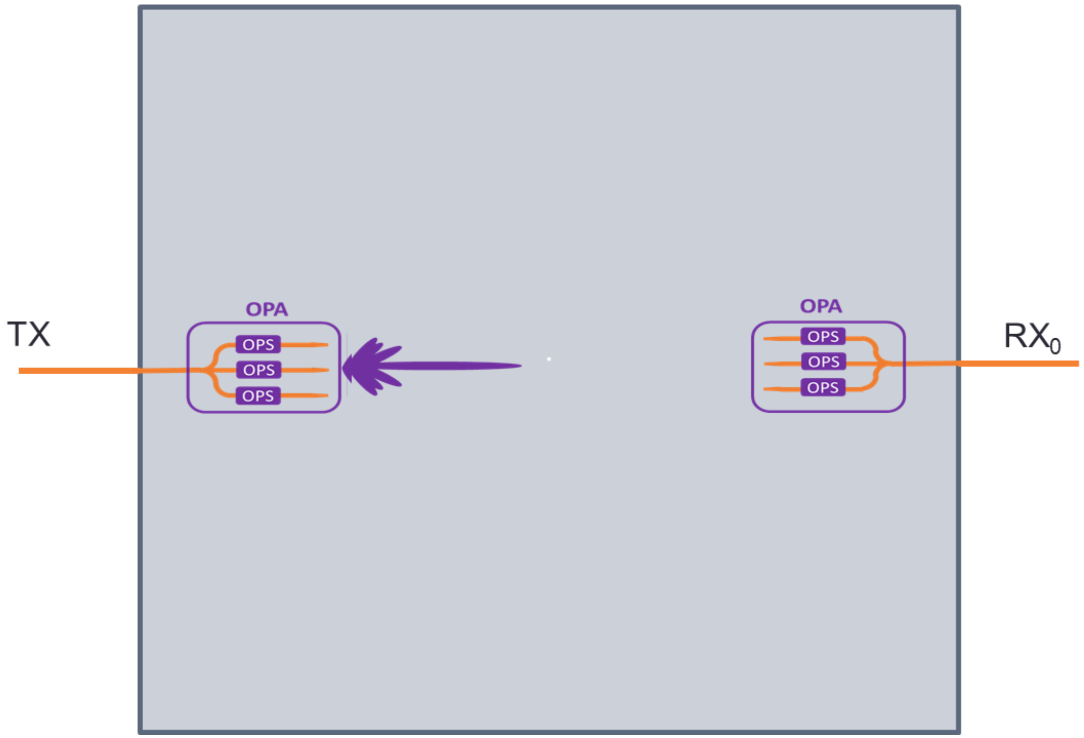

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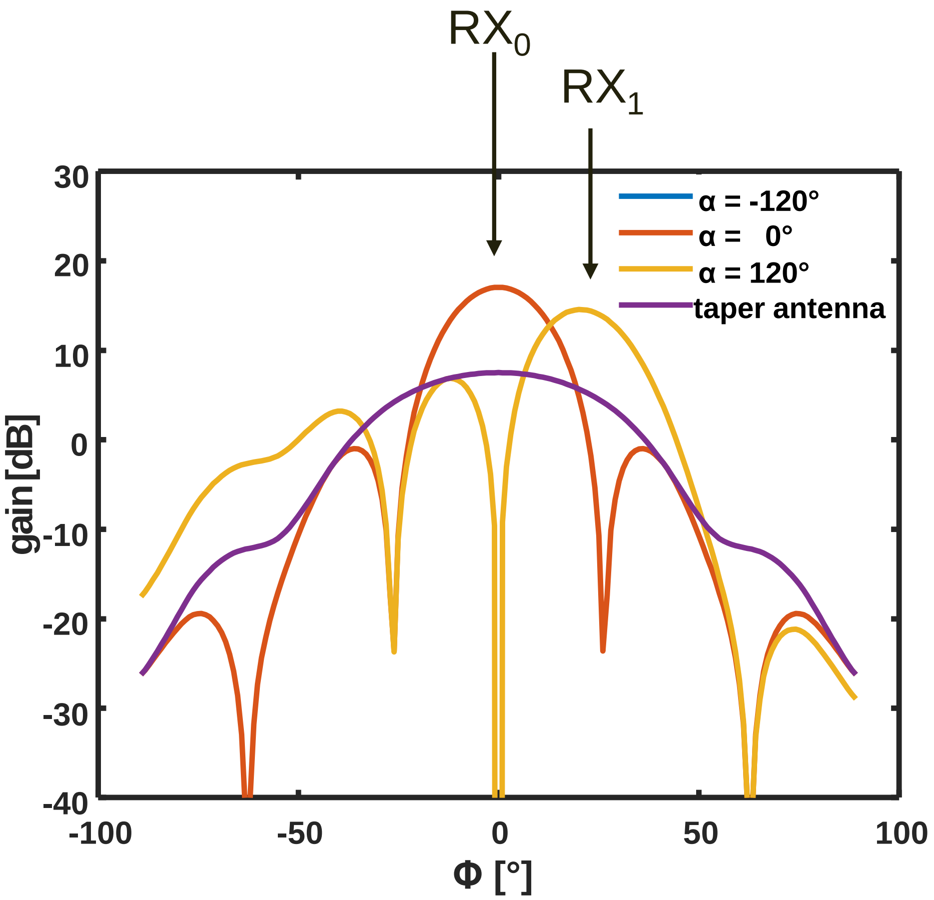
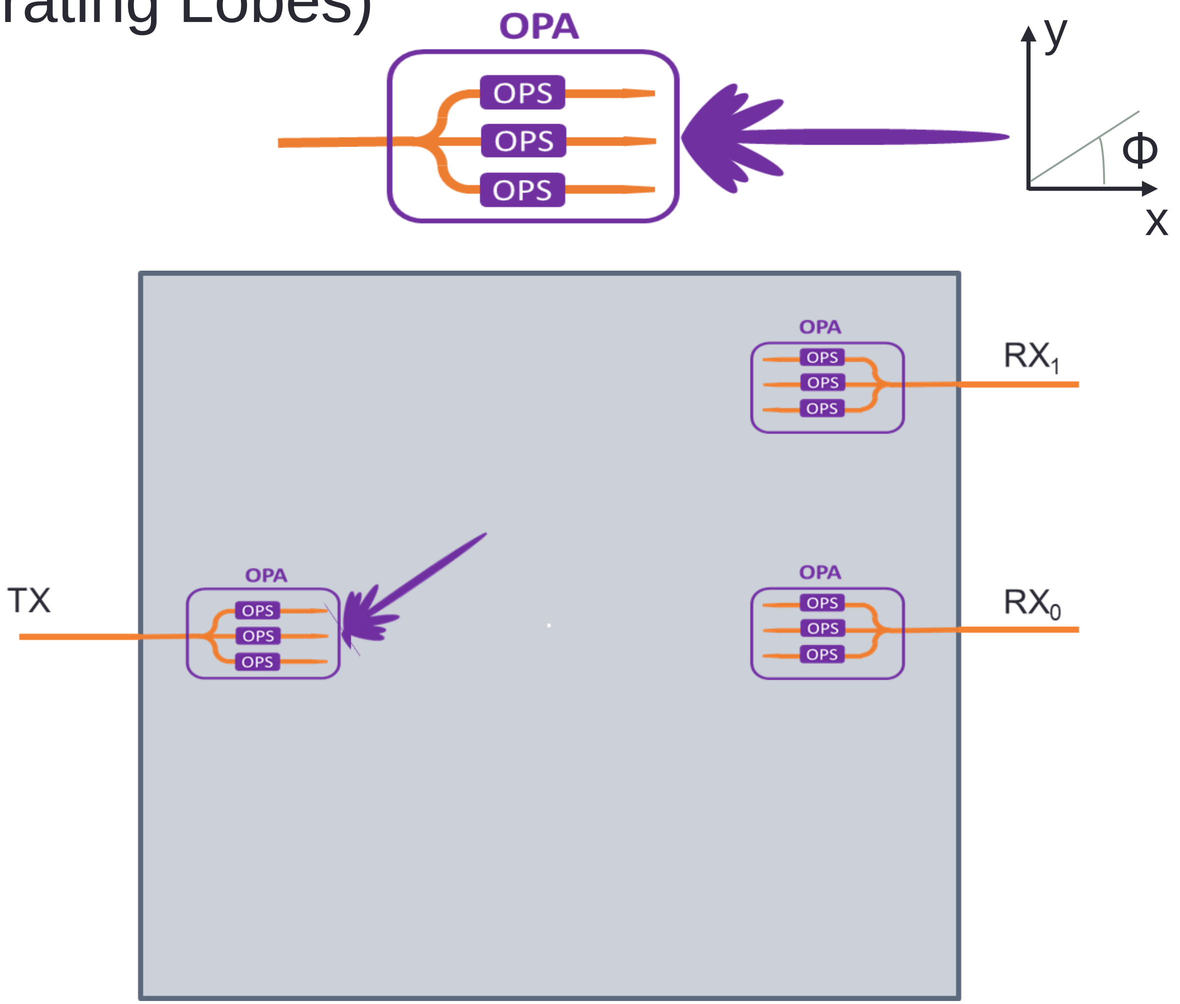
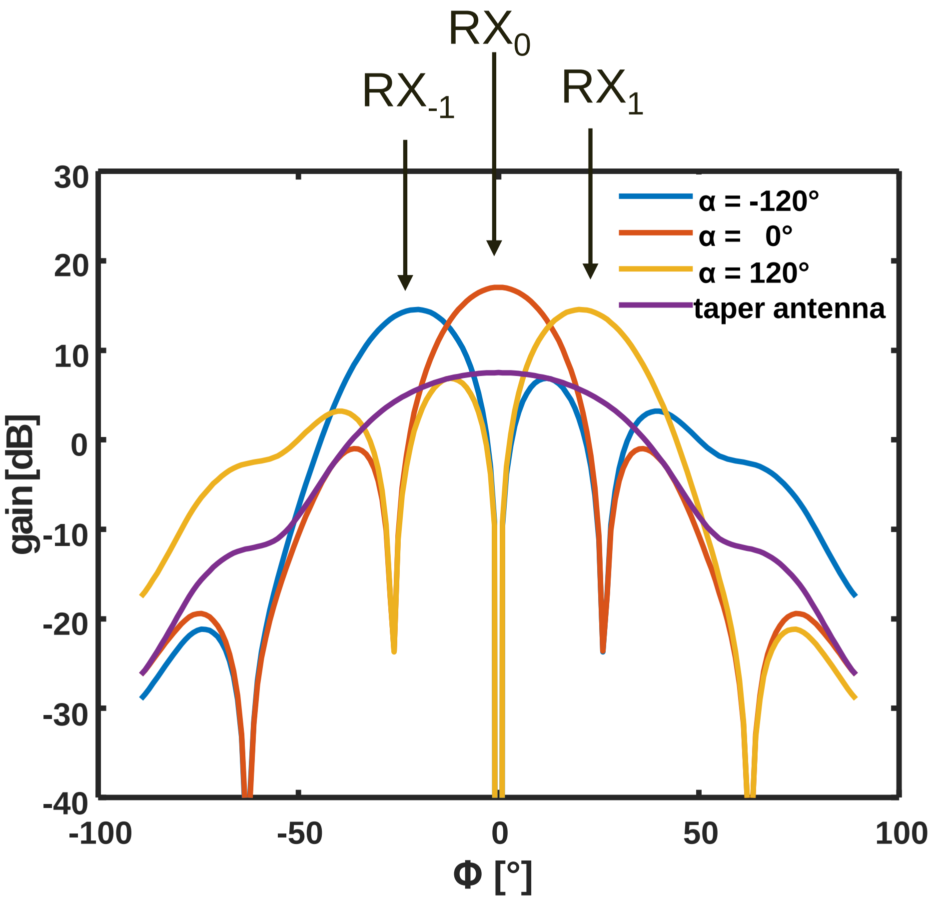
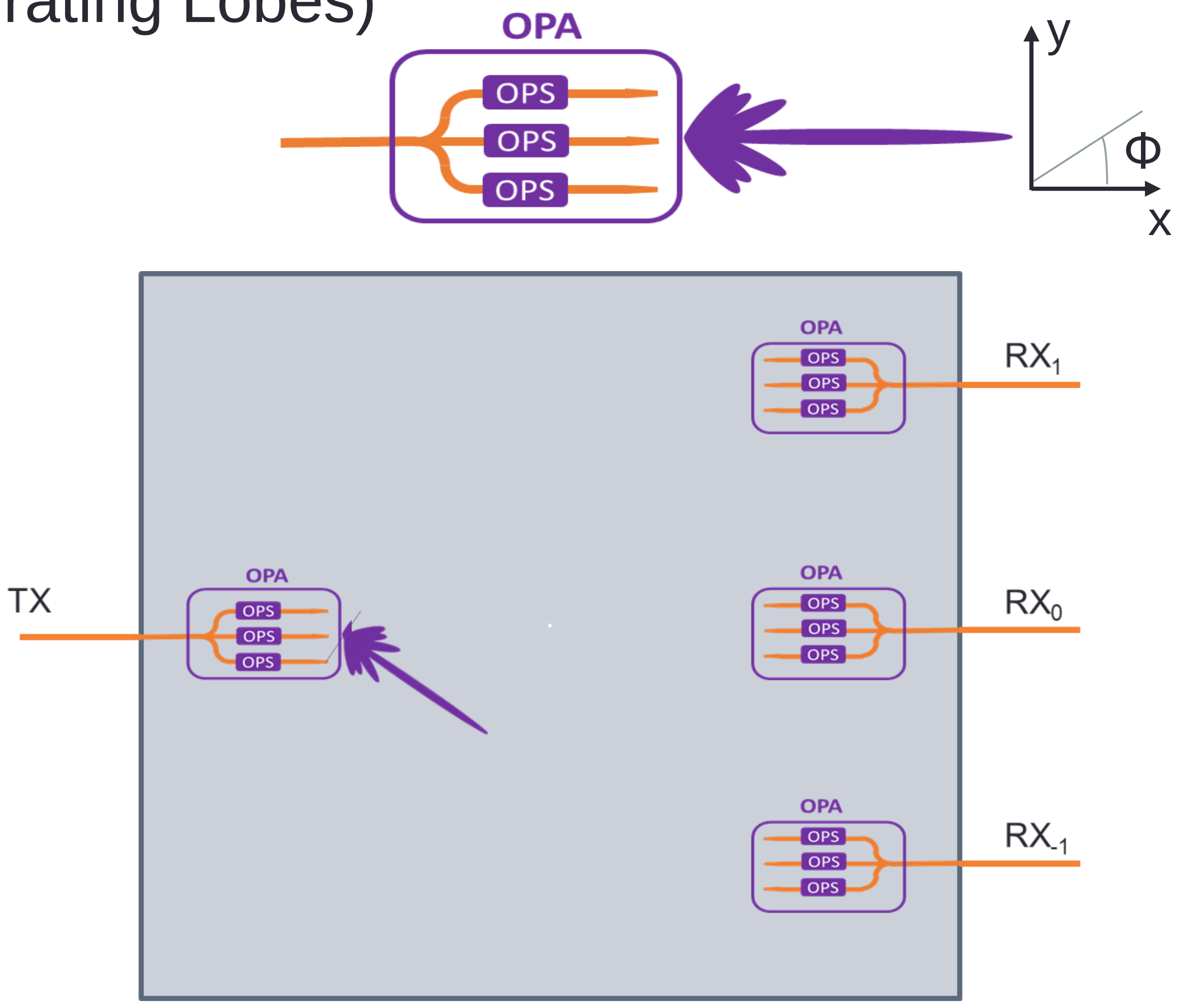




Design of a 1 × 3 Optical Phased Array

- Antenna Distance $d_{ant} < \lambda/n_{SiO2}$ (No Grating Lobes)





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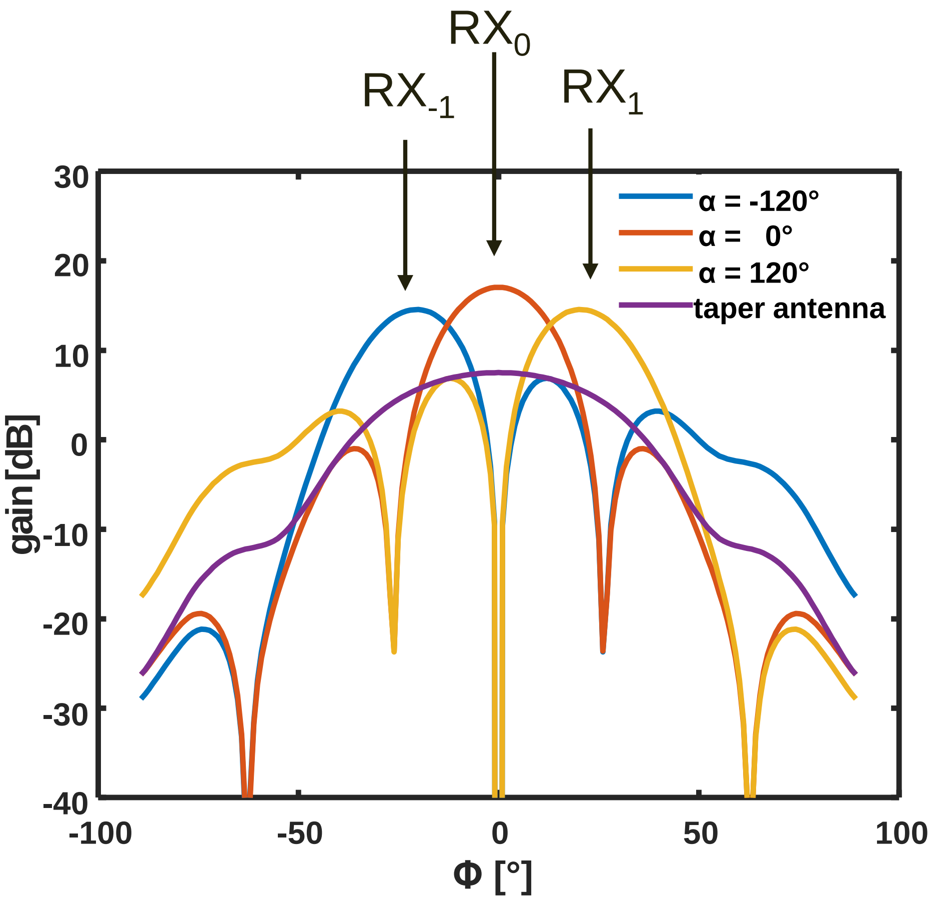

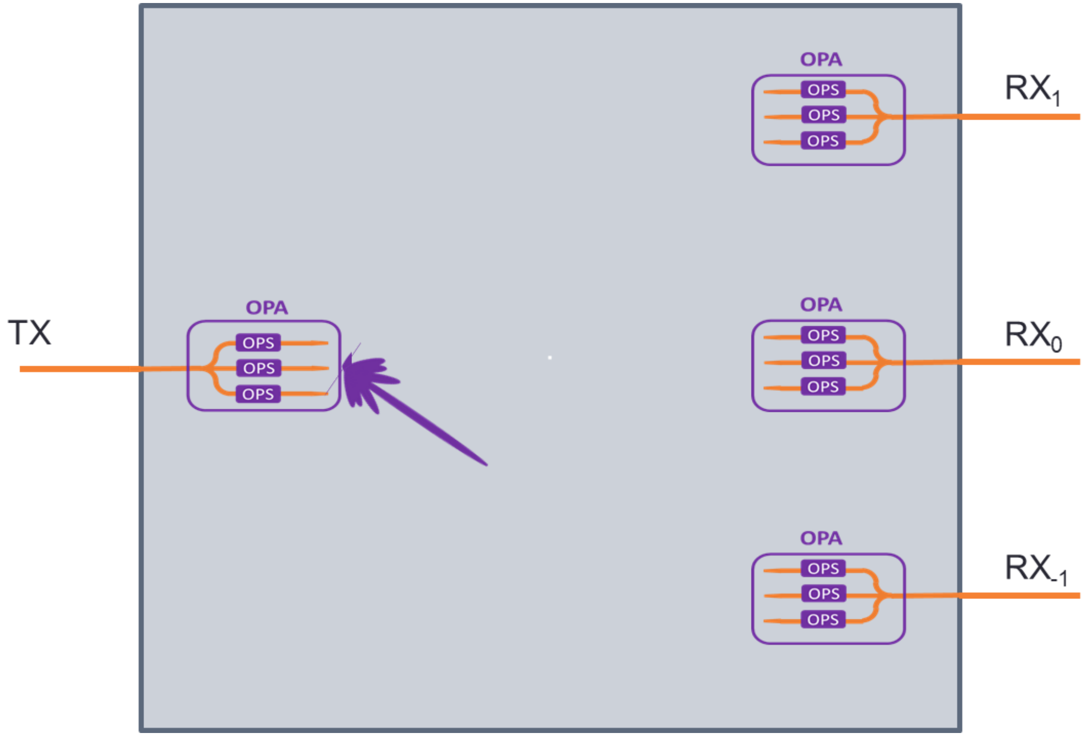

- Interference can be minimized by suitably placing the receivers: $y_{\pm 1} = \pm\, d_{link} \tan(\Phi_{null})$

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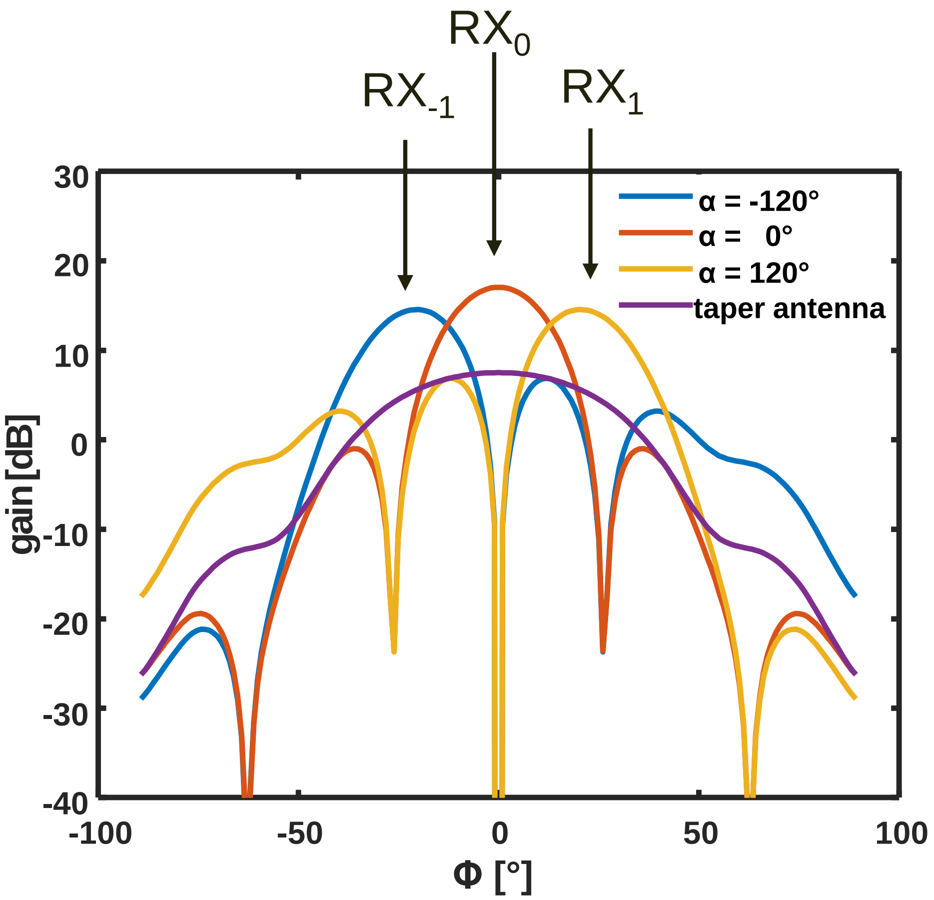
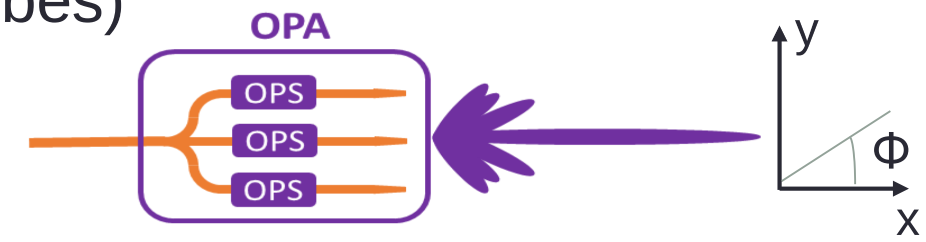
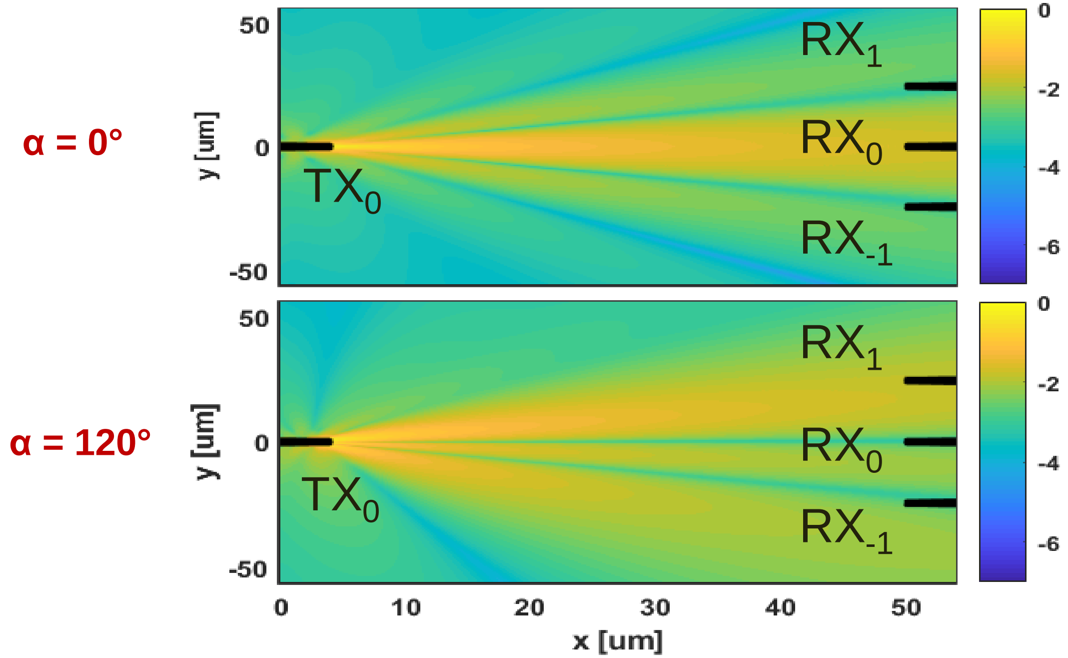




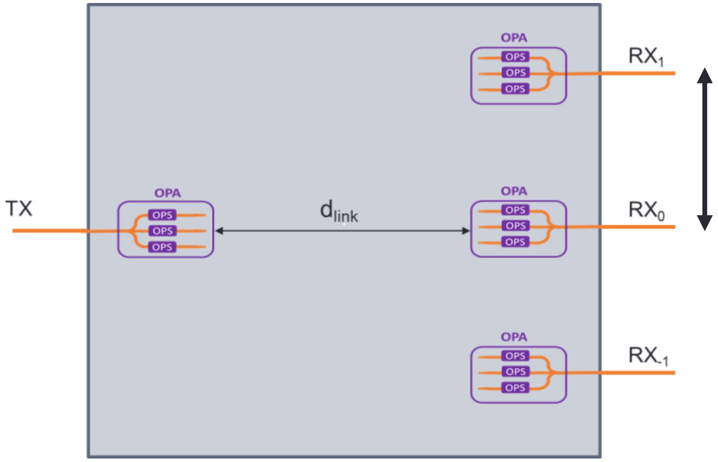


- Interference can be minimized by suitably placing the receivers: $y_{\pm1} = \pm\, d_{link} \tan(\Phi_{null})$

Taper length L_{taper} = 2 µm
Antenna Distance d = ¾ λ/n_{SiO2}
λ = 1550 nm, n_{SiO2} = 1.45

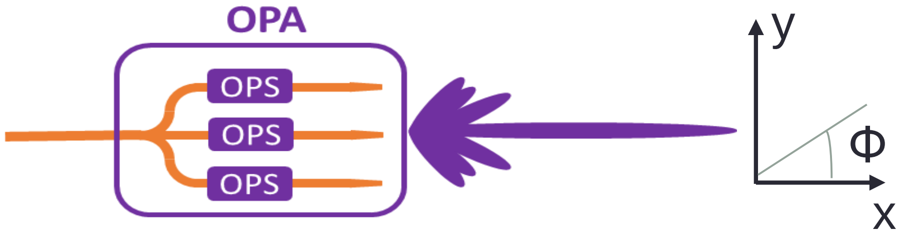
Design of a 1 × 3 Optical Wireless Interconnection Block

- 3D FDTD simulation of a 1 × 3 Interconnection Block



OPA Distance 24.5 μm

d_{link} = 50 μm



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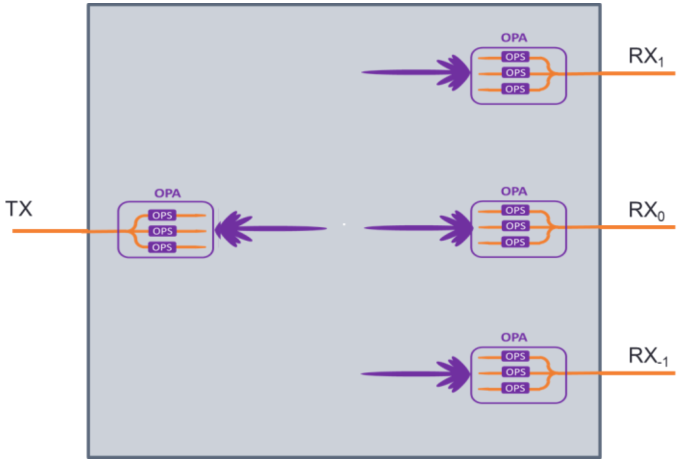
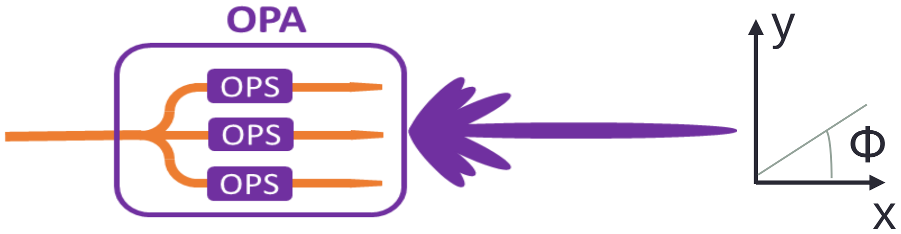
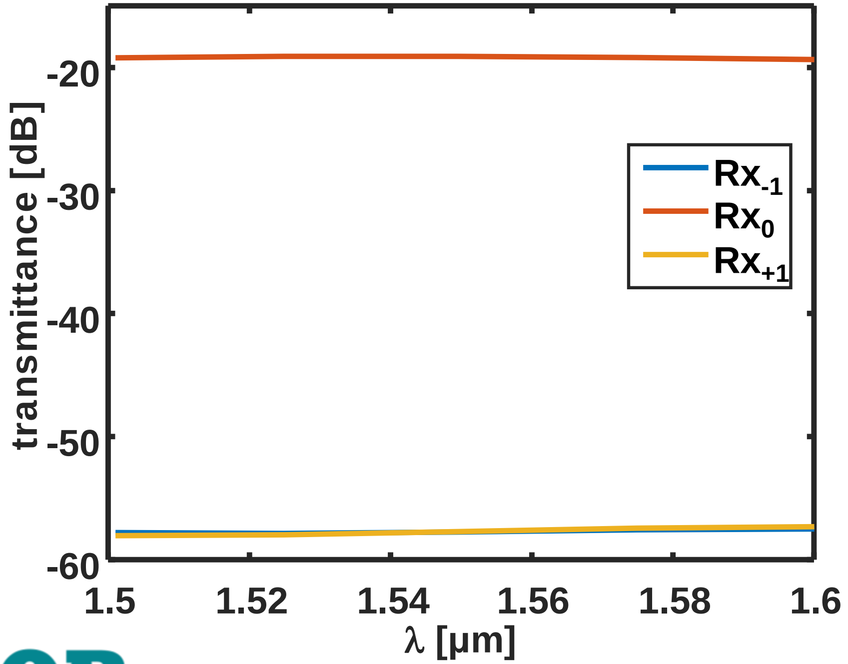




α_{TX}=0°, α_{RX1}=0°, α_{RX0}=0°, α_{RX-1}=0°



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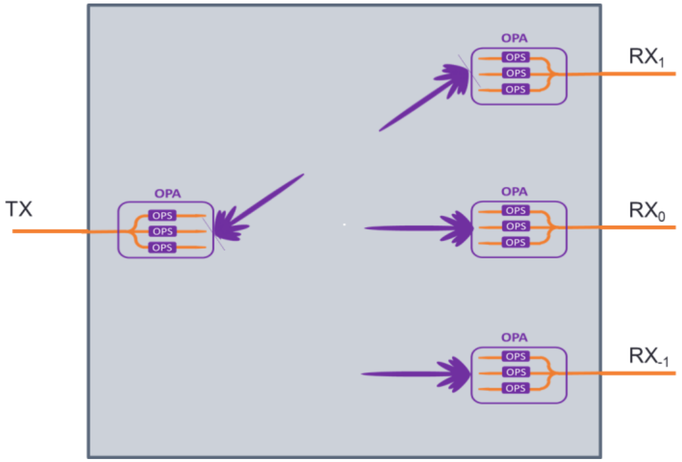
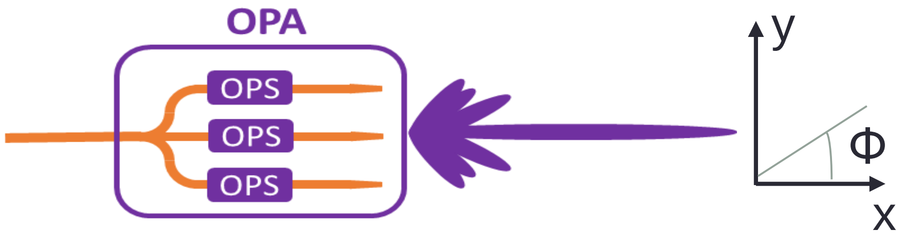
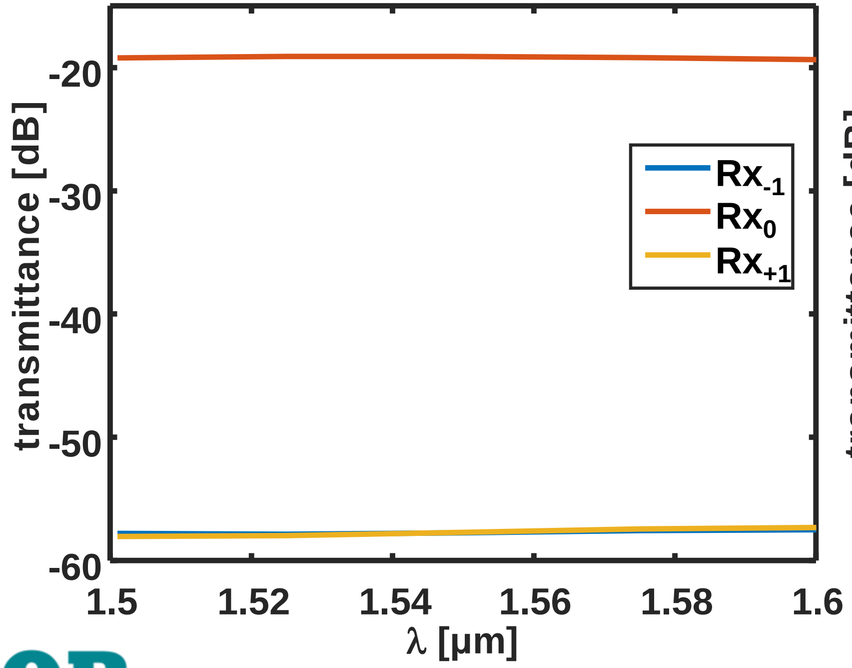
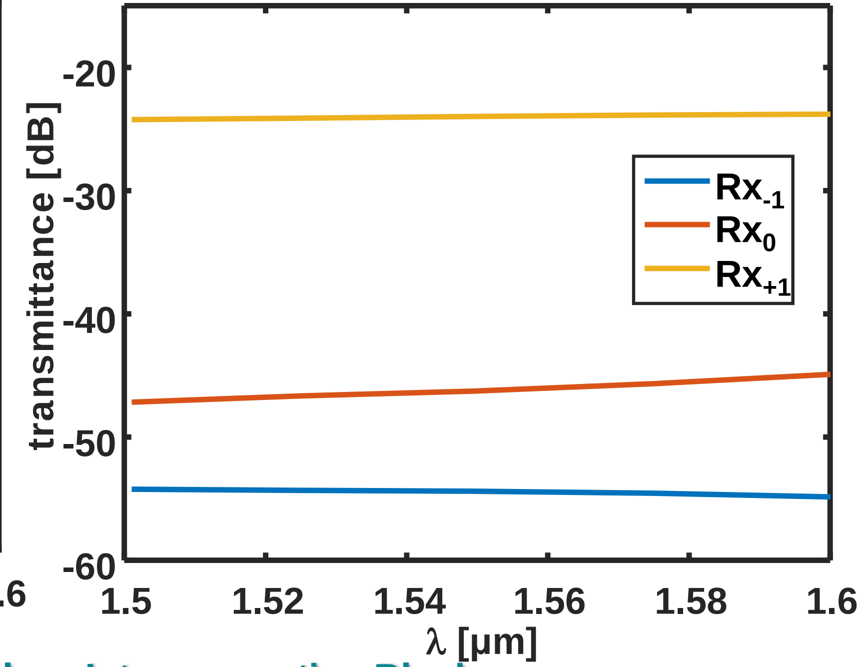




α_{TX}=120°, α_{RX1}=-120°, α_{RX0}=0°, α_{RX-1}=0°





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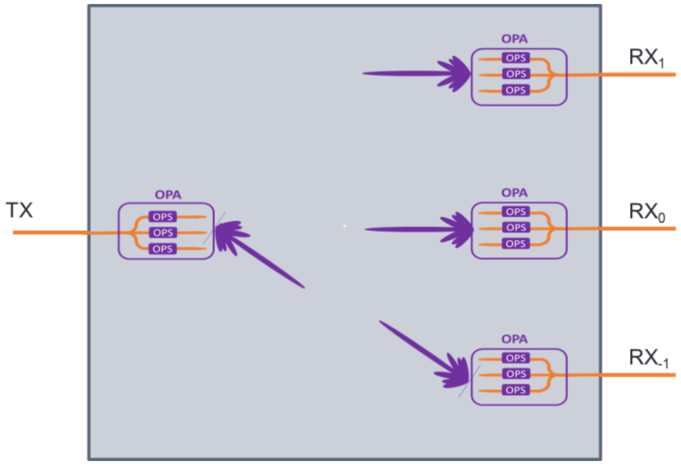
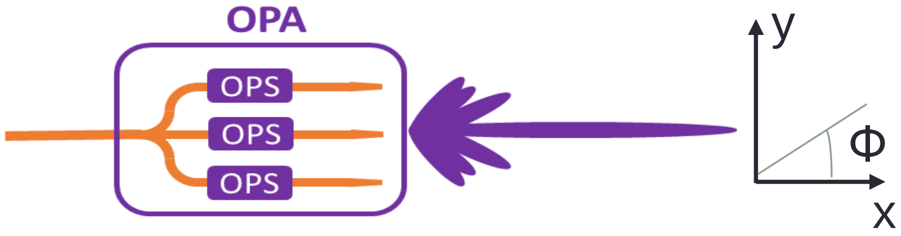
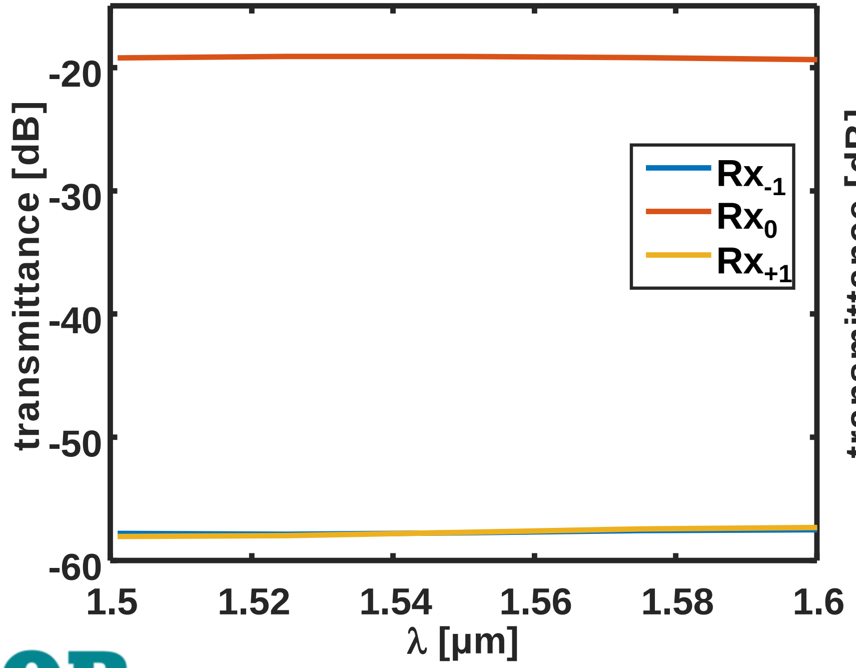
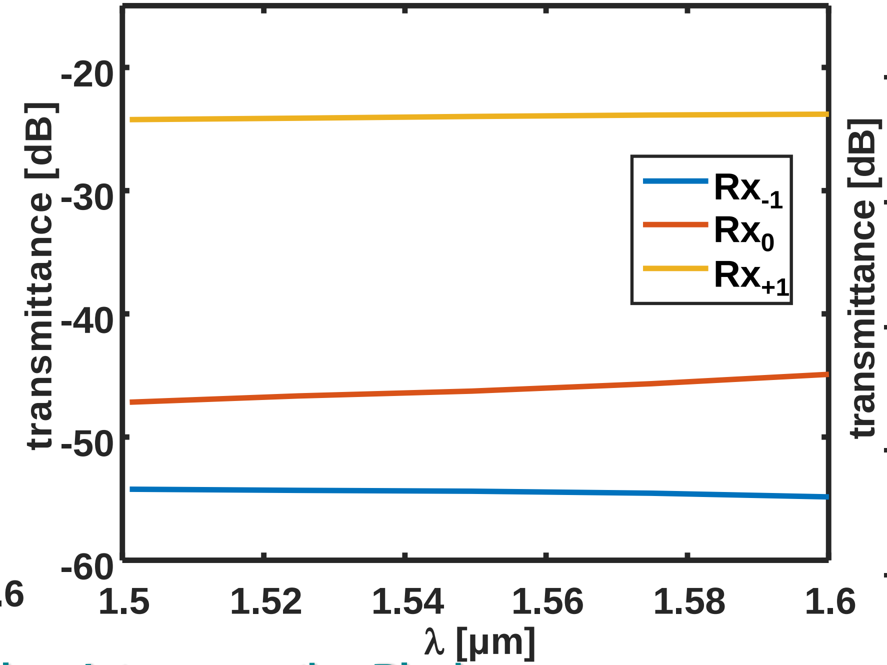
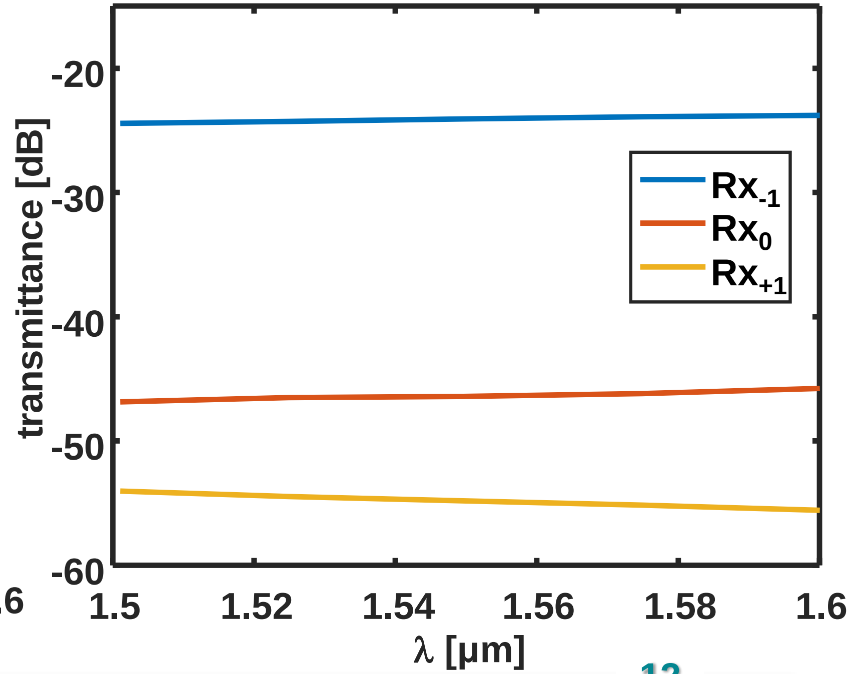




α_{TX}=-120°, α_{RX1}=0°, α_{RX0}=0°, α_{RX-1}=120°







Design of a 1 × 3 Optical Wireless Interconnection Block

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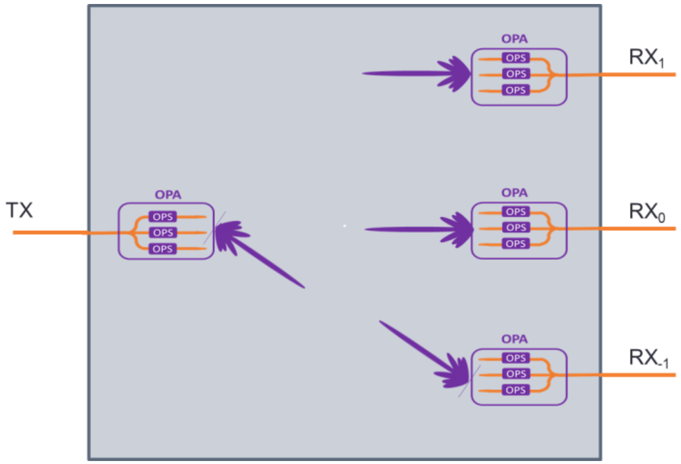
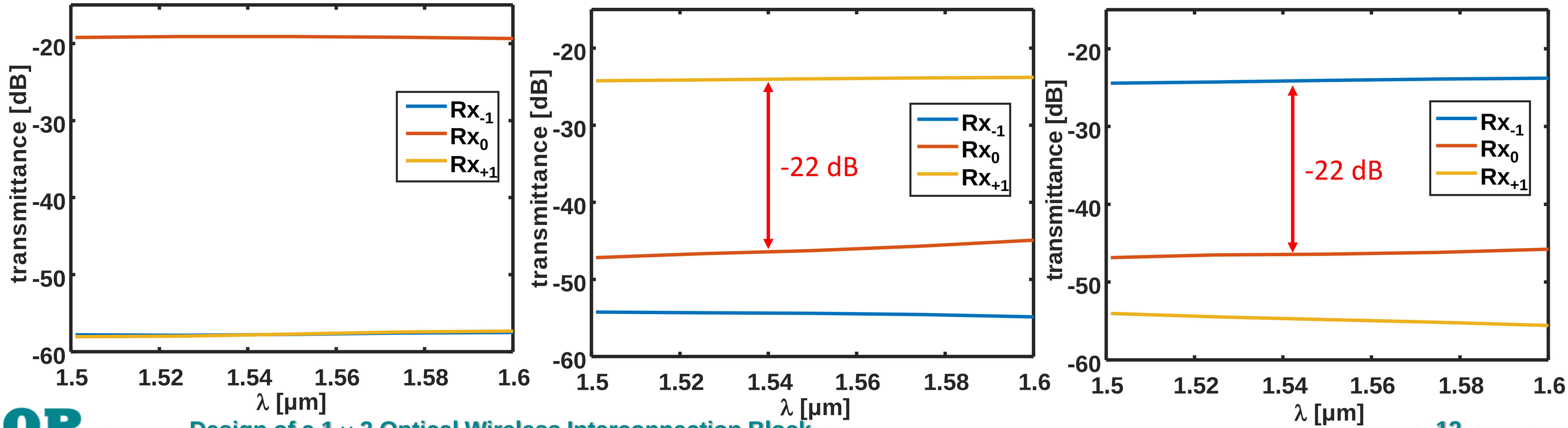


- The worst-case crosstalk (-22 dB) occurs between RX$_0$ and either RX$_{+1}$ or RX$_{-1}$

α_{TX}=-120°, α_{RX1}=0°, α_{RX0}=0°, α_{RX-1}=120°



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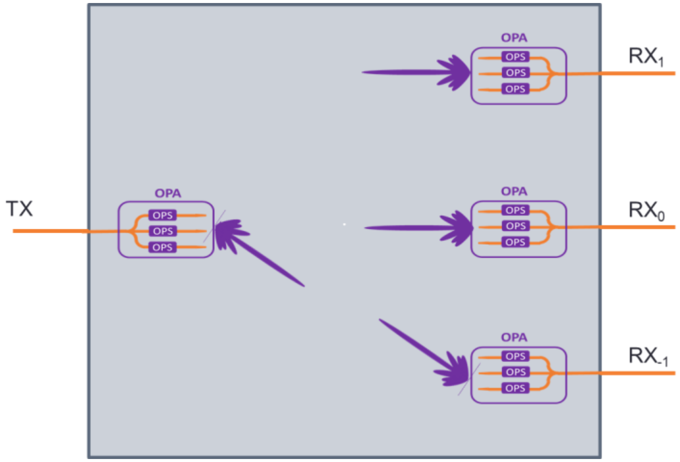
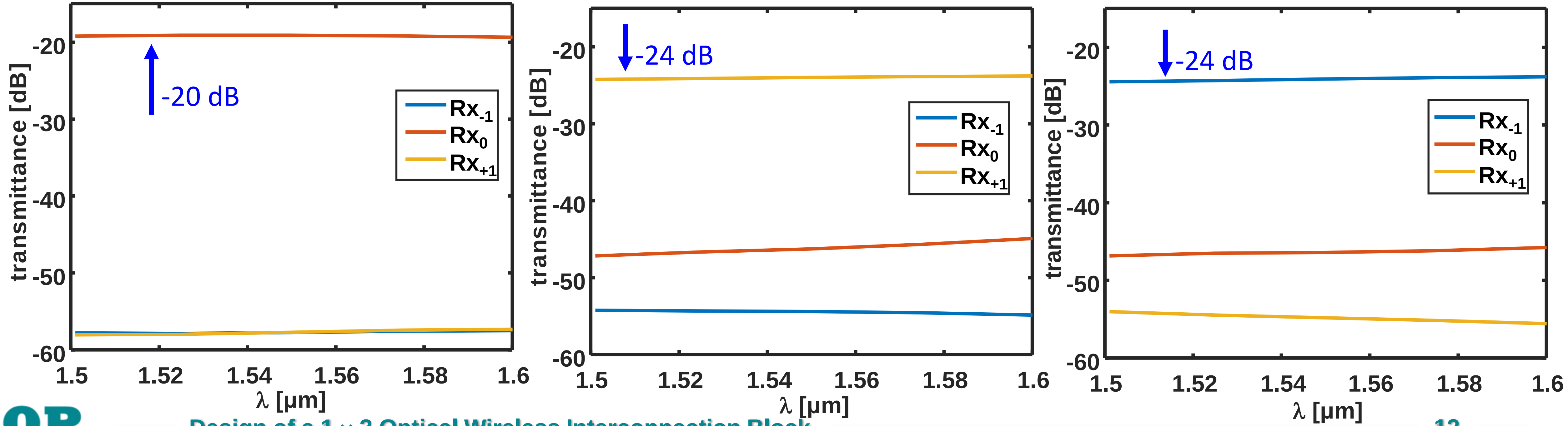


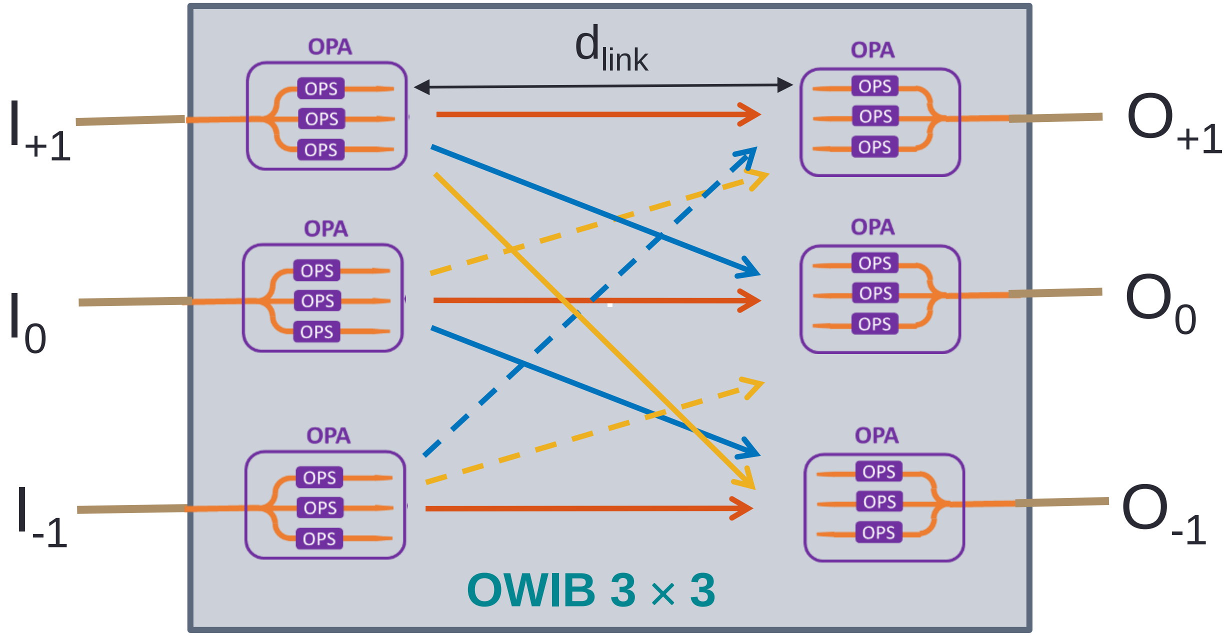
- The worst-case crosstalk (-22 dB) occurs between RX_0 and either RX_{+1} or RX_{-1}
- Insertion losses are about 20 dB for α=0°, and 24 dB for α=120°

α_{TX}=-120°, α_{RX1}=0°, α_{RX0}=0°, α_{RX-1}=120°



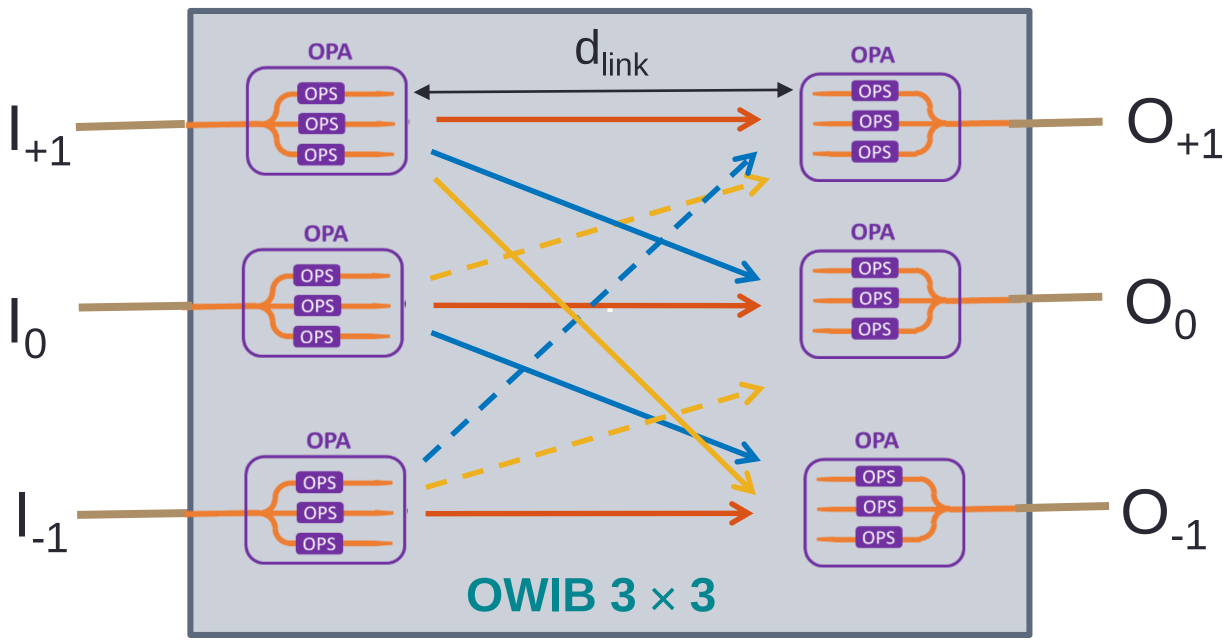
Design of a 3 × 3 Optical Wireless Interconnection Block

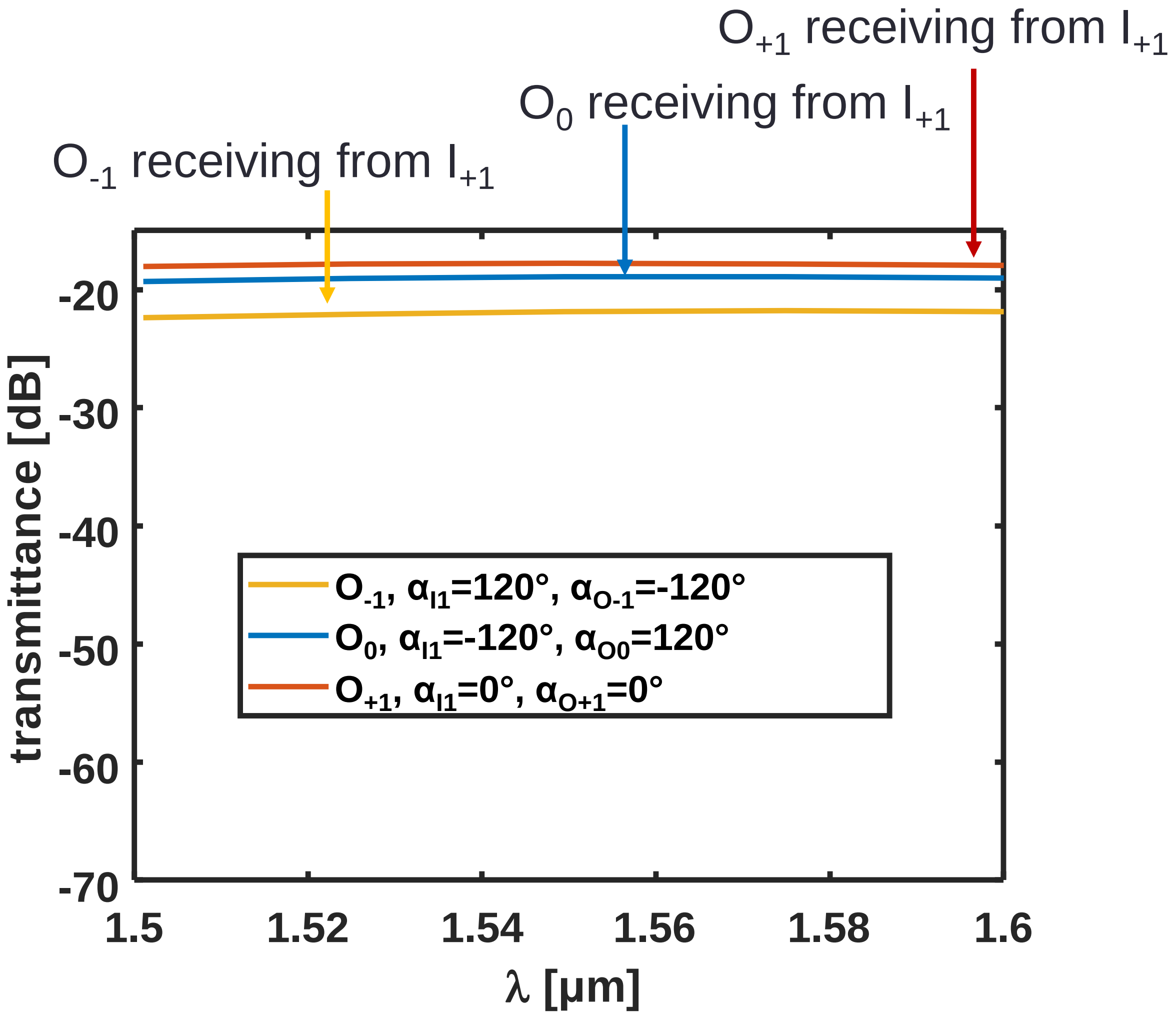
- 3D FDTD simulation of a 3 × 3 Optical Interconnection Block



Design of a 3 × 3 Optical Wireless Interconnection Block

- 3D FDTD simulation of a 3 × 3 Optical Interconnection Block





G. Calò et al., "Design of reconfigurable on-chip wireless interconnections through Optical Phased Arrays", submitted

Conclusions

- On-Chip Optical Wireless Interconnection investigated as a possible alternative/integration to waveguide-based Optical Networks On-Chip
  - Antennas for OWiNoC: Optical Vivaldi Antenna
  - The Optical Communication Link: optimization of the layout
- Fabrication and Measurements
  - Positive effects on the link budget induced by vertical confinement
- A new perspective: wideband switching
  - Possibility of using Optical Wireless Interconnections to realize wideband optical switching exploiting Optical Phased Arrays
  - 3×3 Optical Wireless Interconnection Block