Keio University

Research presentation:

High performance silicon AWG with geometrically improved interface between slab and waveguide array

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Agenda

- Introduction
- Aim of research
- Research method and results
- Conclusion

Introduction

Framework of AWGs

- One of the most used photonic component in optical networks : increase capacity of transmission and flexibility

- Optical wavelength de/multiplexer

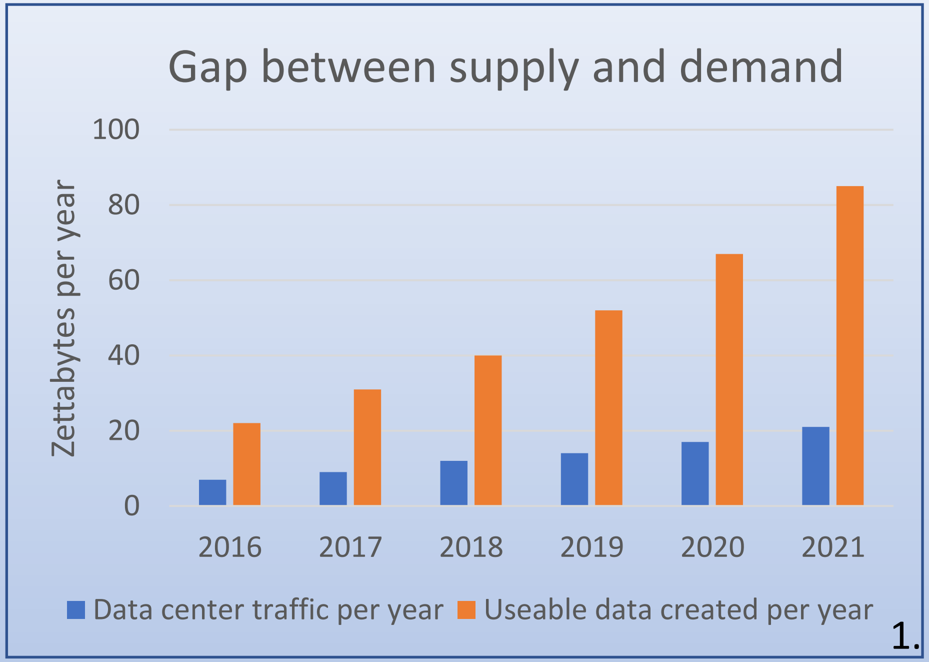
  Appli.

  → modulator, photodiode, WDM device, optical coupler/splitter

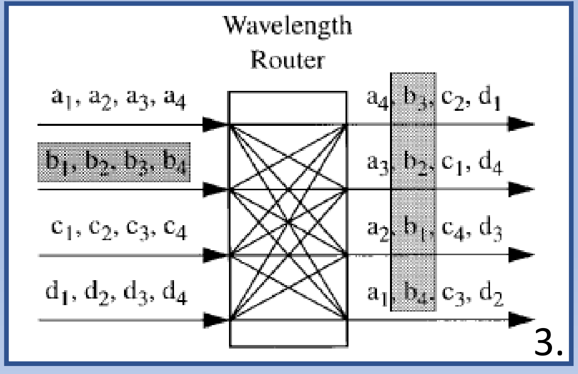
- Compact device, single-mask planar waveguide technology

- At first in Silica, now being developed using Silicon to increase integration density and performances

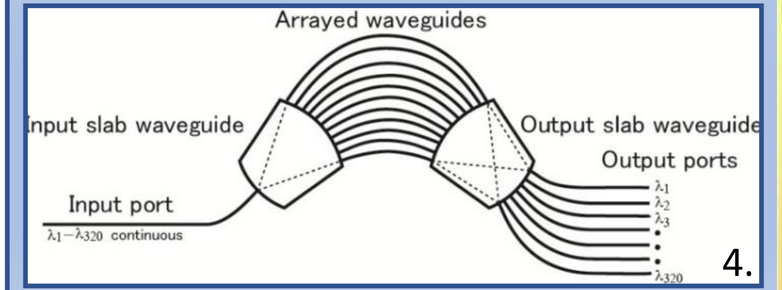
Issues



Data center

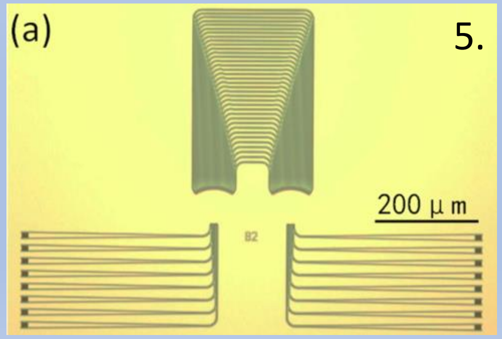


Router in Optical networks



Demultiplexing →

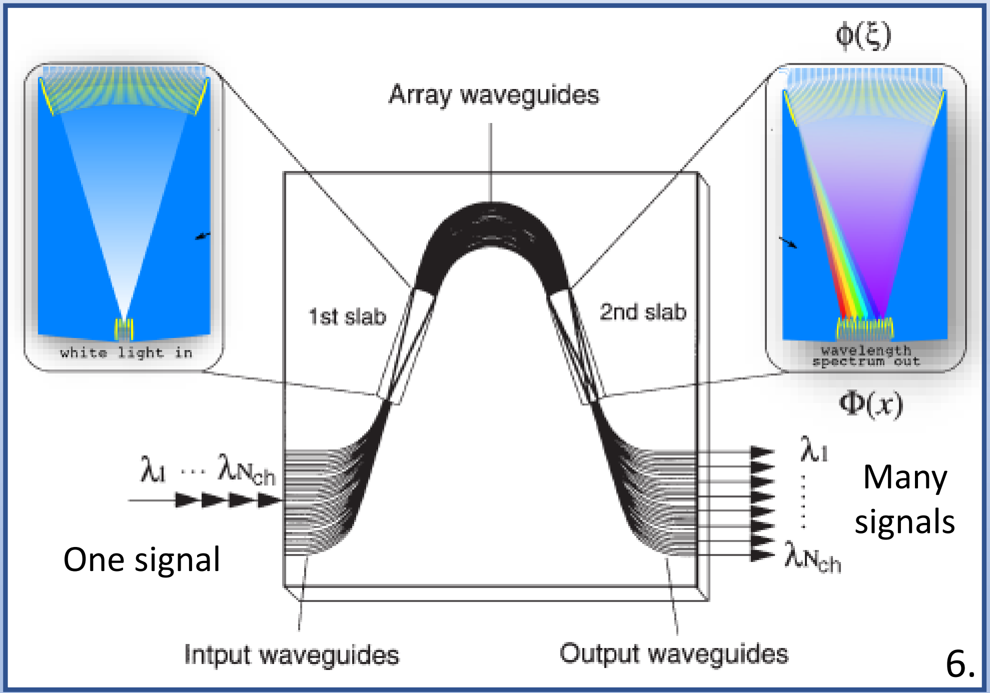
← Multiplexing



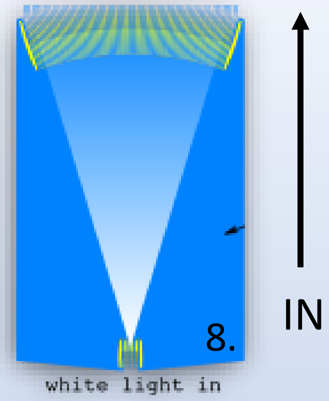
Si single mask

Physical characteristics

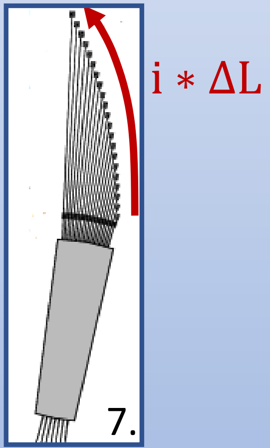
Structure:



Physical principles:



1st slab: diffraction of input signal, copy to each arrayed waveguides

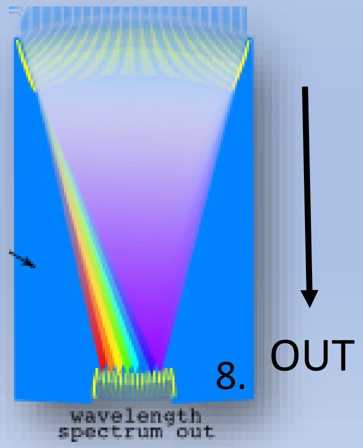


Section view of AWG

Arrayed waveguides: constant length difference ΔL introducing delays between signals

2nd slab: interference of beams

→ Spatial division of wavelength



Silicon photonics

Guiding mechanism

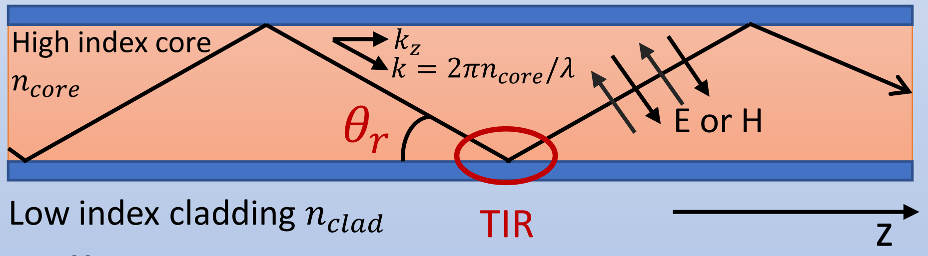
$\theta_{r\_max} = \cos^{-1}(\mathrm{n_{clad}}/\mathrm{n_{core}})$ with

$\mathrm{n_{Si}} = 3.47, \mathrm{n_{SiO_2}} = 1.44, \mathrm{n_{Ge-SiO_2}} = 1.45$

Better waveguiding mechanism for Silicon

Optical confinement

TIR : total internal reflection

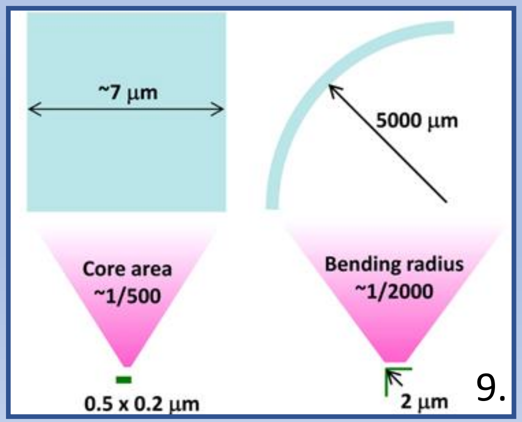


Miniaturization

Core area 500 times smaller

Bending radius 2000 times smaller

- Increase integration density
- Compact : energy efficient
- CMOS compatible and robust



Drawbacks

High n waveguides :

- Extremely sensitive to phase errors

Reduce margin of error of both the design and fabrication

Increase the overall crosstalk

- Higher propagation losses
- Scattering/transition losses

Increase the overall crosstalk

Aim of research

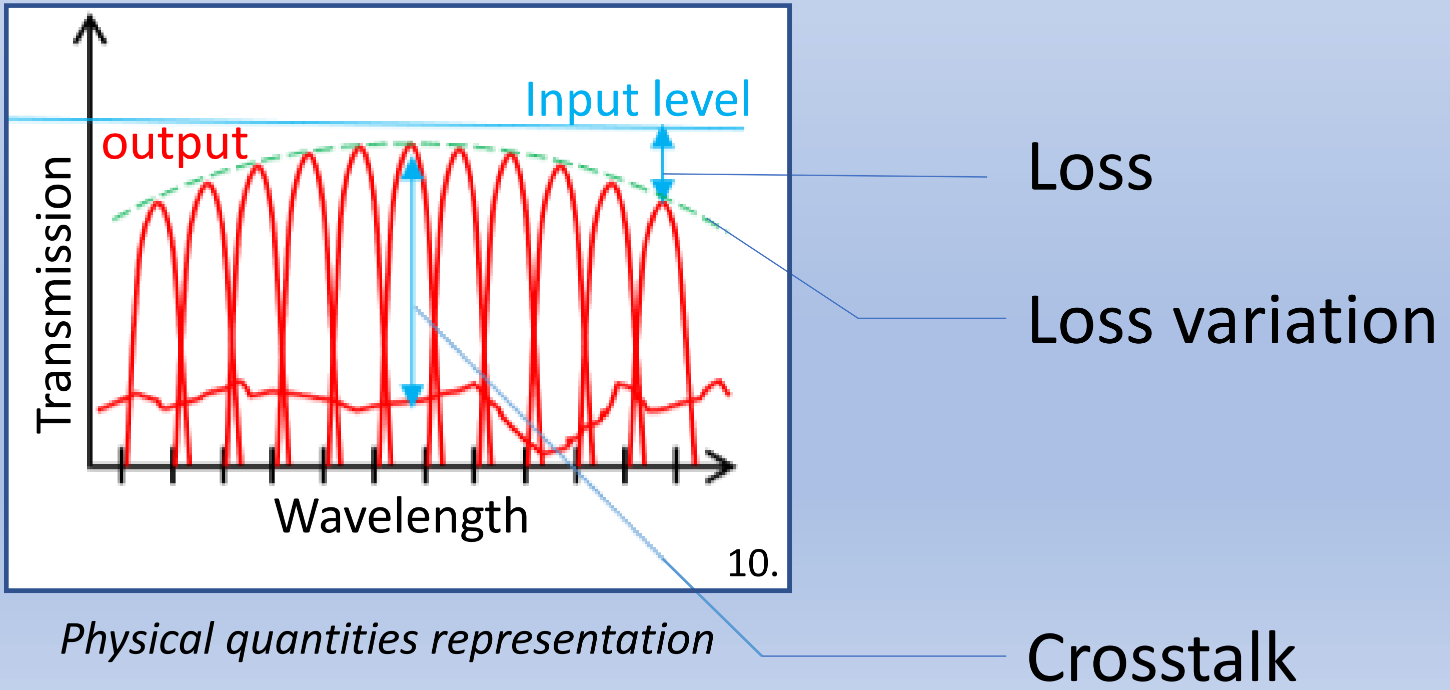
Goal : High performance Si AWG

By reducing:

- Loss
- Loss variation
- Crosstalk

Method

- Introducing new modifications
- Optimization methods



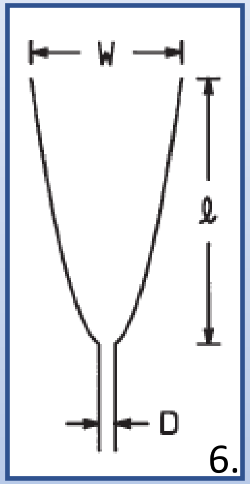
Physical quantities representation

Research Method

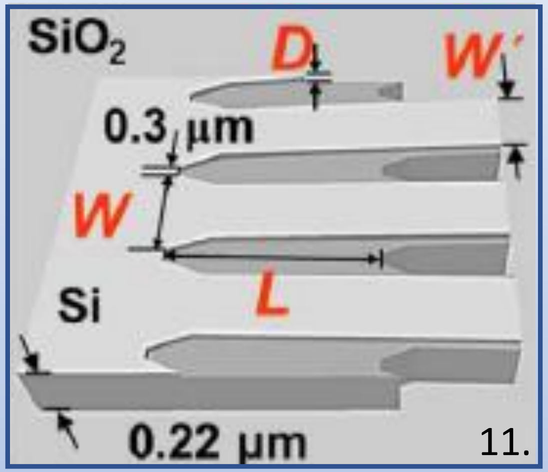
Proposal of new AWG structure

Background

Adiabatic transition



Tapers



Etching

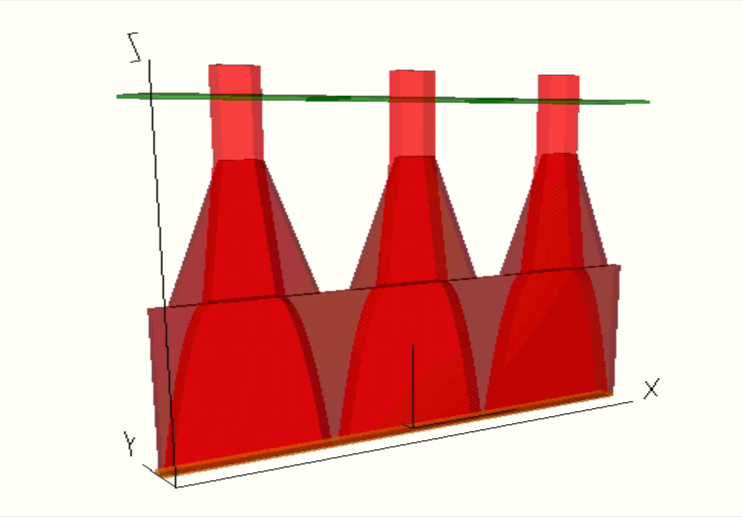
Smoother transition

Tapers : mode-size converter to reduce planar waveguide and single mode waveguide mismatching

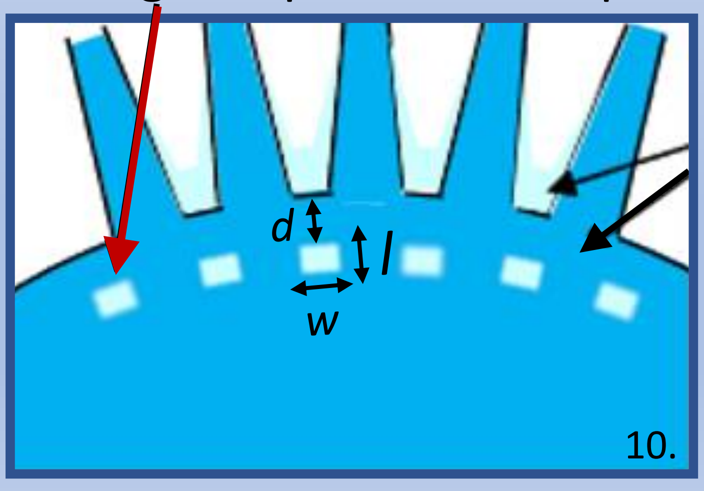
Etching : suppressing multimode generation and the scattering due to the optical field mismatch effect

New improvements

New taper structure : 2 stages



Slab etching and parameters optimization



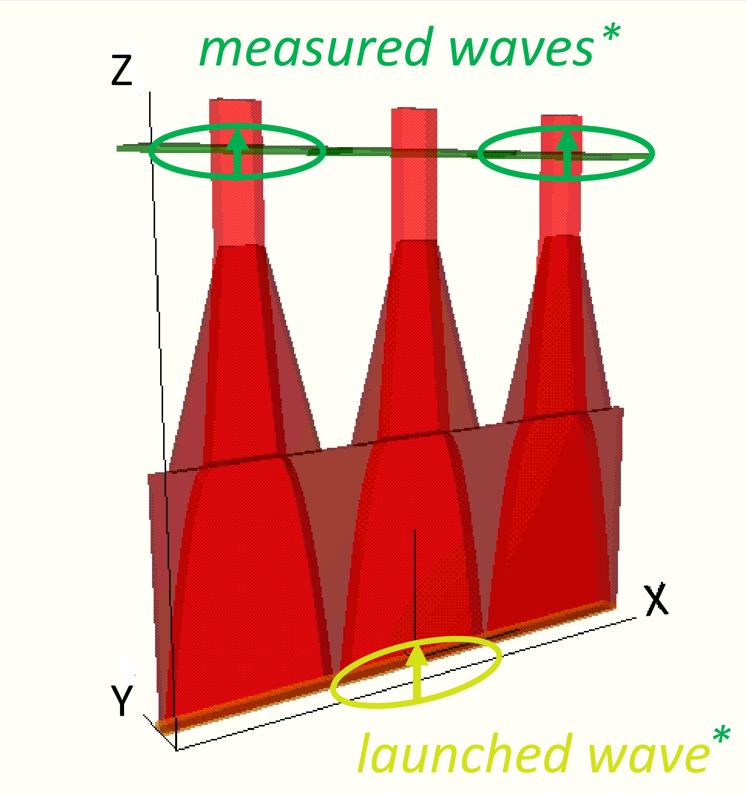
Etched regions

Wavefront Matching Method (WMM)

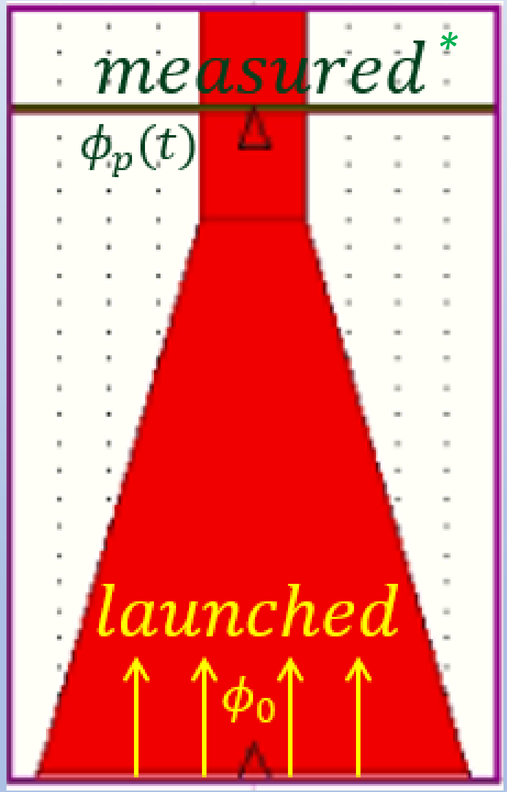
Measurement setup and metrics

Geometrical Setup

Crosstalk



Power



*Measurement planes in green in following slides

Metrics

Efficiency η in mode m

$$\eta = \frac{1}{4P_m P_{\text{src}}} \left| \iint_A d\mathbf{A} \cdot \mathbf{E} \times \mathbf{H}_m^* \right|^2$$

→ Optimize for fundamental mode (Overlap integral)

Power S(t) crossing the measurement site

$$S(t) = \frac{1}{S_0} \mathrm{Re}\left[\int_A [\mathbf{E}(\mathbf{r},t) \times \mathbf{H}^*(\mathbf{r},t)] \cdot dA. \right.$$

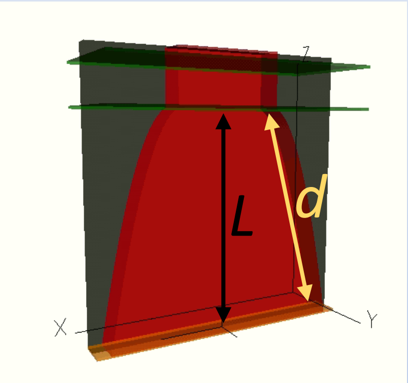
→ Compute Crosstalk and Loss

Taper two stages optimization

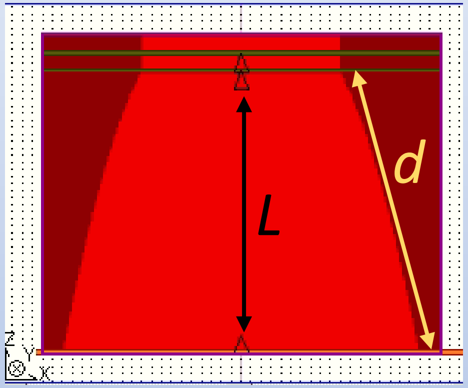
1st stage of optimization

Parabolic

3D view

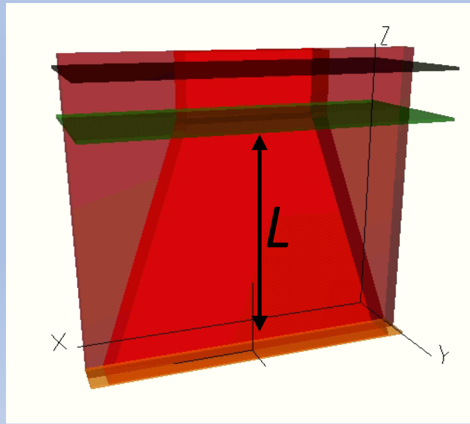


2D view

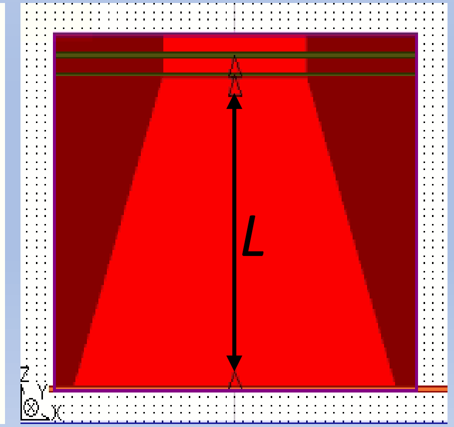


Linear

3D view



2D view

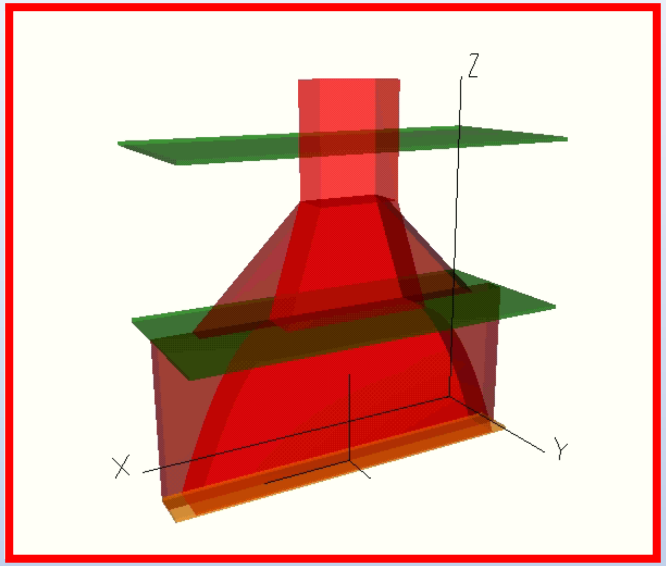


2 STAGES

Rib

Taper

2nd stage of optimization

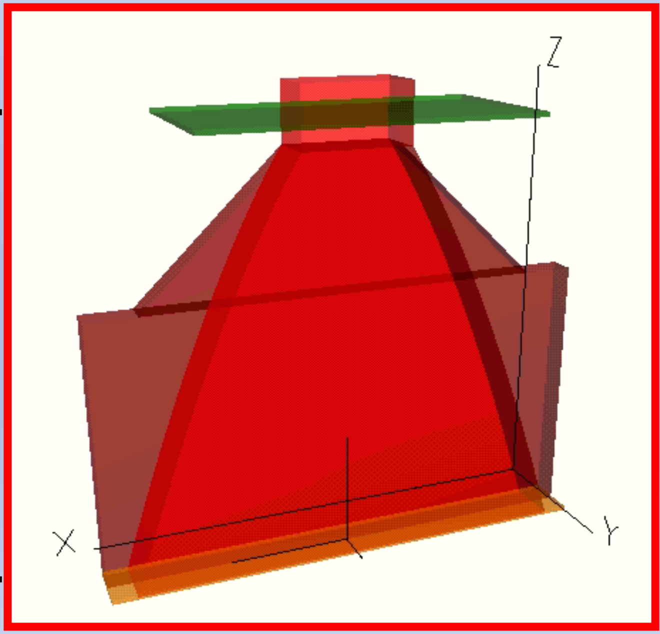


Lrib

L

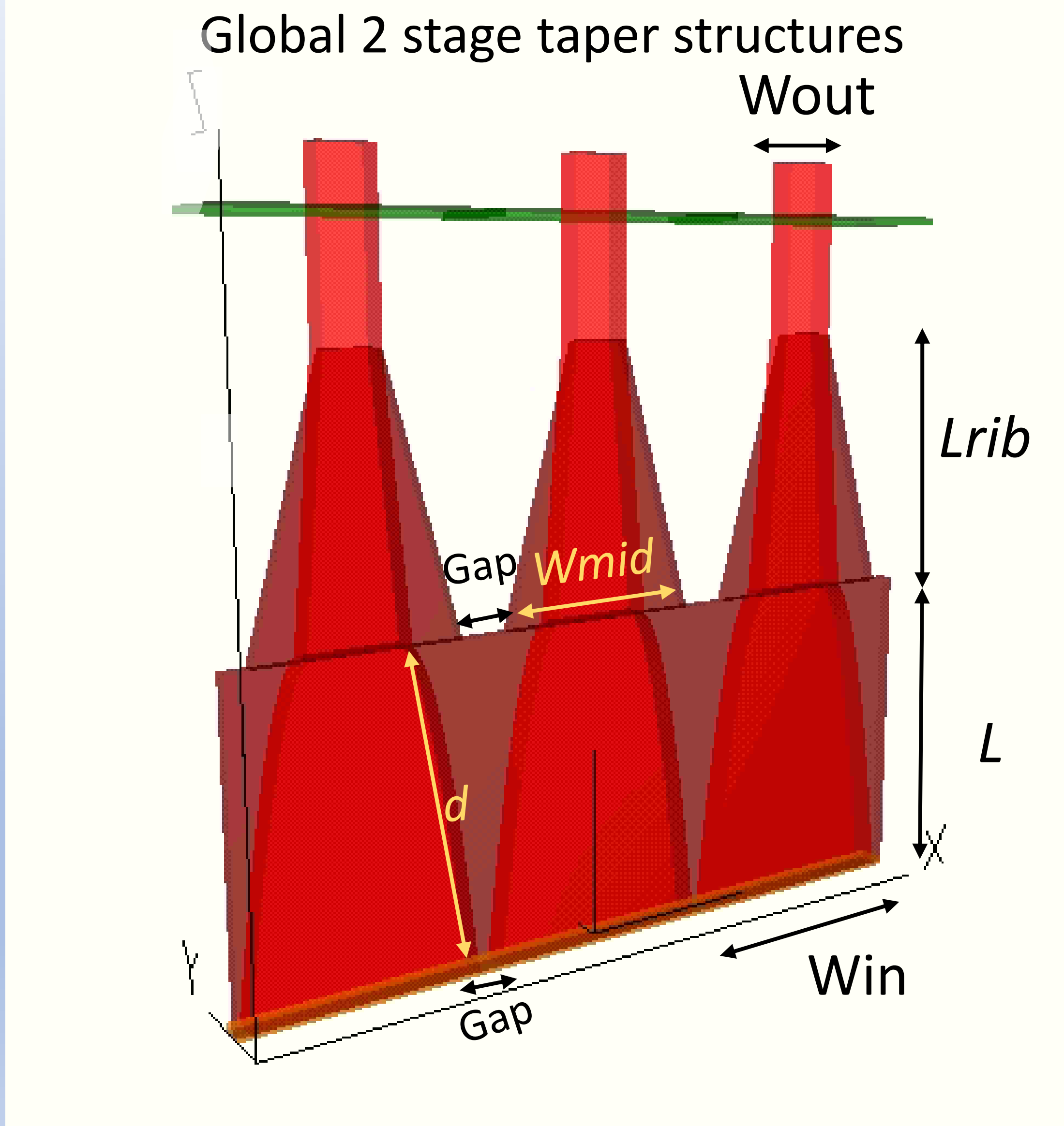
COMBINED

Taper + Rib



L + Lrib

Taper two stages optimization (cont.)



Optimization parameters :

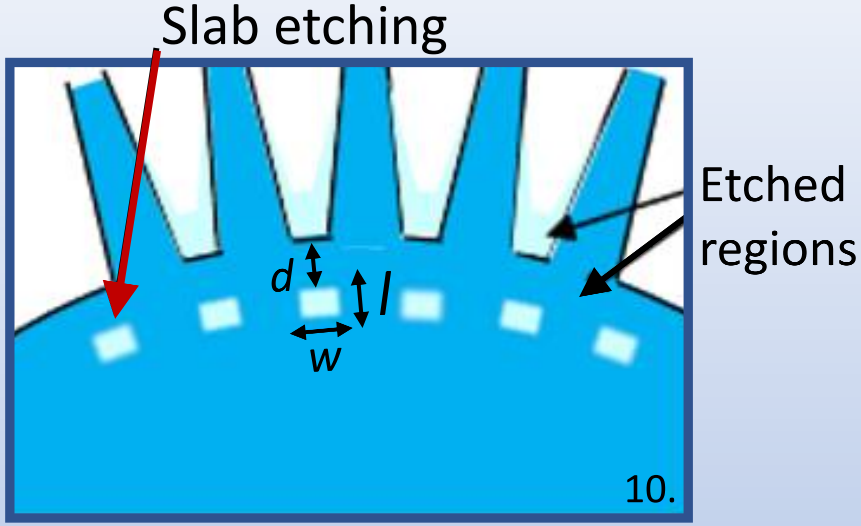
Parameter symbol	physical meaning
L	length of taper
Lrib	length of rib structure
Wmid	width of rib waveguide
d	pitch of the parabolic taper

Fixed:

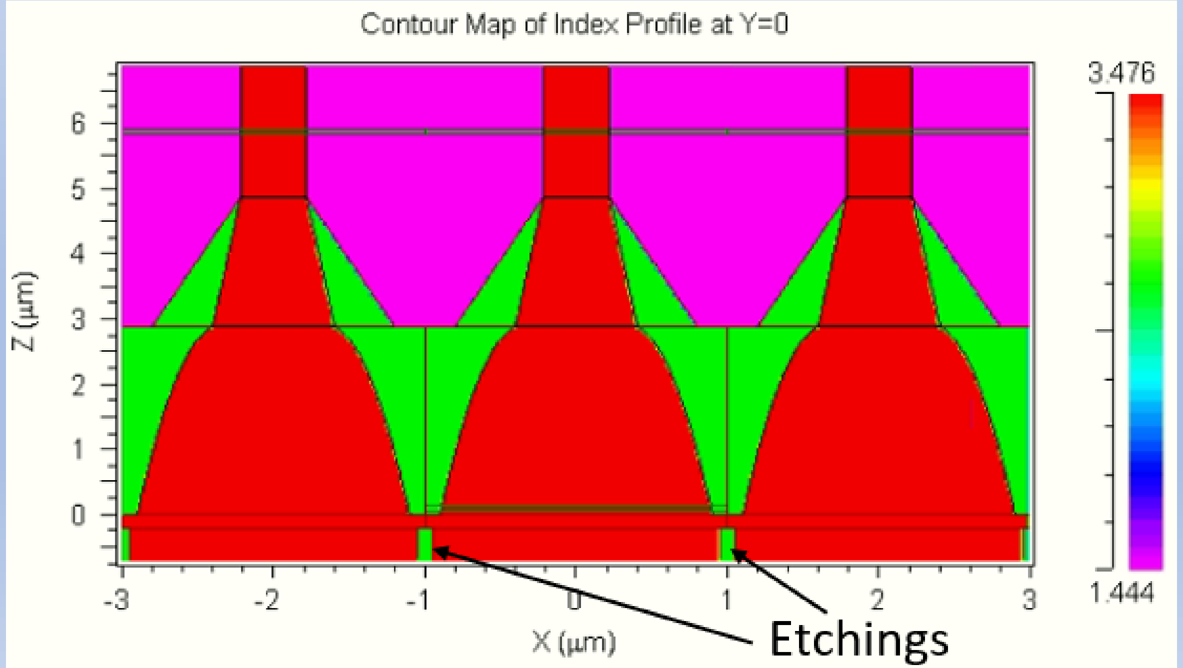
- Taper input width (Win)
- Single mode waveguide width (Wout)
- Gaps

Etching optimization

Artistic view



Layout Y-cut

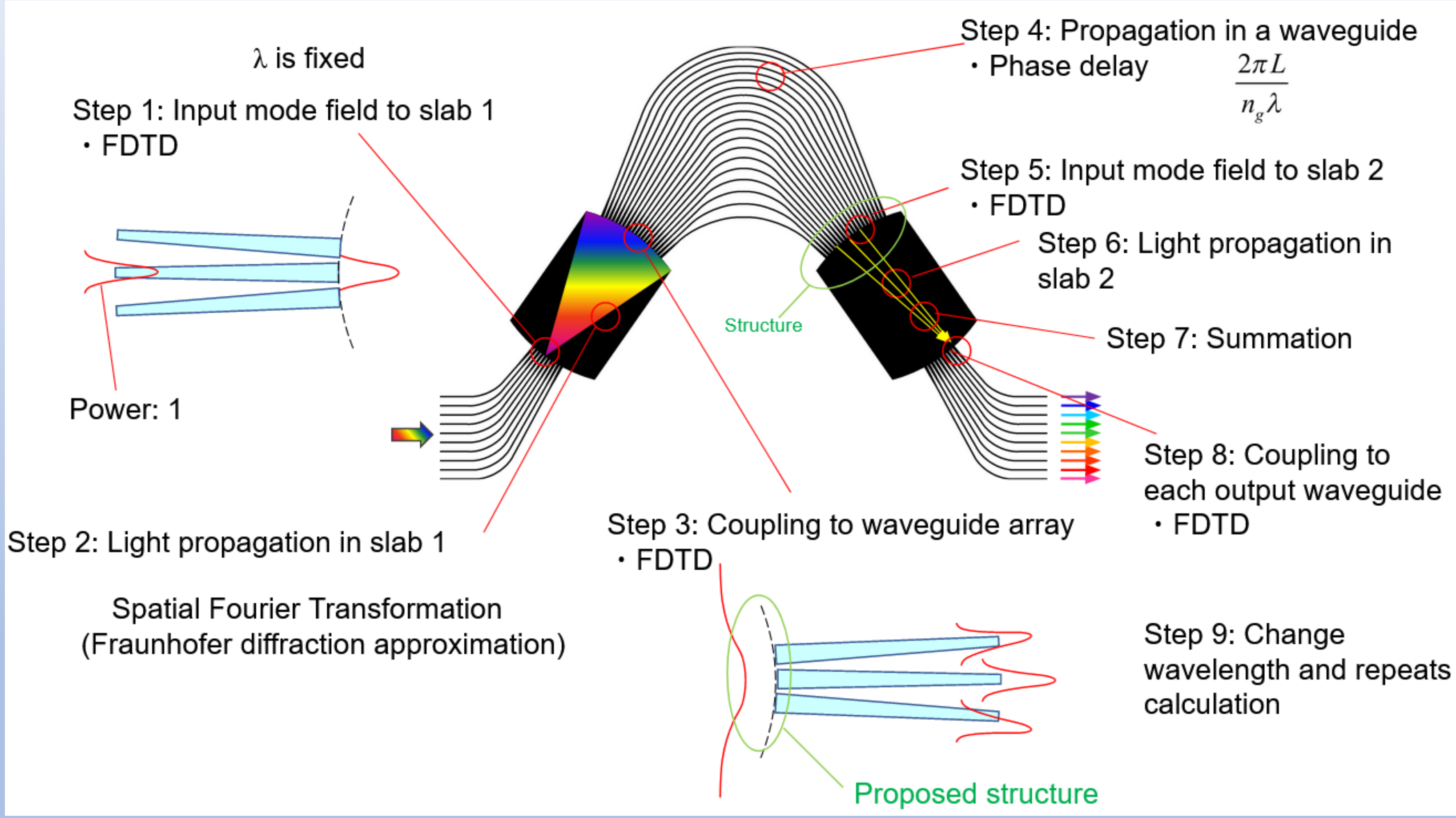


Optimization parameters :

Parameter symbol	physical meaning
detch	etching distance relative to the slab interface
letch	length in z-direction of the etching area
wetch	width in x-direction of the etching area

Find *detch*, *letch* and *wetch* by maximizing the metrics under minimum resolution constraints

Overall AWG characteristics



9 steps including:

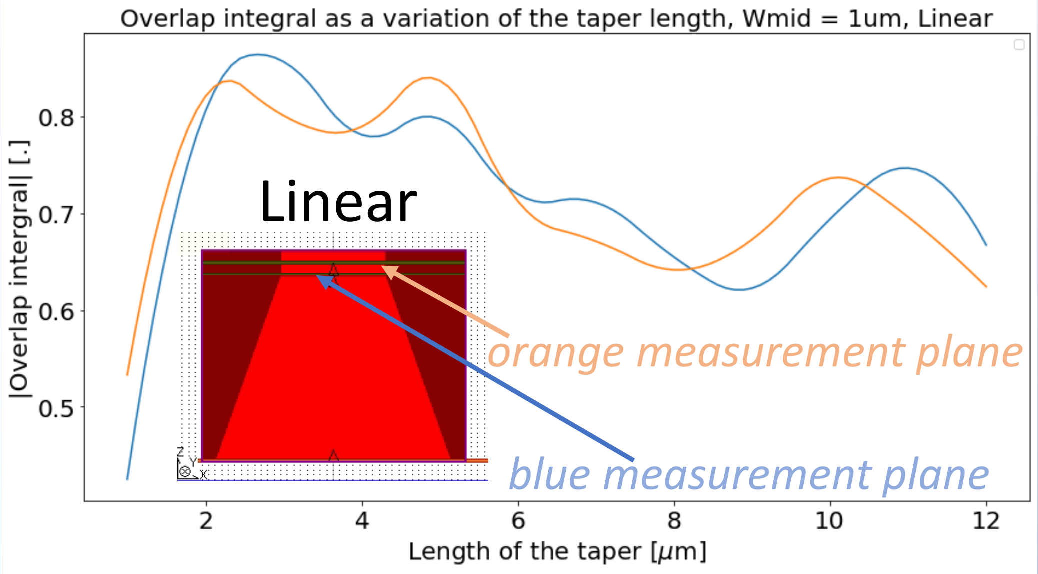
- FullWave FDTD
- Fourier transform
- Custom algorithm

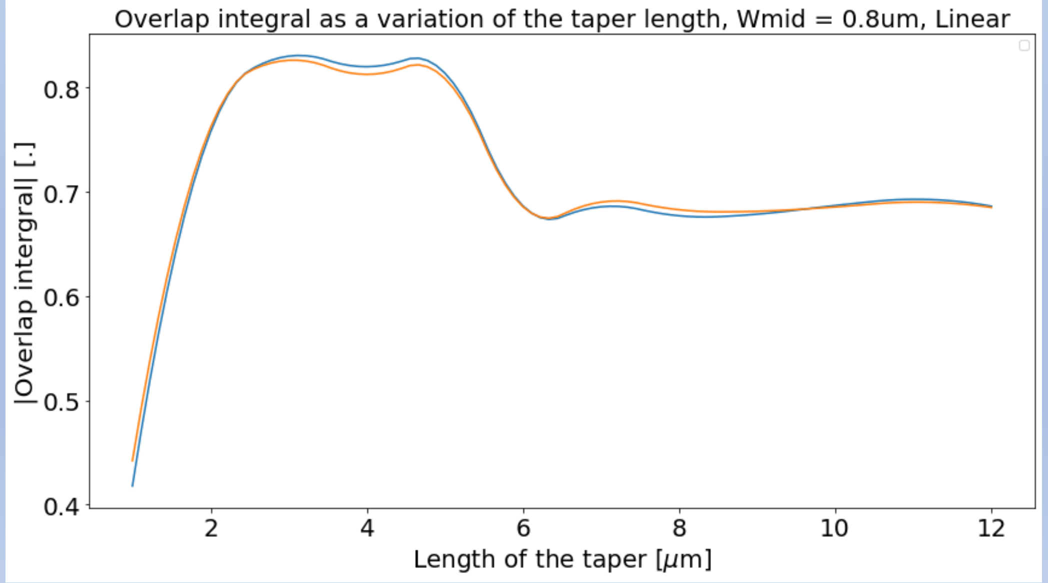
Simulation and Results

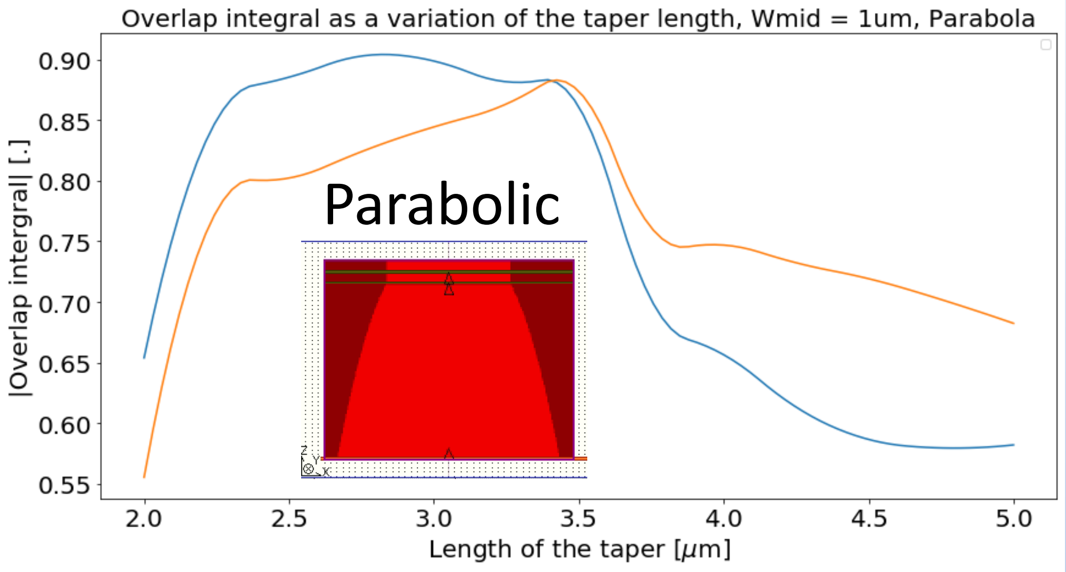
First stage : Taper optimization

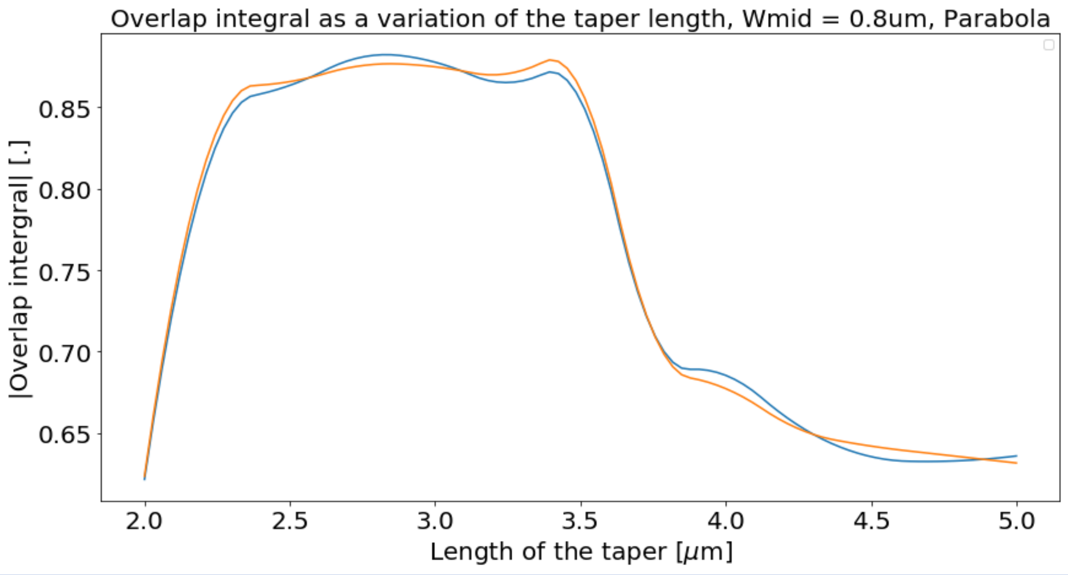
3D FDTD Overlap data

Parabolic ➔ Better Transmission





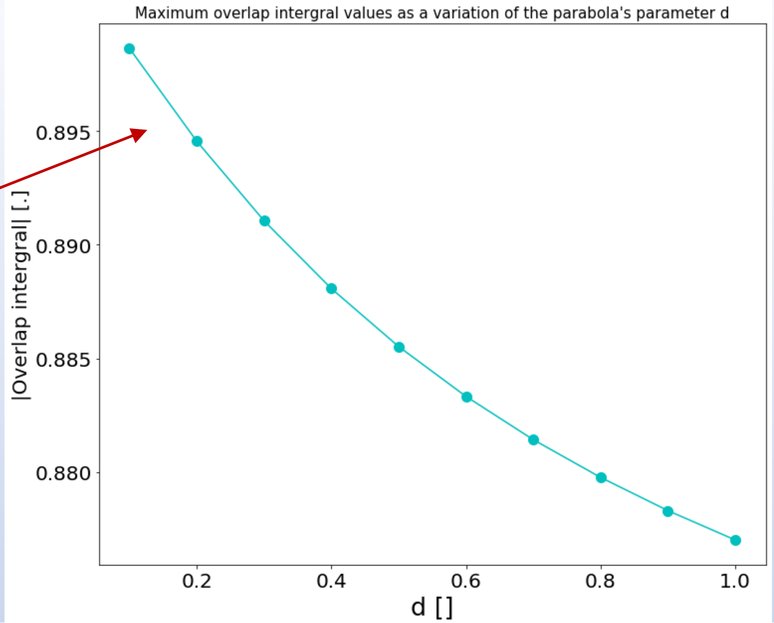


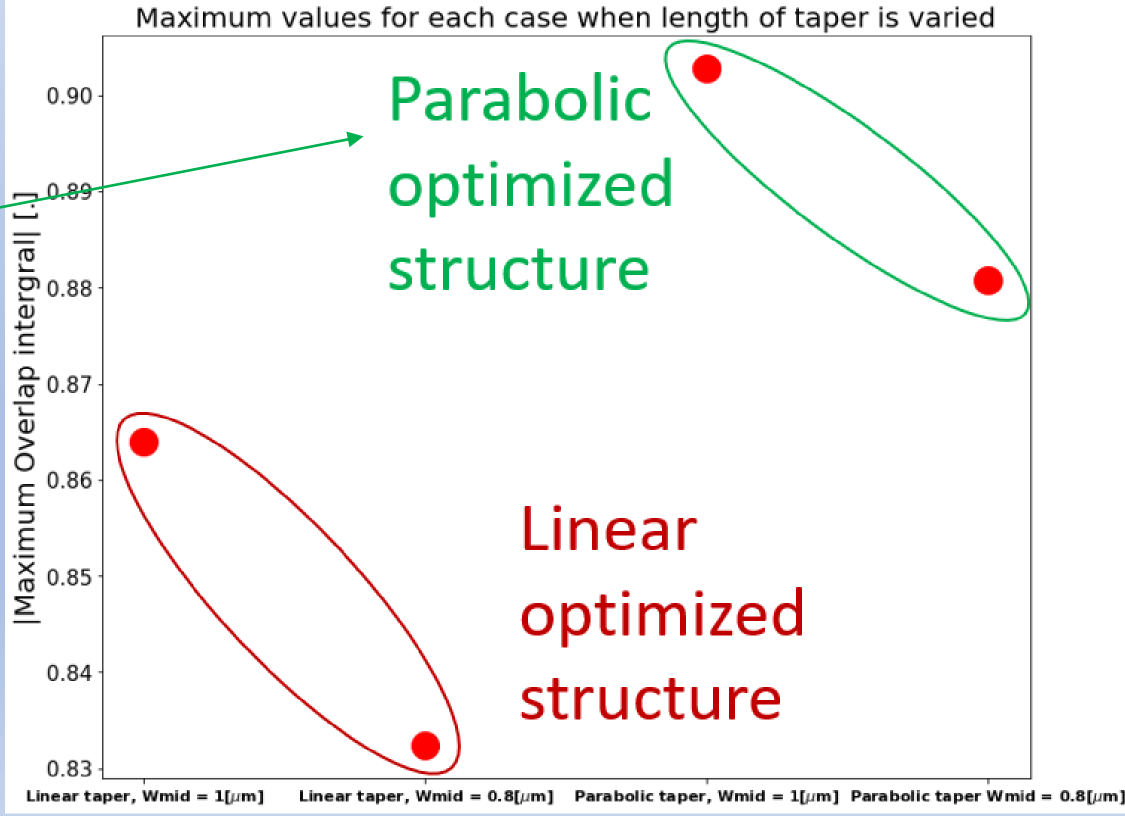


First stage : Taper optimization

- Taper length is optimized to give better output characteristics for various *Wmid* (0.8um, 1um)
- Parabolic taper's slope *d* can be tuned to improve the overlap and power at the output
- Parabolic taper exhibits better characteristics than linear tapers

Smaller *d* is better





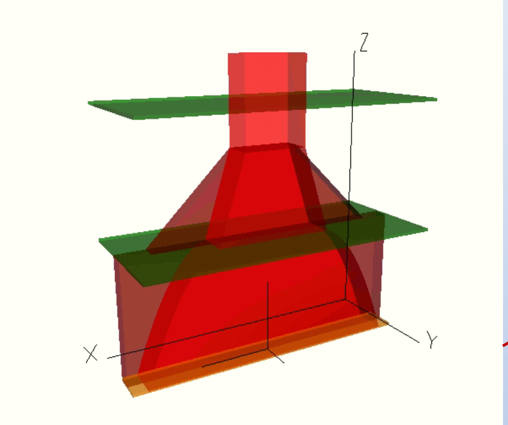
First stage is optimized with :

- L = 2.8um
- *d* = 0.1
- Parabolic taper
- *Wmid* = 1um

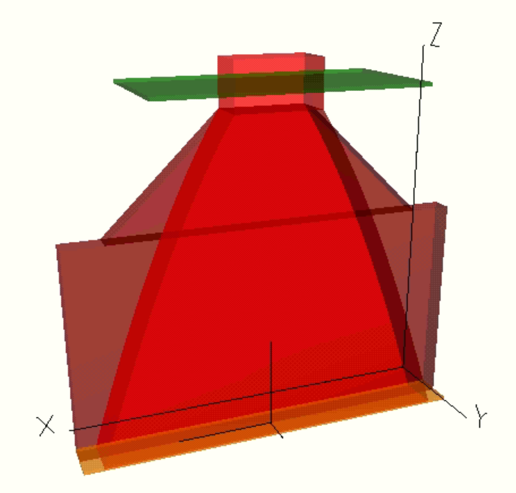
Second stage

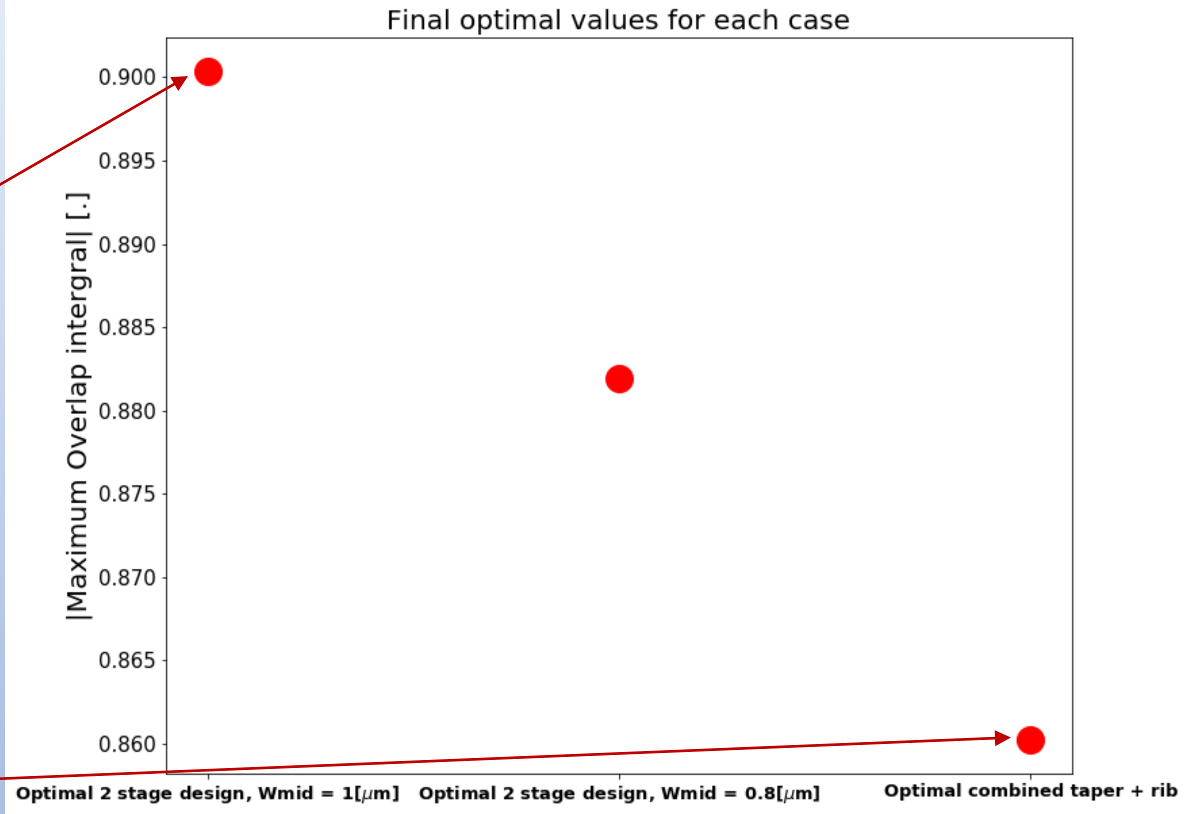
- Second stage optimized in the same way, given first stage best *L, d, Wmid* and *parabolic:*

2 stages



Combined



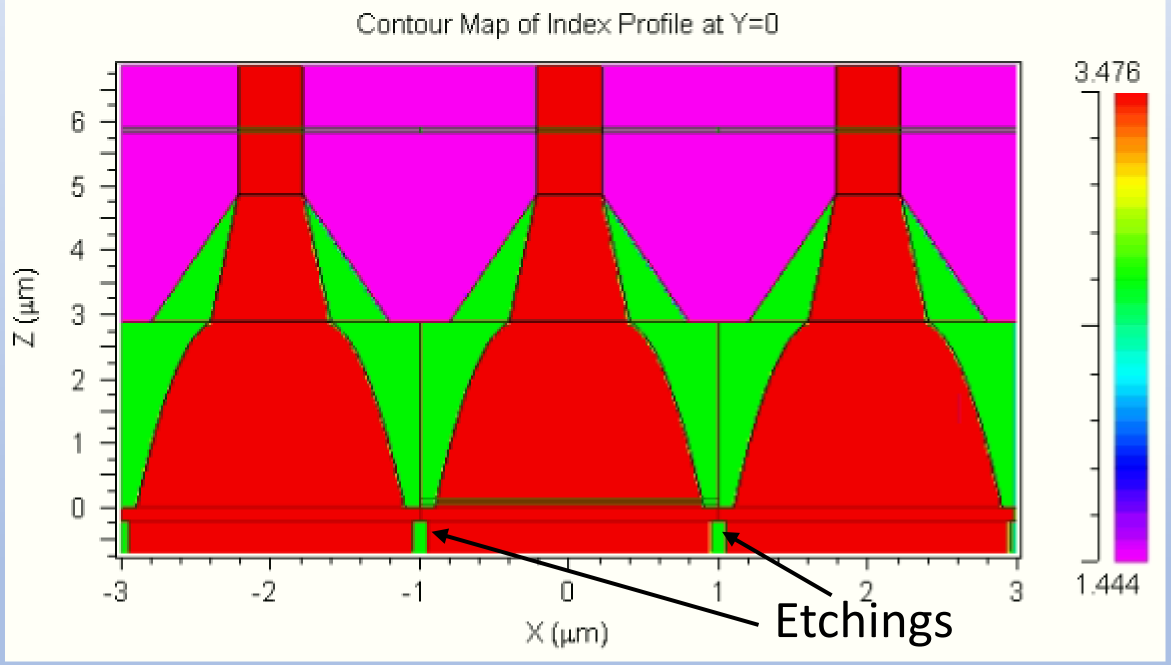


Second stage is optimized with :

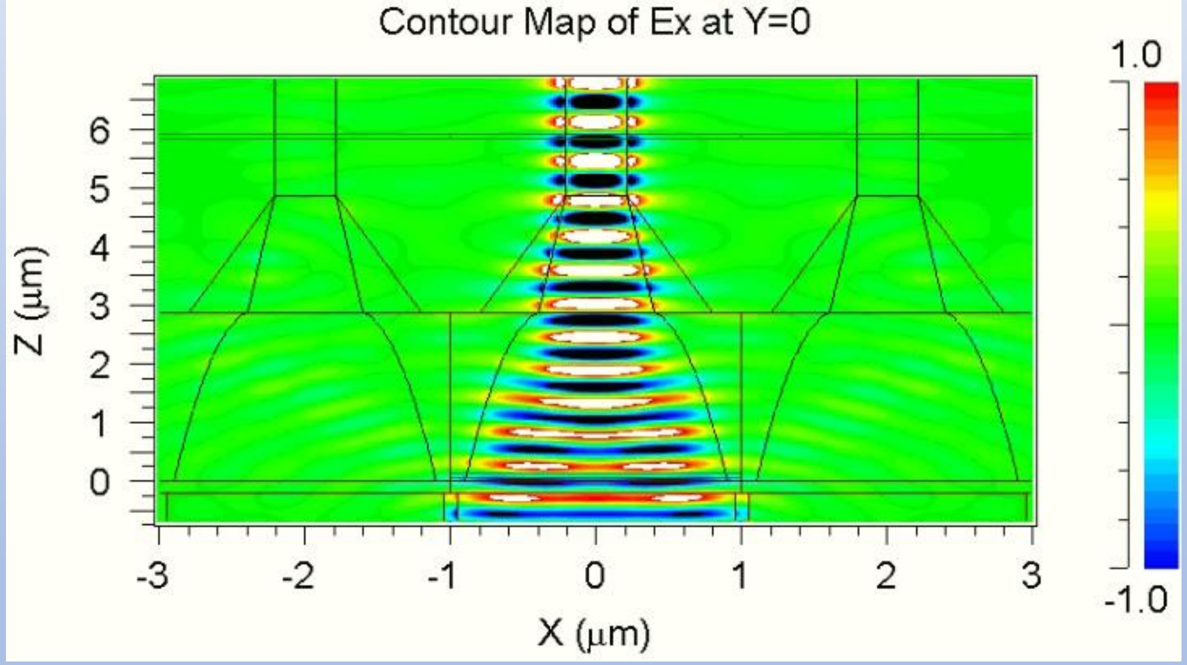
- *Lrib* = 2um
- *Wmid* = 1um
- 2 stage is better than combined structure

Slab etching : 3 parameters optimization

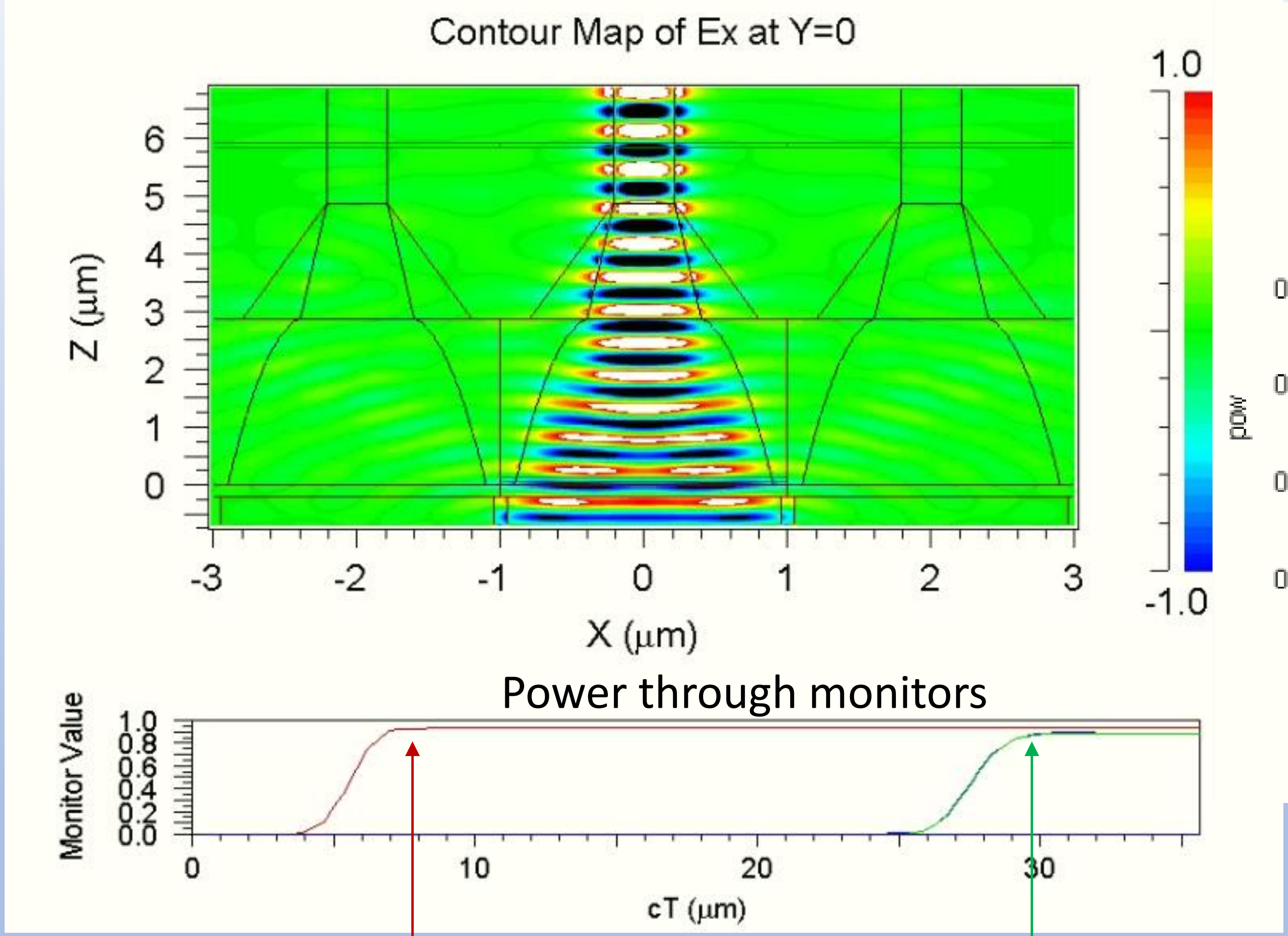
Index profile showing simulated interface



3D FDTD simulations: higher power intensity



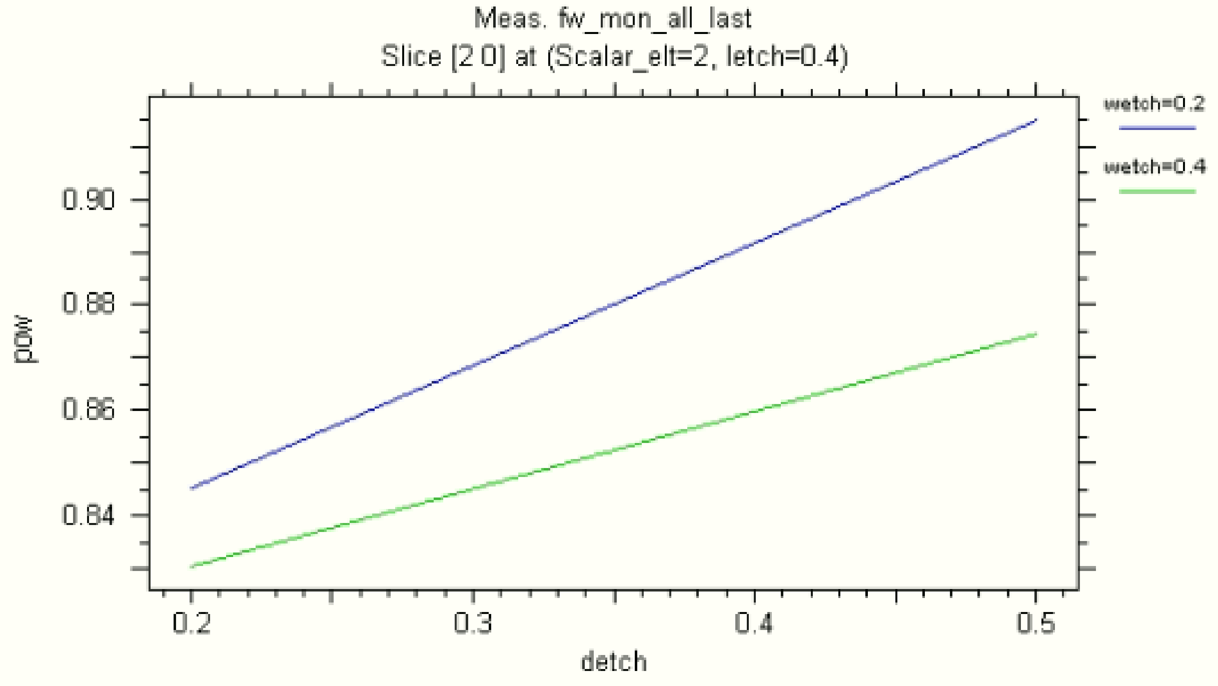
Slab etching : 3 parameters optimization



Launched Power

Output Power

Optimal design output



Optimized with :

- *letch* = 0.4um
- *detch* = 0.5um
- *wetch* = 0.2um

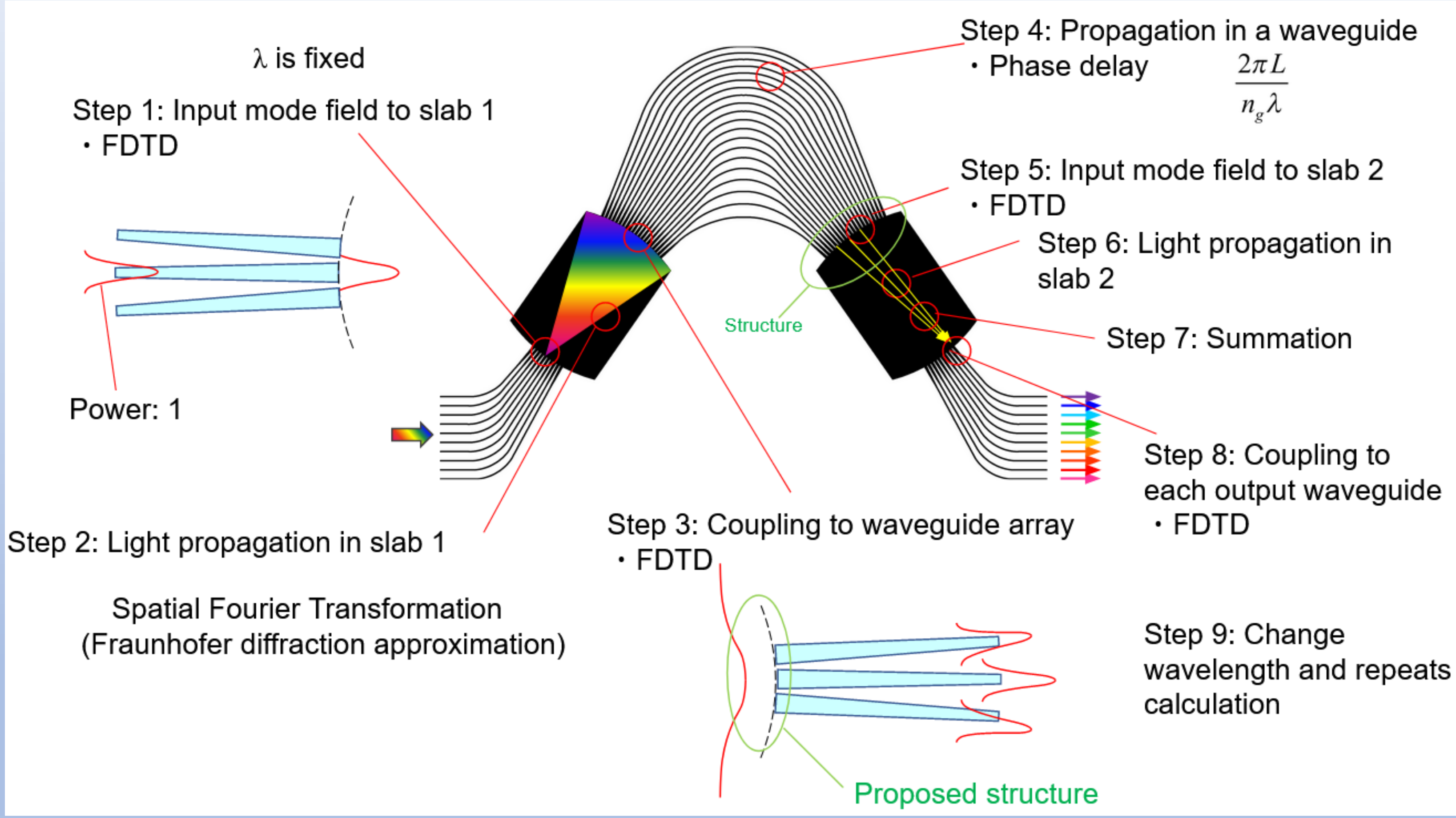
Values:

- Crosstalk = -26 dB
- Loss = 0.3 dB

Final values

Optimal design or parameters	Value
Optimal structure	2 stage design
Optimal taper	parabolic
Optimal L	$2\ \mu m$
Optimal $Lrib$	$2.8\ \mu m$
Optimal $Wmid$	$1\ \mu m$
Optimal d	0.1
Optimal $letch$	$0.4\ \mu m$
Optimal $detch$	$0.5\ \mu m$
Optimal $wetch$	$0.2\ \mu m$

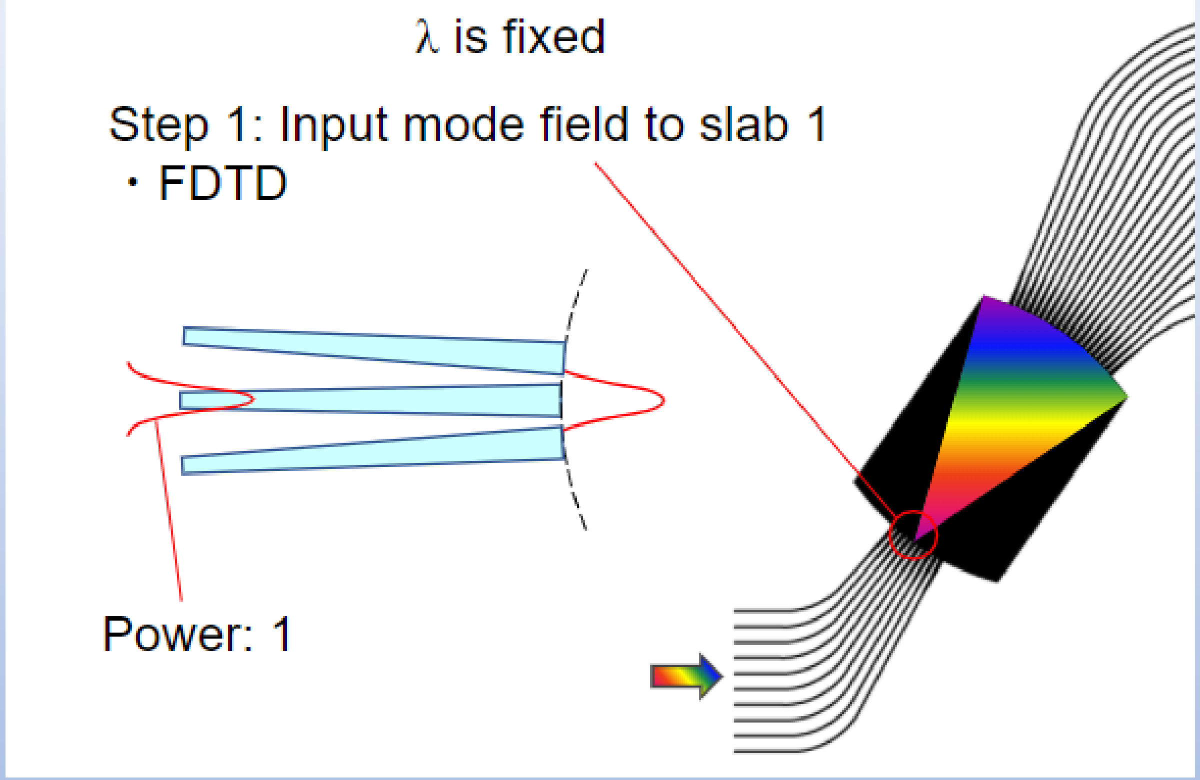
Overall AWG characteristics results



9 steps including:

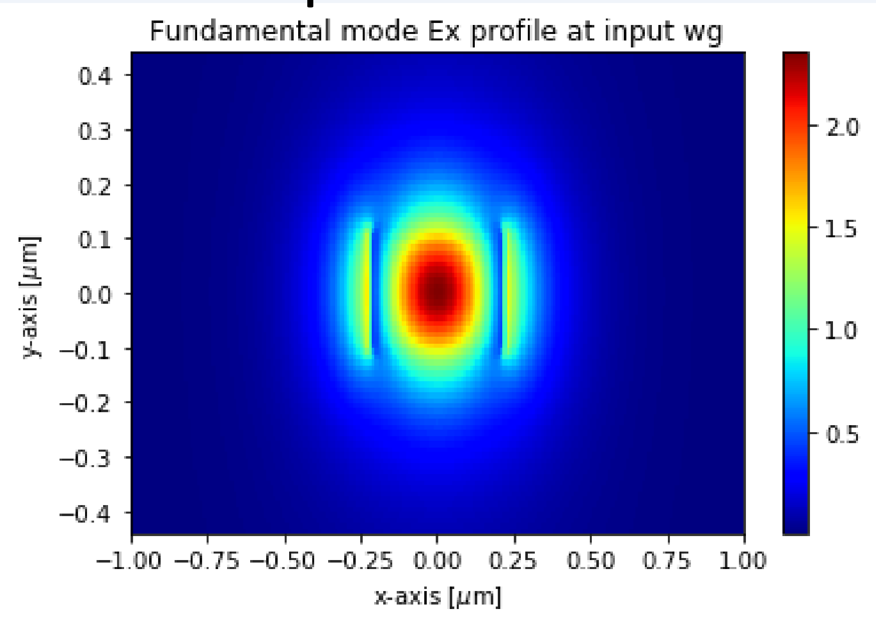
- FullWave FDTD
- Fourier transform
- Custom algorithm

Input

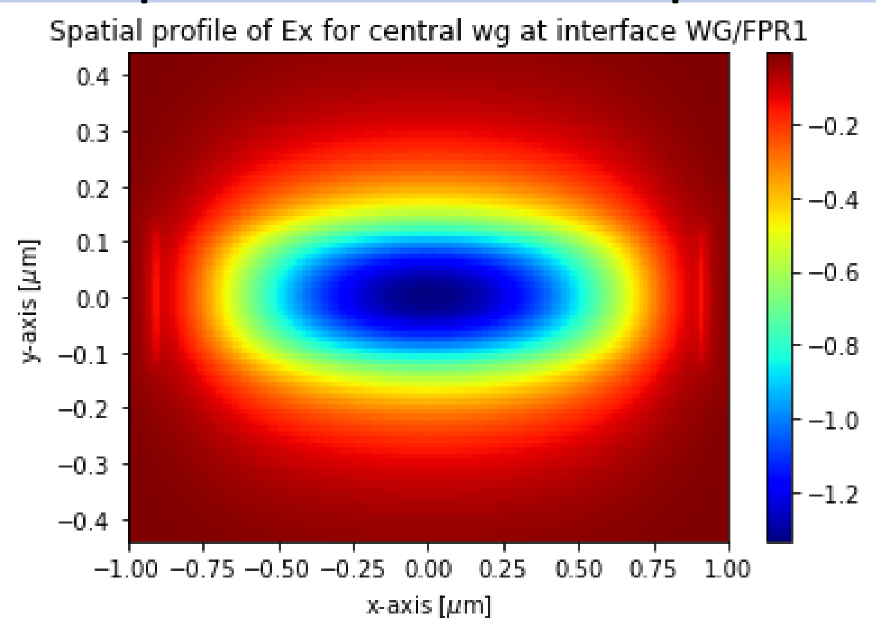


- Solving mode by FEM
- Launching at input waveguide
- FDTD computation
- FPR input beam

Input beam

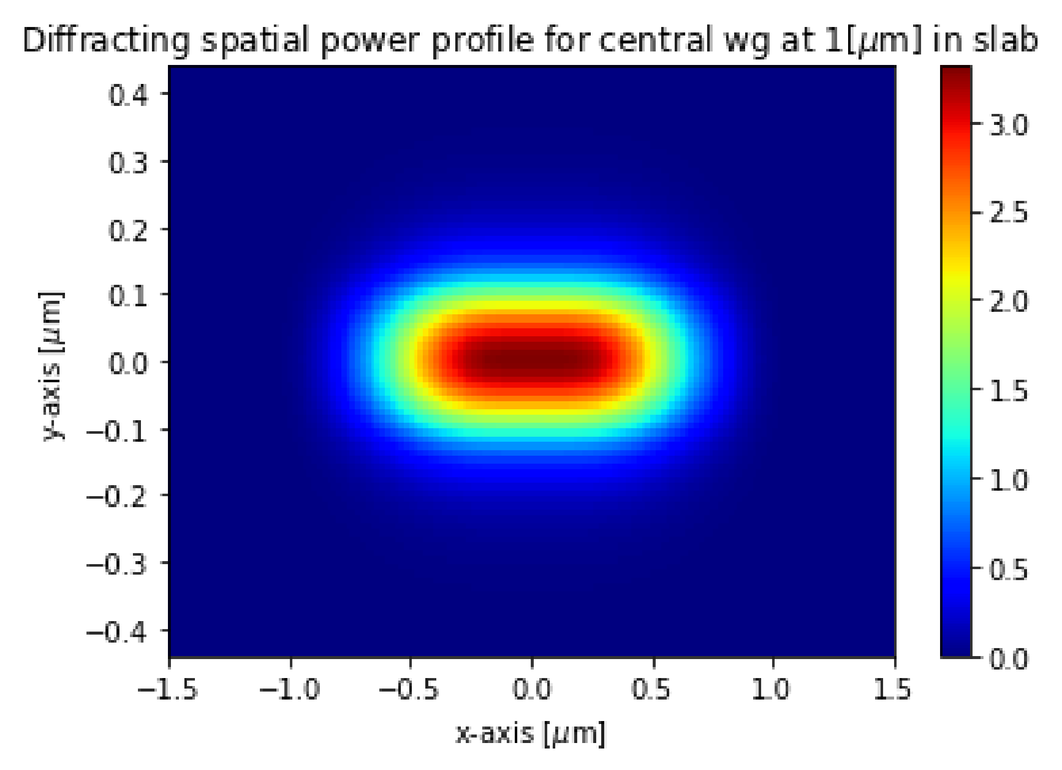


Input beam after taper



First FPR : diffracting beam

Diffraction direction



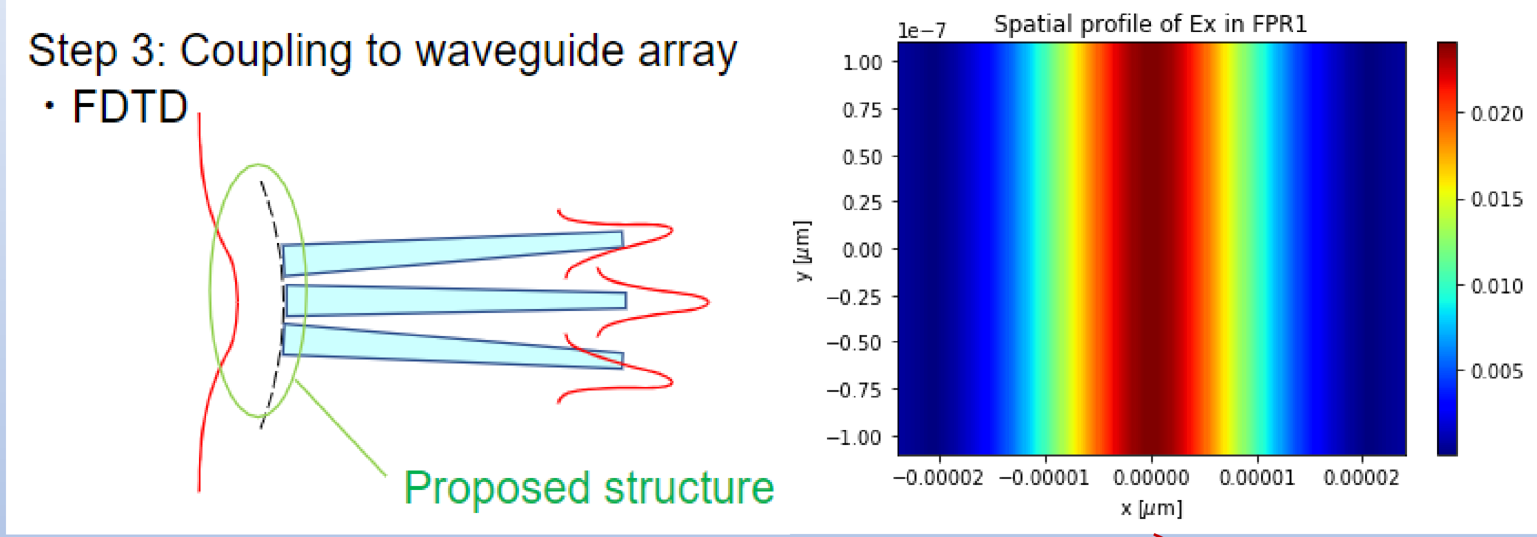
Enclosed direction

Beam diffraction along x-axis in first FPR

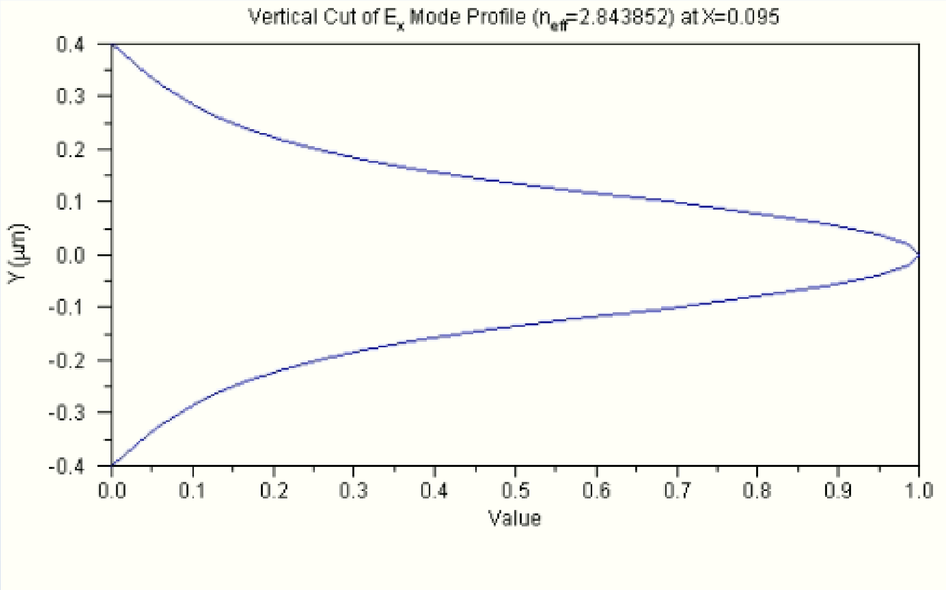
→ Fraunhofer diffraction

Slab enclose beam y-axis in first FPR

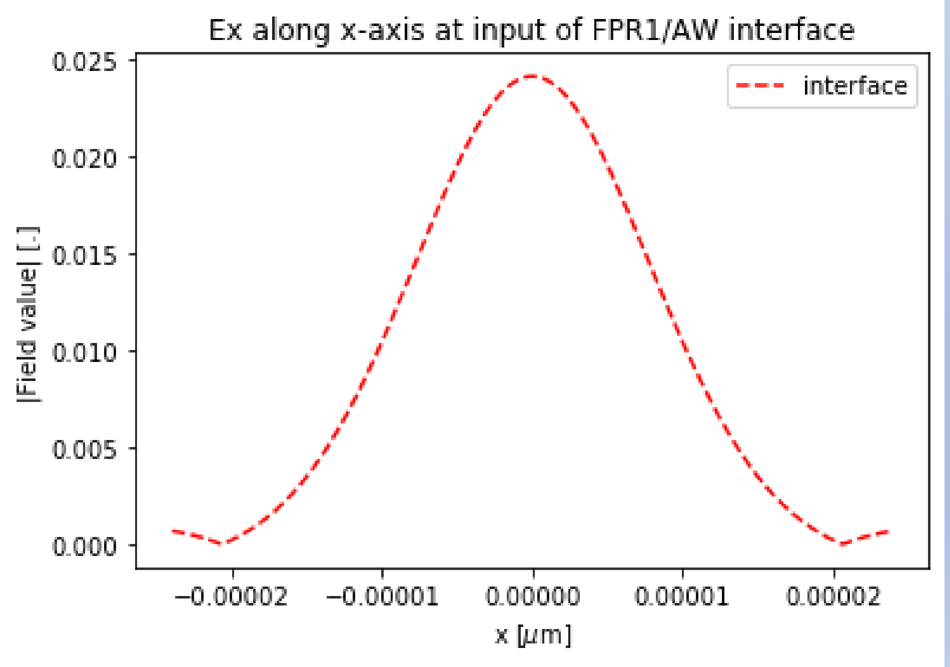
Coupling to Array



y-axis



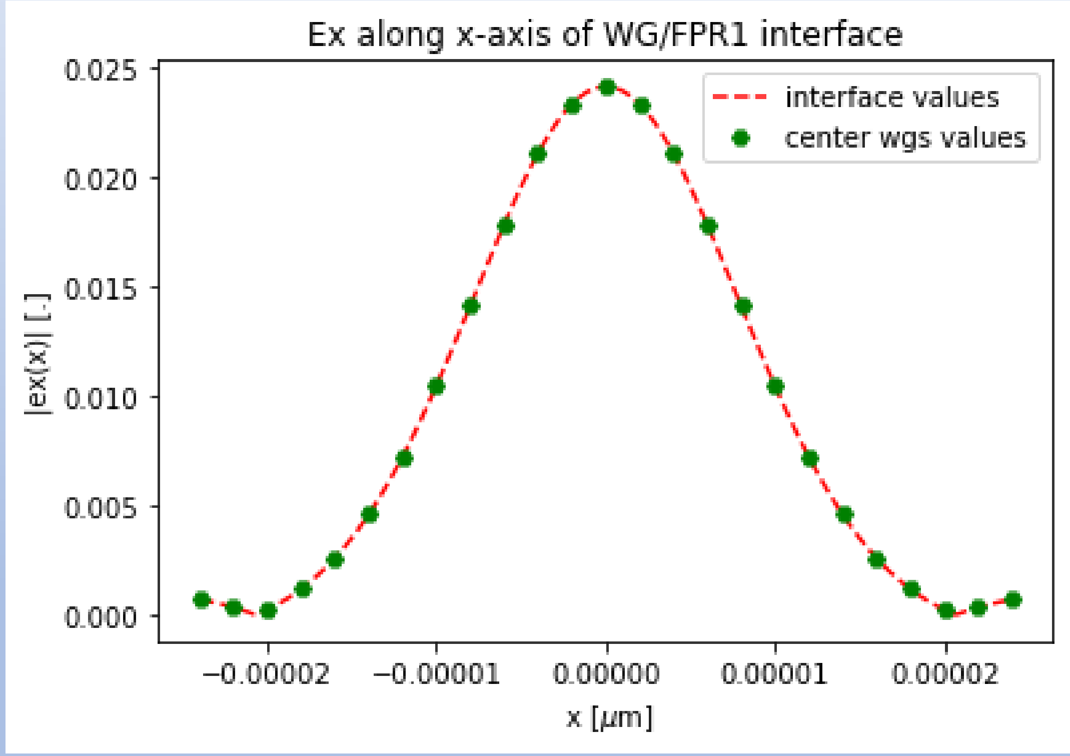
x-axis



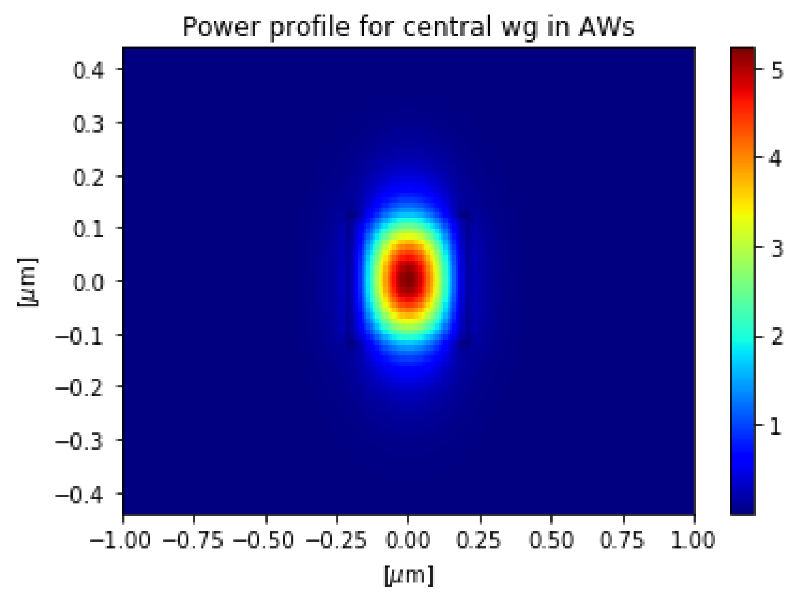
- Diffracted beam reaches waveguide array
- Measuring profile

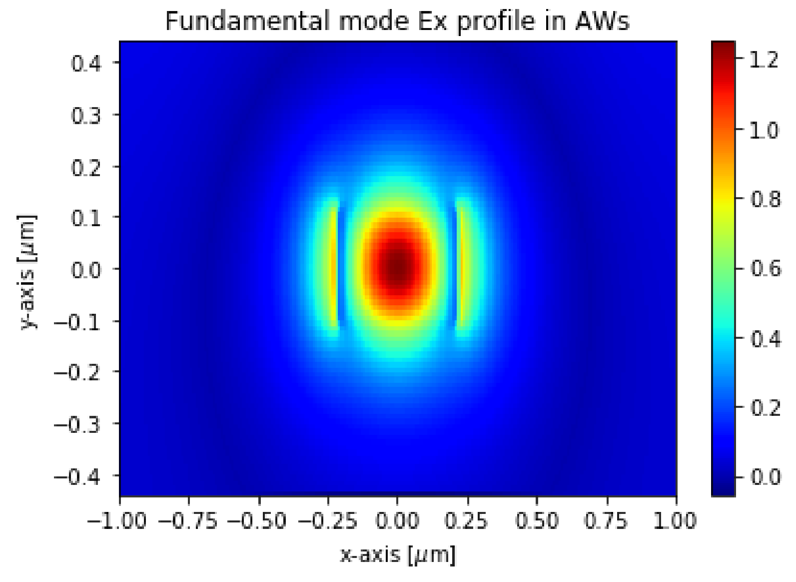
Arrayed Waveguides

Field sampled by the waveguide array



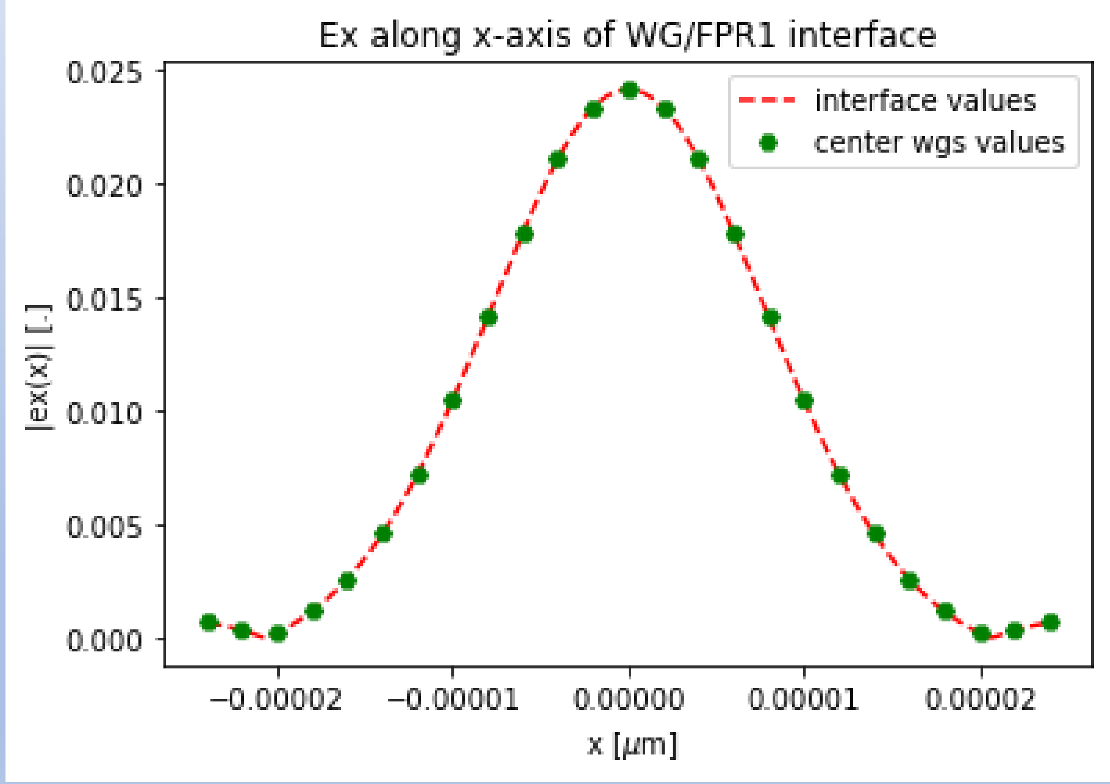
Power and Ex in each waveguide

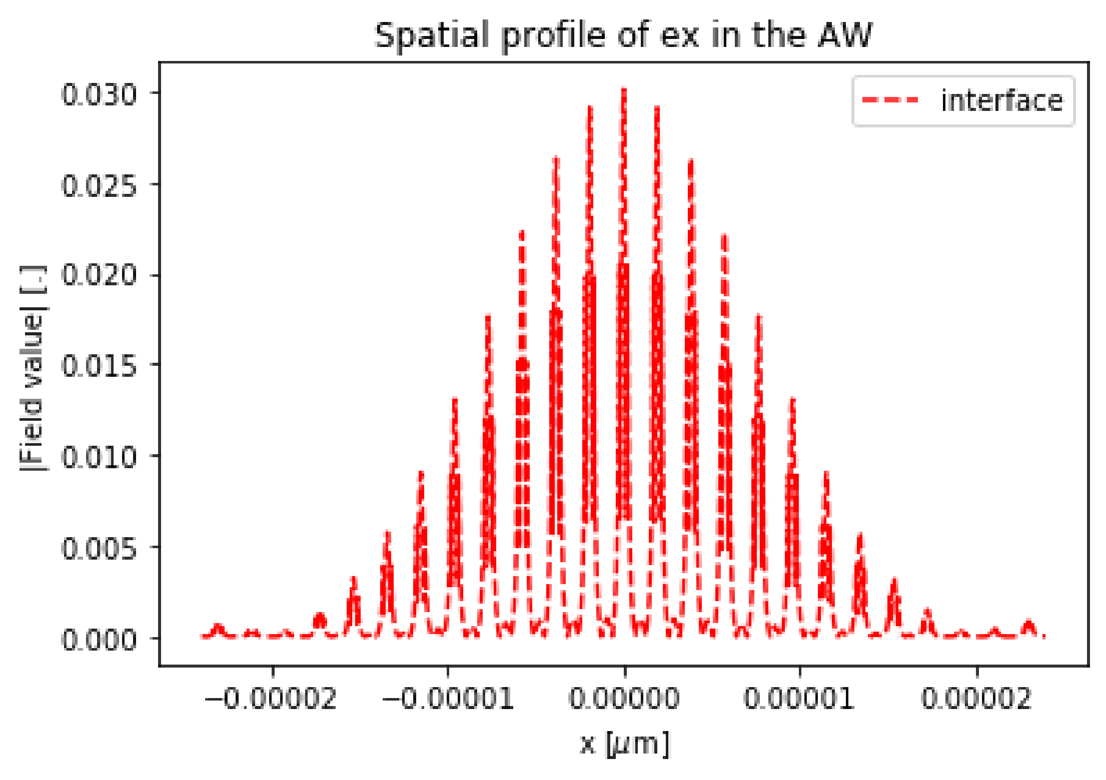




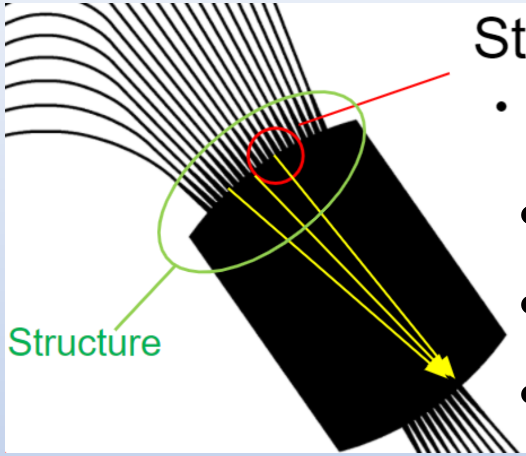
Arrayed Waveguides (cont.)

Field sampled by the waveguide array





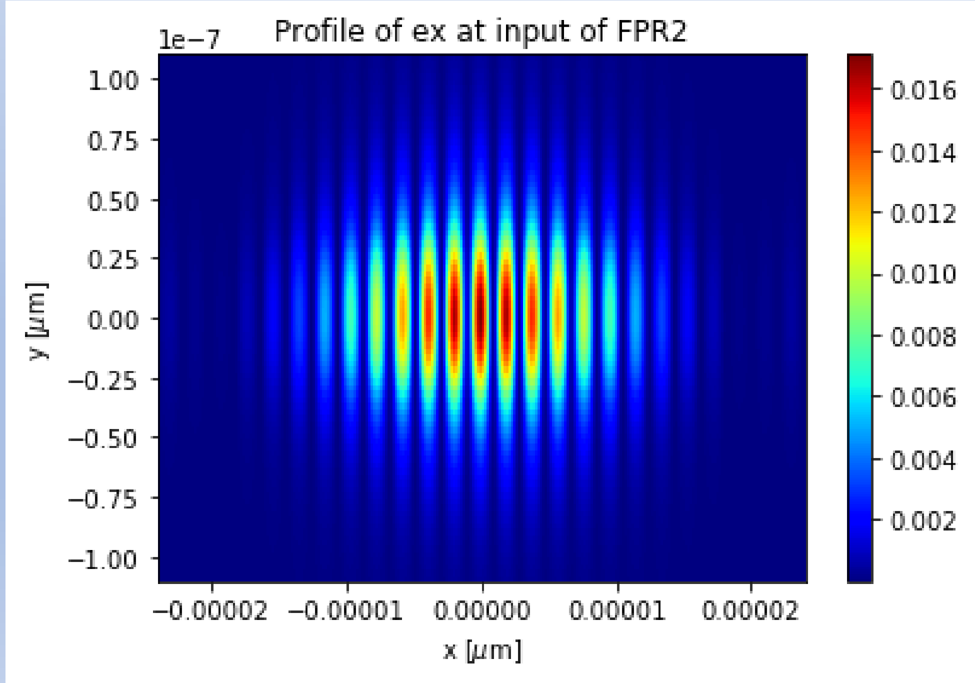
Second FPR input

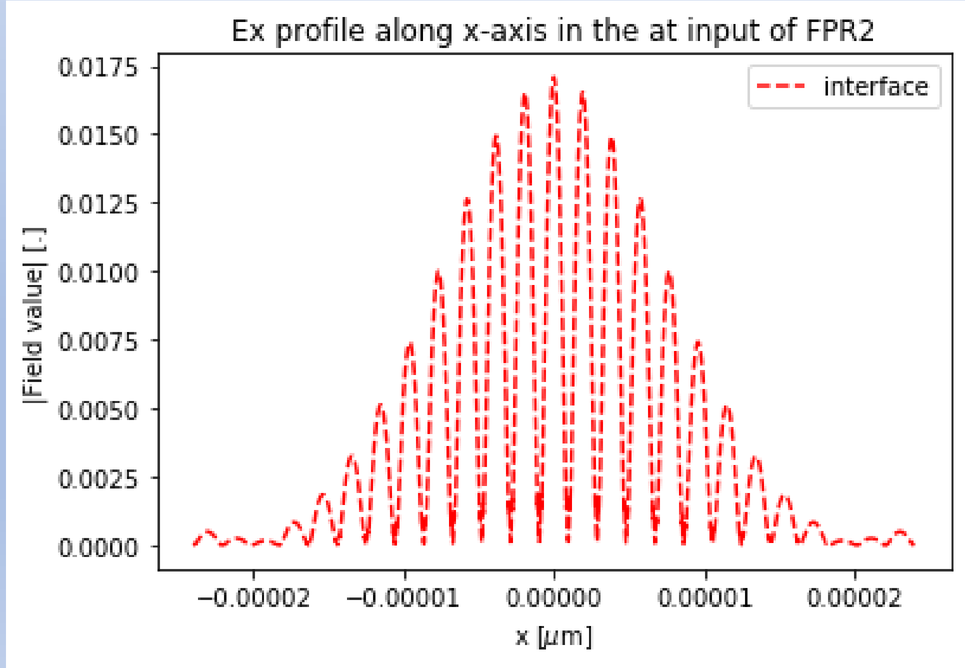


Step 5: Input mode field to slab 2

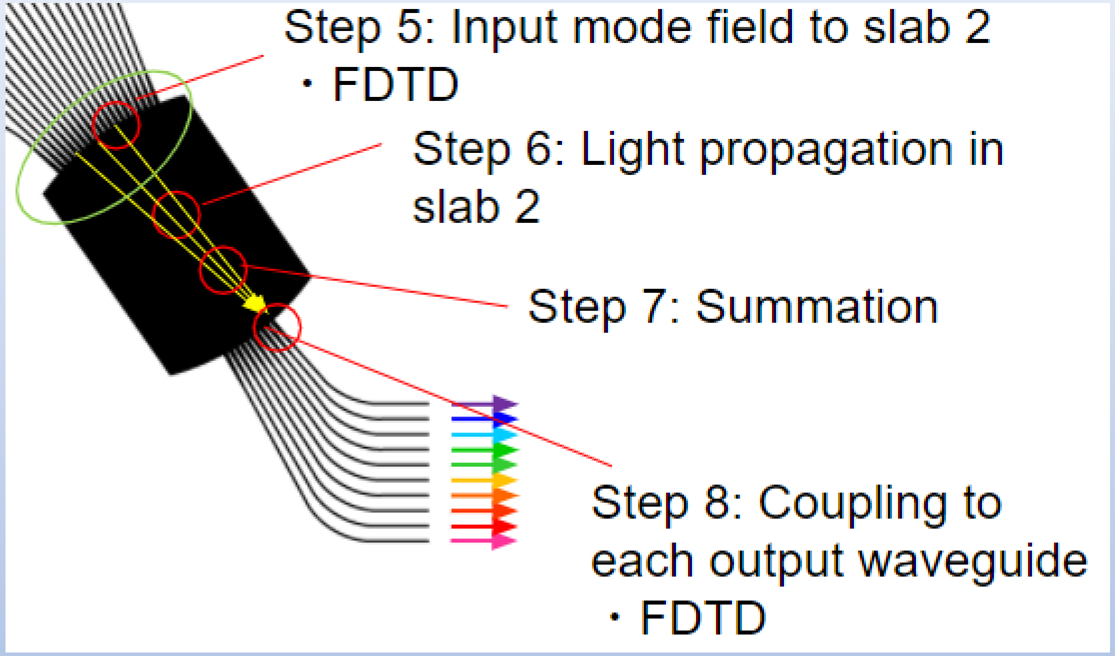
・FDTD

- Taper diffract AWs beams
- FDTD computation
- FPR input beam





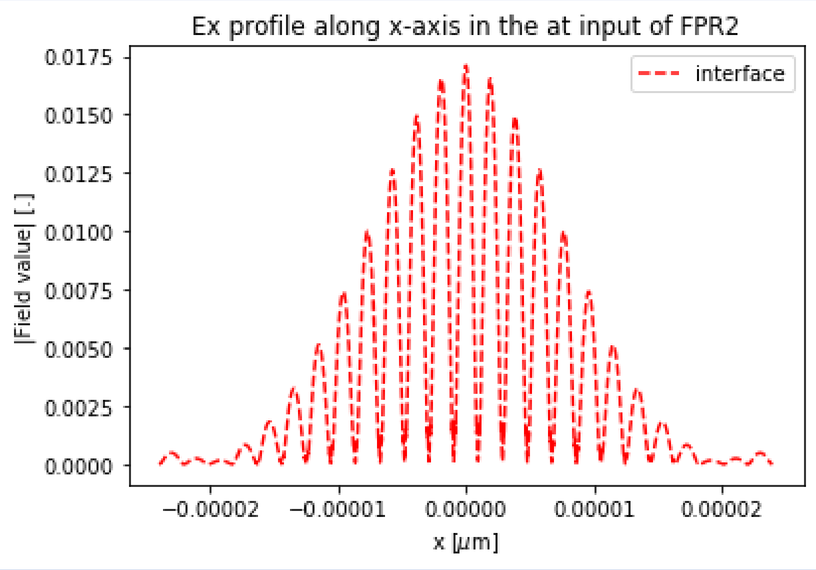
Second FPR

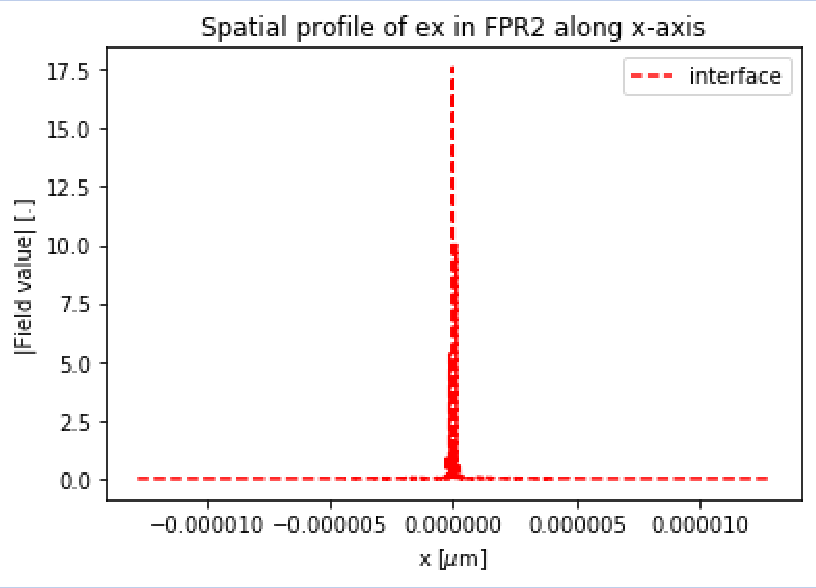


Step 6 & 7

Step 8

FPR2 summed diverging beam





- Diverging beams summed
- Coupling to output wgs
- Repeat process

Final values

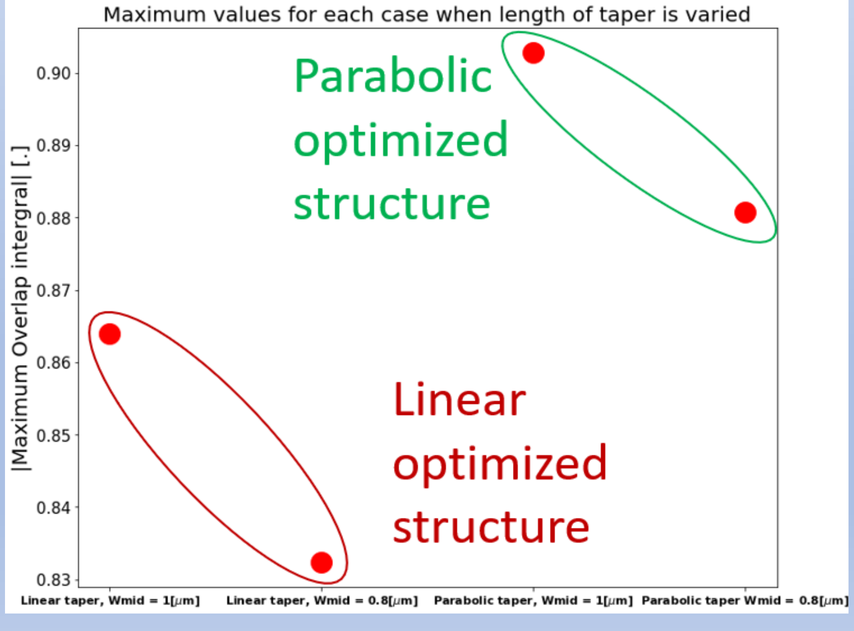
Design parameters	Value
Operational wavelength λ_0	1550 nm
Channel spacing Δ_{CH}	3.2 nm
Frequency channel spacing Δv	400 GHz
Number of channels N_{CH}	1×8
$\Delta\lambda$ (FSR)	25.6 nm
Free spectral range (FSR)	$1.5 \times 25.6 = 38.4$ nm
Focal length of slab waveguide (L_f)	88.803 μm
Number of arrayed waveguides (N)	25
Path difference of arrayed waveguides Δl	26.8998 μm
Separation between the input/output d_{wg}	2 μm
Gap between the waveguide *gap*	0.2 μm
Separation between the arrayed waveguides	2 μm
Central output loss	0.3 dB
Roughly approximated crosstalk	-25 dB

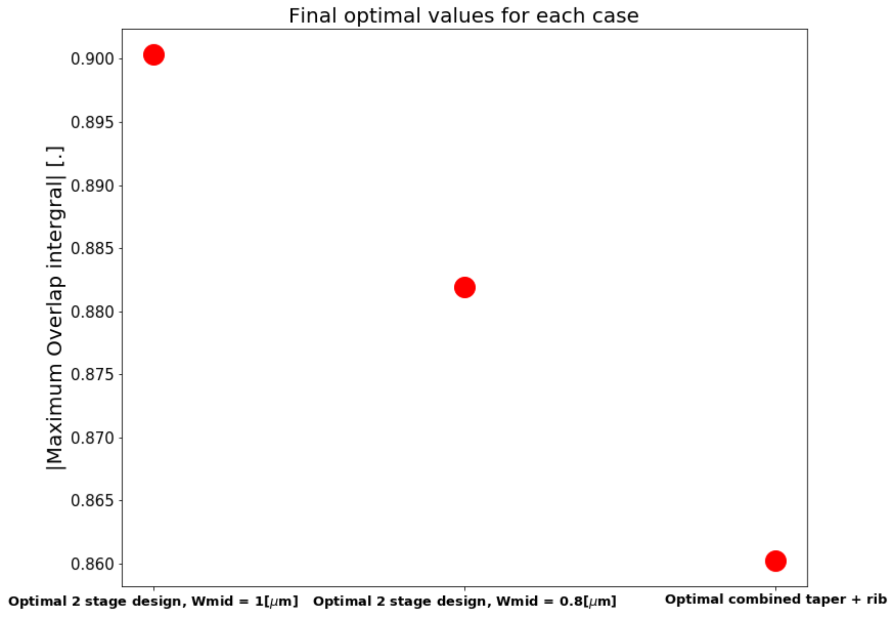
Conclusion

Conclusion

- 1^{st} optimization using tapers design
- 2^{nd} optimization by etching in the slab
- Overall AWG characteristics computed

Optimal design or parameters	Value
Optimal structure	2 stage design
Optimal taper	parabolic
Optimal L	$2\ \mu m$
Optimal $Lrib$	$2.8\ \mu m$
Optimal $Wmid$	$1\ \mu m$
Optimal d	0.1
Optimal $letch$	$0.4\ \mu m$
Optimal $detch$	$0.5\ \mu m$
Optimal $wetch$	$0.2\ \mu m$





Design parameters	Value
Operational wavelength λ_0	1550 nm
Channel spacing Δ_{CH}	3.2 nm
Frequency channel spacing Δv	400 GHz
Number of channels N_{CH}	1×8
$\Delta\lambda$ (FSR)	25.6 nm
Free spectral range (FSR)	$1.5 \times 25.6 = 38.4$ nm
Focal length of slab waveguide (L_f)	$88.803\ \mu m$
Number of arrayed waveguides (N)	25
Path difference of arrayed waveguides Δl	$26.8998\ \mu m$
Separation between the input/output d_{wg}	$2\ \mu m$
Gap between the waveguide gap	$0.2\ \mu m$
Separation between the arrayed waveguides	$2\ \mu m$
Central output loss	0.3 dB
Roughly approximated crosstalk	-25 dB

Thank you

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