Photonics Research Group

Silicon Nano-Photonics based Arrayed Waveguide Gratings

Shibnath Pathak

Promotors: Prof. Wim Bogaerts & Prof. Dries Van Thourhout

UNIVERSITEIT GENT

imec

Photonics Research Group

"a wafer of silicon with oxide cladding"

"the art of playing with light in all its forms"

Silicon Nano–Photonics based Arrayed Waveguide Gratings

"Device with nanometer–scale size and accuracy"

"We will talk about rest of the evening"

Shibnath Pathak

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Evolution in Communication

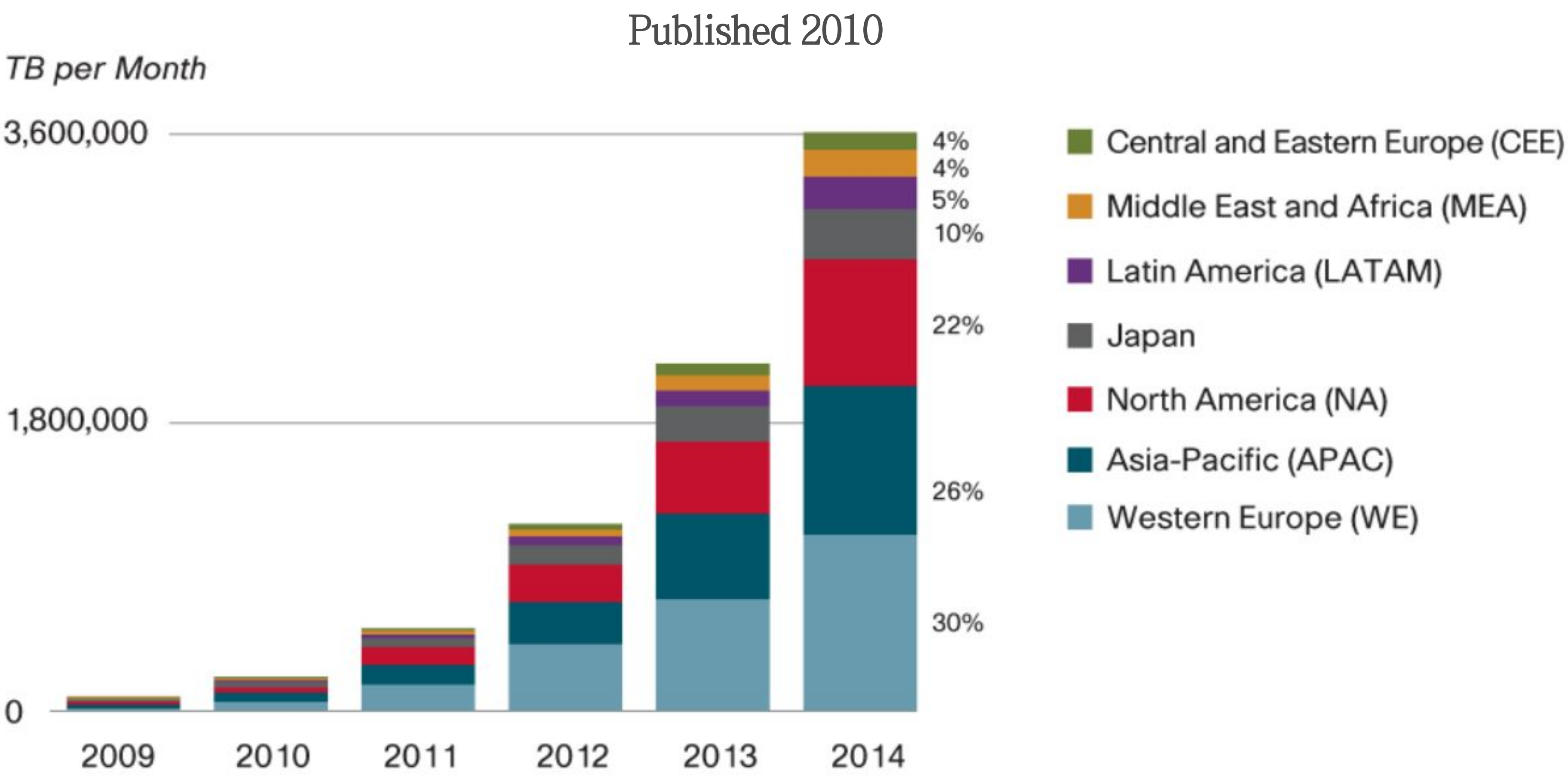
Evolution in Communication

High speed Data

Today's requirements

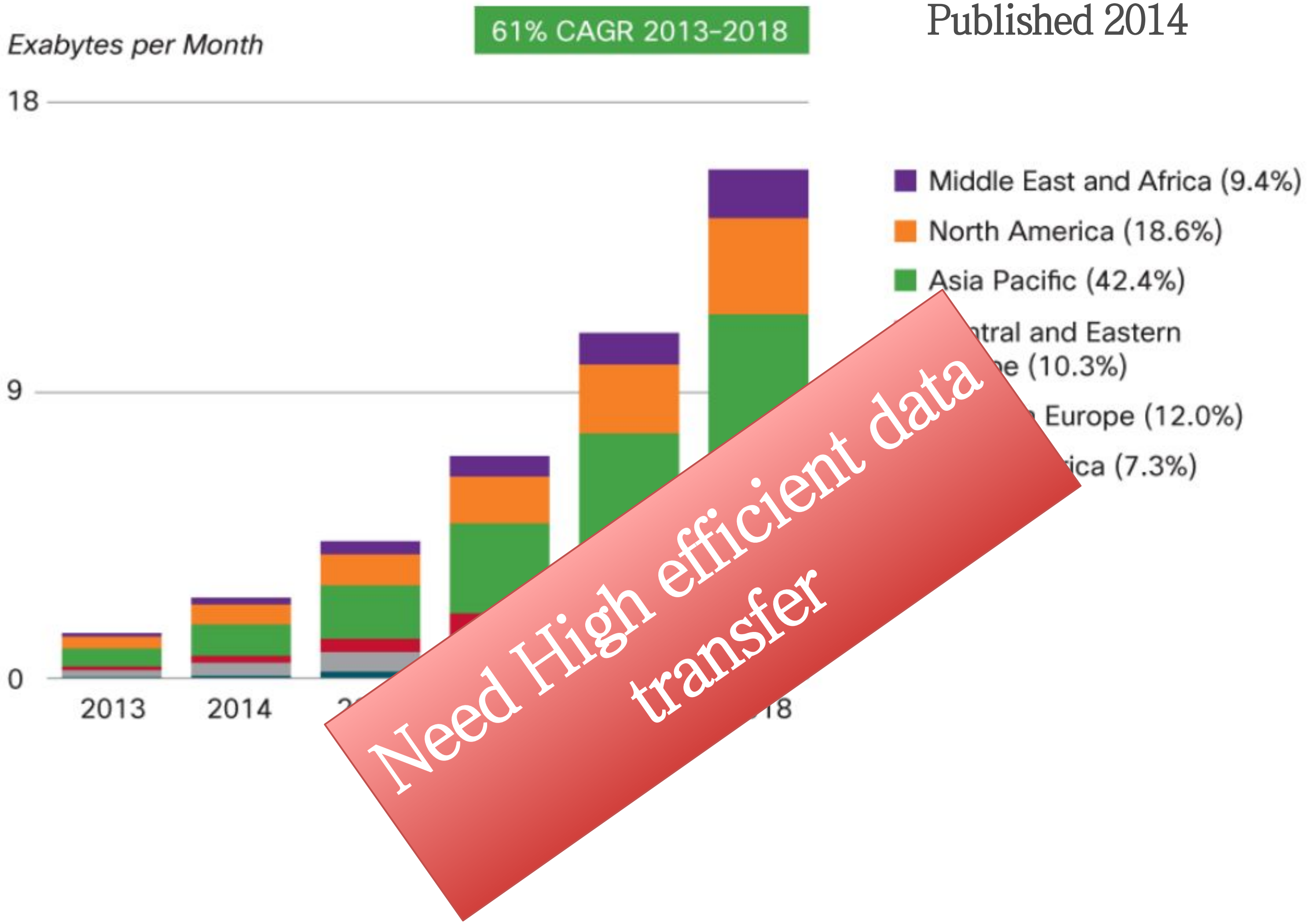
High speed Data

Global Mobile Data Traffic Forecast

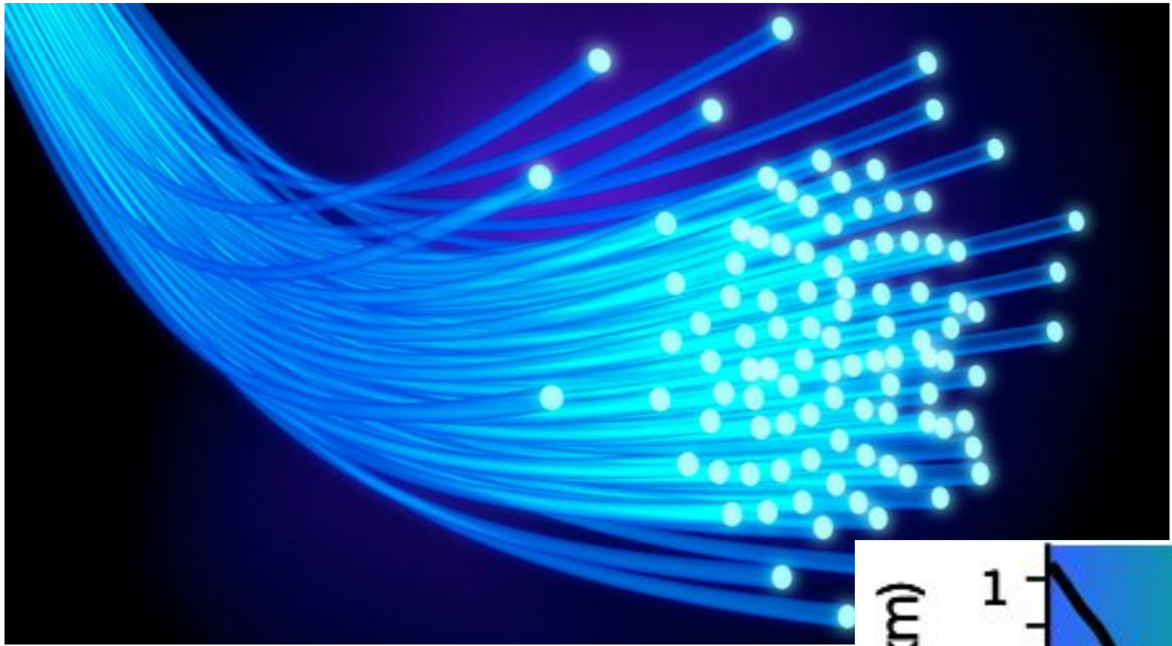


Global Mobile Data Traffic Forecast

Published 2014



Optical Fiber

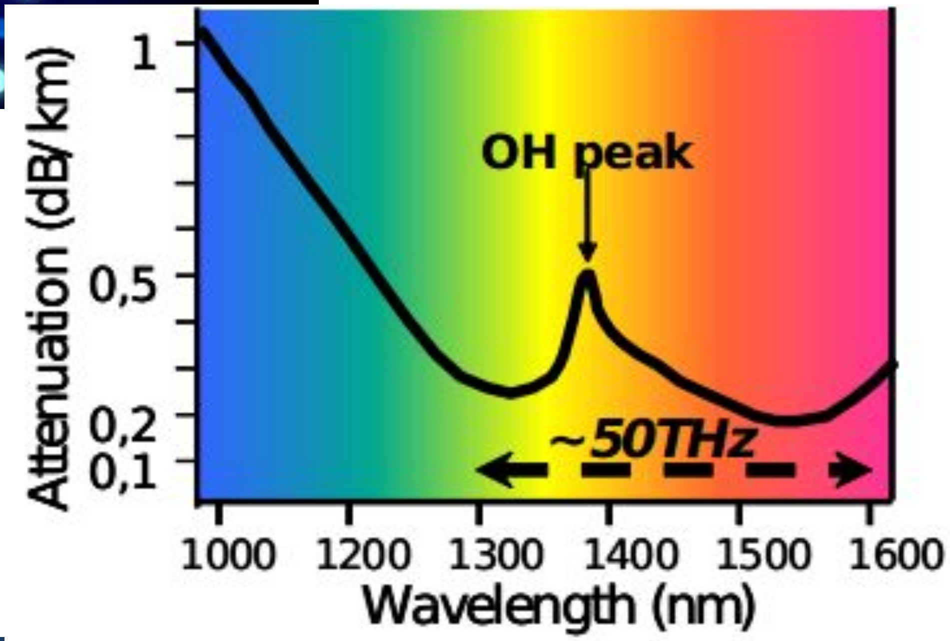


Very low attenuation

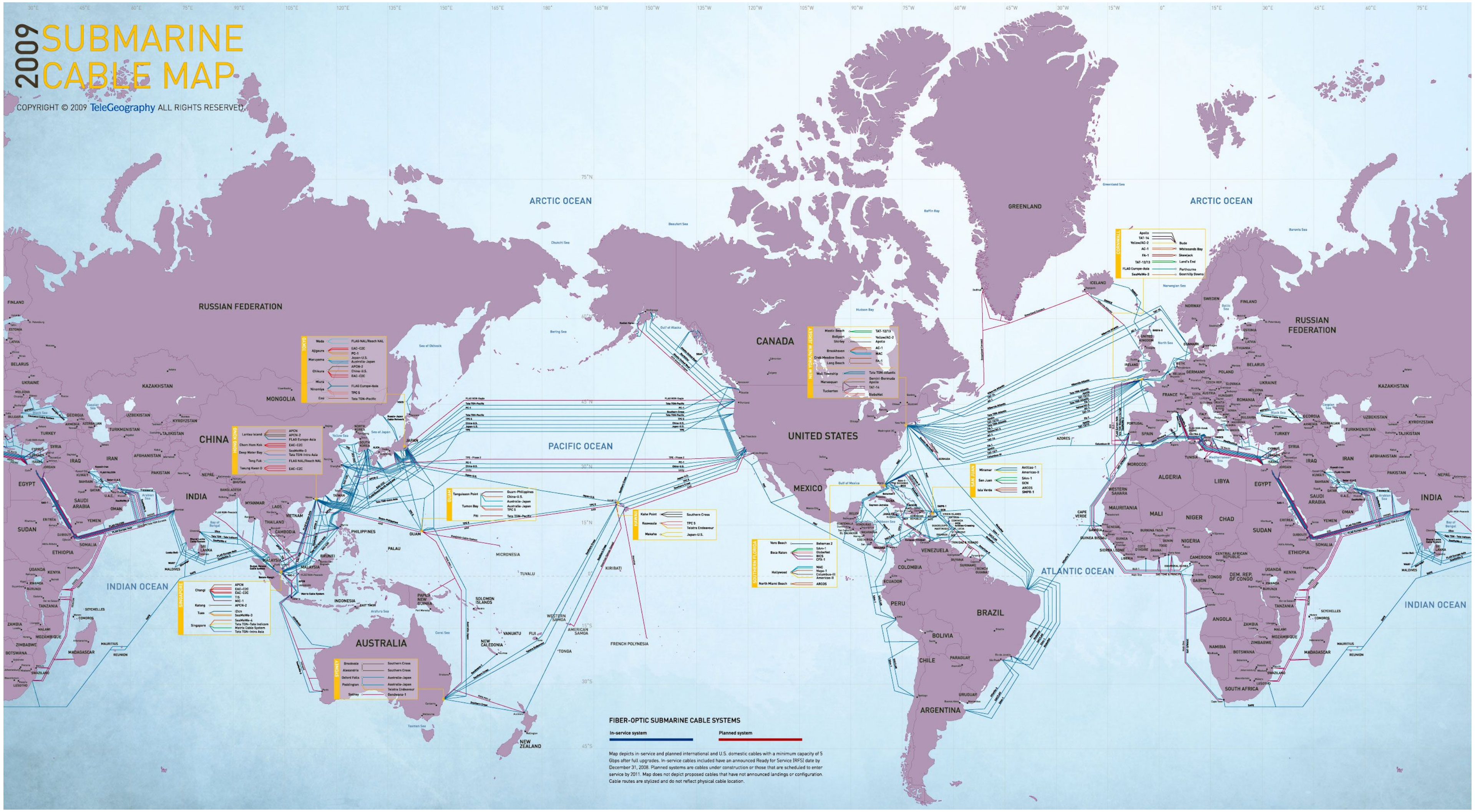
0.3dB/km @ 1310nm

0.2dB/km @ 1550nm

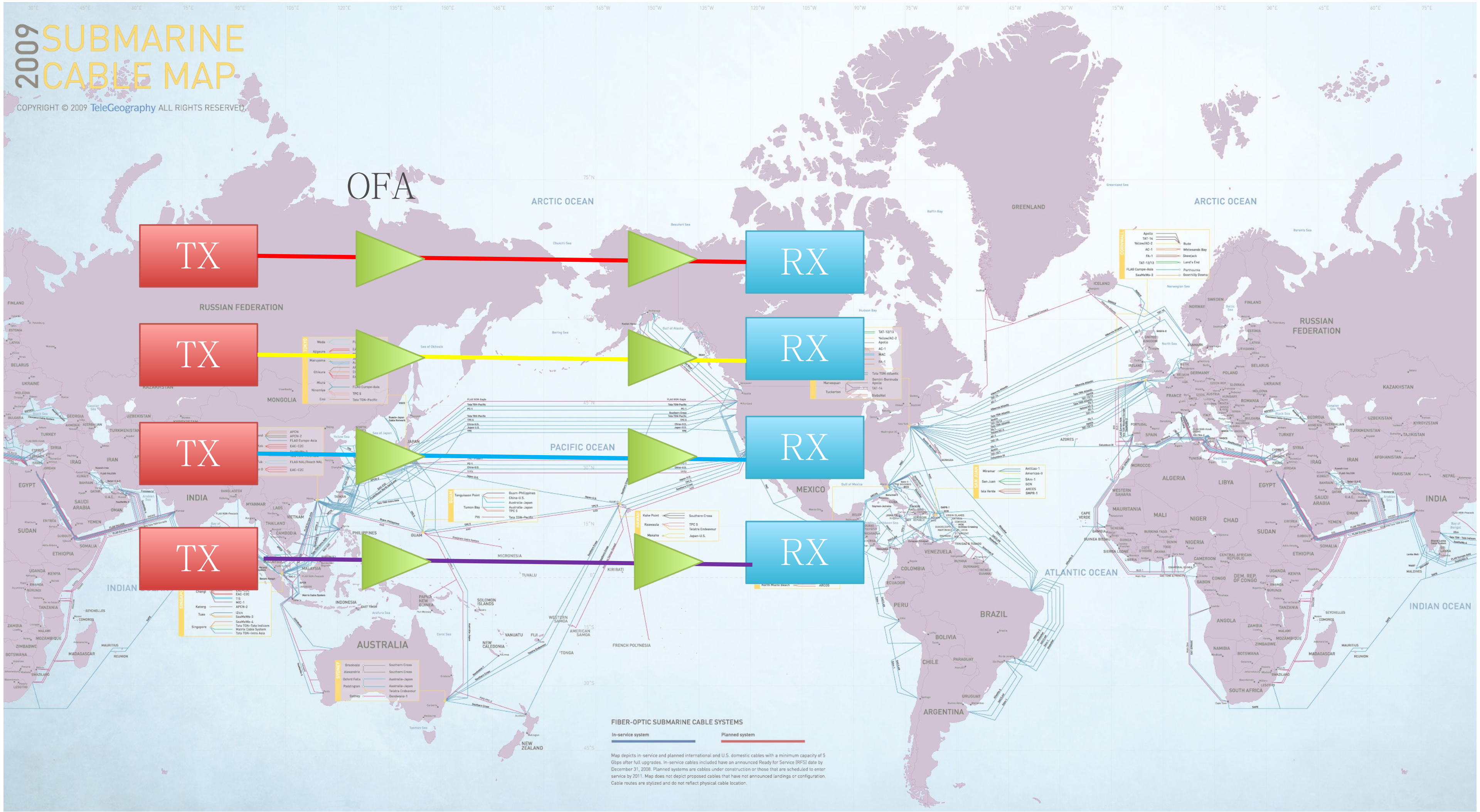
Huge available bandwidth Virtually 50THz



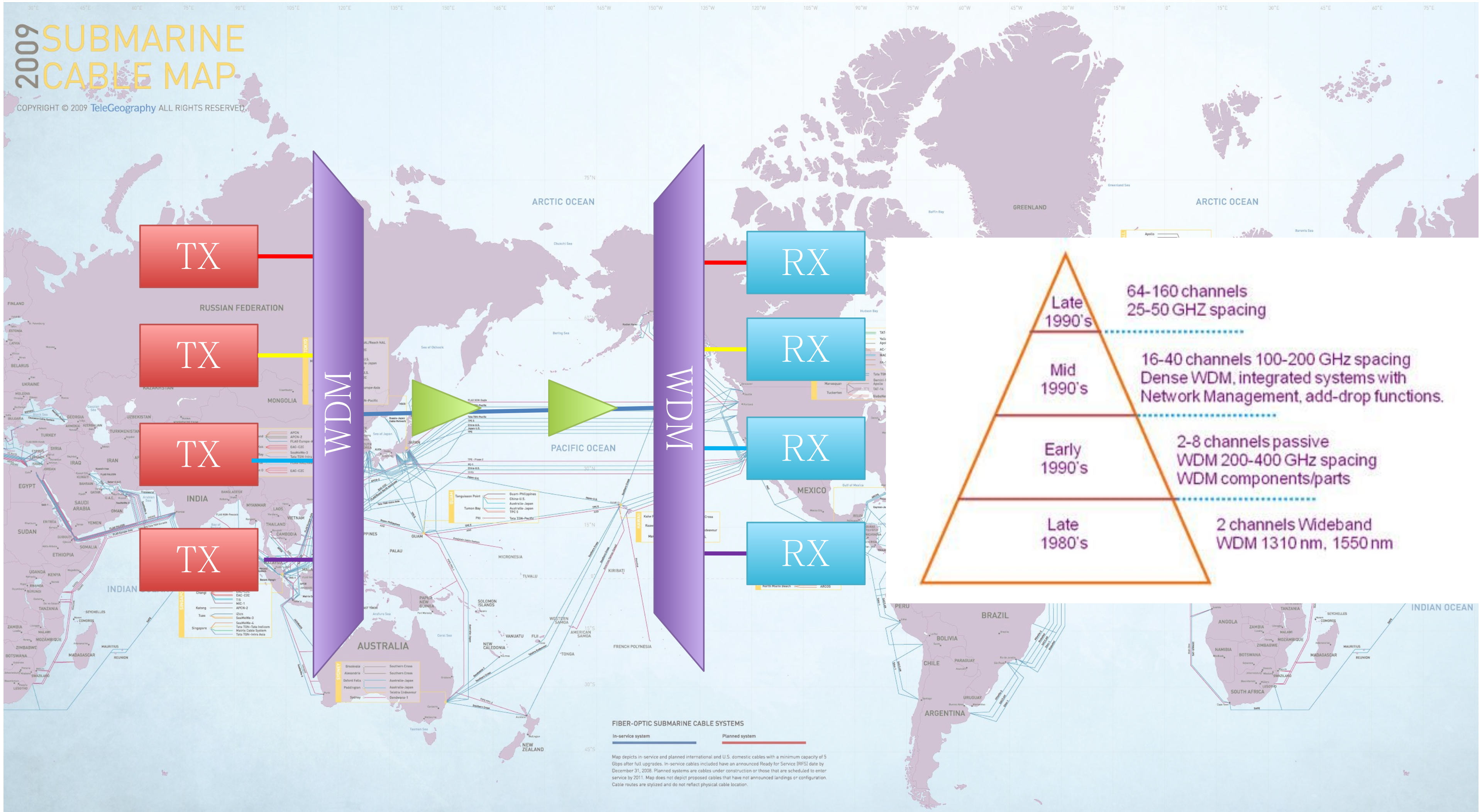
Optical Fiber



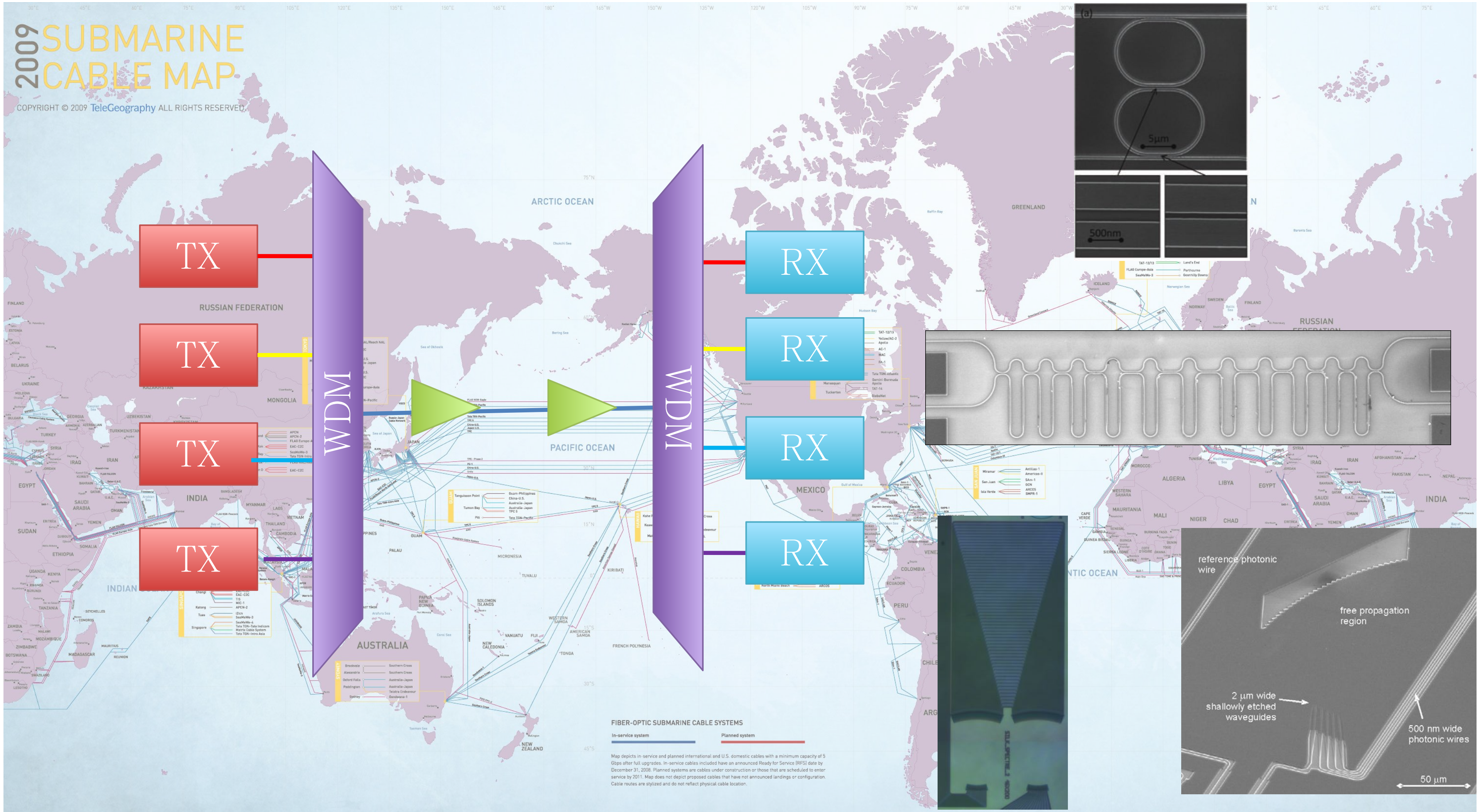
Optical Fiber



Wavelength Division Multiplexing (WDM)

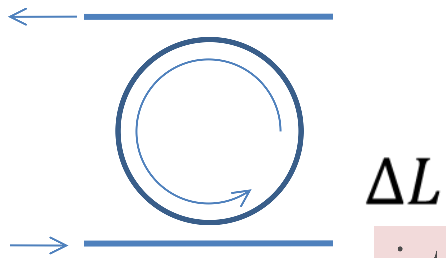


Wavelength Division Multiplexing (WDM)

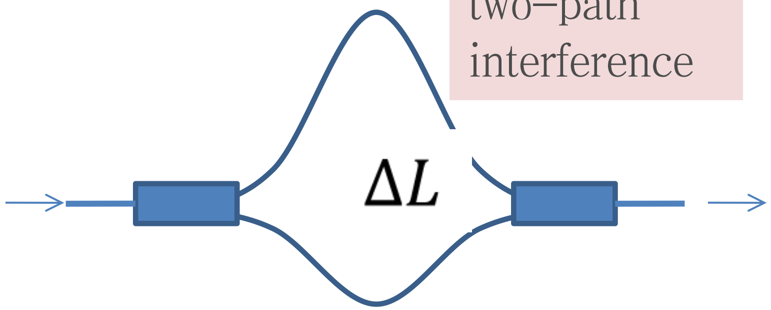


WDM: Optical delay

Ring resonators



interference
with self
(resonance)



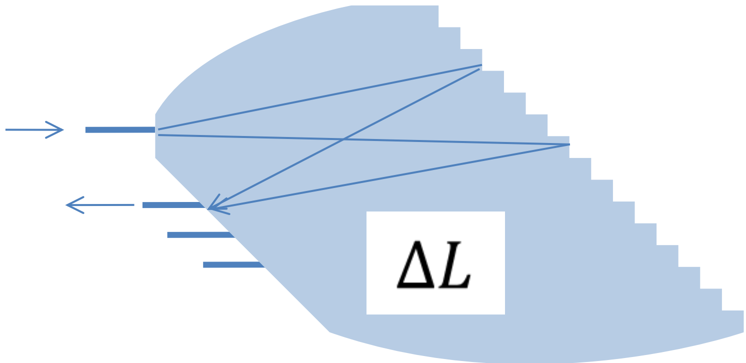
two–path
interference

Mach–Zehnders

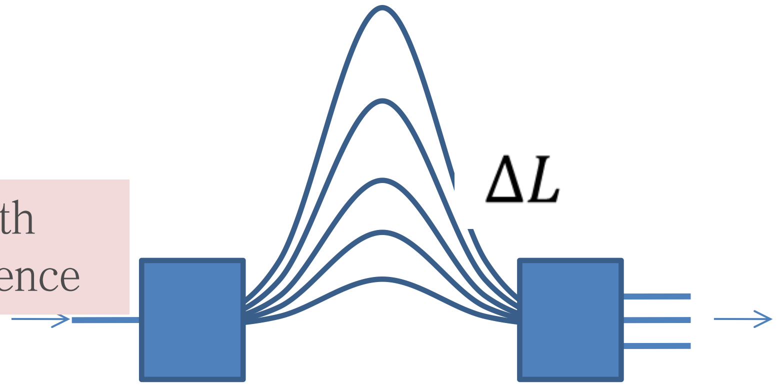
wavelength filter condition

$$m \cdot \lambda = \Delta L \cdot n_{eff}$$

Echelle gratings



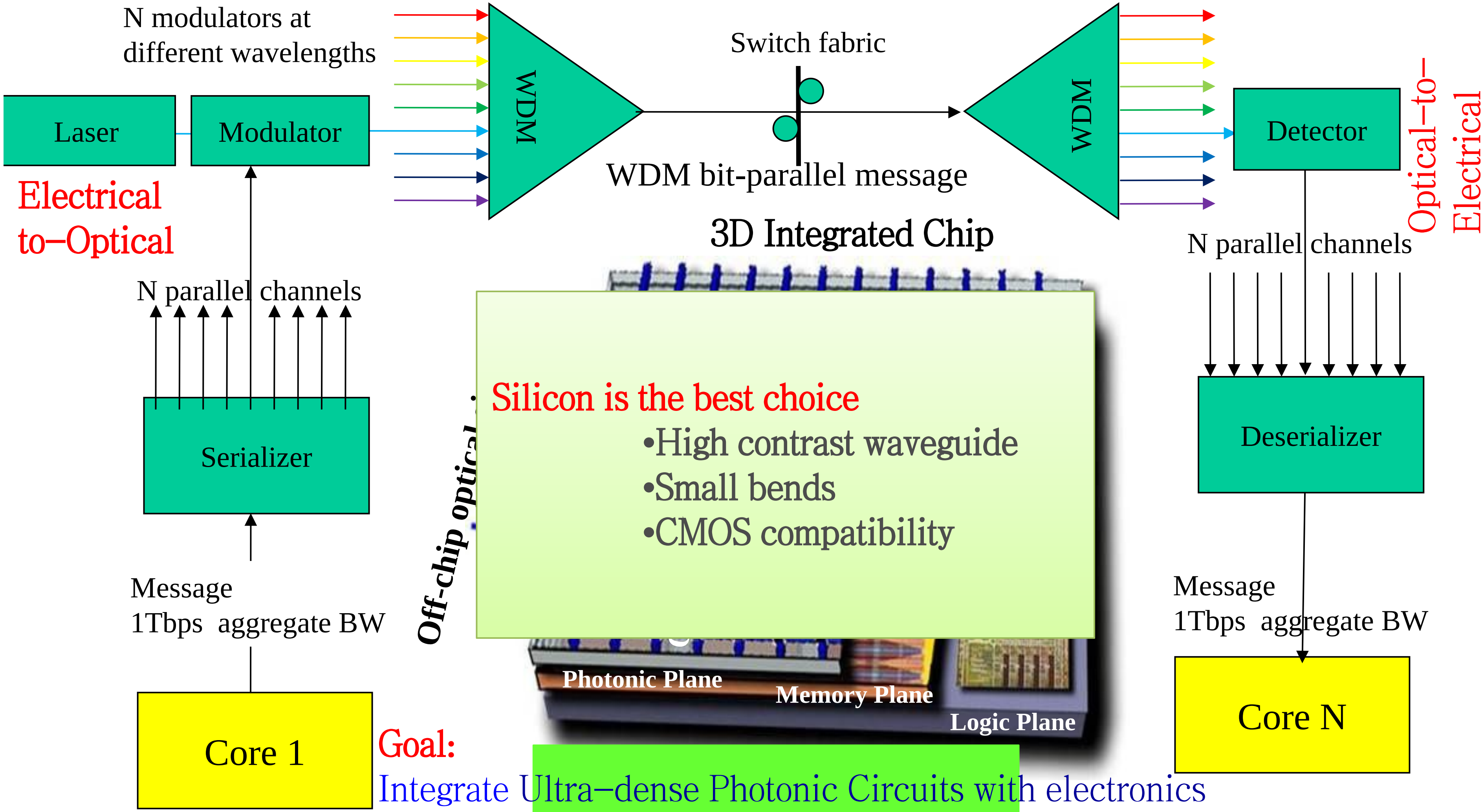
multipath
interference



Arrayed waveguide gratings

IBM Vision for 2020: On-chip interconnect

Nano-photonics for Optically connected 3-D Supercomputer Chip



Silicon is the best choice

- High contrast waveguide
- Small bends
- CMOS compatibility

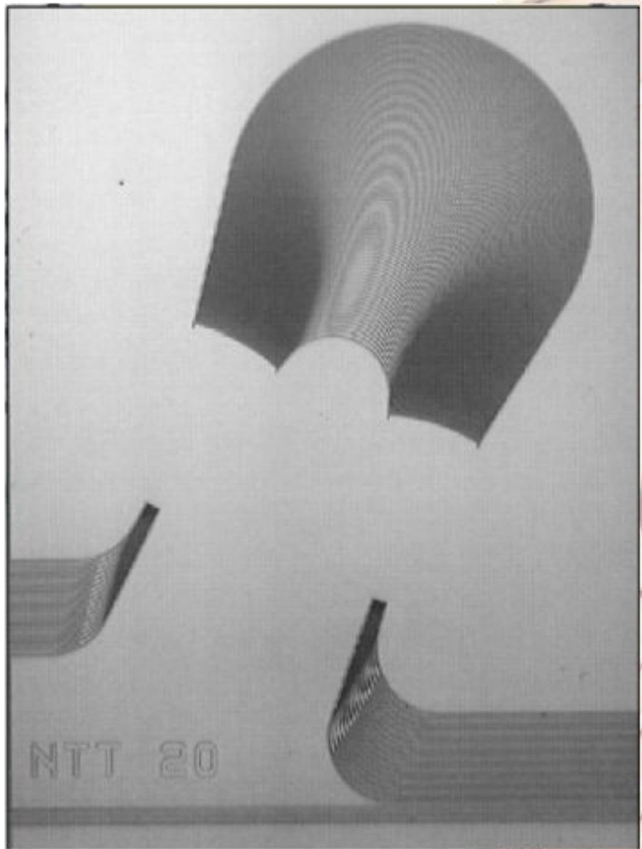
Goal:

Integrate Ultra–dense Photonic Circuits with electronics

– Allow on–chip optical routing and interconnect

Silicon AWG

40 X 100 GHz Silica AWG



Bend Radius 1mm
Core 3.5X3.5 μm²
Device Size 9X12 mm²
n_core = 1.482 n_clad = 1.44

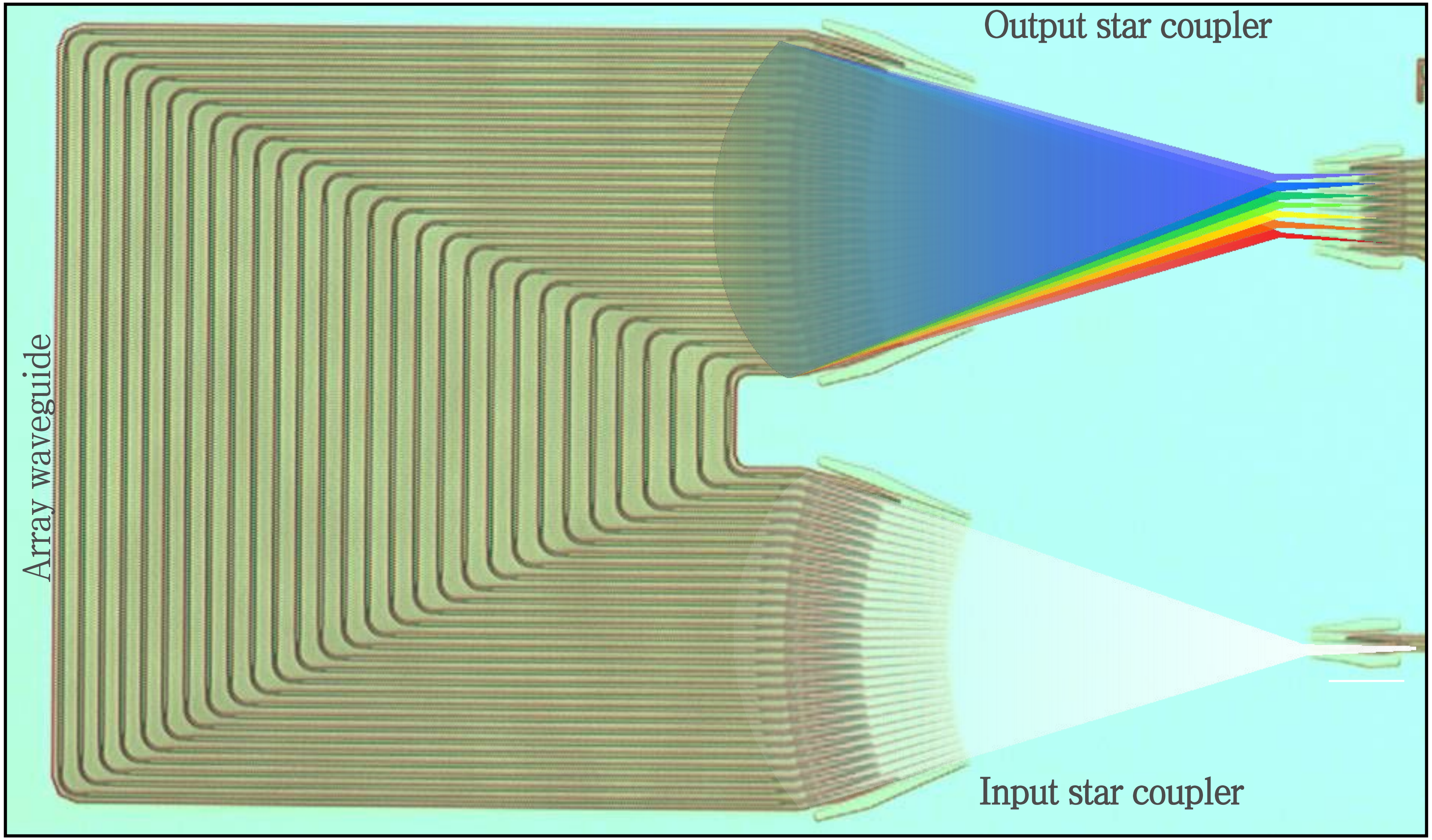
64 X 50 GHz InP AWG

Bend Radius 0.5mm
Core 2.0X0.5 μm²
Device Size 3.6X7 mm²
n_core = 3.3 n_clad = 1.7

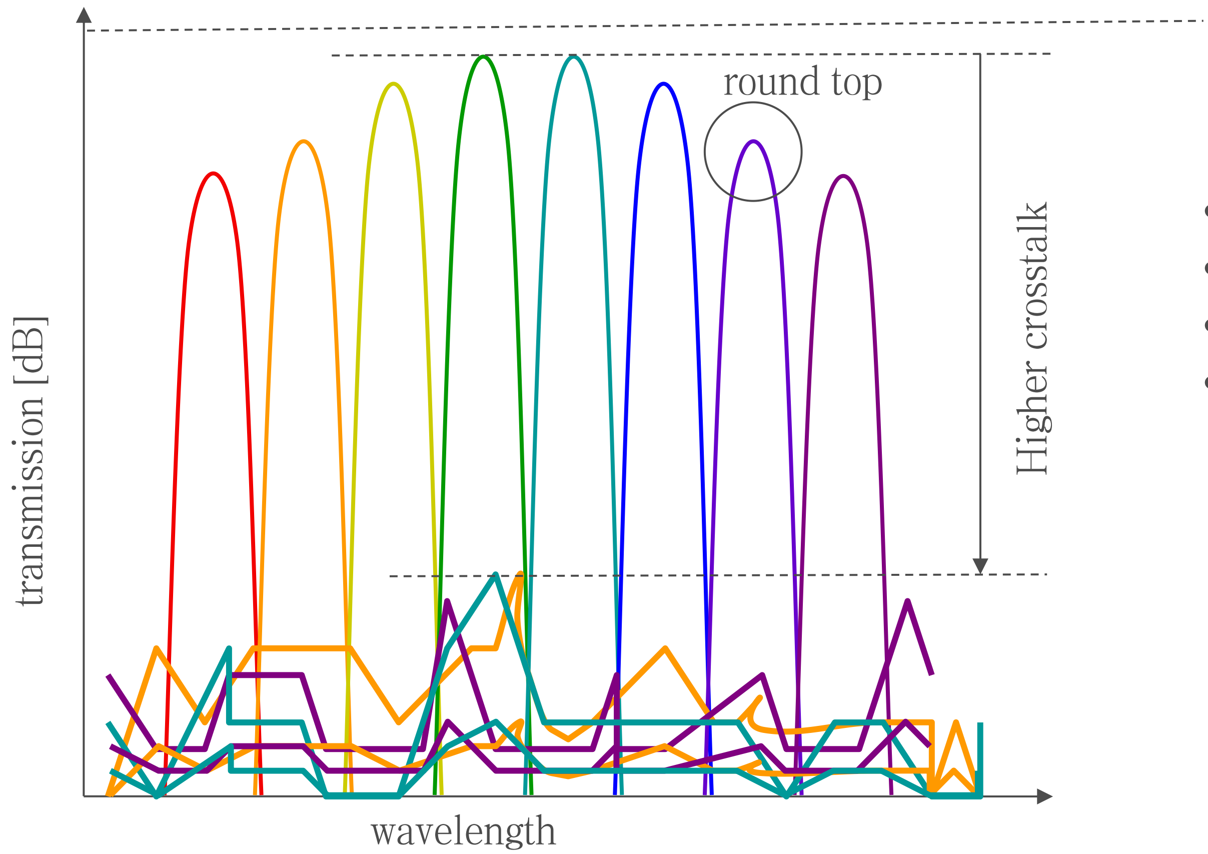
16 X 200 GHz Silicon AWG

Bend Radius 0.005mm
Core 0.8X0.22 μm²
Device Size 0.850X0.340 mm²
n_core = 3.48 n_clad = 1.44

Arrayed Waveguide Grating (AWG)



Problems in Silicon AWG



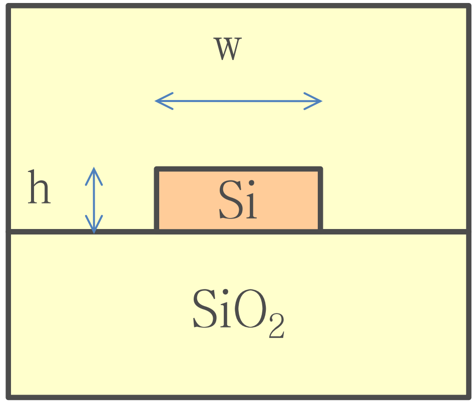
- High Insertion Loss
- High Crosstalk
- Channel Spacing Mismatch
- Round Top

High Sensitivity

wire width $$\frac{\partial\lambda}{\partial w} \approx 1\,{}^{nm}/_{nm}$$

wire height $$\frac{\partial\lambda}{\partial h} \approx 2\,{}^{nm}/_{nm}$$

temperature $$\frac{\partial\lambda}{\partial T} \approx 0.08\,{}^{nm}/_{K}$$



Good geometry control is required

Structure the outline

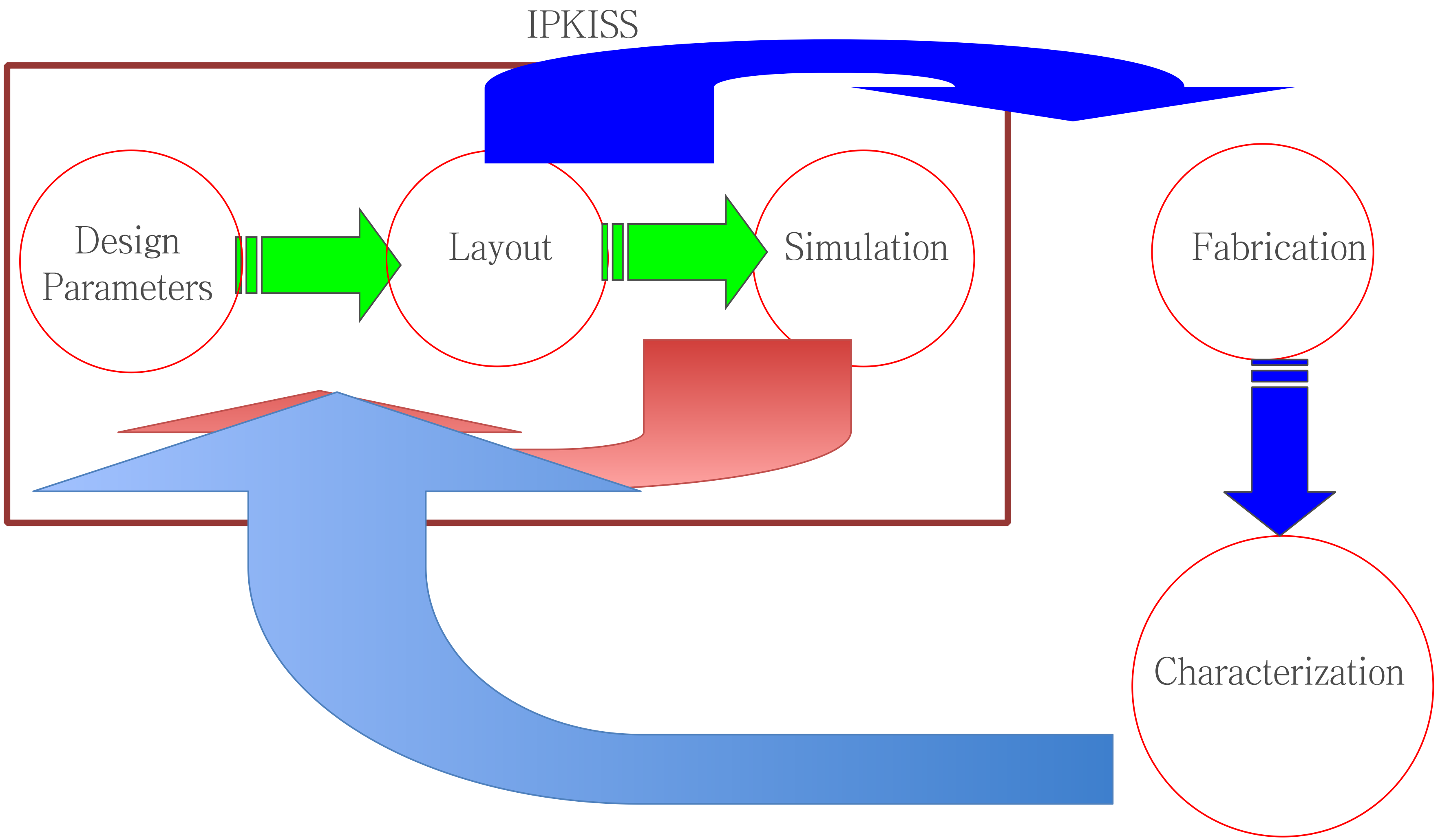
+ Our approach
+ Our results
+ Conclusions

Structure the outline

– Our approach
  - Design
  - Simulation
  - Fabrication
  - Measurement

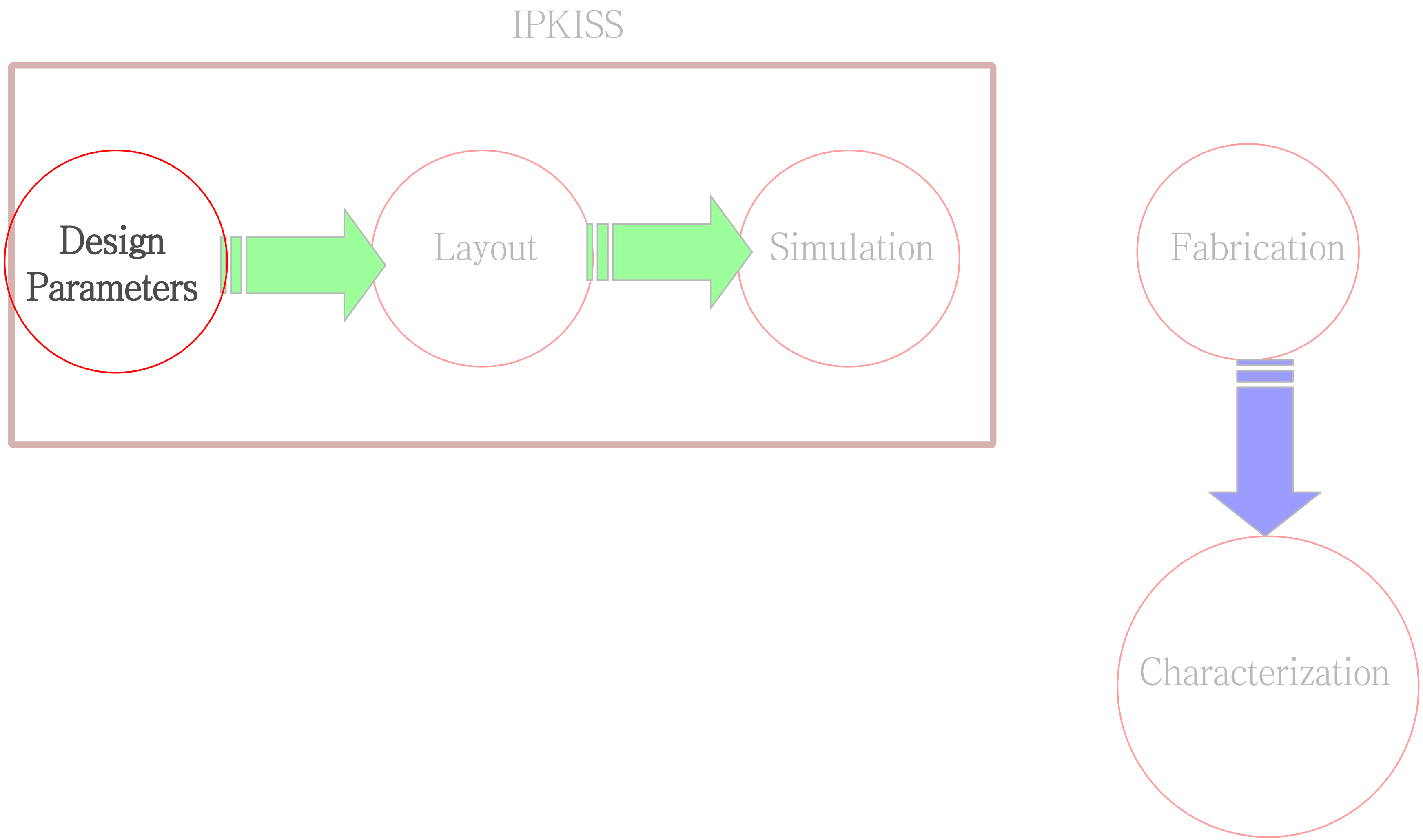
+ Our results
+ Conclusions

Framework



IPKISS
Design Parameters
Layout
Simulation
Fabrication
Characterization

Framework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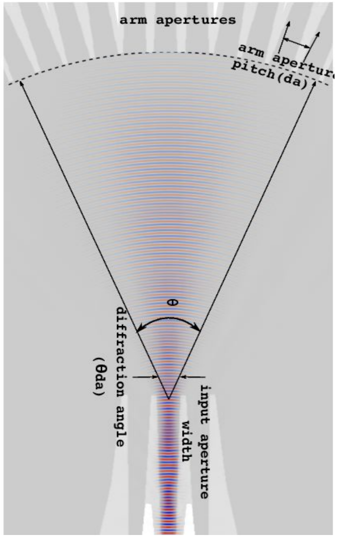
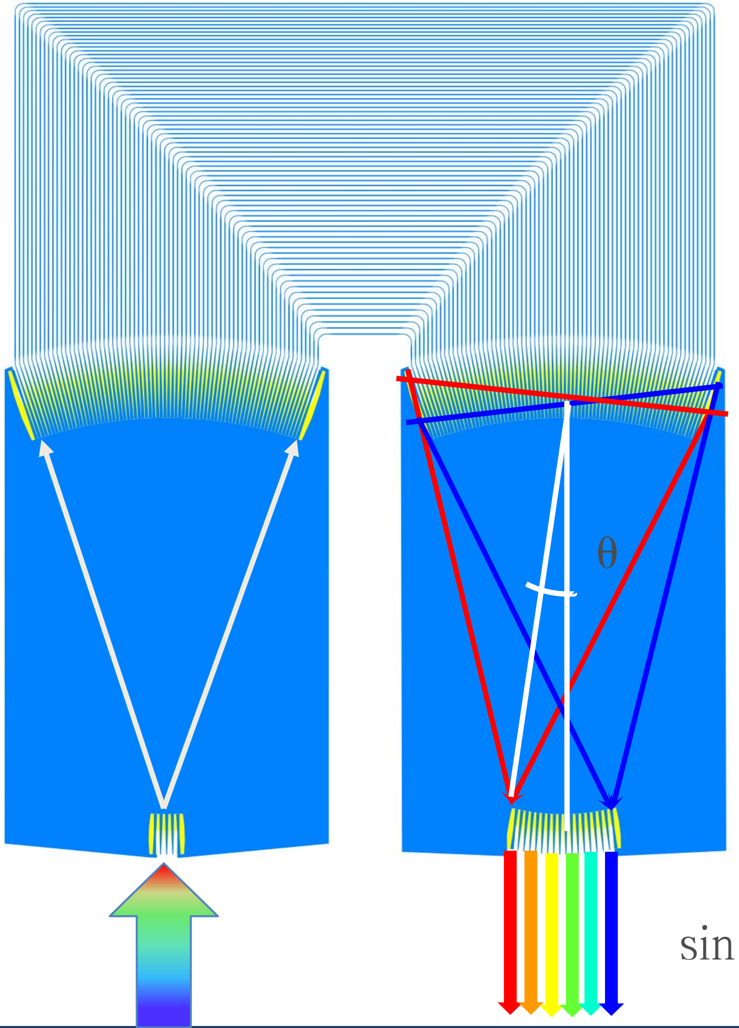
Design Parameters

$$Ra = \frac{d_a \cdot N_{arms}}{\theta_{da}}$$





$$\text{坡}L = m \cdot \lambda_c / n_{wg}(\lambda c)$$

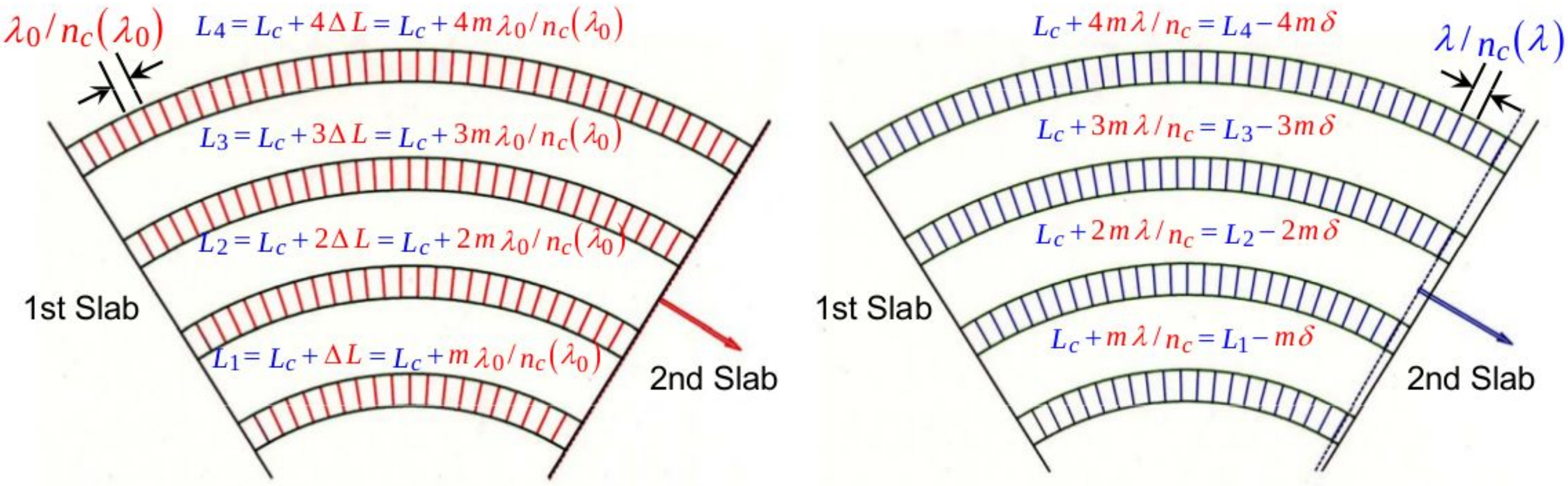
$$\sin\theta = \frac{n_{wg}(\lambda) \cdot \lambda_c \text{埿} n_{wg}(\lambda_c) \cdot \lambda}{m \cdot n_{wg}(\lambda_c) \cdot n_{slab}(\lambda) \cdot d_a}$$

Phase Fronts in Array waveguides

$\lambda = \lambda_0$

$$\boxed{\Delta L = m\frac{\lambda_0}{n_c(\lambda_0)} \Rightarrow \lambda_0 = \frac{n_c \Delta L}{m}}$$

$\lambda < \lambda_0$

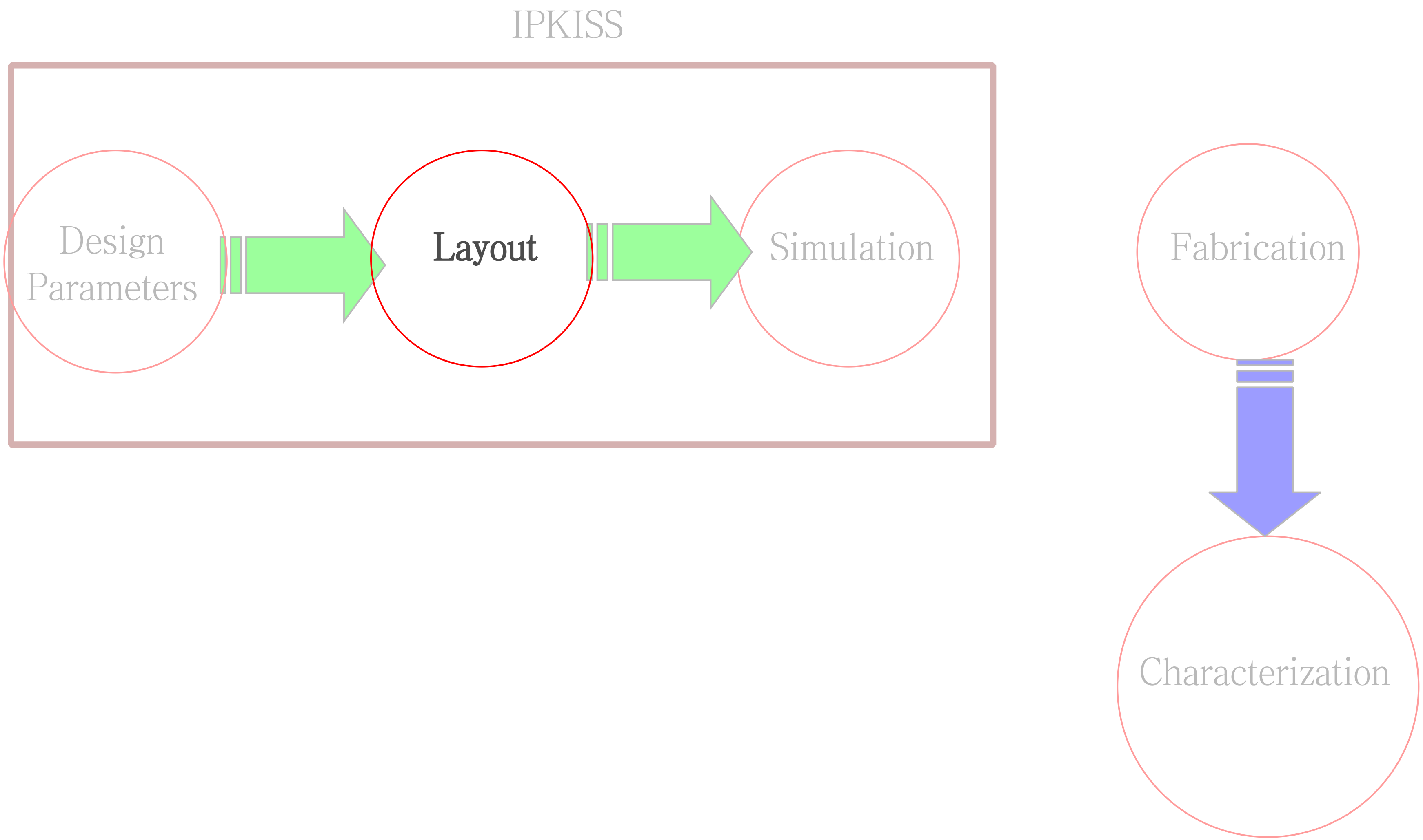


$$\delta = \frac{\lambda_0}{n_c(\lambda_0)} - \frac{\lambda}{n_c(\lambda)}$$

(a) Phase relation for $\lambda = \lambda_0$

(b) Phase relation for $\lambda < \lambda_0$

Framework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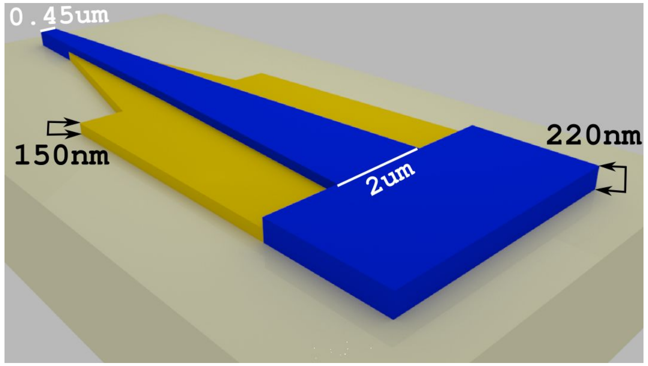
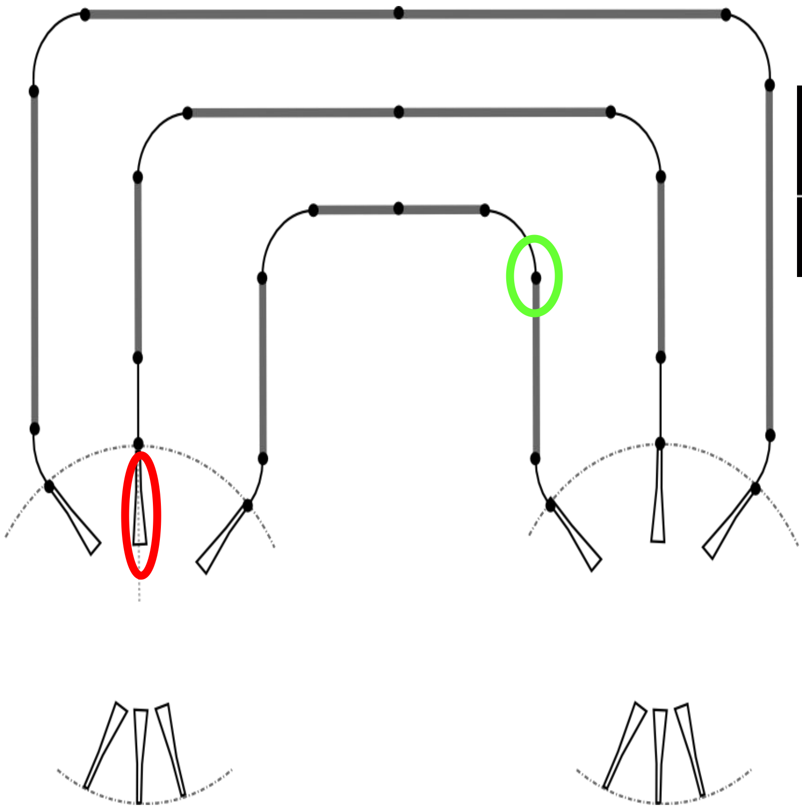
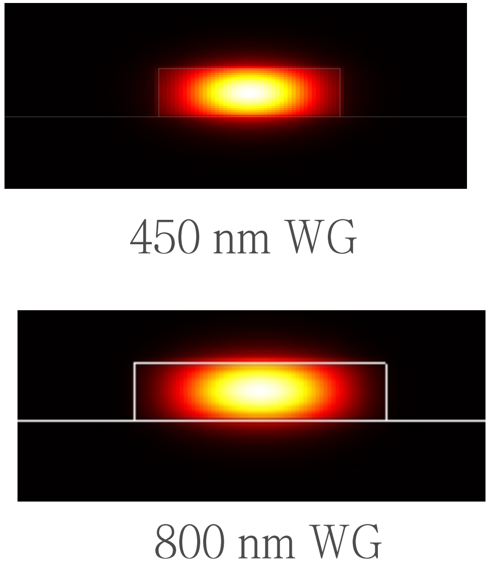
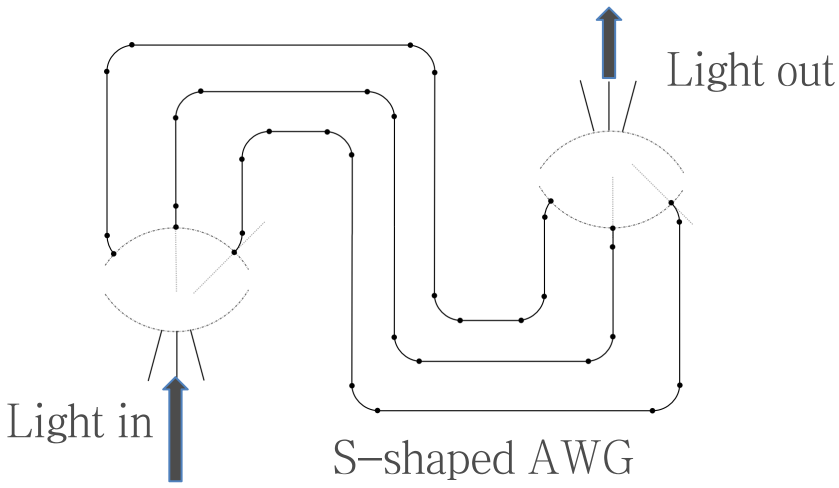
Design of Silicon AWG

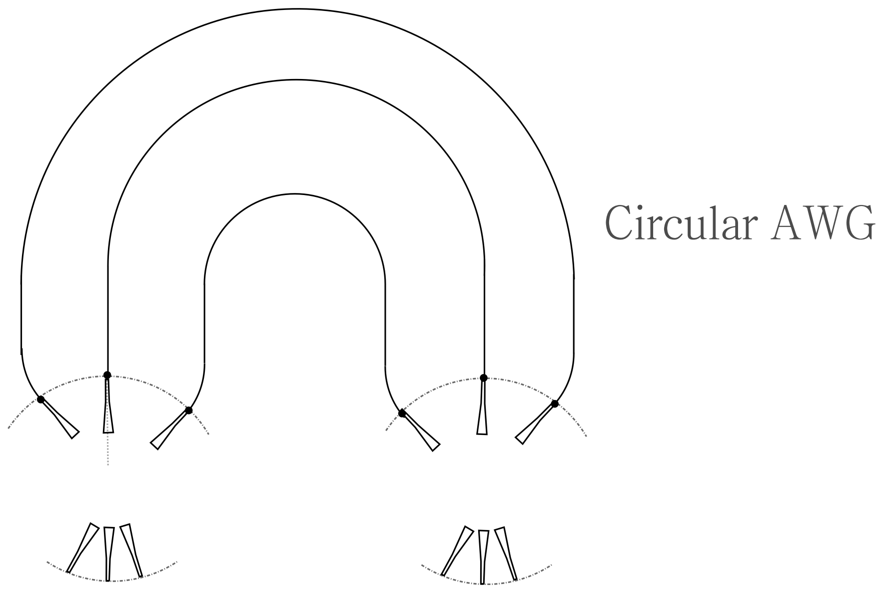


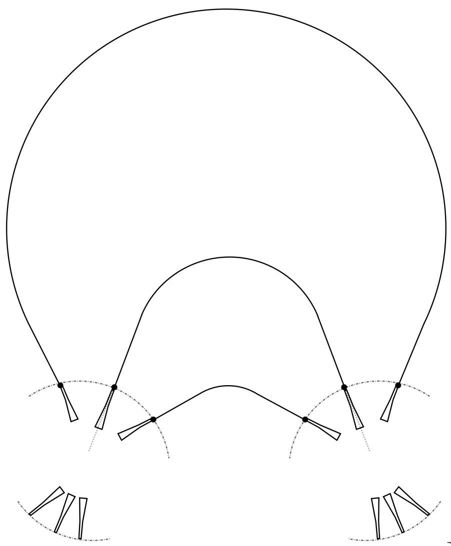


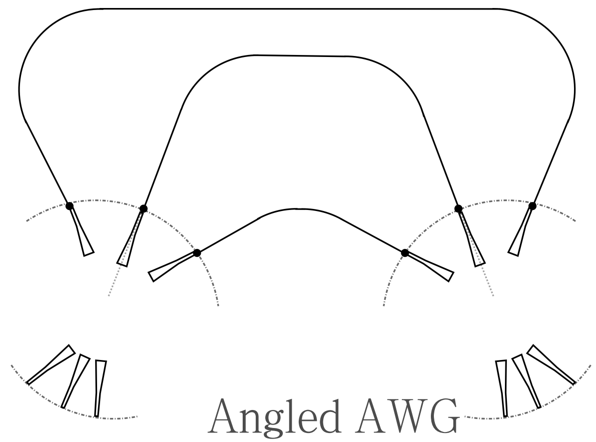


Different shaped AWGs

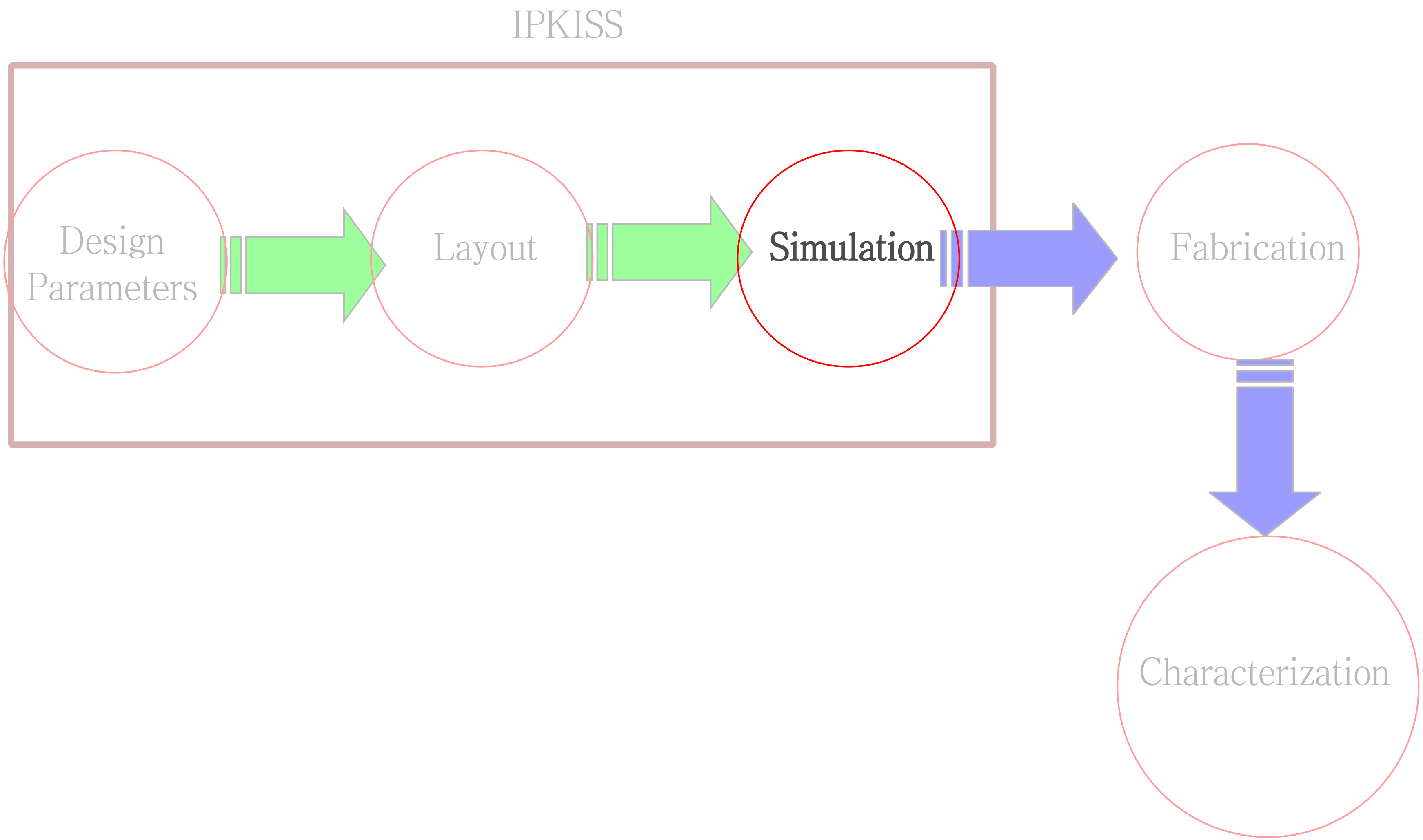








Framework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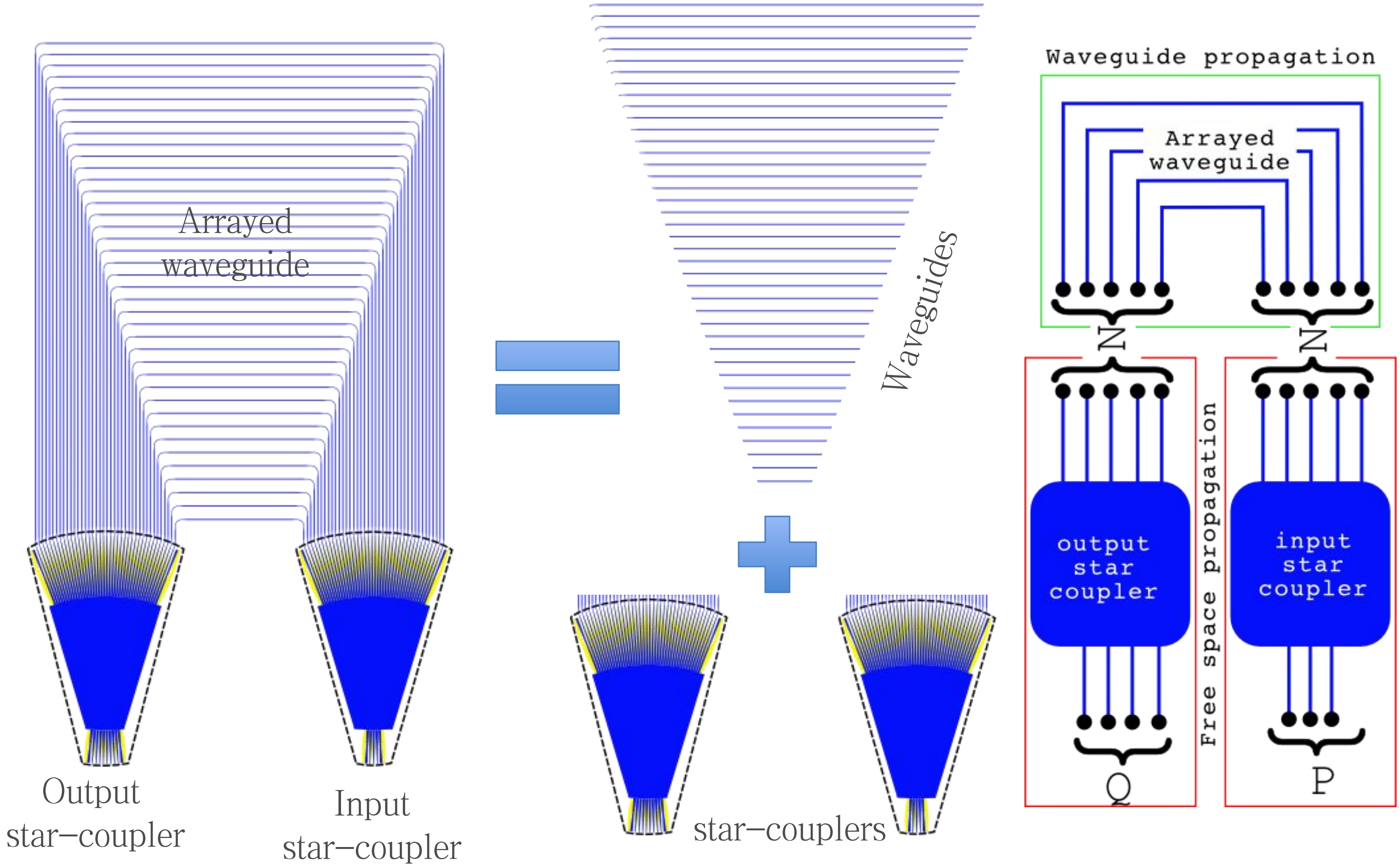
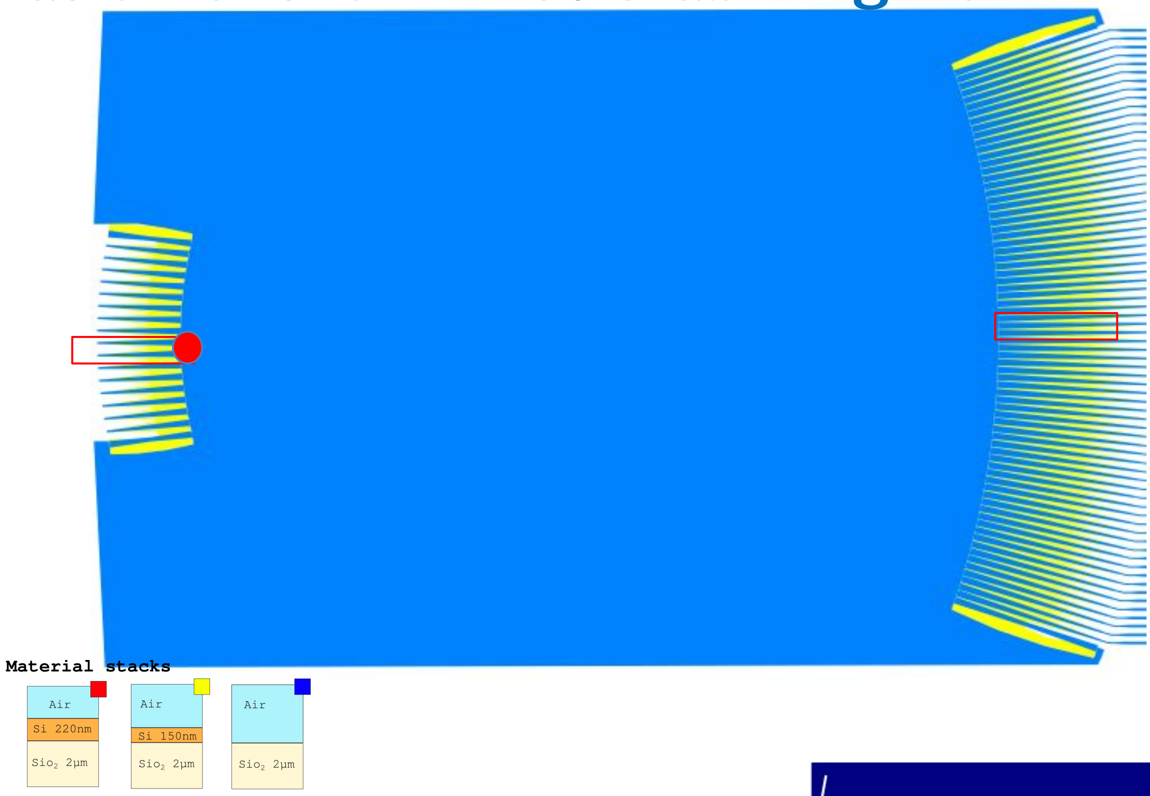
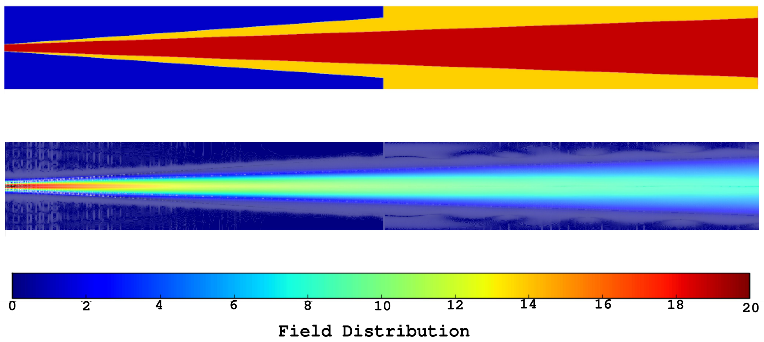
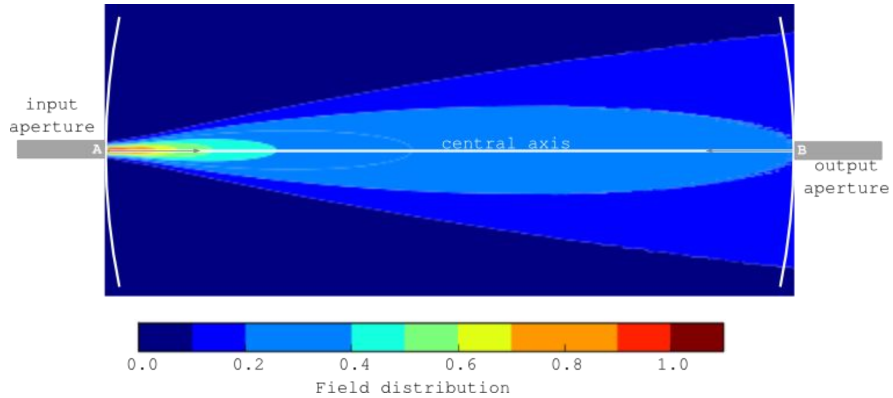
Simulation of the AWG: Decomposition



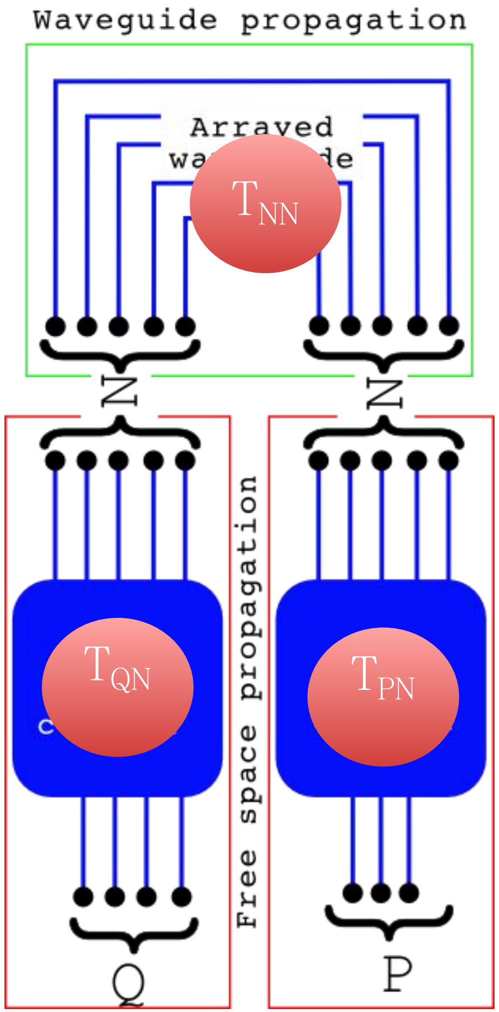
Simulation of the AWG: Slab Engine





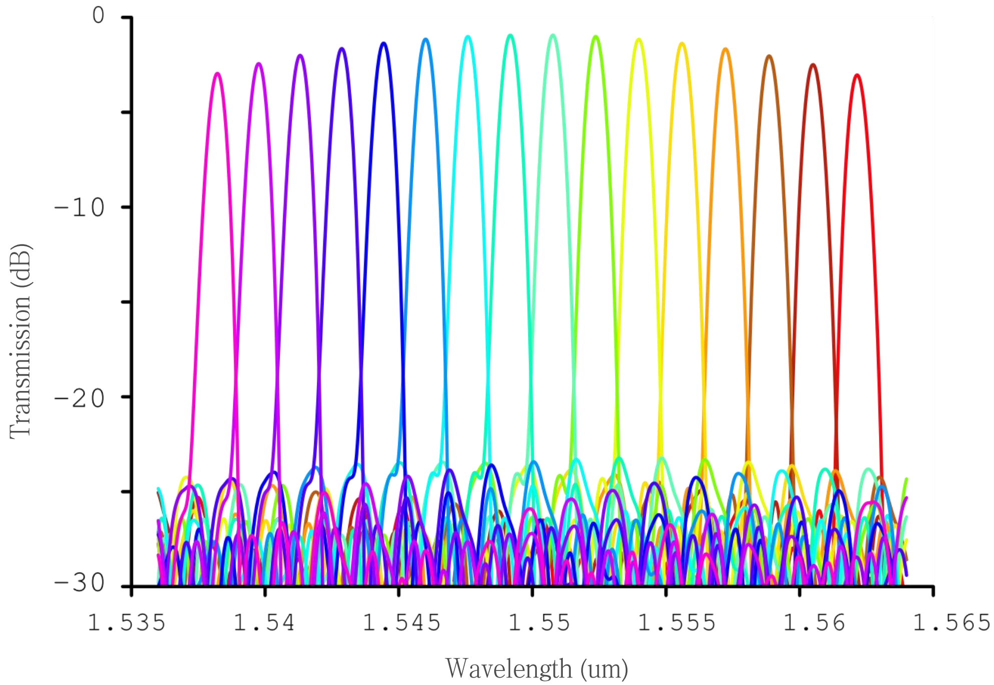


Simulation of the AWG

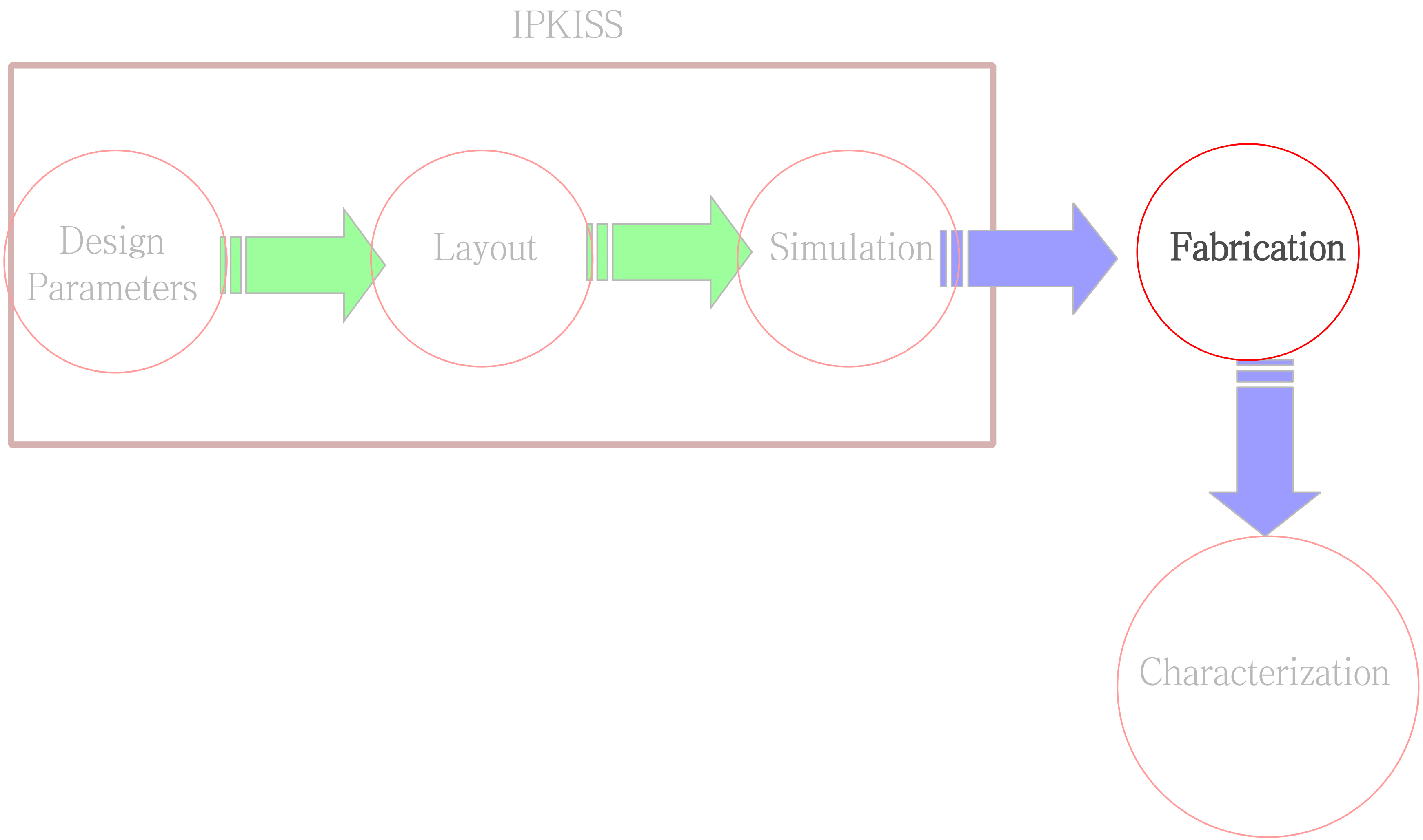


$$T_{QP} = T_{QN}.T_{NN}.T_{PN}^{T}$$

Simulation 16x200 GHz AWG



Framework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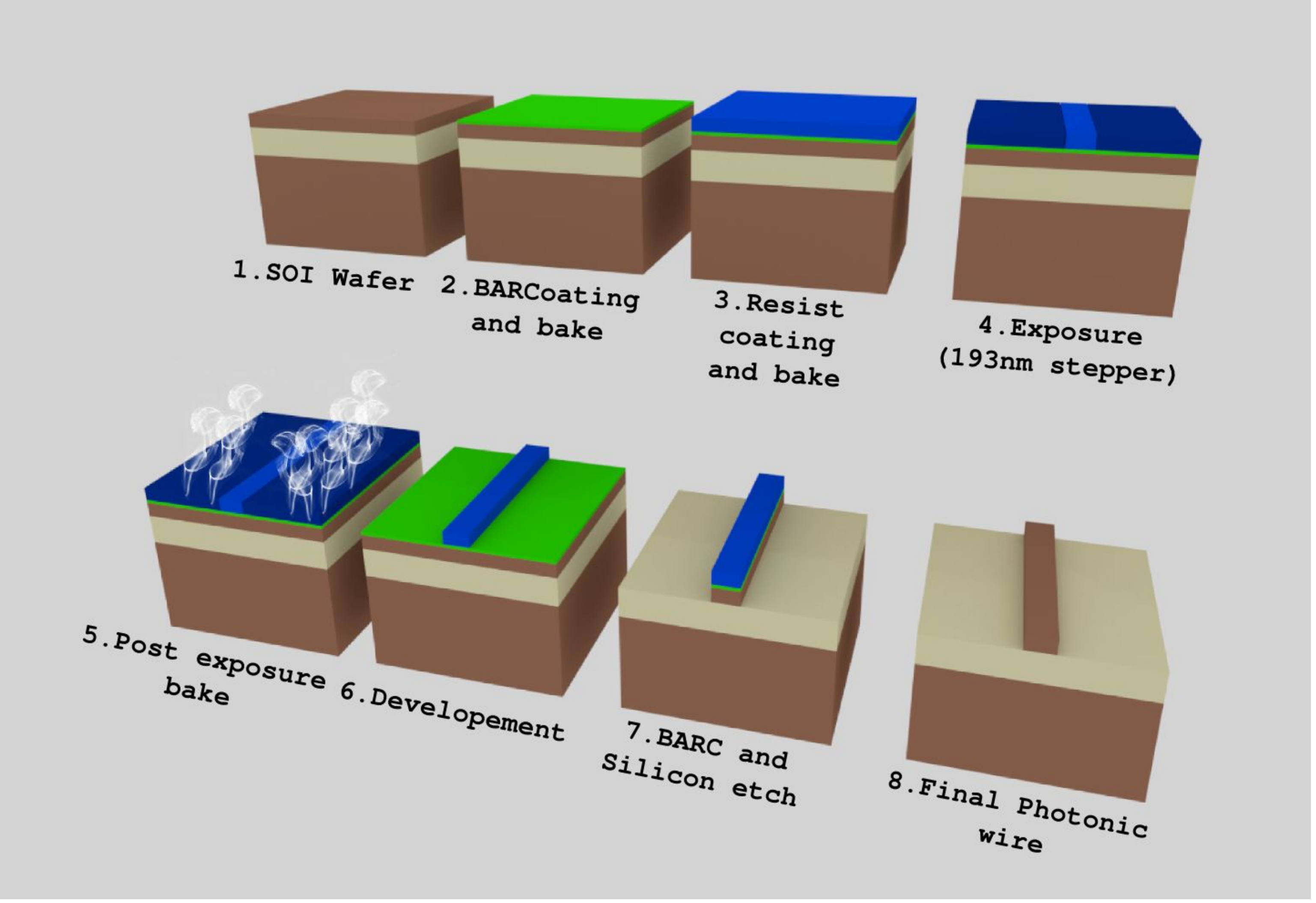
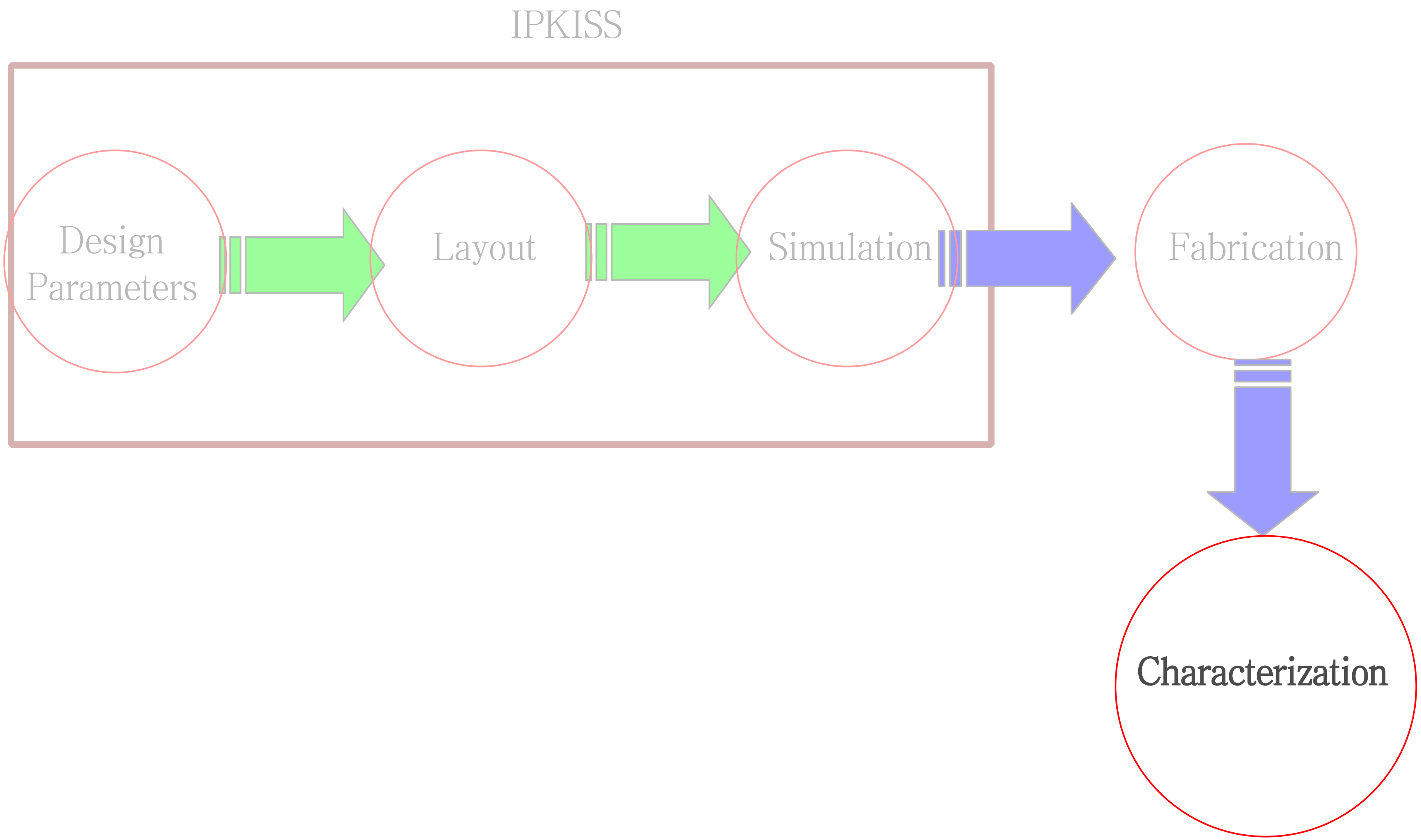
Fabrication



Framework


IPKISS
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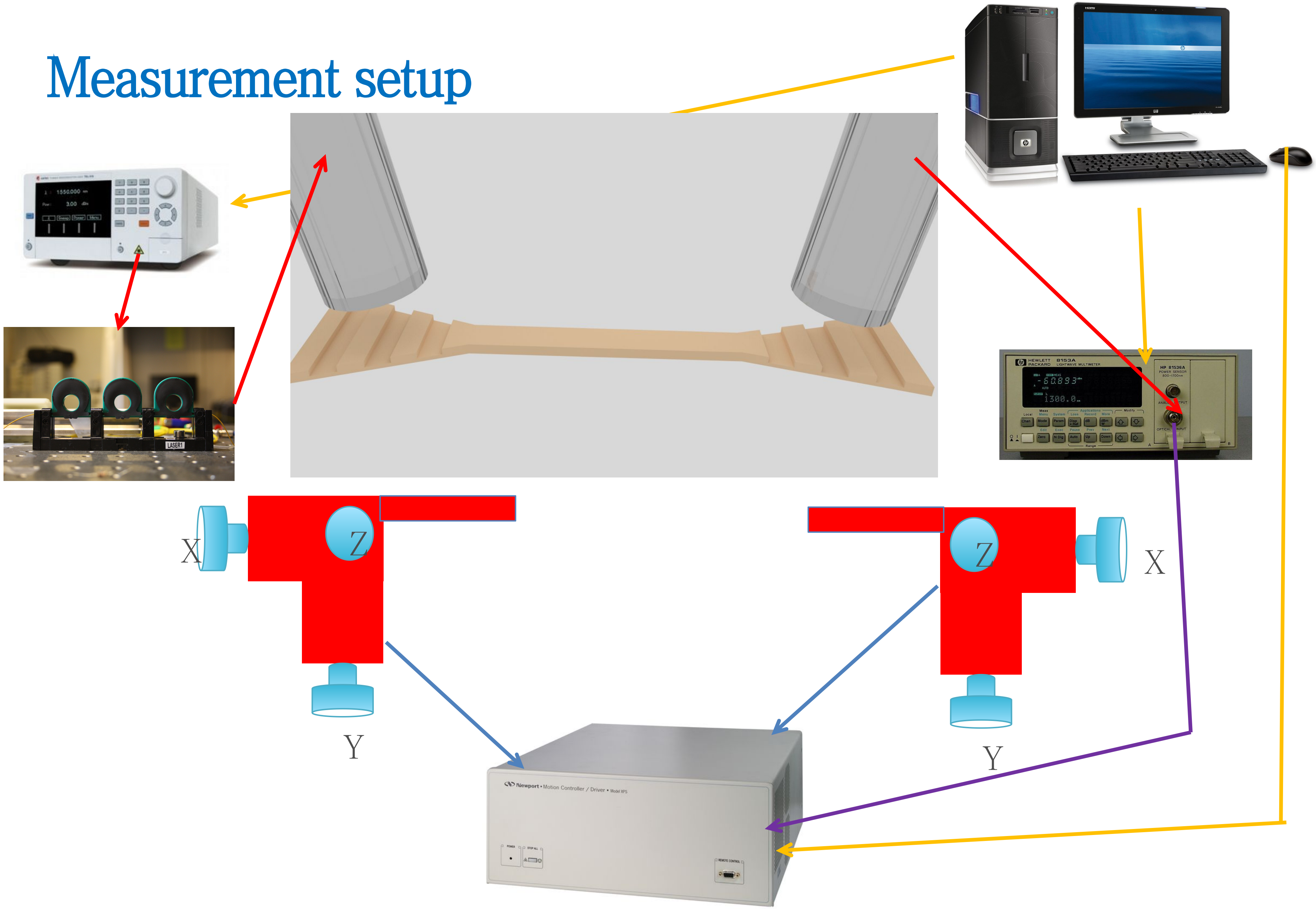
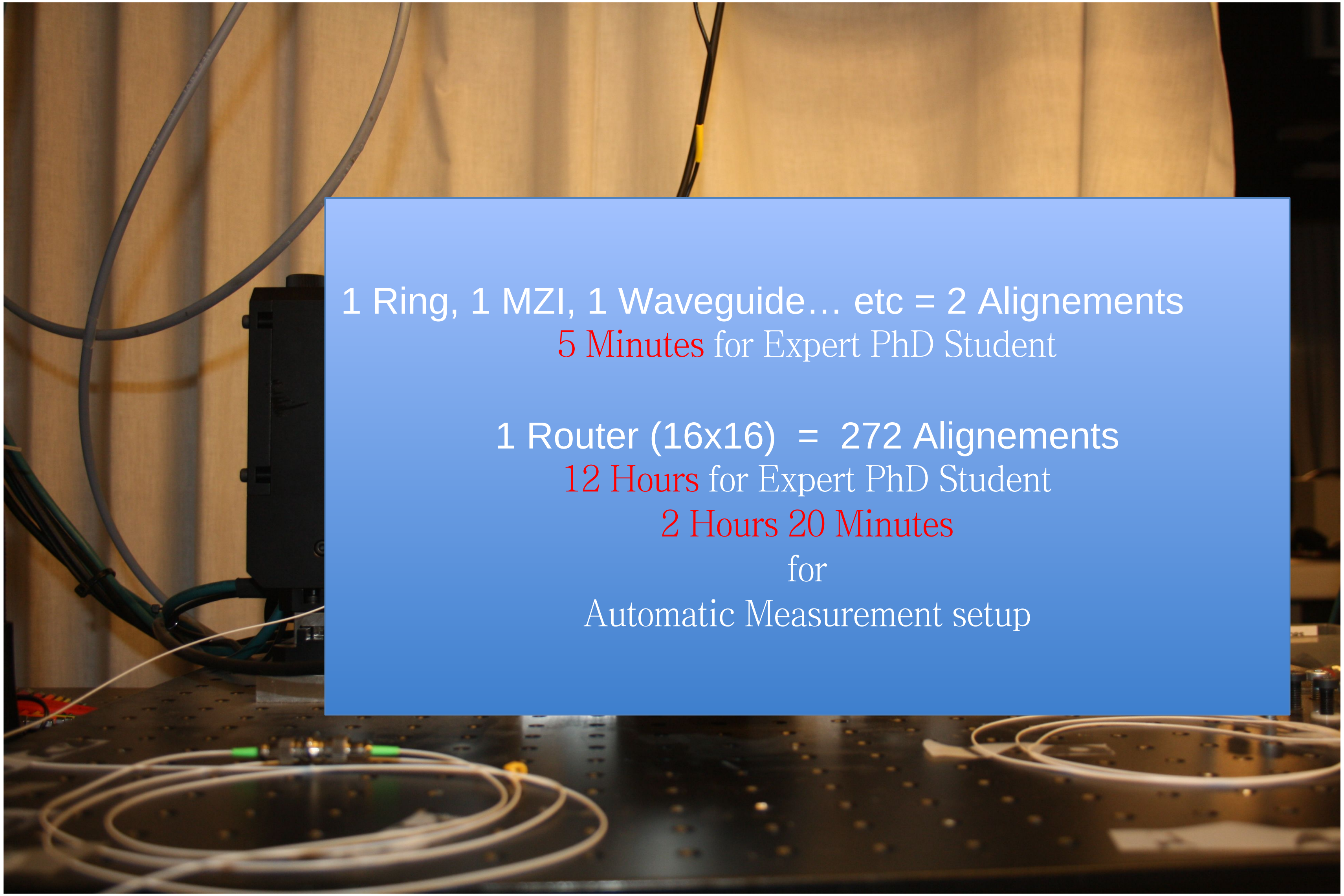
Measurement setup



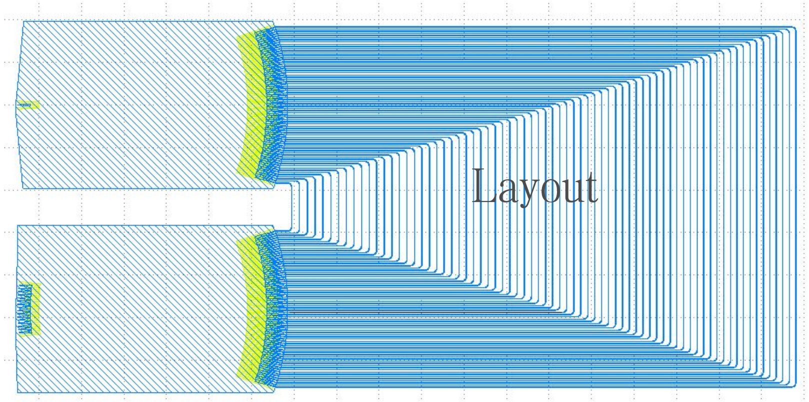
Automatic Setup

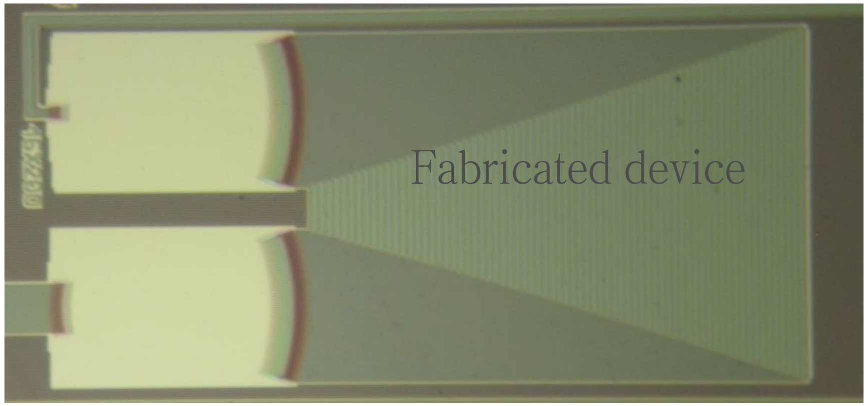


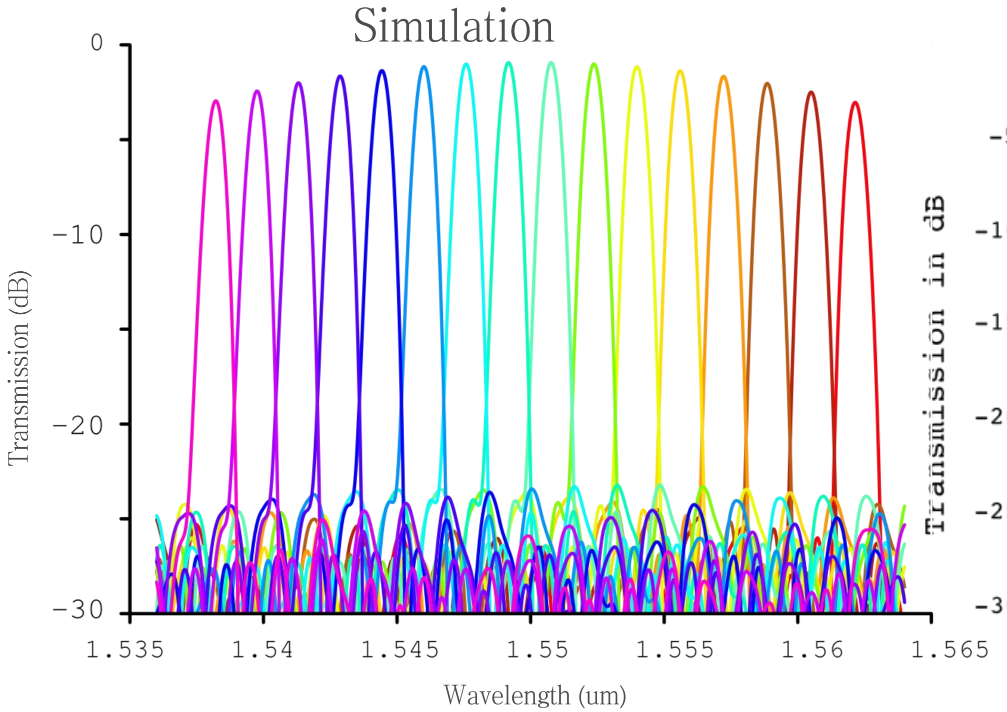
1 Ring, 1 MZI, 1 Waveguide… etc = 2 Alignements
5 Minutes for Expert PhD Student

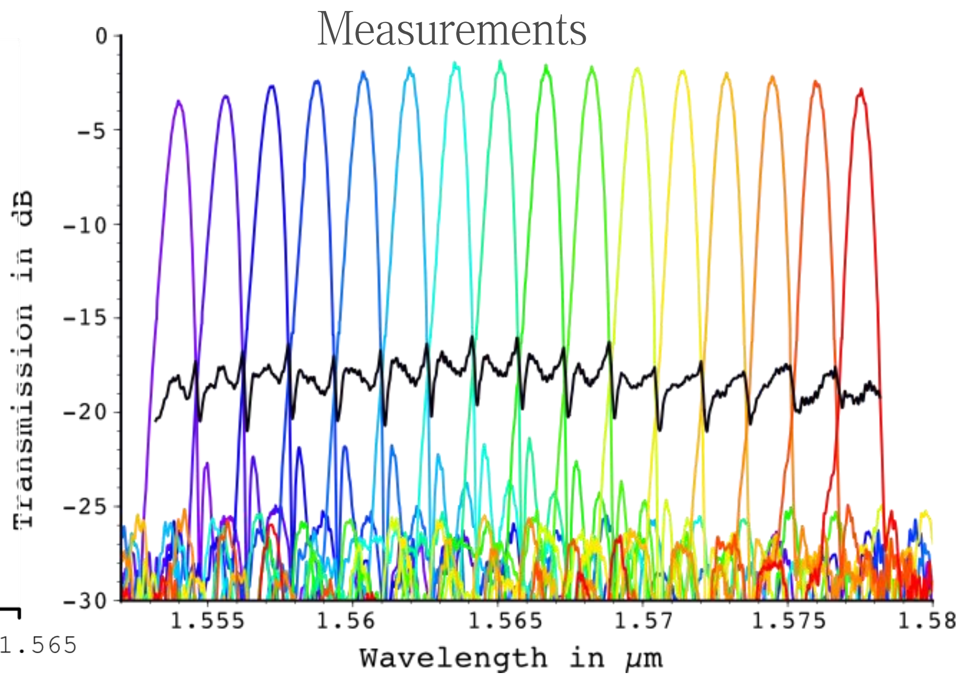
1 Router (16x16) = 272 Alignements
12 Hours for Expert PhD Student
2 Hours 20 Minutes
for
Automatic Measurement setup

Layout – Simulation
Fabrication– Measurements (16x200 GHz AWG)







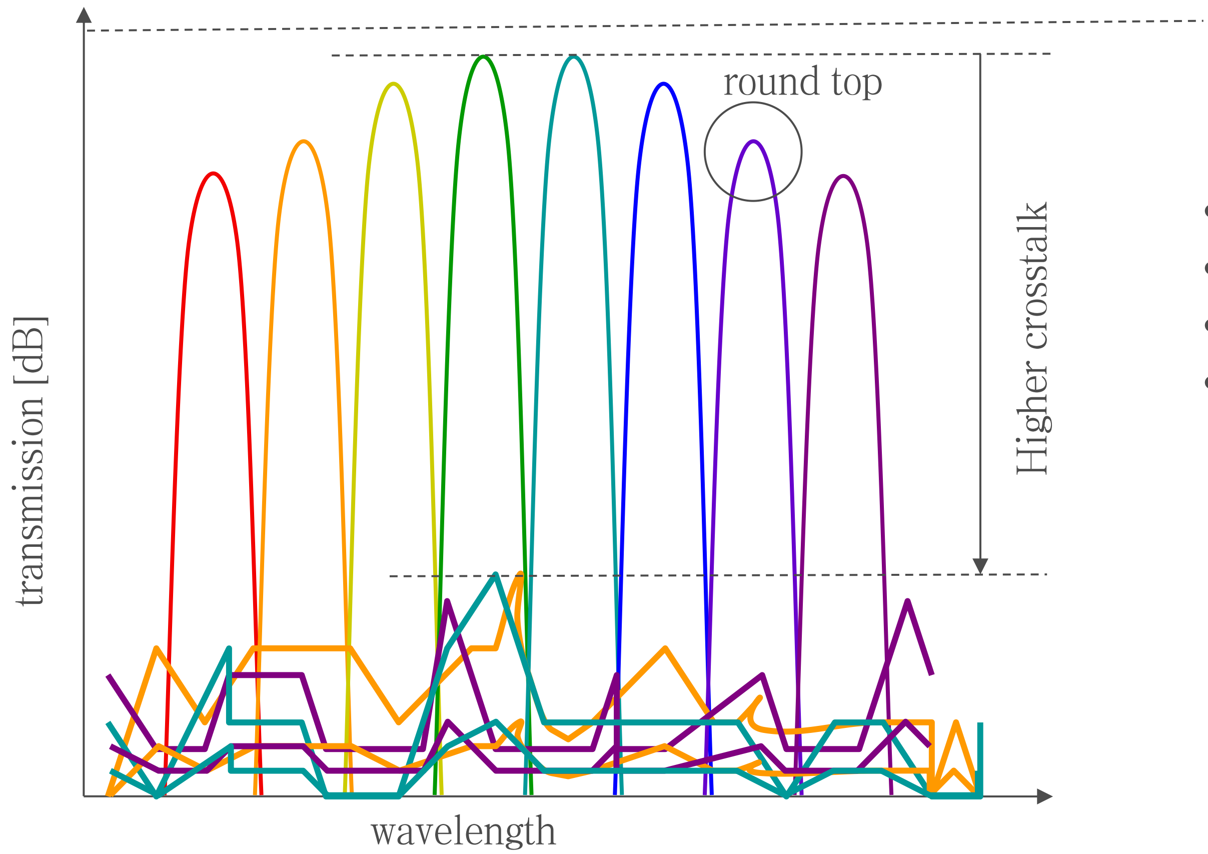


Structure the outline

+ Our approach
– Our results
  - Insertion Loss and Non–uniformity
  - Crosstalk
  - Channel mismatch
  - Round top to flattop
  - Switch

+ Conclusions

Problems in Silicon AWG



- High Insertion Loss
- High Crosstalk
- Channel Spacing Mismatch
- Round Top

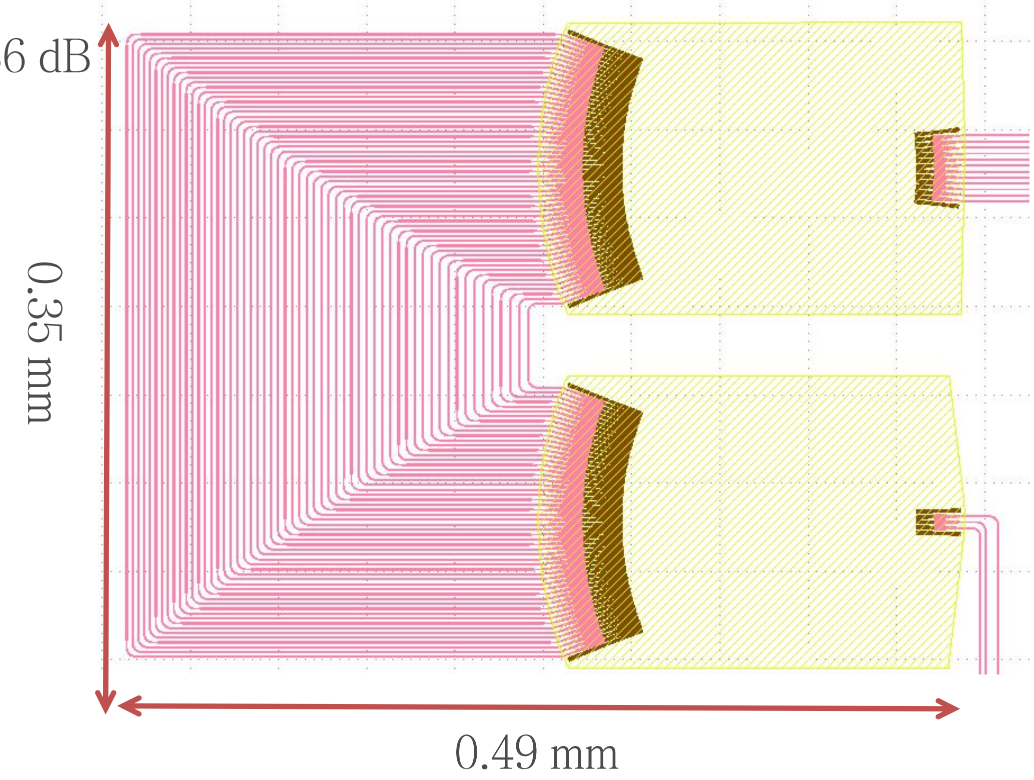
Insertion Loss of AWG

Propagation loss of a Si wire: 2dB/cm

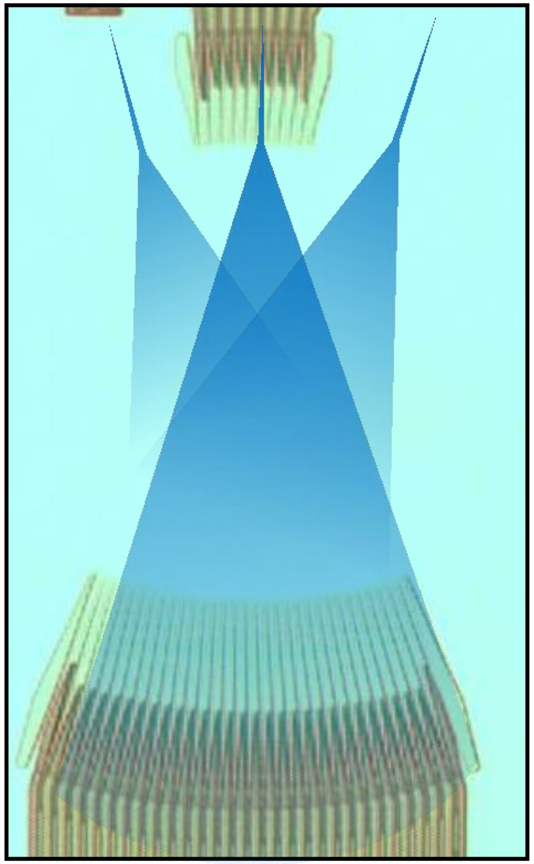
For a 12X400 GHz AWG Path travel by the Light is: ~1 mm

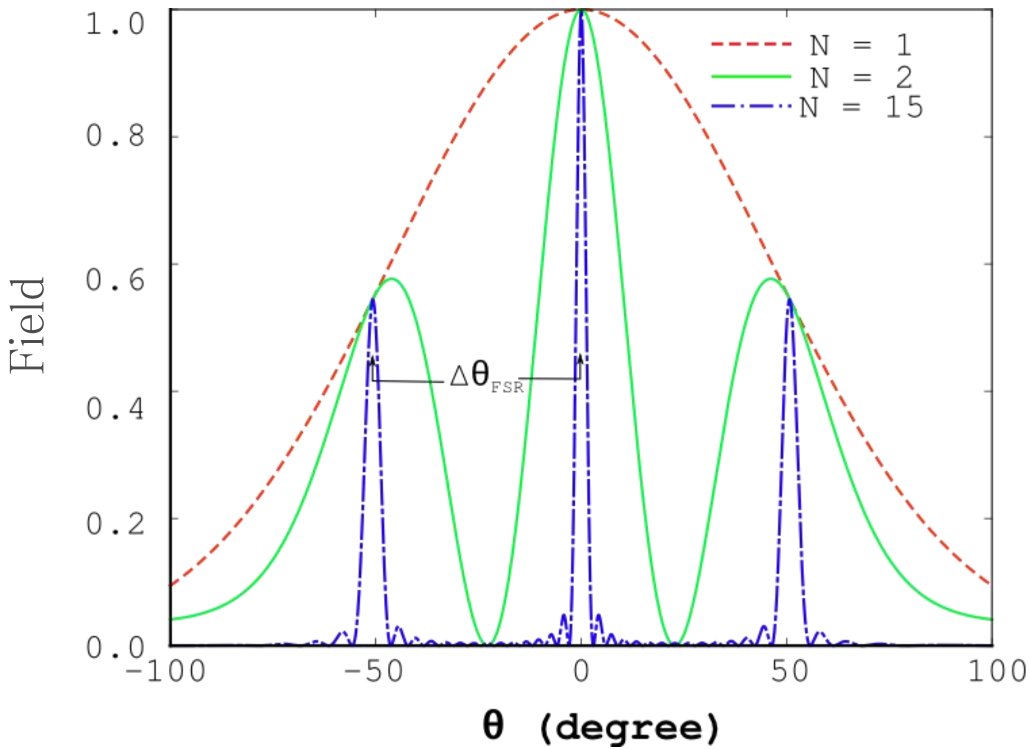
But Insertion Loss of the AWG is: –1.336 dB

Possibility in Design

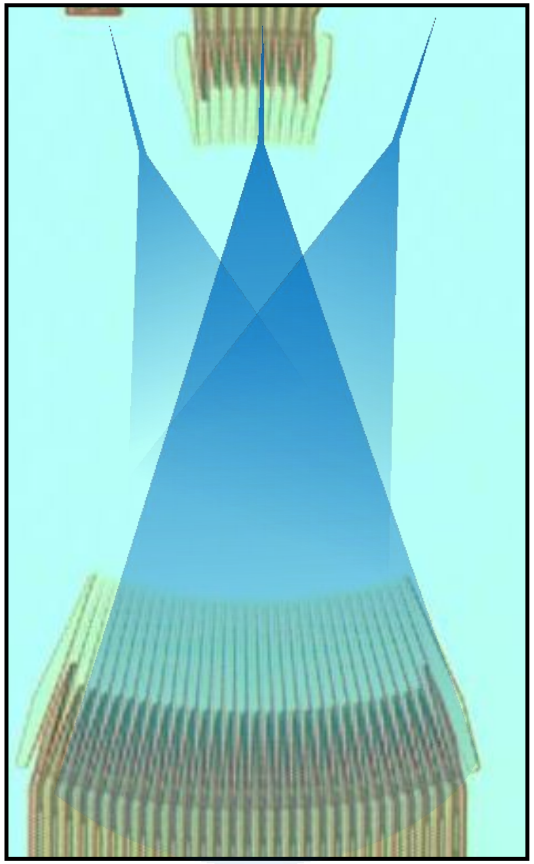


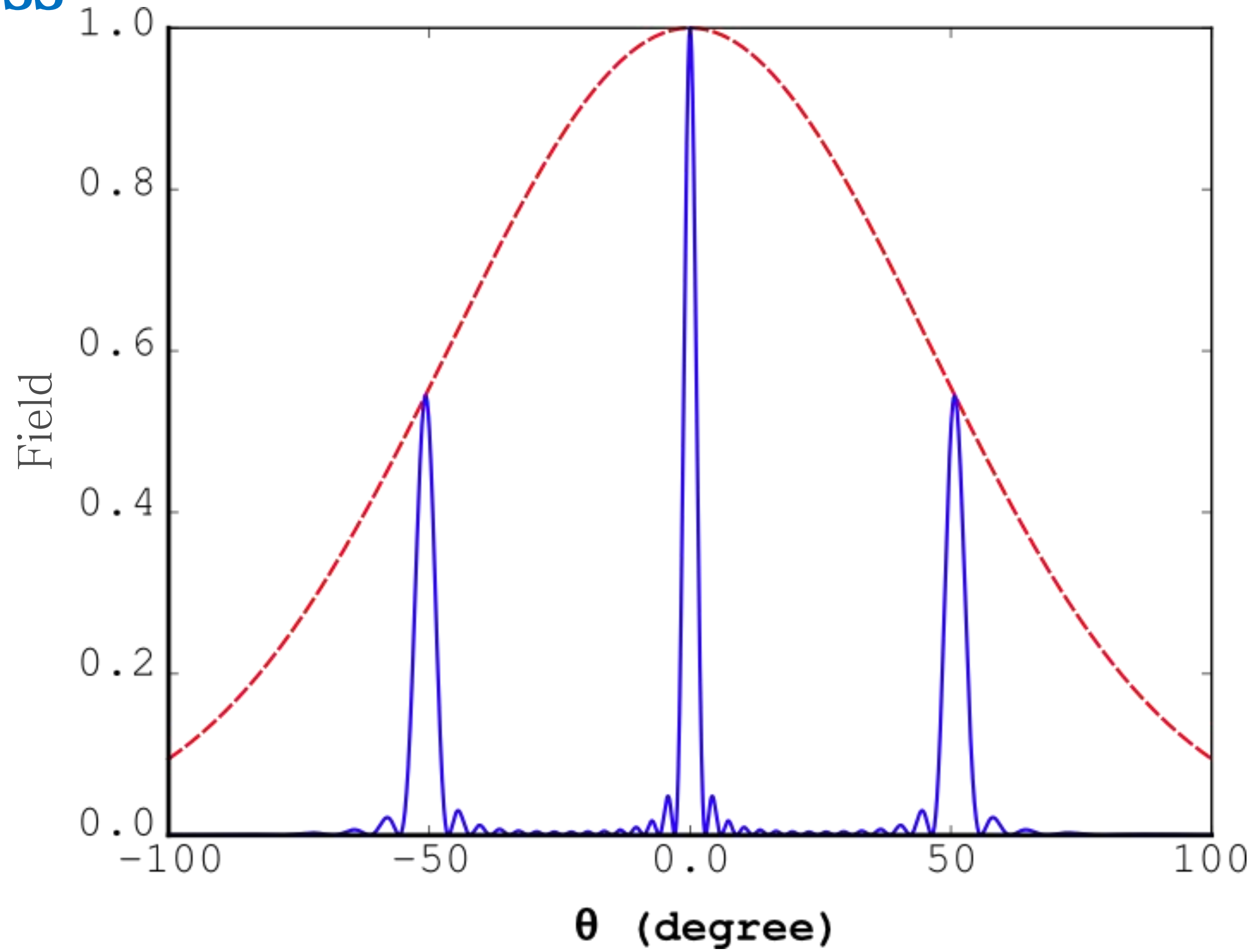
Insertion Loss of AWG: Design improvement



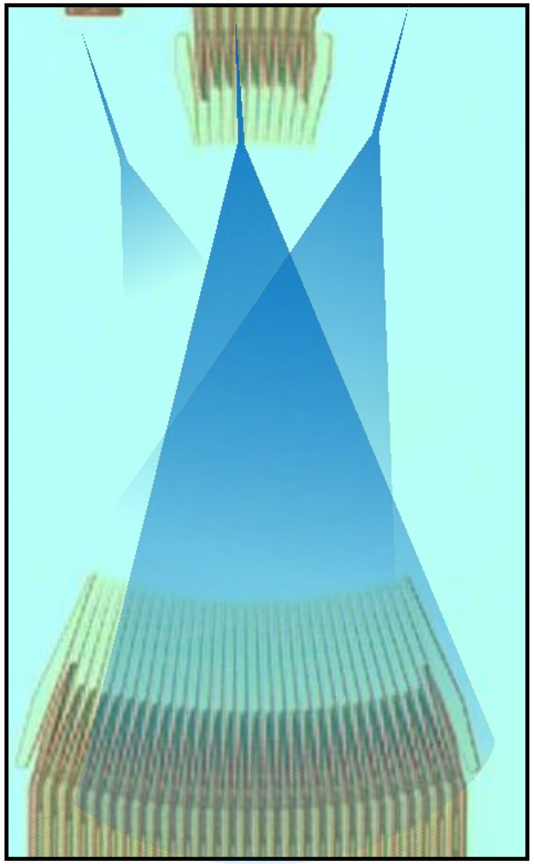


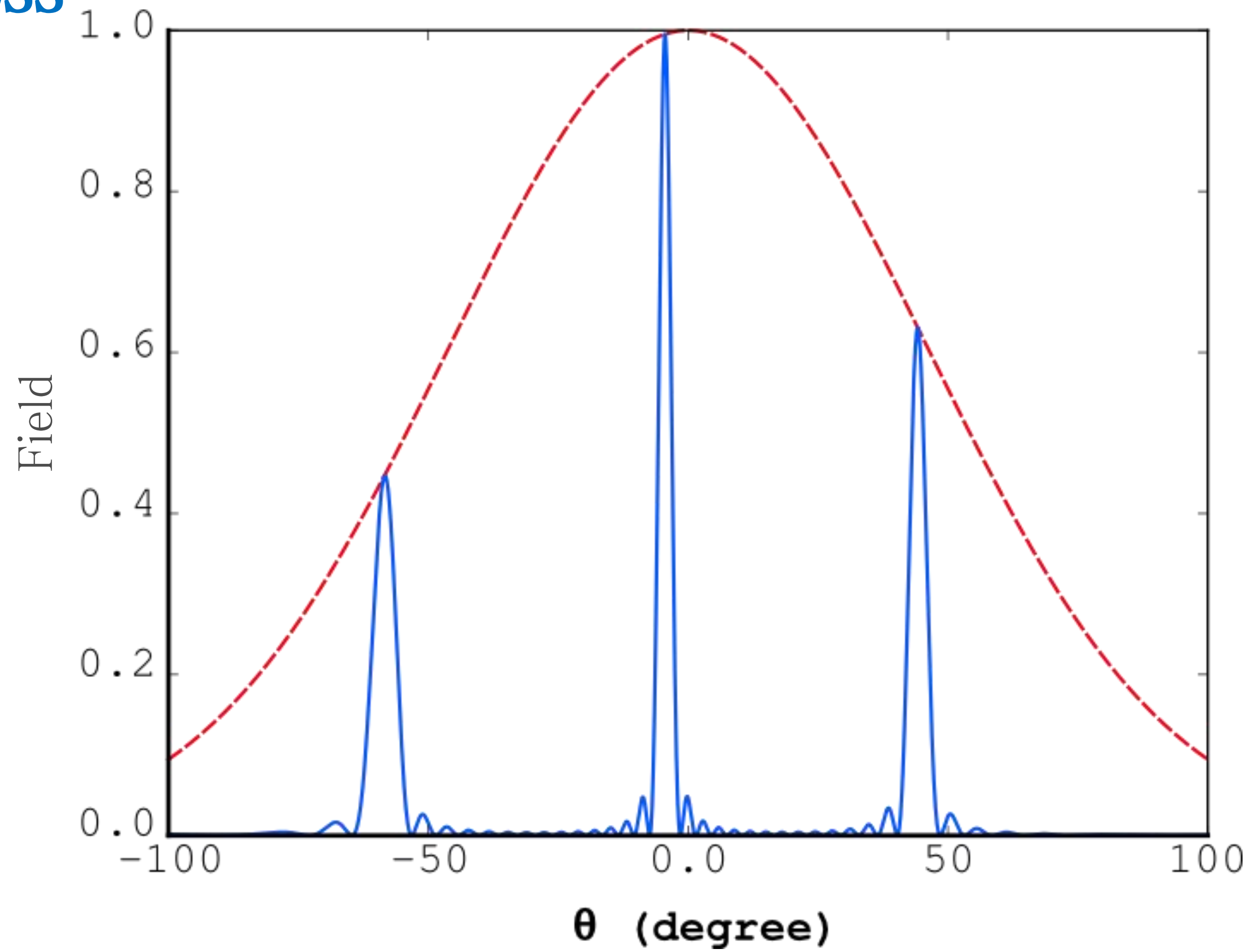
Non–uniformity loss



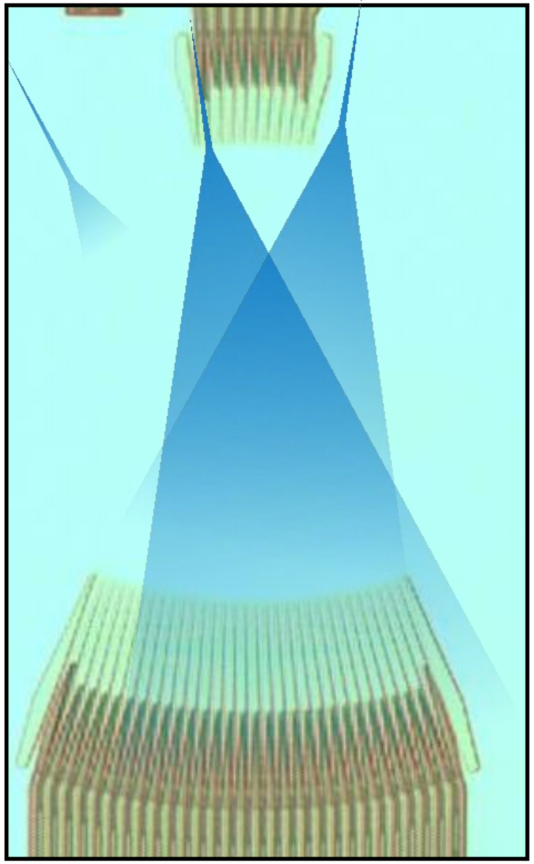


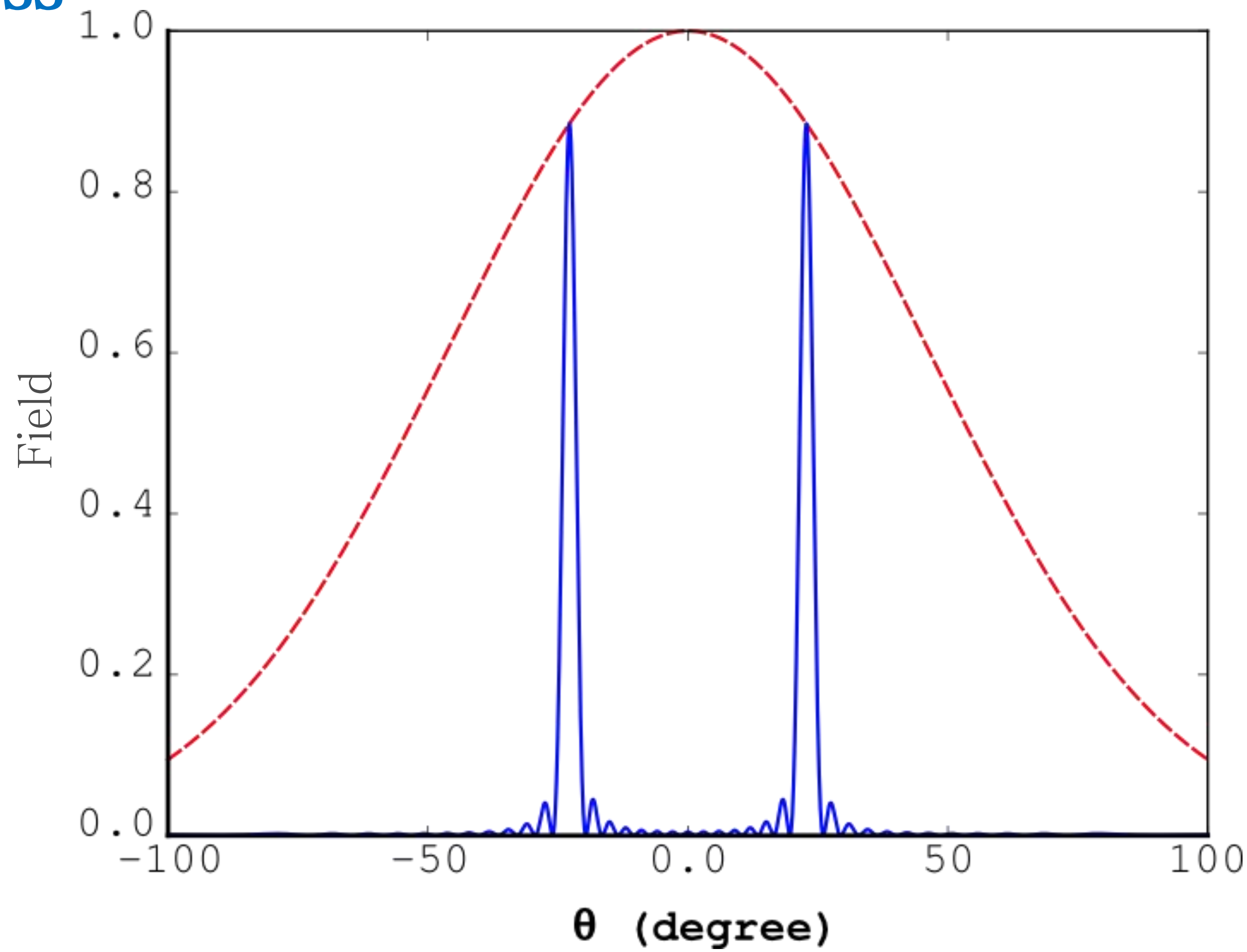
Non–uniformity loss





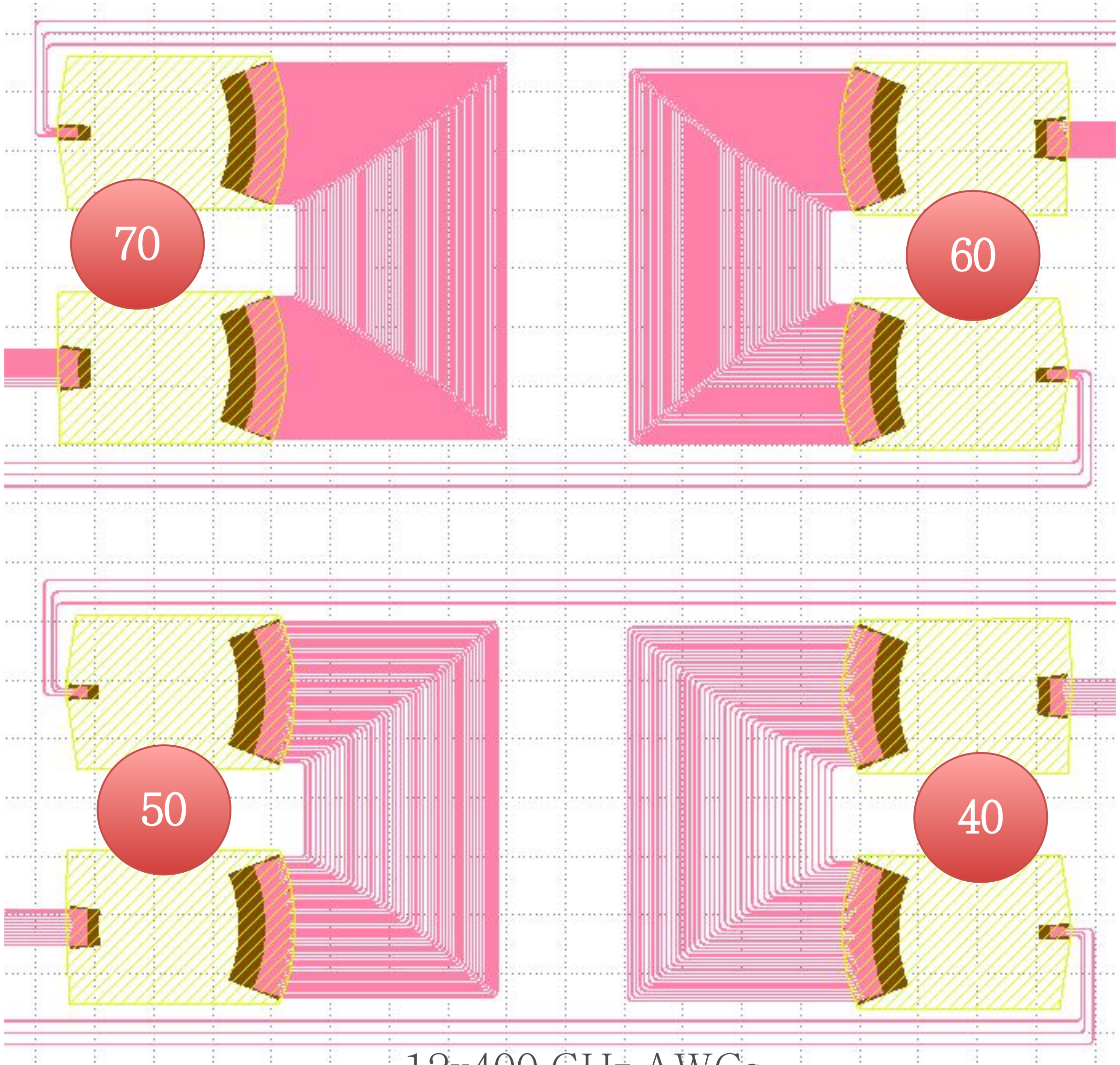
Non-uniformity loss





Side channel will have 3dB extra loss compare to the Center Channel

Insertion Loss and non-uniformity



12x400 GHz AWGs

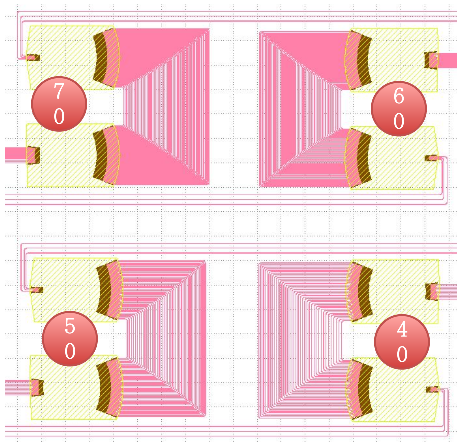
Add more waveguides

Narrow down the arm apertures

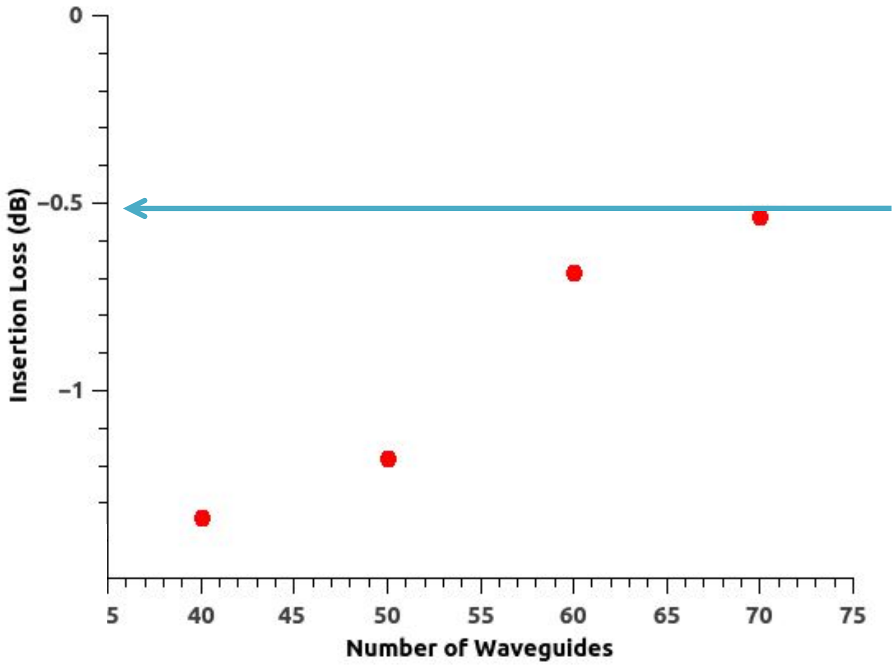
Constant focus

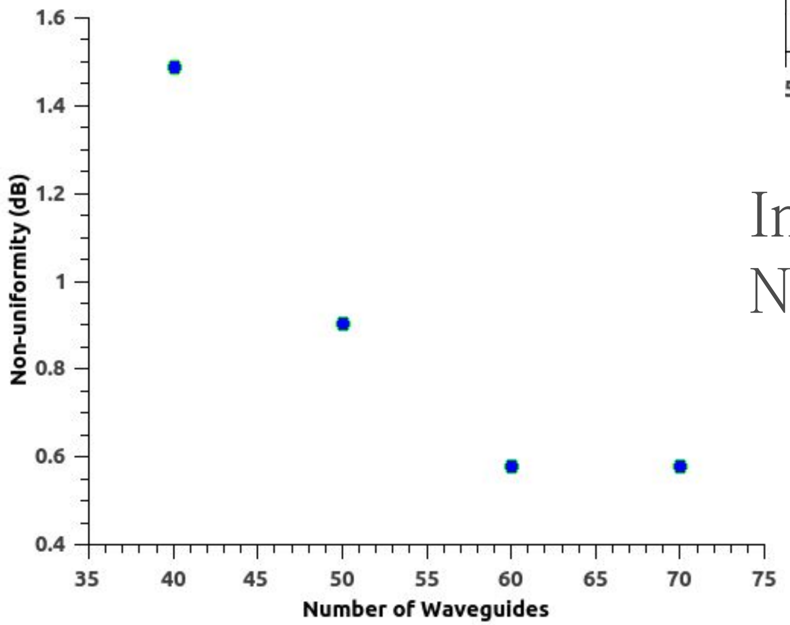
Non-uniformity should improve

Insertion Loss and non-uniformity



12x400 GHz AWGs





Insertion Loss improve to −0.5 dB

Non−uniformity improve to 0.6 dB

Structure the outline

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    - Channel mismatch
    - Round top to flattop
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+ Conclusions

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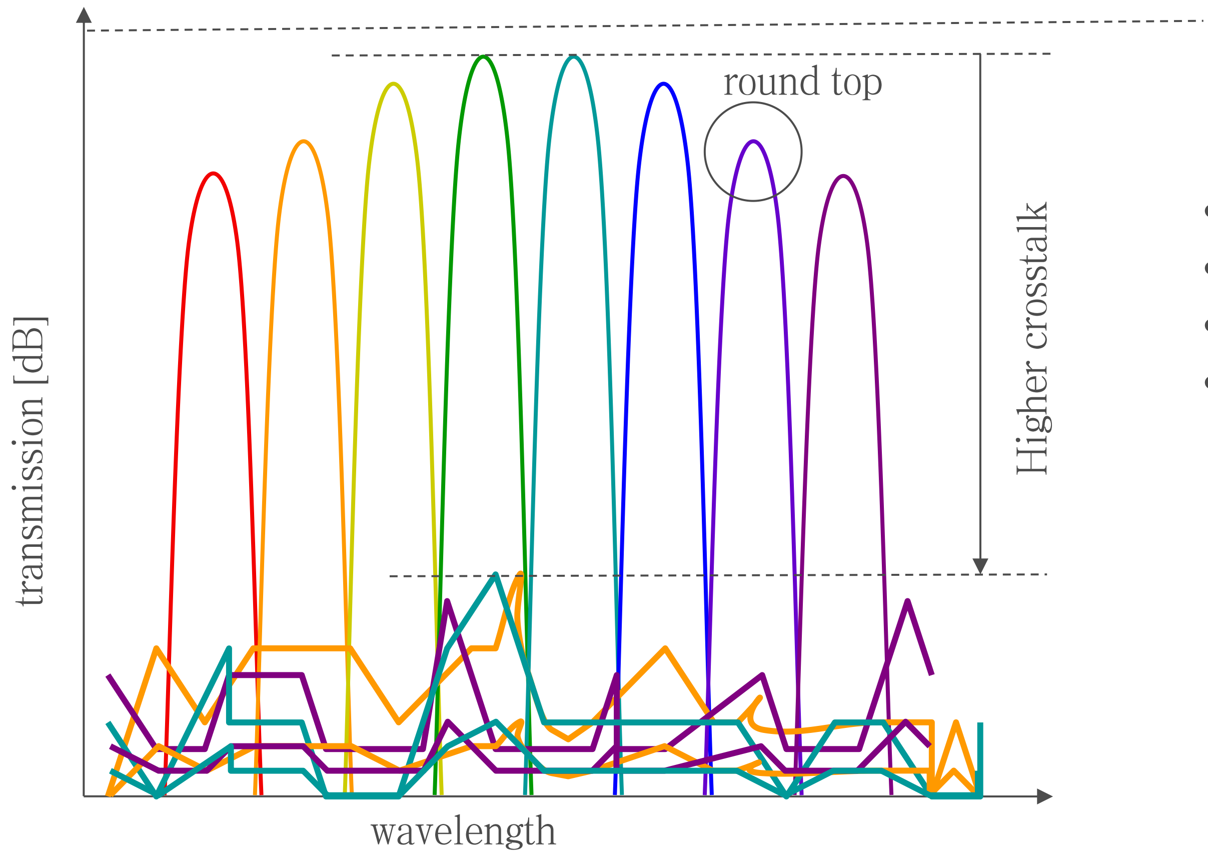
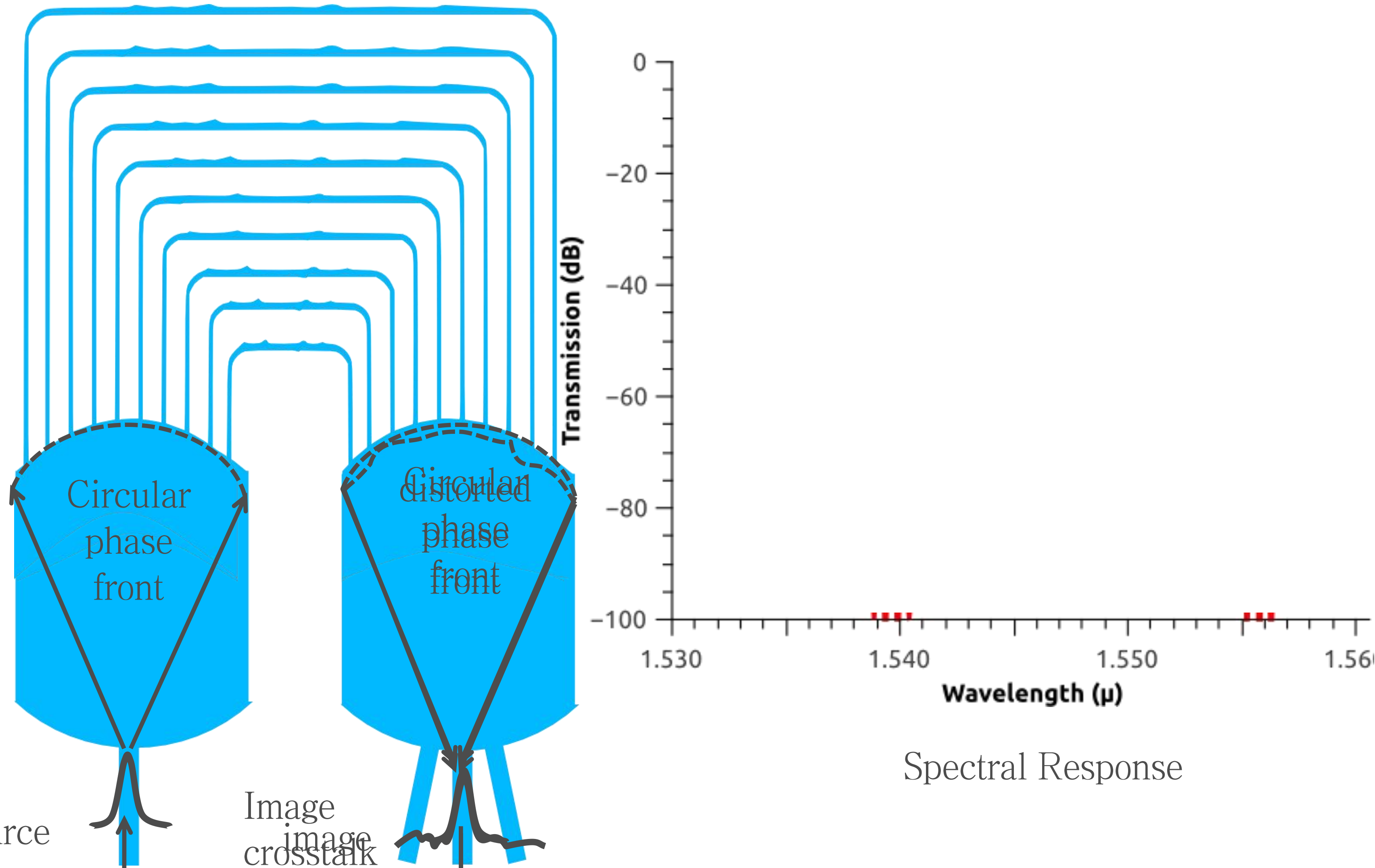


- ~~High Insertion Loss~~
- High Crosstalk
- Channel Spacing Mismatch
- Round Top

Crosstalk: Phase error

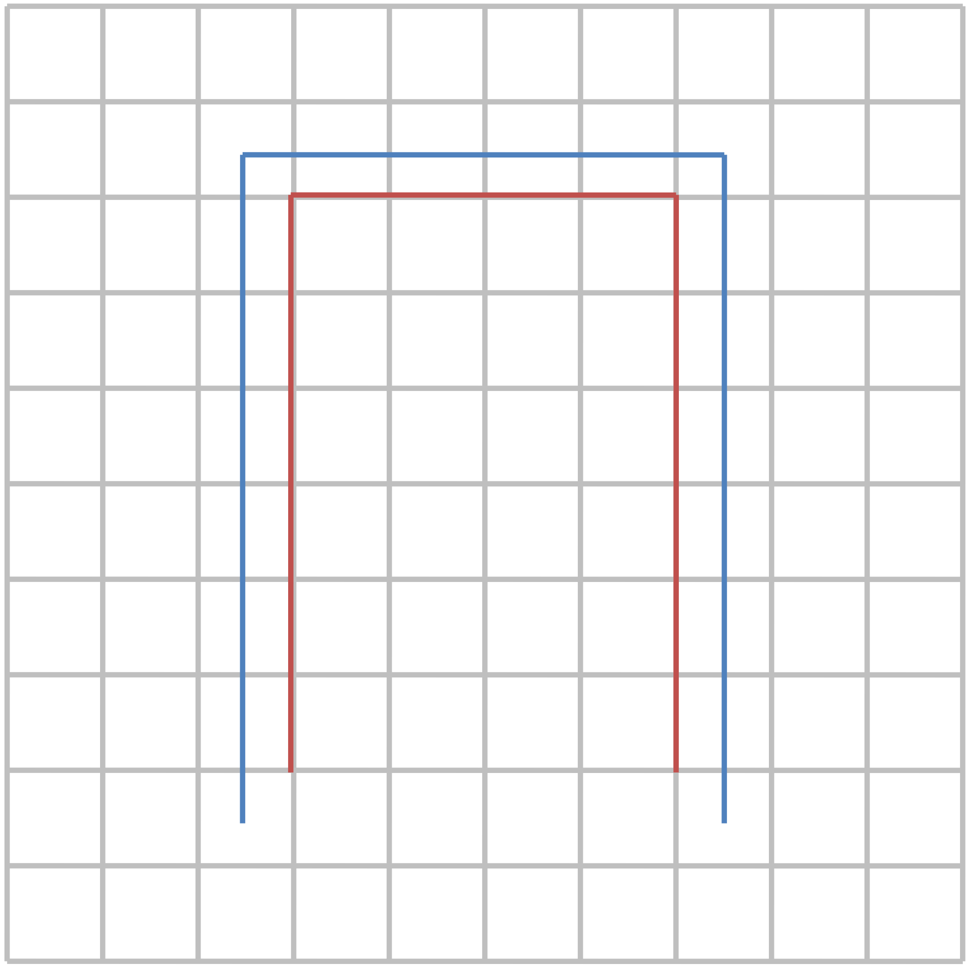
perfectly controlled delays all contributions arrive in phase

real-life delays phase errors at the output



Spectral Response

Crosstalk of AWG: mask grid

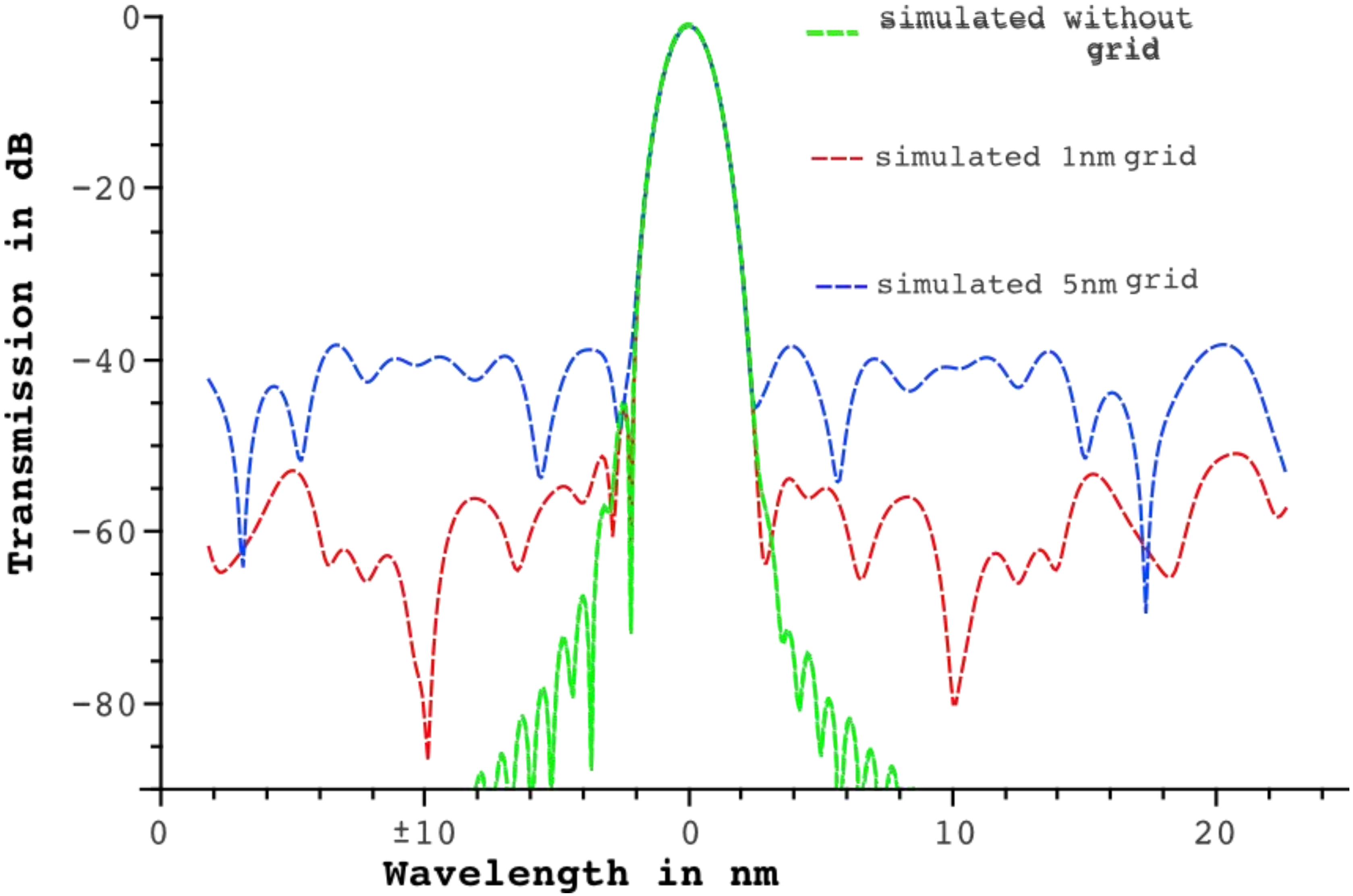


Length deviation

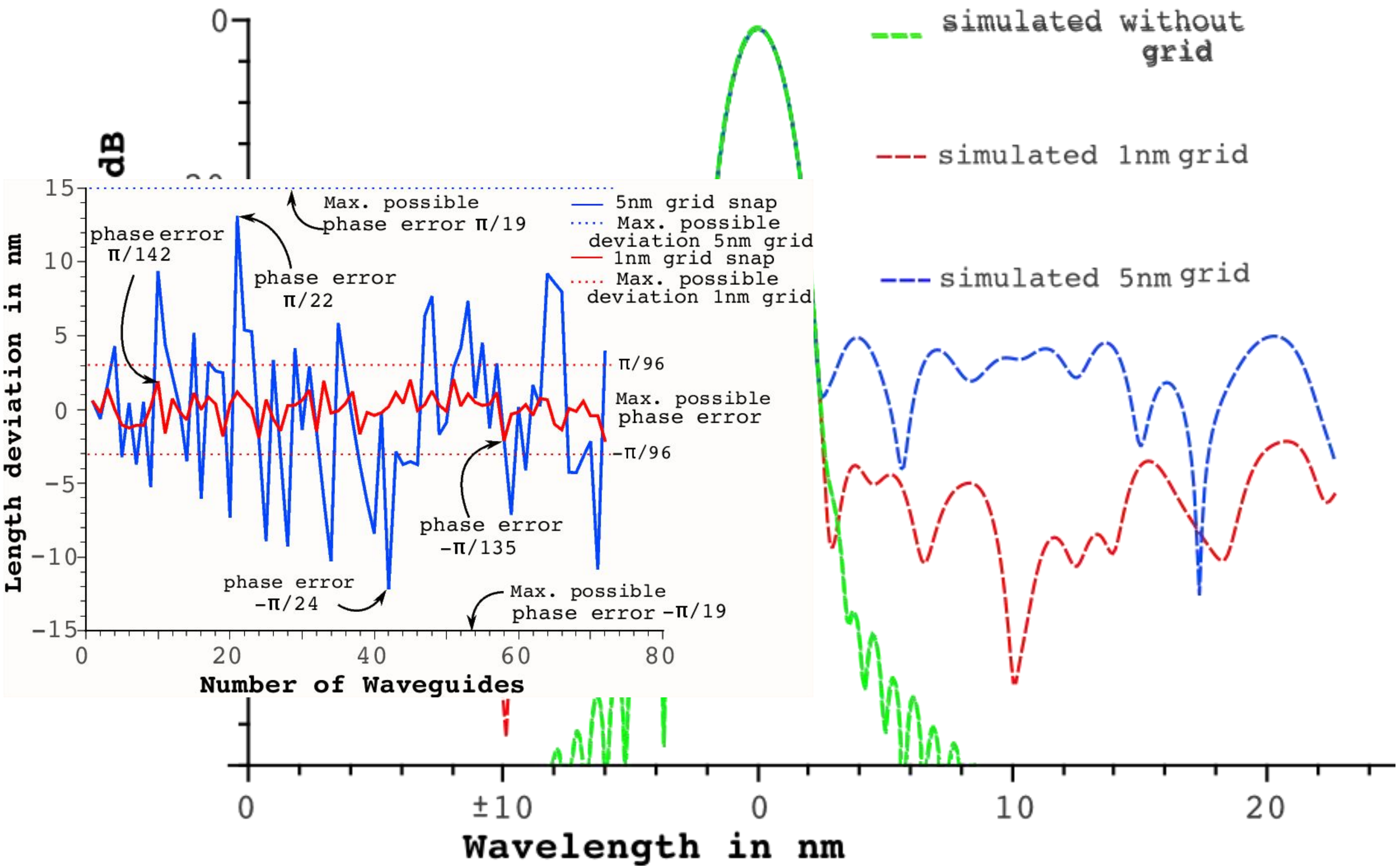
[illegible] a

a is mask grid width

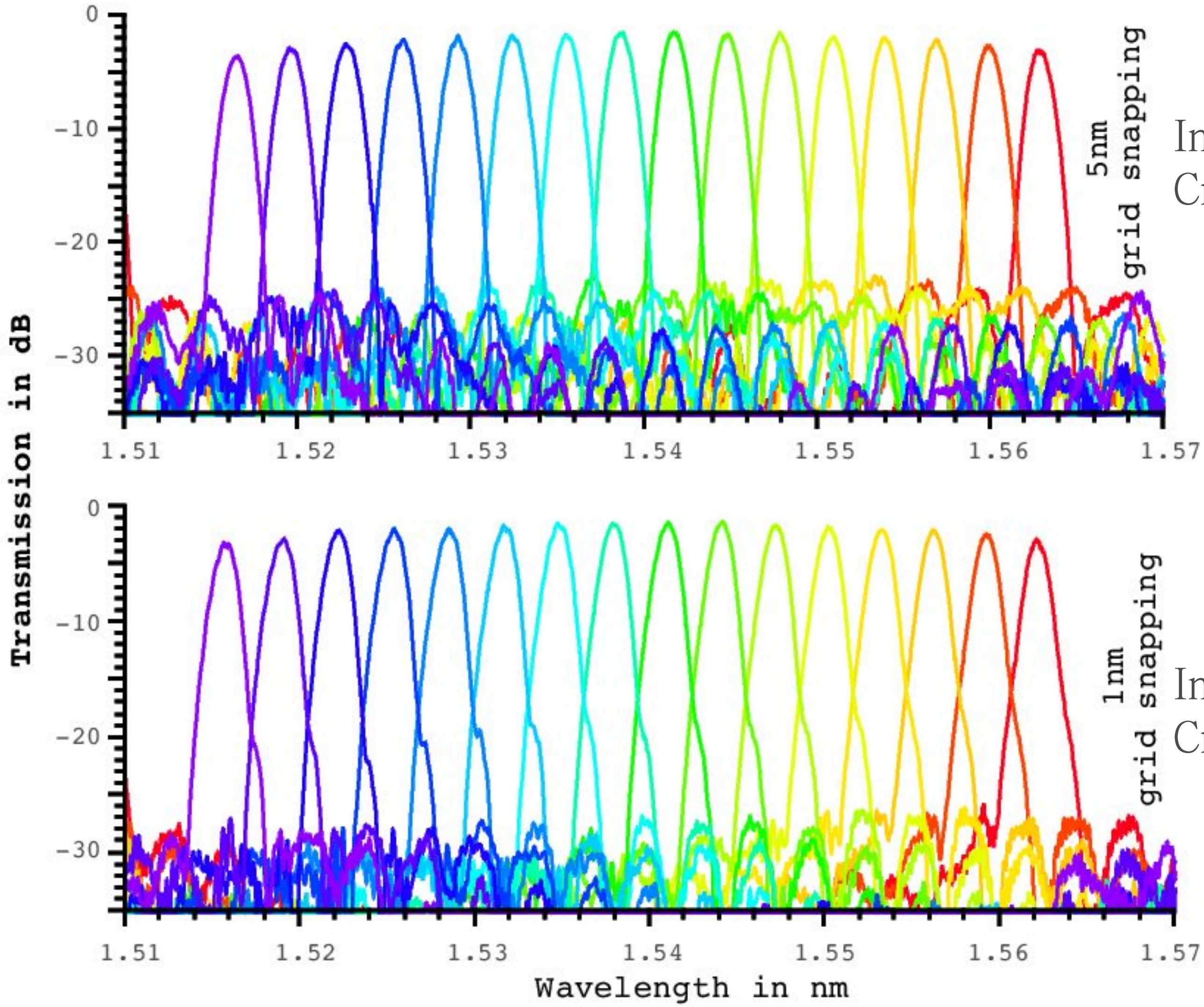
Crosstalk of AWG: Simulation 16X400 GHz AWGs



Crosstalk of AWG: Simulation 16X400 GHz AWGs



Crosstalk of AWG: Measured 16X400 GHz AWGs



Insertion loss −1.5 dB
Crosstalk −21 dB

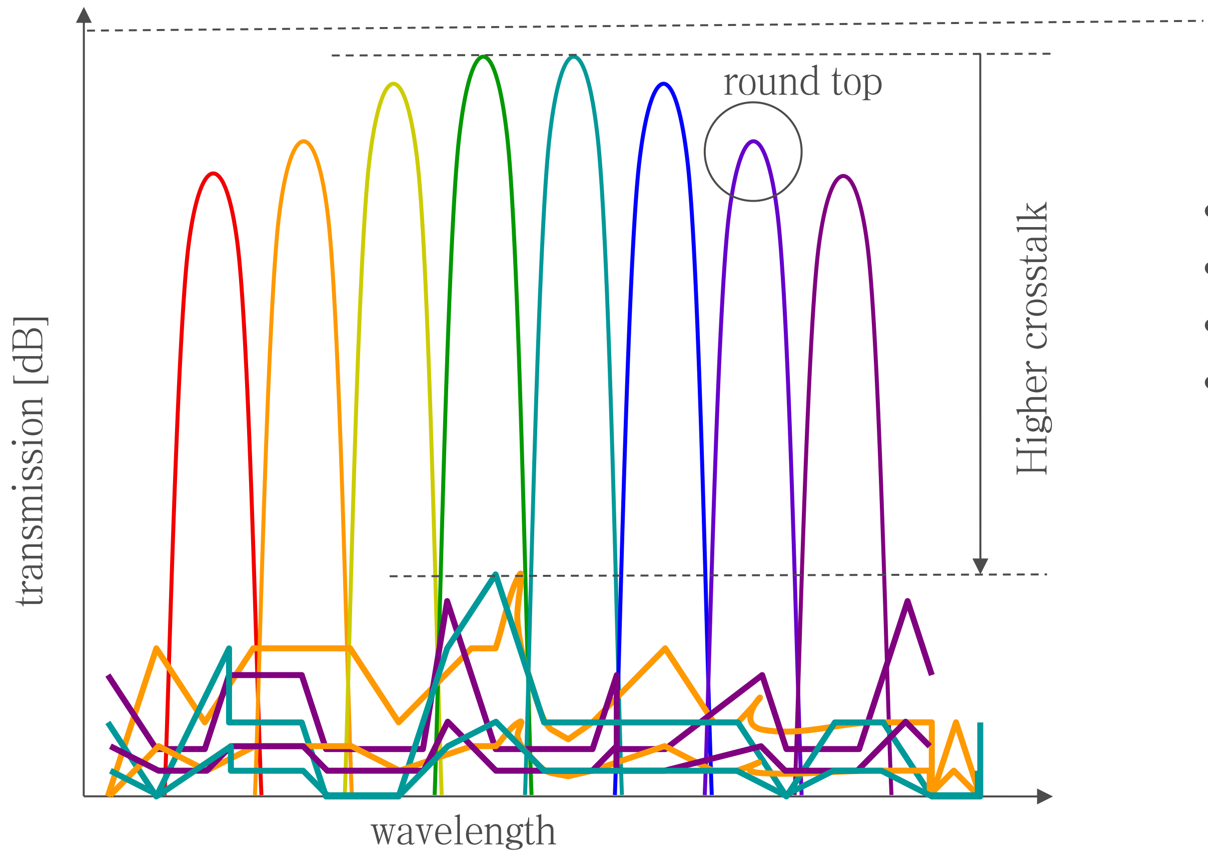
Insertion loss −1.5 dB
Crosstalk −26 dB

Structure the outline

+ Our approach
– Our results
  - Insertion Loss and Non–uniformity
  - Crosstalk
  - Channel mismatch
  - Round top to flattop
  - Switch

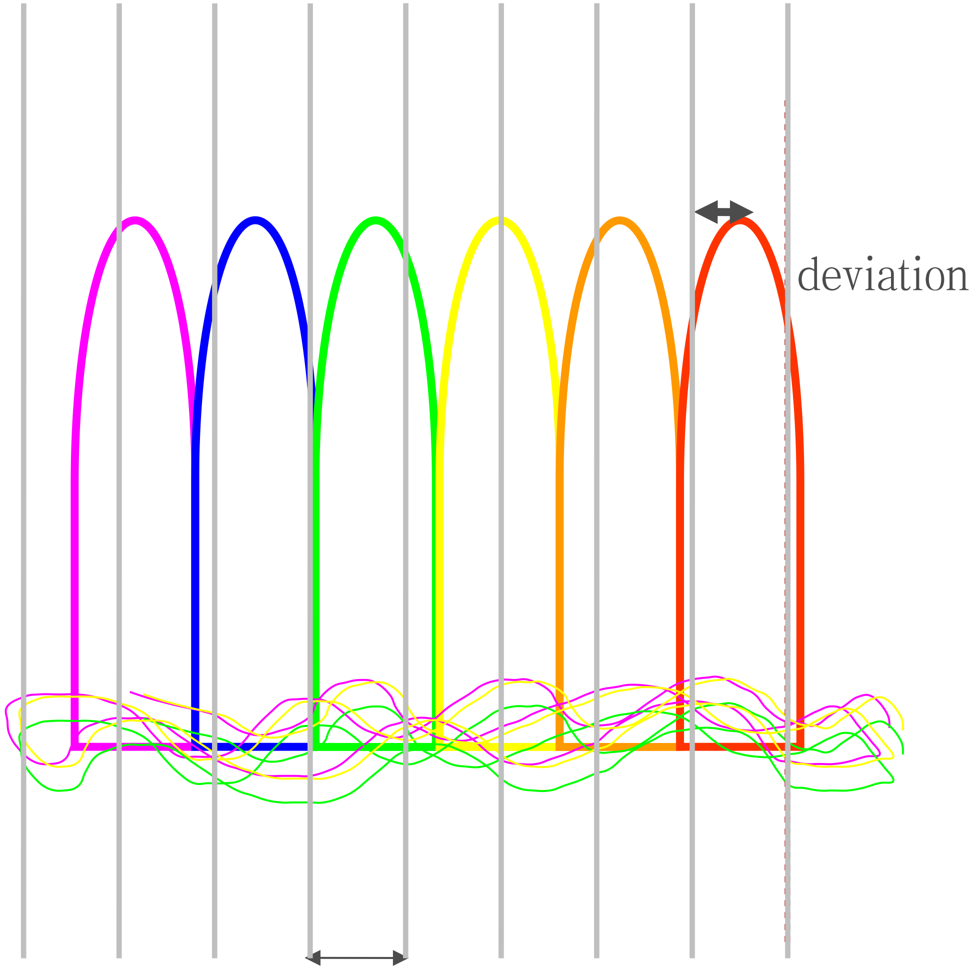
+ Conclusions

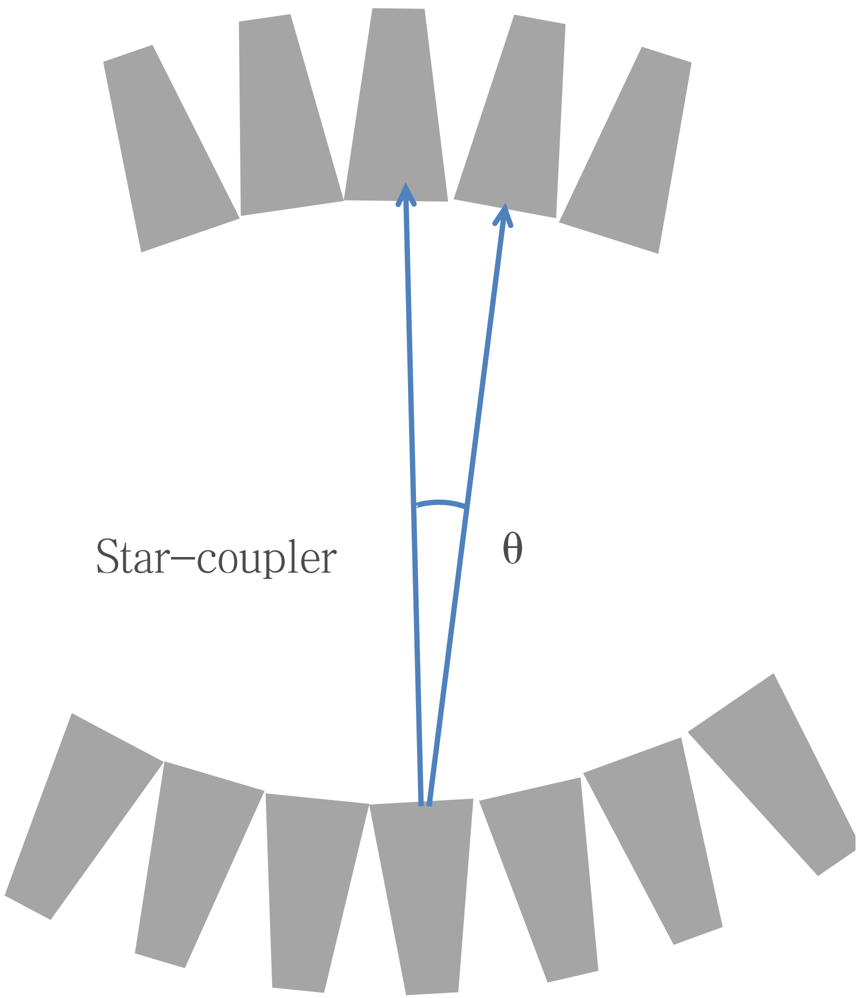
Problems in Silicon AWG



- ~~High Insertion Loss~~
- ~~High Crosstalk~~
- Channel Spacing Mismatch
- Round Top

Channel spacing mismatch





Formula for output position

Formula 1

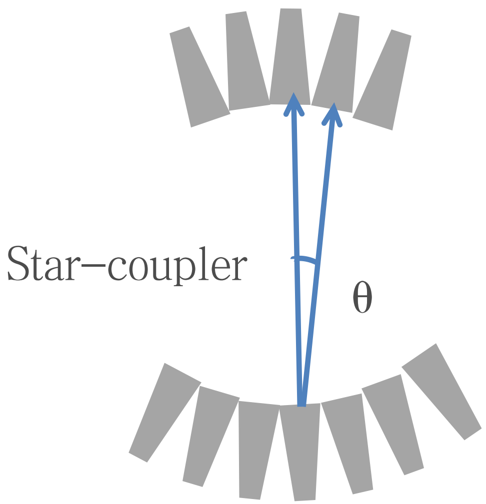
$$\sin\theta = m\cdot\frac{\mathrm{n}_{wg}(\lambda)\cdot\lambda_c - \mathrm{n}_{wg}(\lambda_c)\cdot\lambda}{\mathrm{n}_{wg}(\lambda_c)\cdot\mathrm{n}_{slab}(\lambda)\cdot\mathrm{d}_a}$$

Theoretically more accurate formula but need accurate n_{wg} for all wavelengths

Formula 2

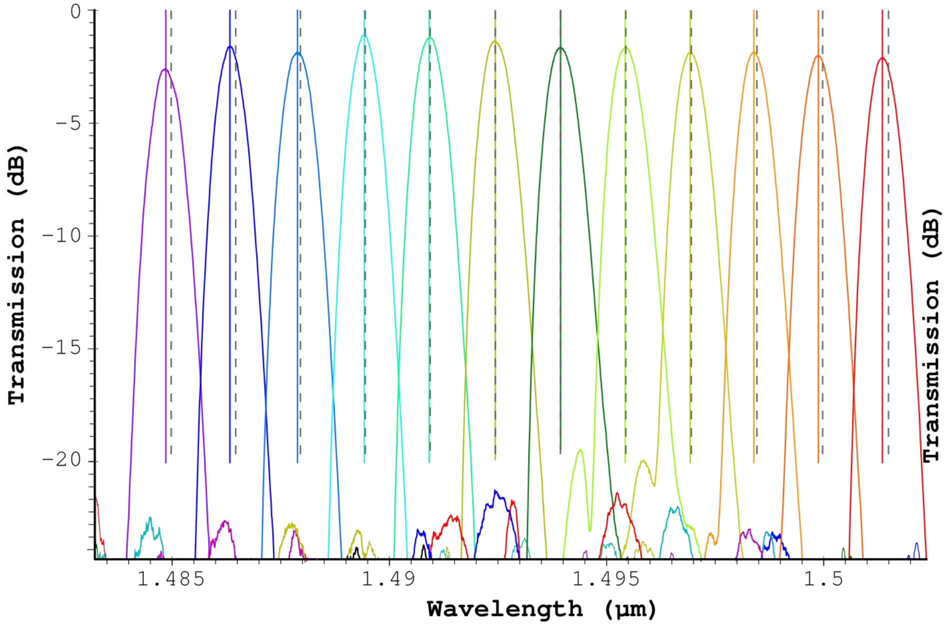
$$\frac{\mathrm{d}\theta}{\mathrm{d}\nu} = -\frac{m\lambda_c^2\mathrm{n}_{g,wg}}{\mathrm{n}_{slab}\mathrm{n}_{wg}(\lambda_c)\mathrm{d}_a c}$$

Theoretically less accurate formula but need accurate n_{wg} for center wavelength and accurate n_{group}

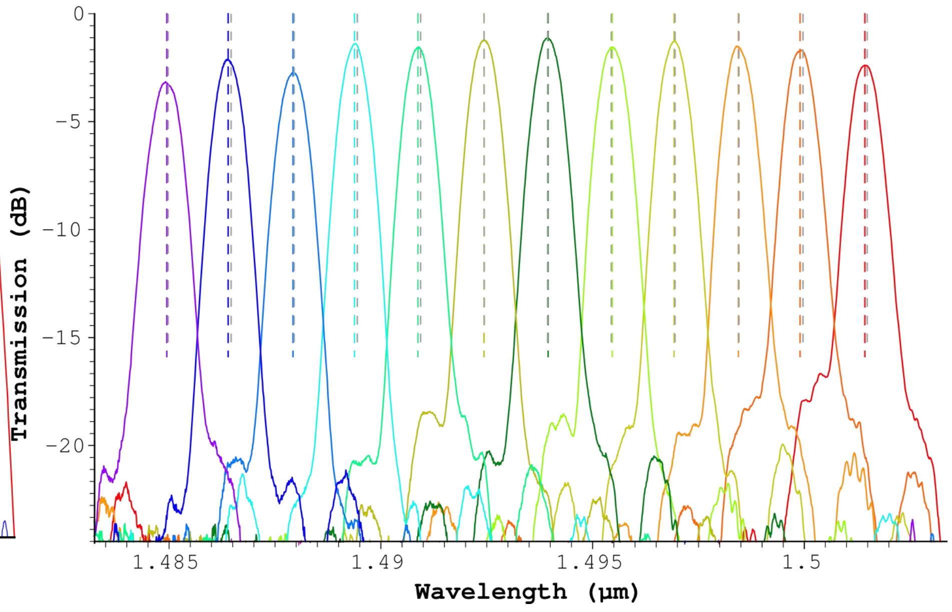


Improvement in channel spacing: 12x200 GHz AWG

Formula 1



Formula 2



Best fitted channel spacing 201.9 GHz

Maximum deviation 19.0 GHz

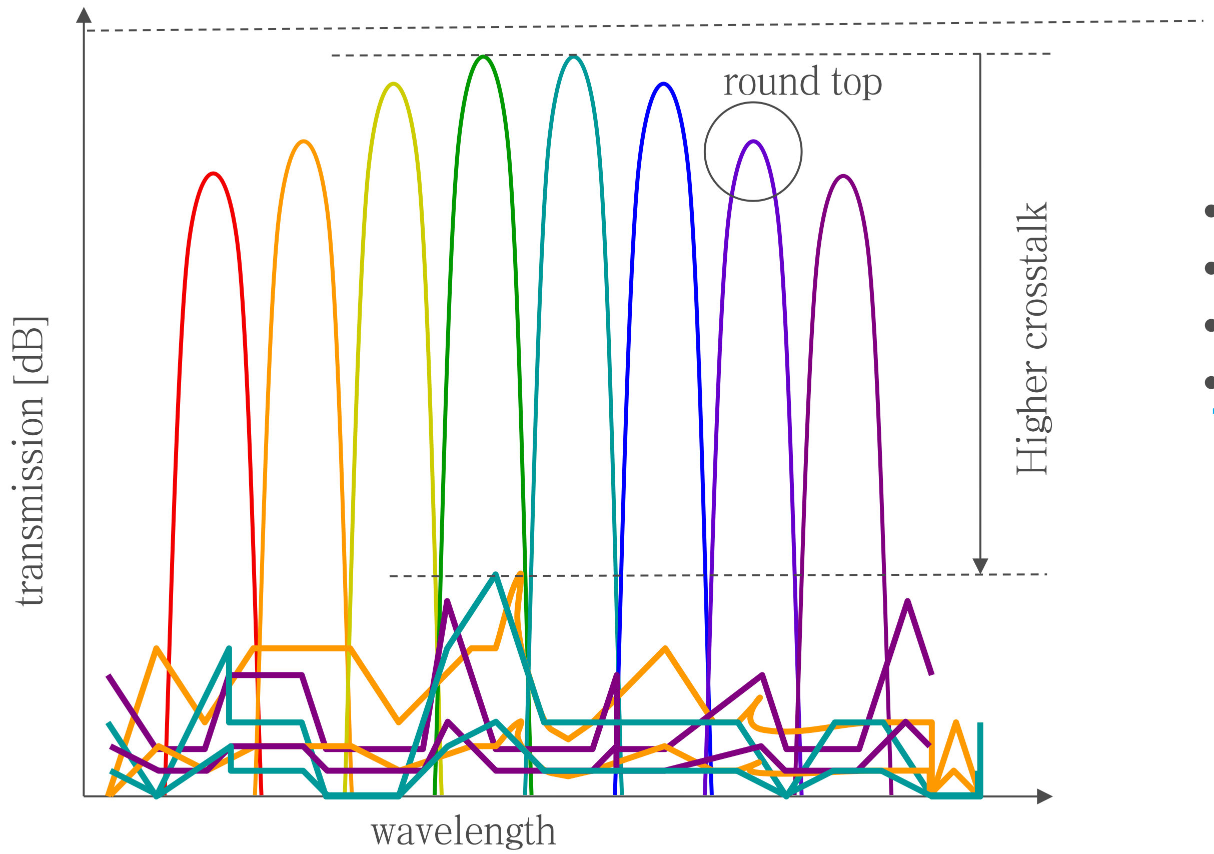
Maximum deviation 12.9 GHz

Structure the outline

+ Our approach
– Our results
  - Insertion Loss and Non-uniformity
  - Crosstalk
  - Channel mismatch
  - Round top to flattop
  - Switch

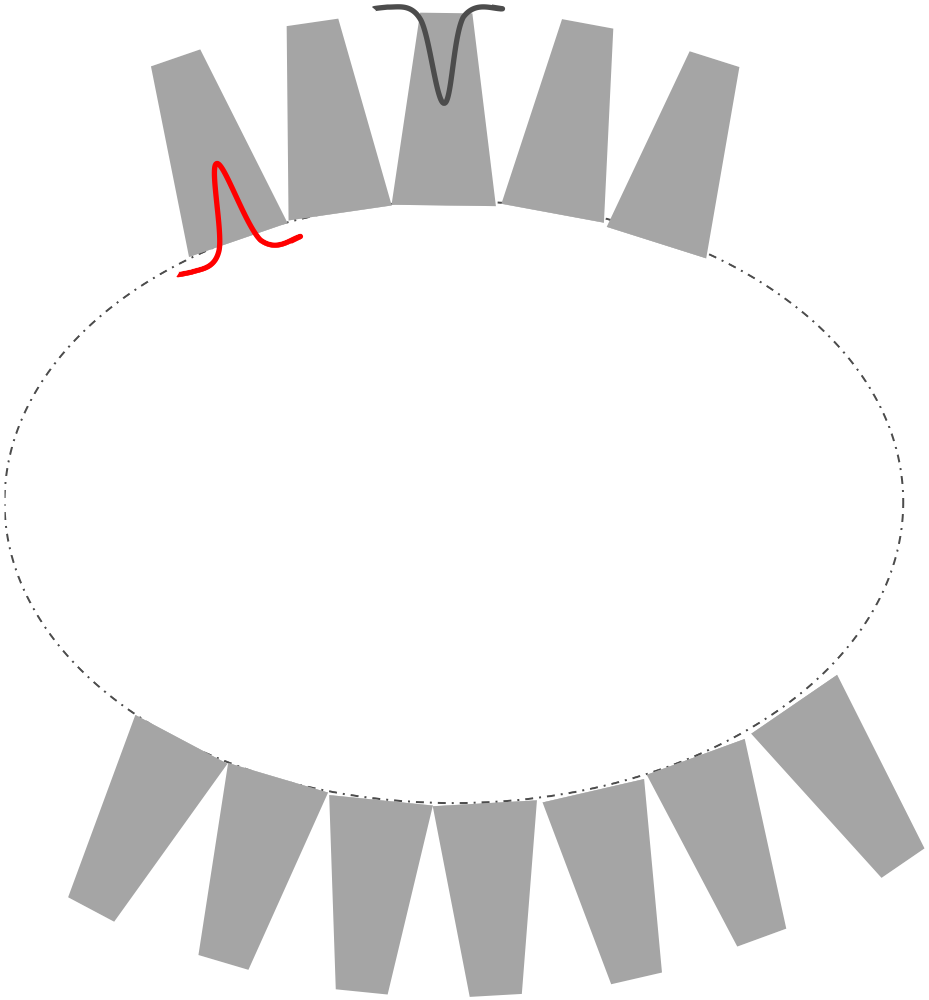
+ Conclusions

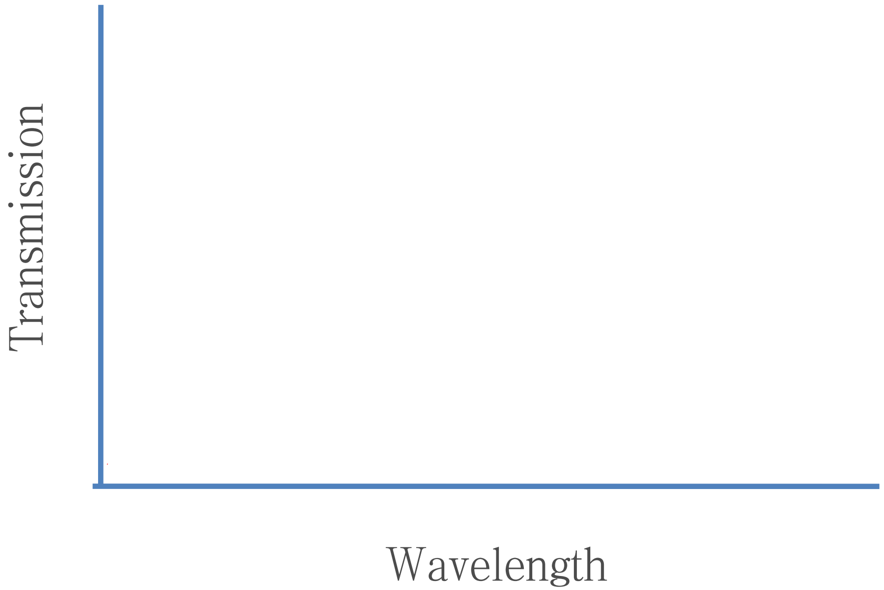
Problems in Silicon AWG



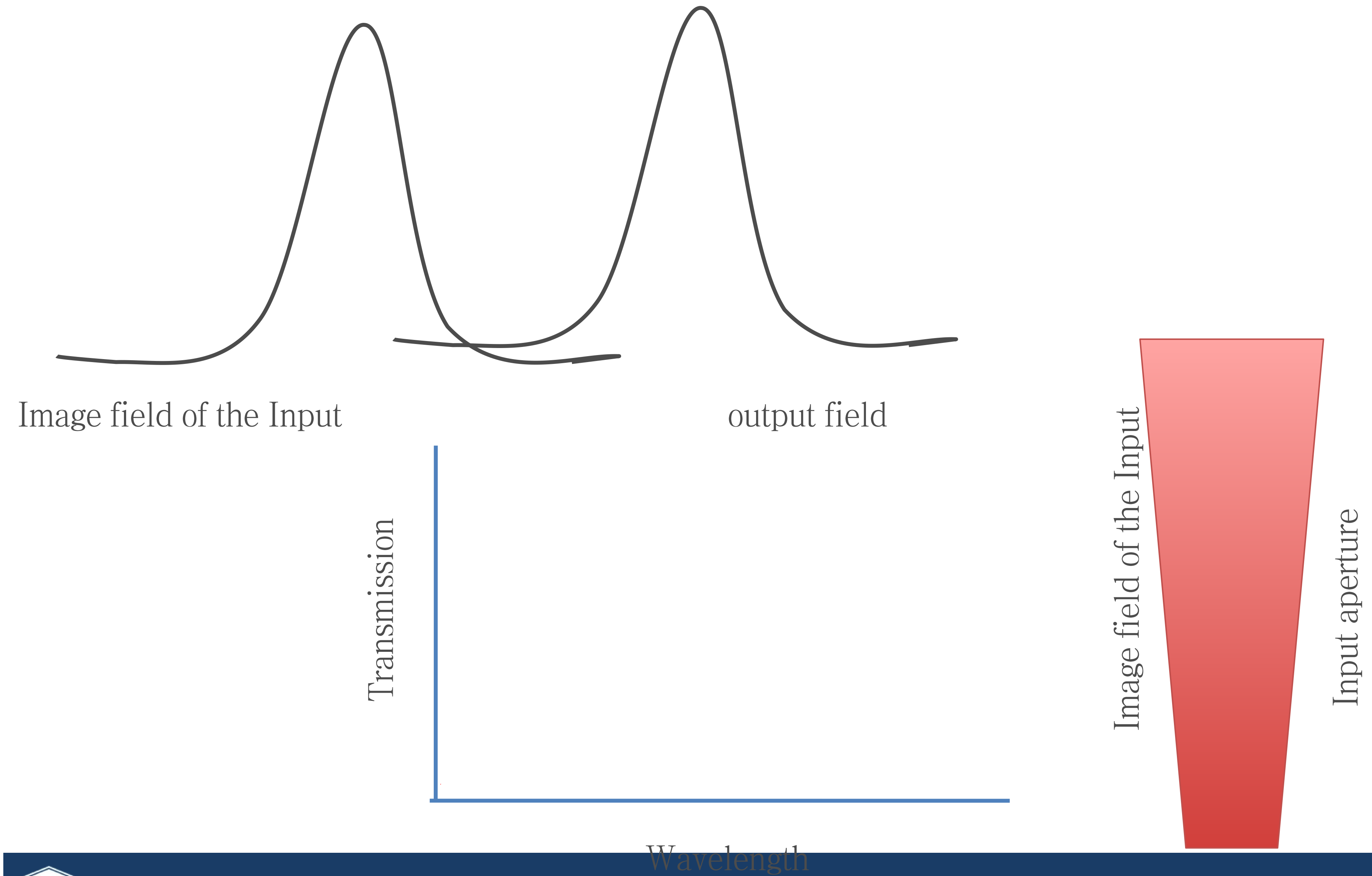
- ~~High Insertion Loss~~
- ~~High Crosstalk~~
- ~~Channel Spacing Mis~~match
- Round Top

Second Star-coupler: Round Top

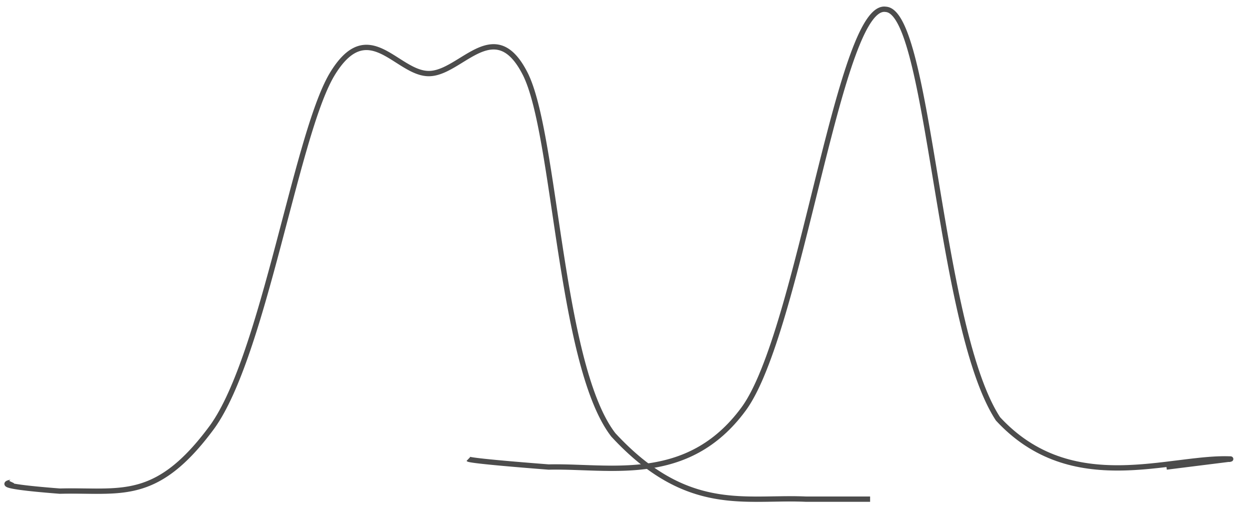


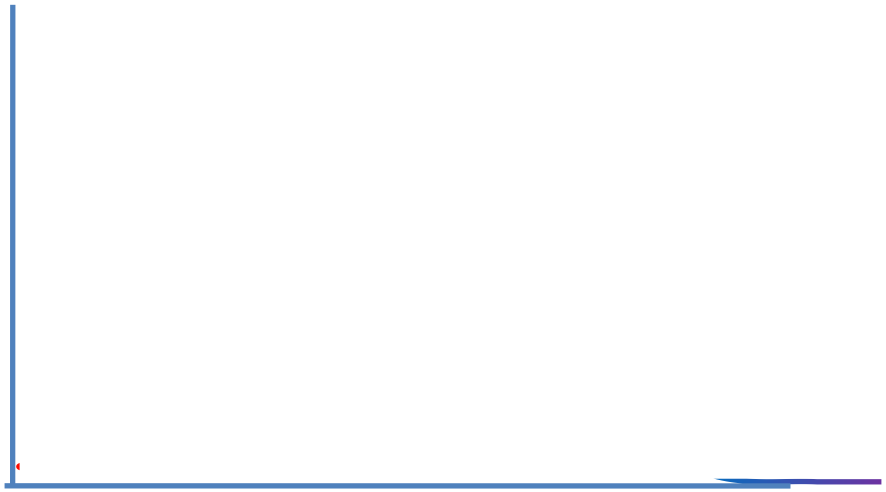


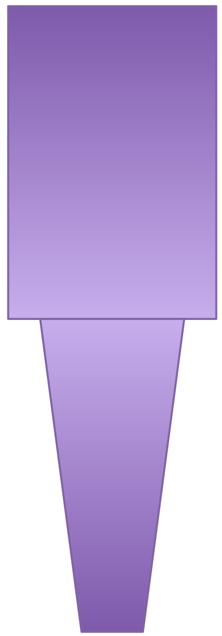
Second Star-coupler: Convolution



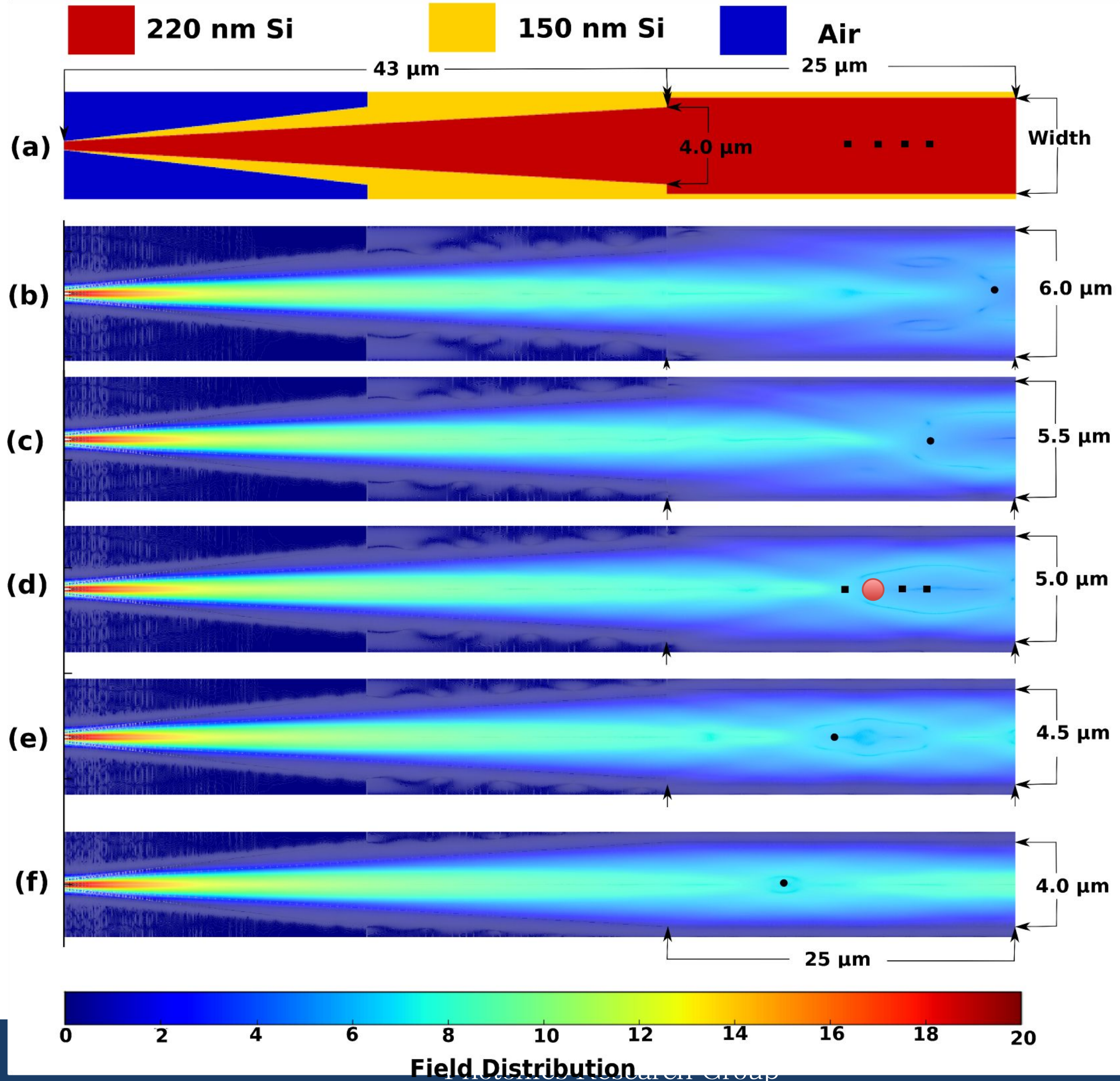
Second Star-coupler: Convolution



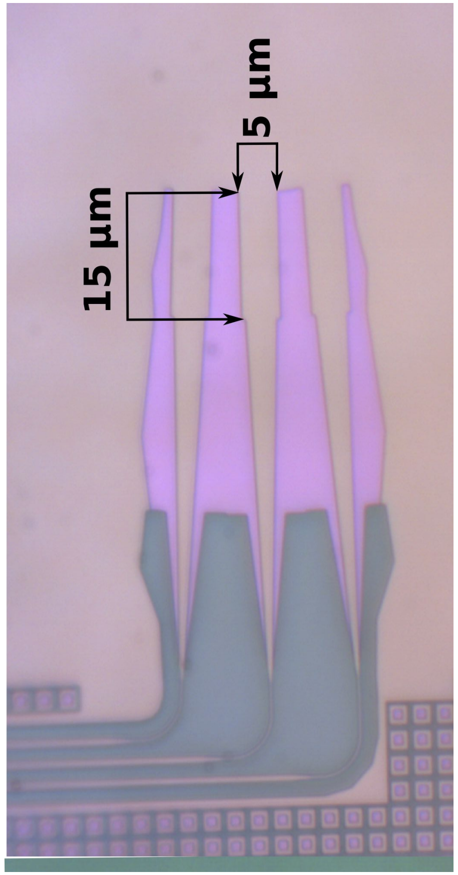




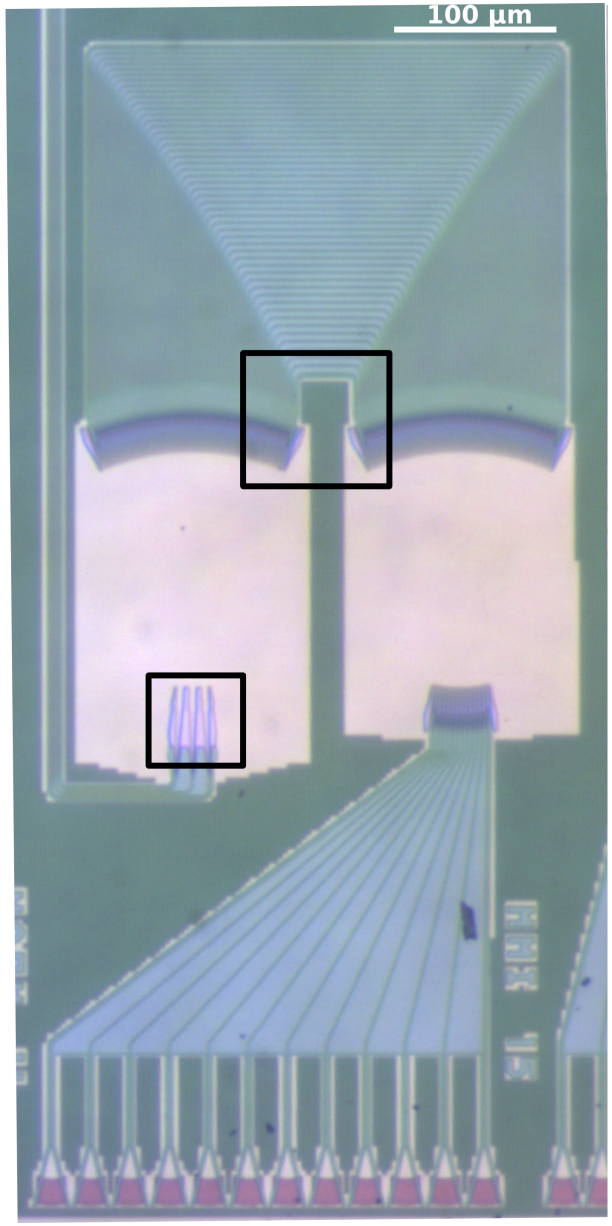
MMI aperture: Simulation



Fabricated MMI–AWG

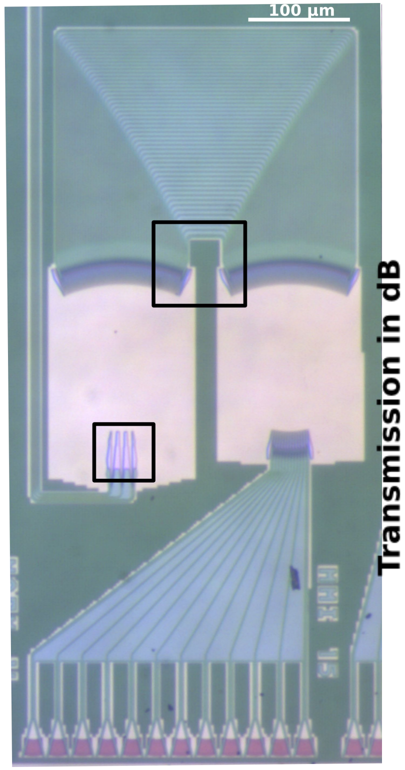


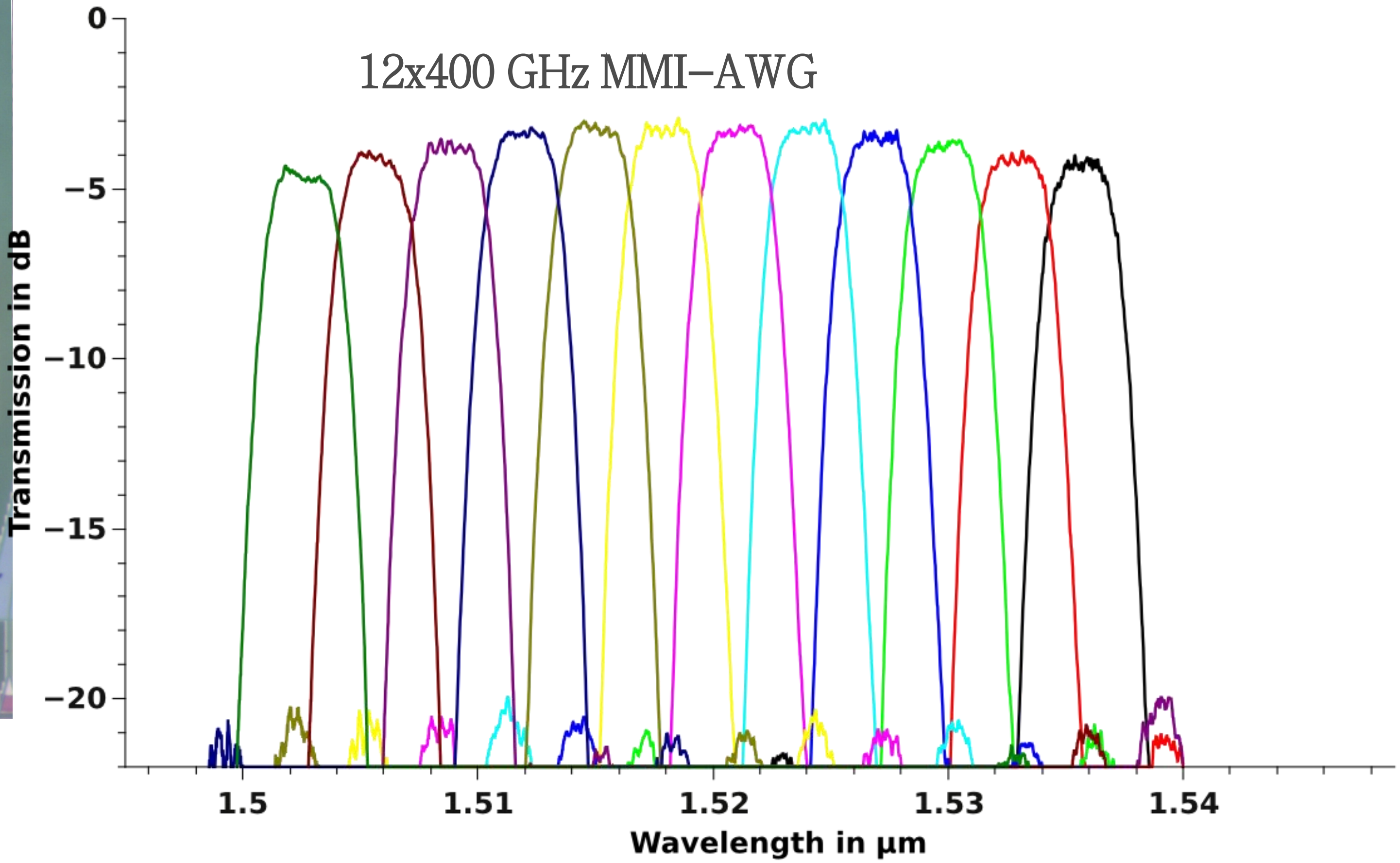
MMI aperture



12x400 GHz MMI–AWG

Measurement Results of MMI-AWG

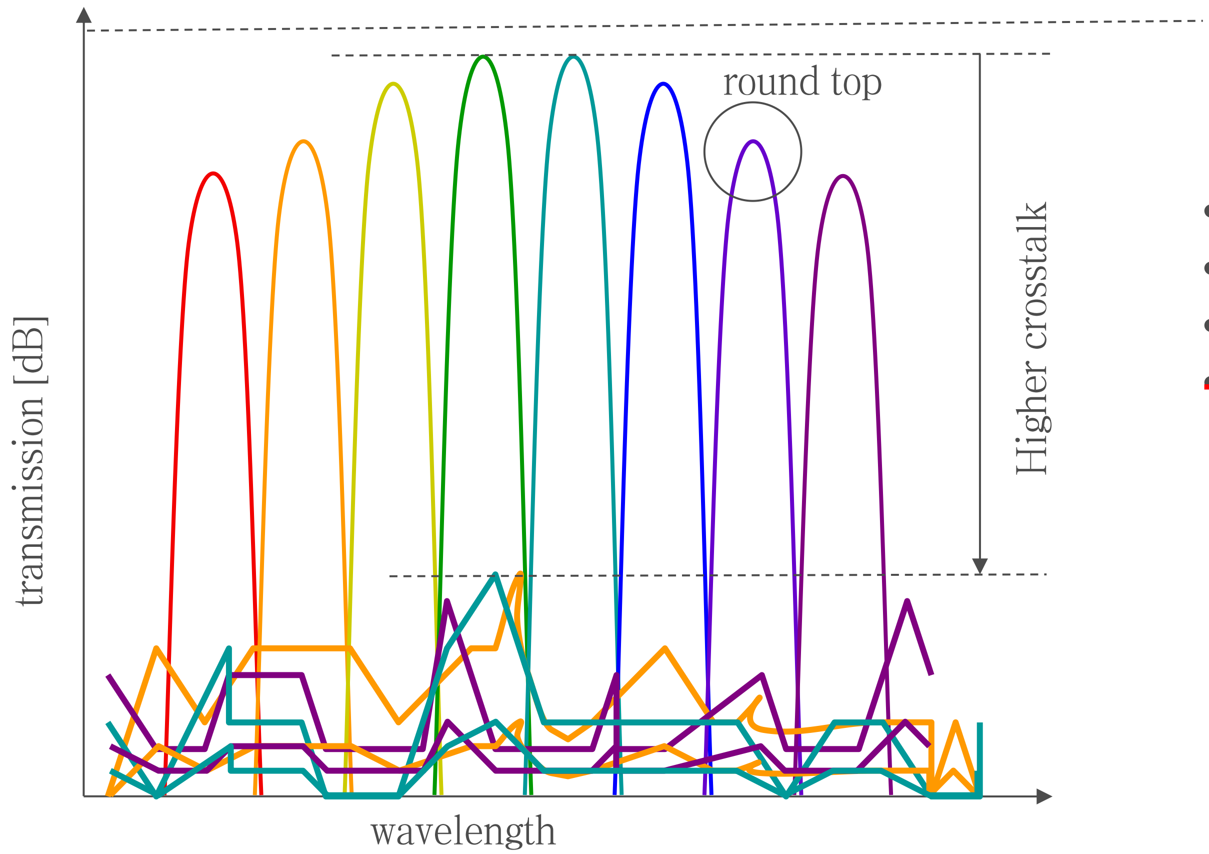




Insertion loss −2.07 dB
Crosstalk −19.5 dB

Aspect ratio (1dB bandwidth/ 10 dB bandwidth)
0.5

Problems in Silicon AWG



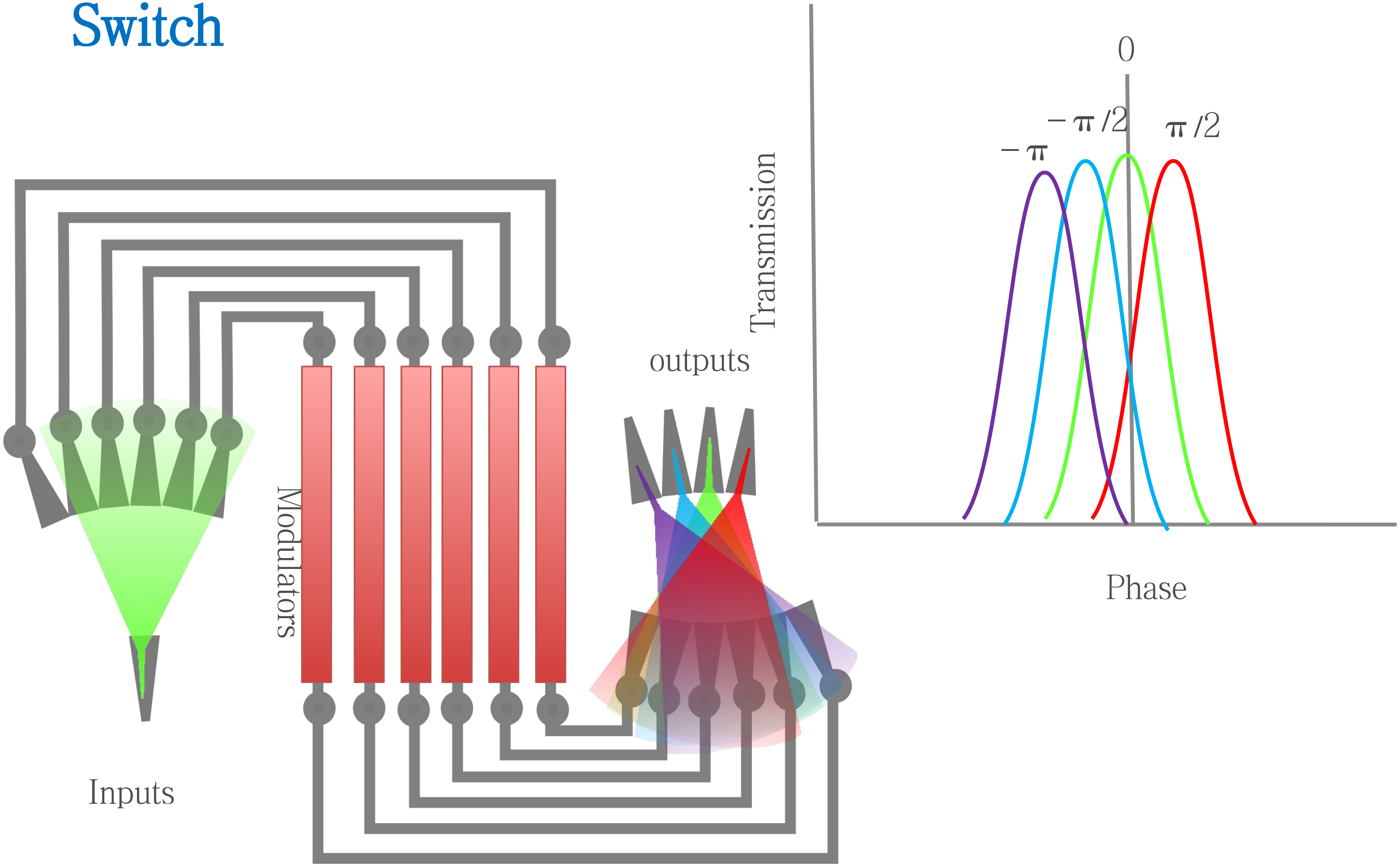
- ~~High Insertion Loss~~
- ~~High Crosstalk~~
- C~~hannel Spacing Misma~~tch
- ~~Round Top~~

Structure the outline

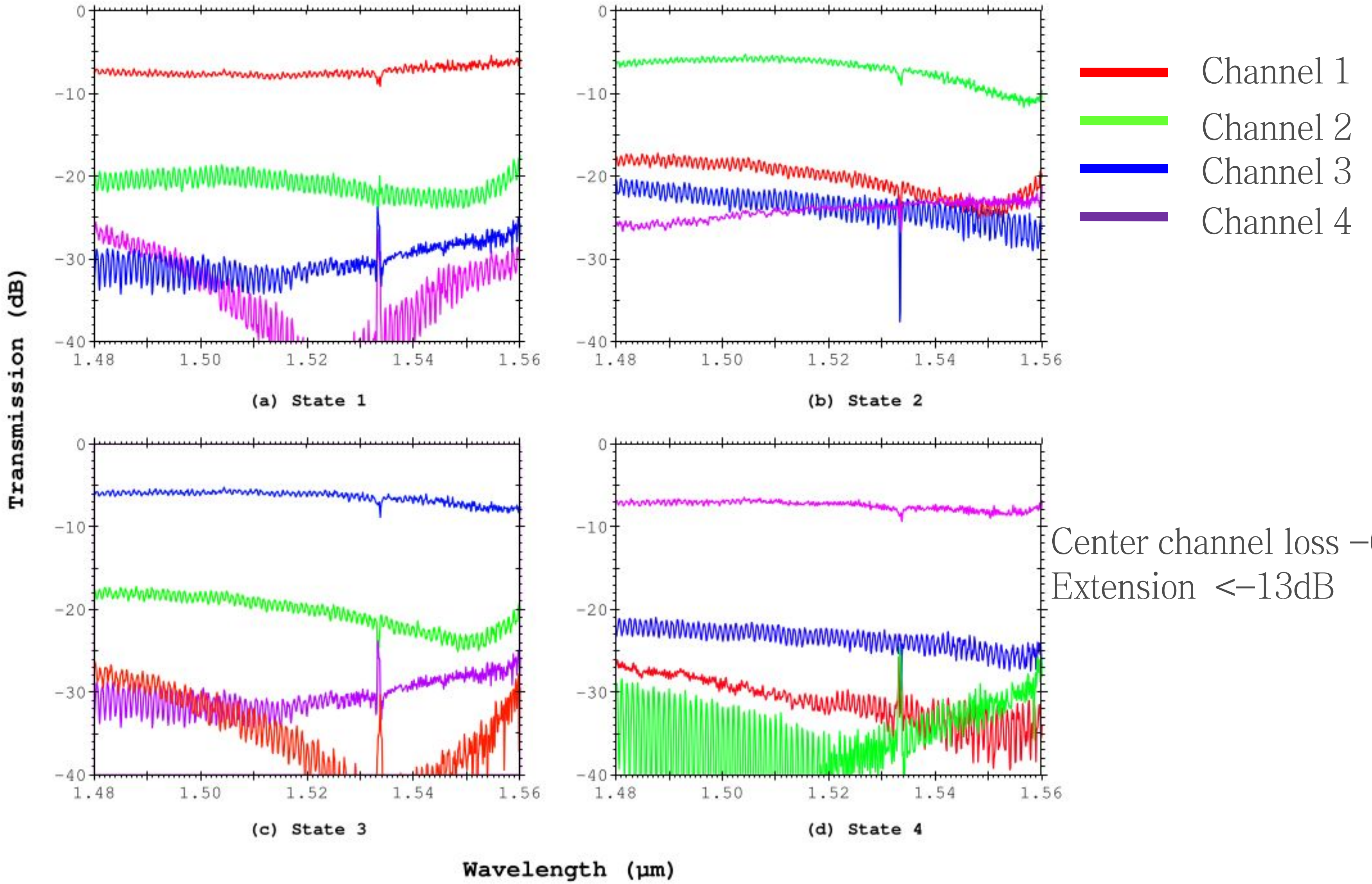
+ Our approach
– Our results
  - Insertion Loss and Non–uniformity
  - Crosstalk
  - Channel mismatch
  - Round top to flattop
  - Switch

+ Conclusions

Switch



Measurement of the switching state

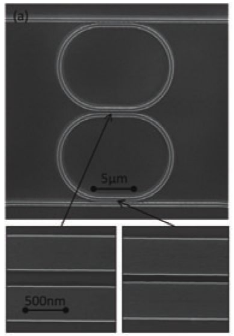


Center channel loss –6 dE
Extension <–13dB

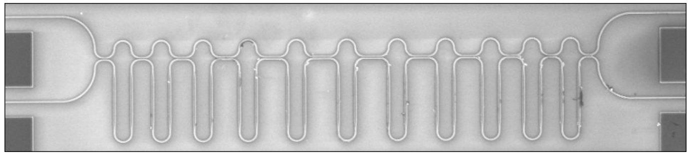
Structure the outline

+ Our approach
+ Our results
– Conclusions
  - comparison with other filters
  - comparison with the world
  - summary

Comparison between the Filters



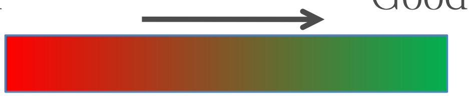
Ring filter



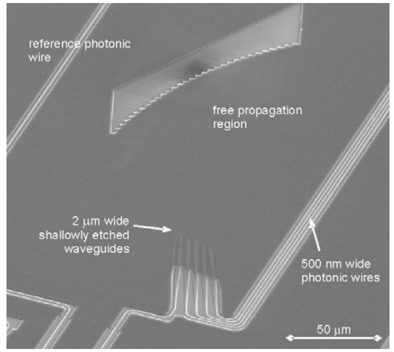
Lattice filter

Bad

Good



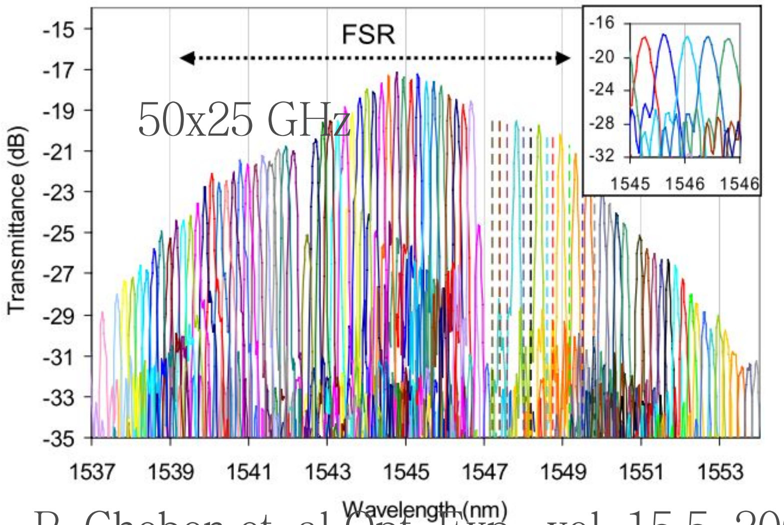
AWG



Echelle gratings

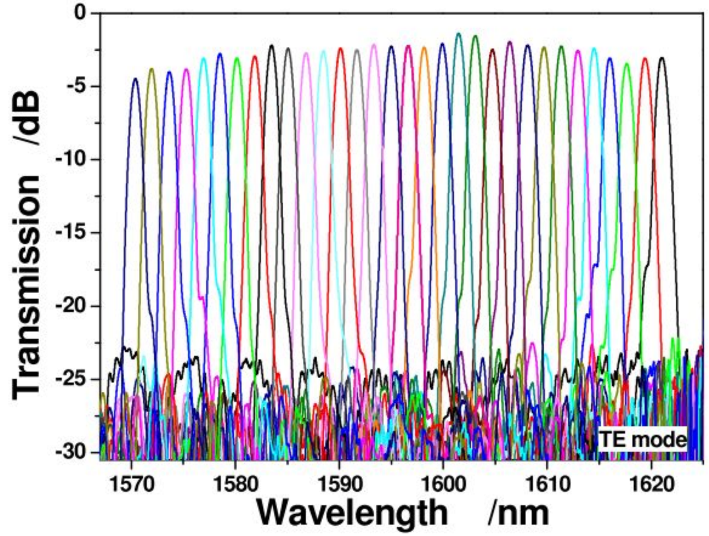
	Ring filter	Lattice filter	AWG	PCG
Fabrication Dependency				
loss				
crosstalk				
Thermal tuning				
Router				
Higher no output				

Comparison with the world

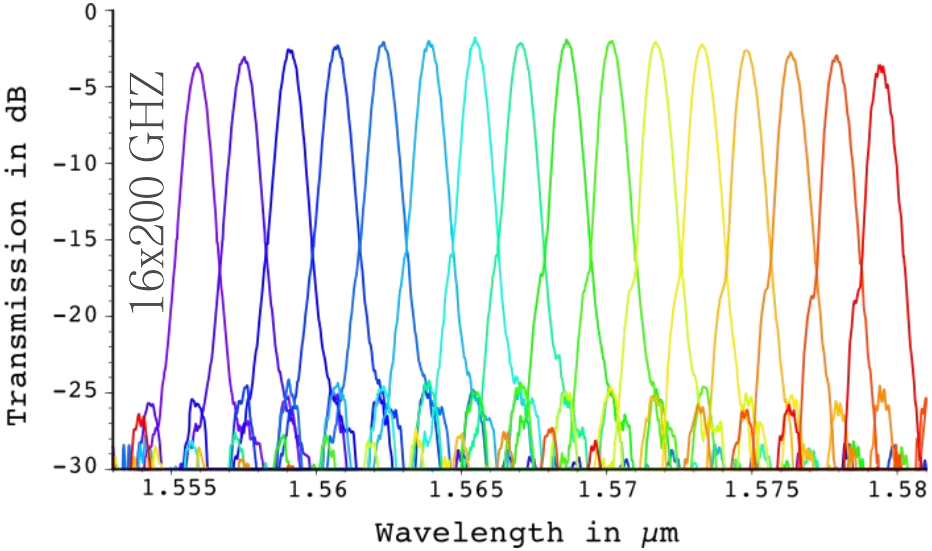


P. Cheben et. al Opt. Exp., vol. 15,5, 2007

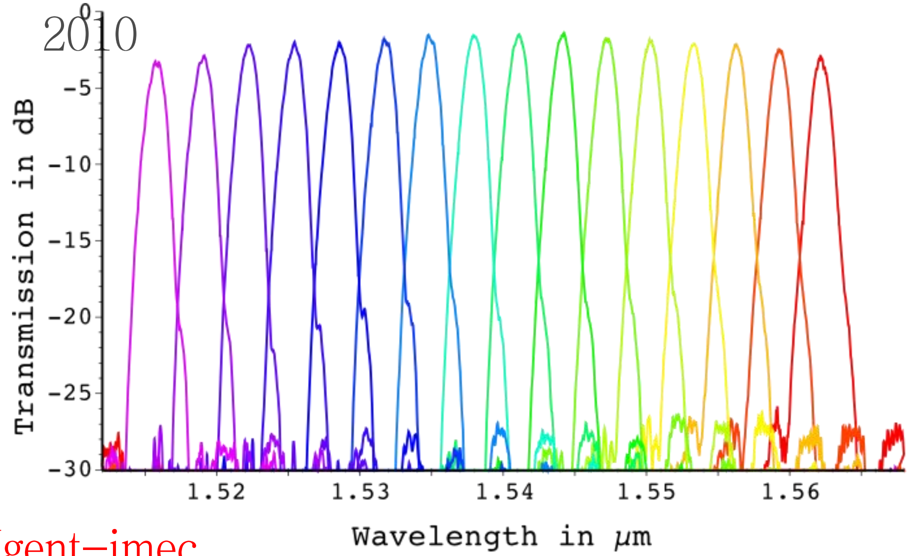
32x200 GHZ



Q. Fang et. Al Opt. Exp., vol. 18, 1, 2010



16x400 GHZ



Ugent–imec

Summary

We studied AWGs on silicon

- –We developed a full method for design–simulation–fabrication– characterization

We approached several problems of AWGs, with significant improvements

- – loss and uniformity
- – grid snapping
- – flat top
- – channel spacing

We made an active AWG switch in silicon

Photonics Research Group

http://photonics.intec.ugent.be

Thank You