# Simulation Methodology for LiDAR on Chip

## Simulation and Design Using RSoft Tools

Note: The purpose of this application note is to demonstrate how RSoft's tools can be used by designers to assist them in designing photonic devices. This document is not intended to create a novel LIDAR-on-chip design.

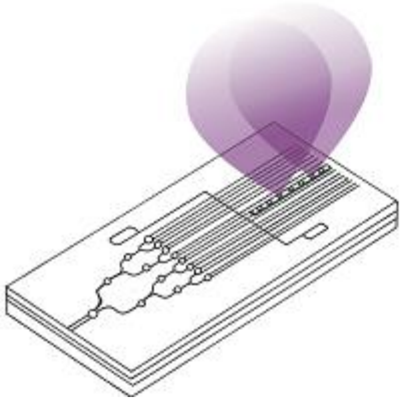
# Outline

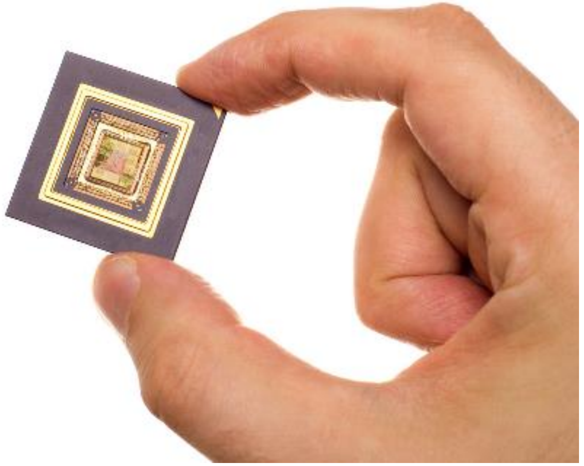
- Introduction
- Overall Design and Simulation Strategy
- Individual Component Simulation
    - Power Splitter
    - Thermal-Optical Phase Shifter
    - Emitting Gratings
- Conclusion

# Introduction

- LIDAR (Light Detection And Ranging) is a critical device for self-driving cars
  - Bulky and clumsy, with 64 lasers
  - Contains moving parts
  - Very expensive, costs more than the car itself
  - Difficult for commercialization
- LIDAR on-chip is an alternative solution to commercialize the technology
  - Compact, integrated on a chip
  - Solid and durable, no moving parts
  - Can be produced cheaply on a large-scale
  - Low prototype efficiency, ≈2 meters!

~$70,000





# Introduction

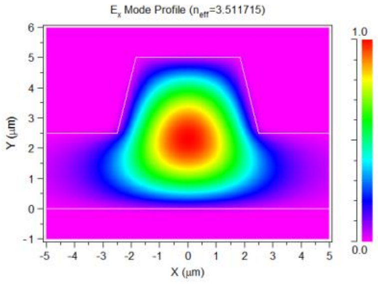
- Design optimization is essential to make an on-chip LIDAR practical for the commercial market
  - Minimize insertion loss and increase output optical power
  - Increase the beam steering range
  - Narrow the emitting beam
  - Reduce the size
- Reliable simulation tools are critical to achieve design tasks
  - Reduce development time and cost
  - Allows design testing/modification without prototype construction

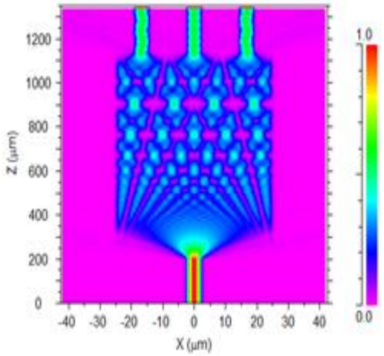
- RSoft provides a variety of simulation tools for optimizing design of various components
  - FemSIM
    - Solves for the mode of optical waveguide
  - BeamPROP

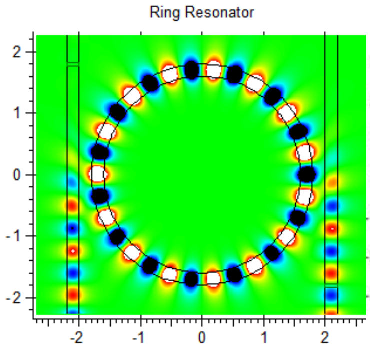
    Traces optical wave propagation in optical waveguide devices
  - FullWAVE

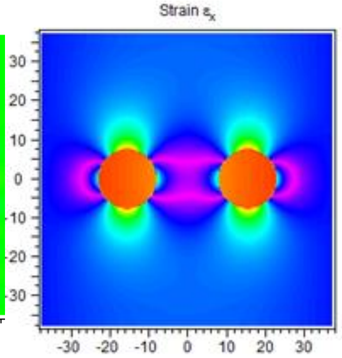
    Simulates omni-directional optical wave propagation

    Analyze the effects of thermal or electric signals on optical wave propagation



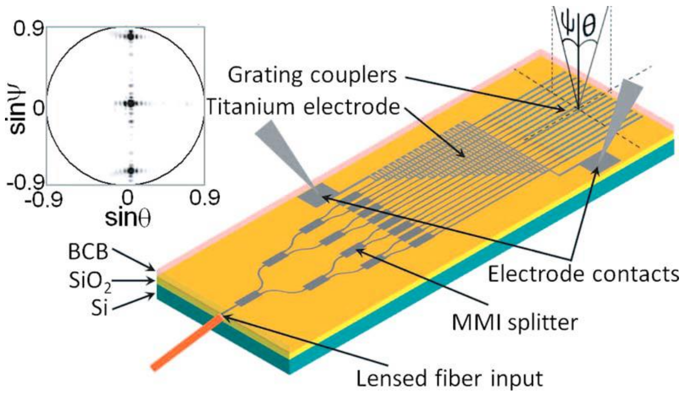






# Overall Design and Simulation Strategy

- Structure by Gent University & IMEC

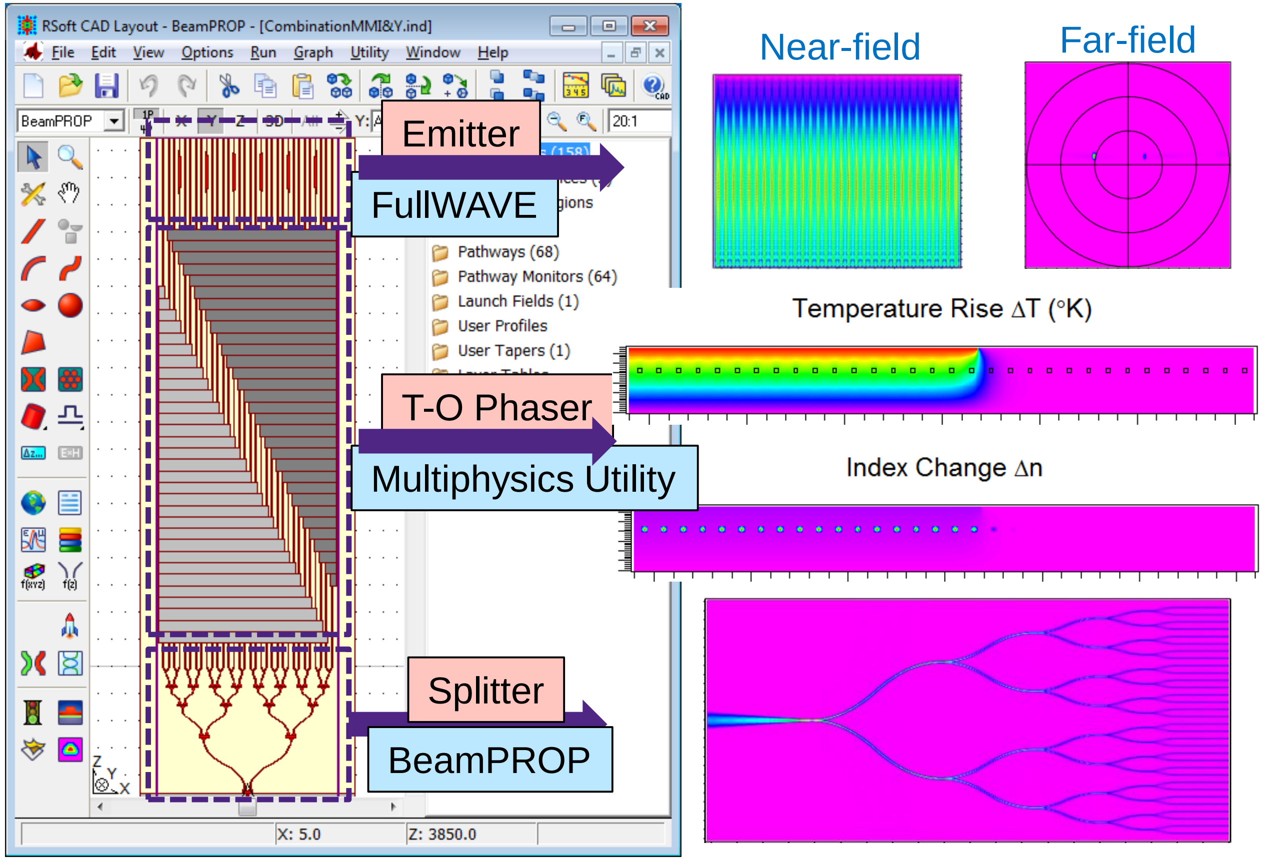


Van Acoleyen, Karel, et al. "Off-chip beam steering with a one-dimensional optical phased array on silicon-on-insulator." *Optics letters* 34.9 (2009): 1477-1479.

- Complicated design layout can be achieved in RSoft

Note: The purpose of this application note is to demonstrate how RSoft’s tools can be used by designers to assist them in designing photonic devices. This document is not intended to create a novel LIDAR-on-chip design.

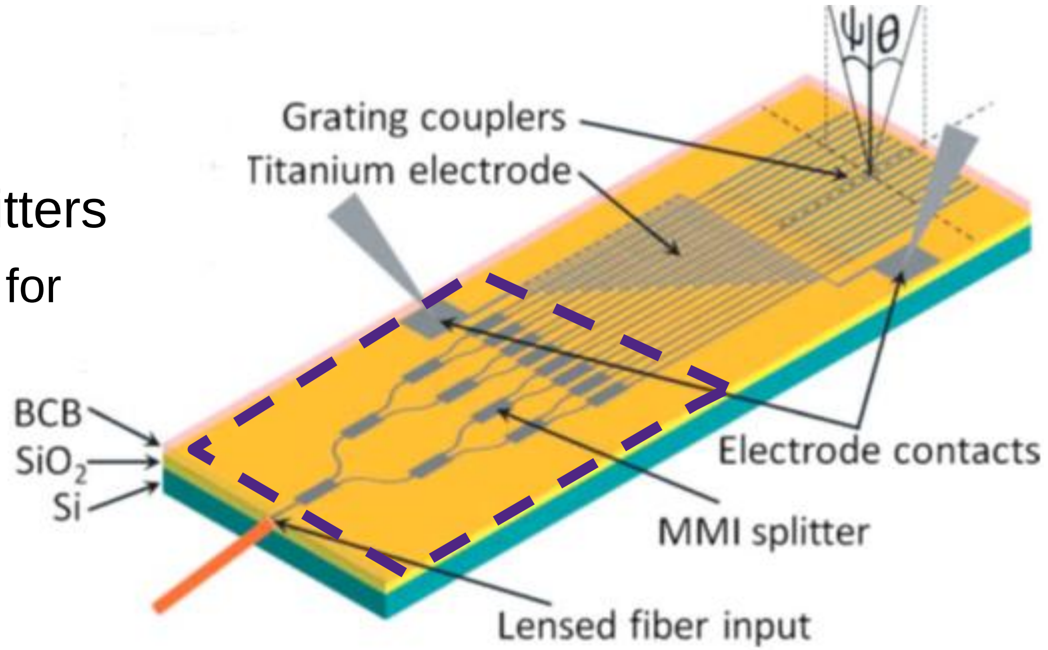
- No single simulation tool can solve the complex problem
- Combined tools have to be used for different elements



Optical power distribution

# Power Splitters

- Design utilizes cascaded 1x2 power splitters
  - Can potentially use 1x2 MMI or Y-Branch for power splitting

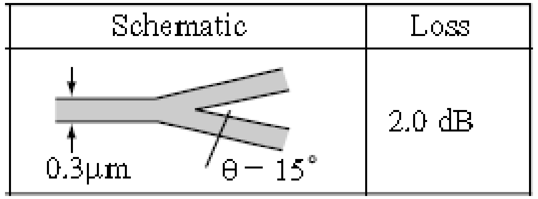


- 1x2 MMI

  - Complex, several parameters to optimize
  - Wavelength sensitive and limited bandwidth
  - Polarization dependent
  - Low insertion loss (~0.3dB)
  - Robust

Van Thourhout, Dries, et al. "Functional silicon wire waveguides." *Integrated Photonics Research and Applications*. Optical Society of America, 2006.

- Y-Branch
  - Simple, 2 S-bends
  - Broadband
  - Polarization independent
  - High insertion loss (~2dB)
  - Less tolerant to asymmetric input



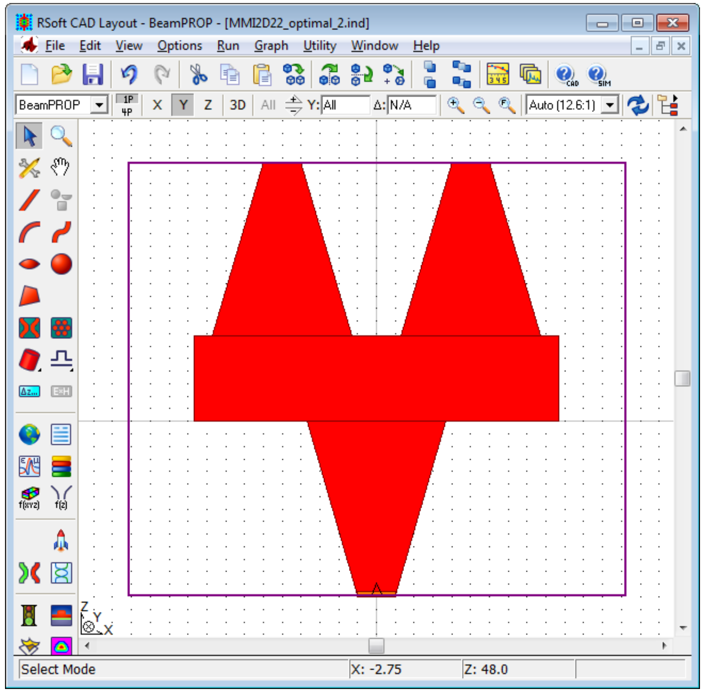
| Schematic | Loss |
|---|---|
| | 2.0 dB |

Sakai, Atsushi, Tatsuhiko Fukazawa, and Toshihiko Baba. "Low loss ultra-small branches in a silicon photonic wire waveguide." *IEICE Transactions on Electronics* 85.4 (2002): 1033-1038.

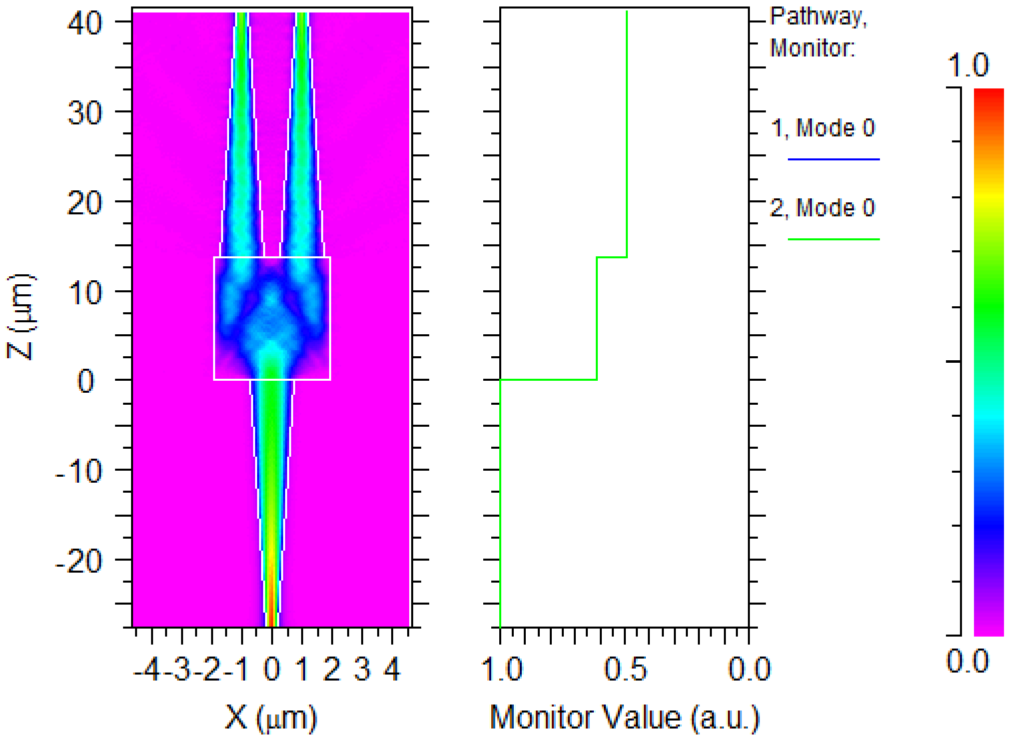
# 1x2 MMI

*MOST Optimization*

- There are several parameters to optimize
  - MMI width & length
  - Taper length & width
  - Separation is fixed at 2µm



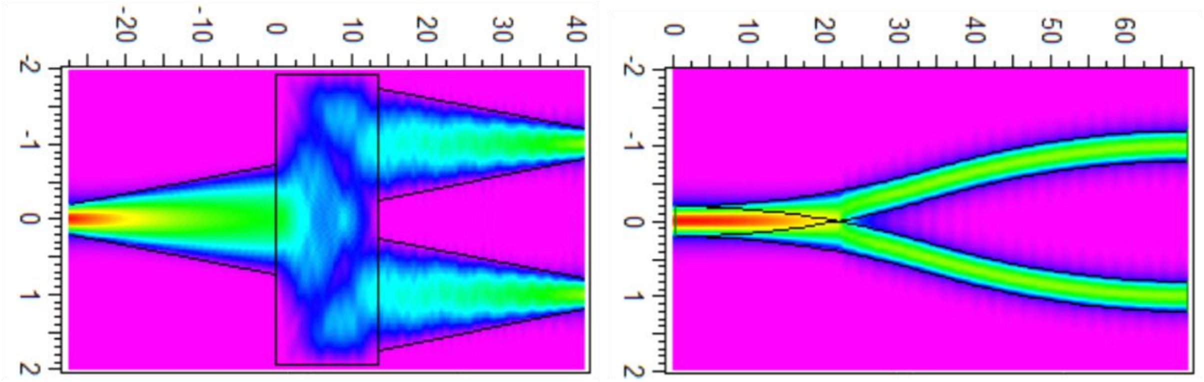
- Optimized structure by 2D-EIM BeamPROP
  - Done in minutes!
  - Splitting power ≈ 49.3%



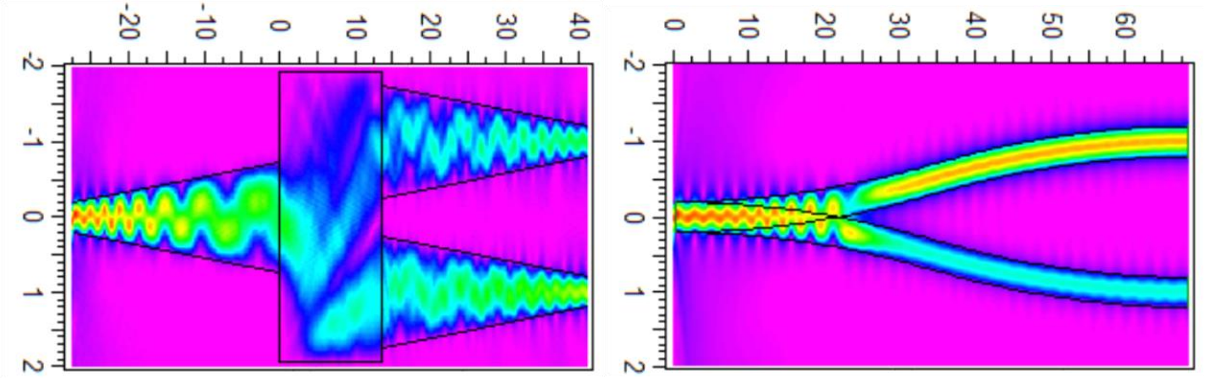
# 1x2 Power Splitter

*Comparison between MMI and Y-branch*

- Symmetric input

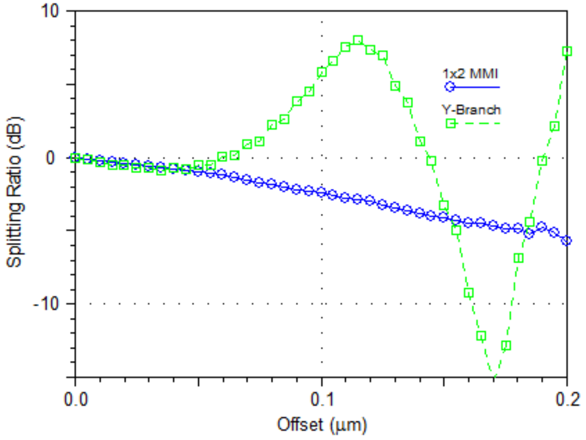


- Asymmetric input

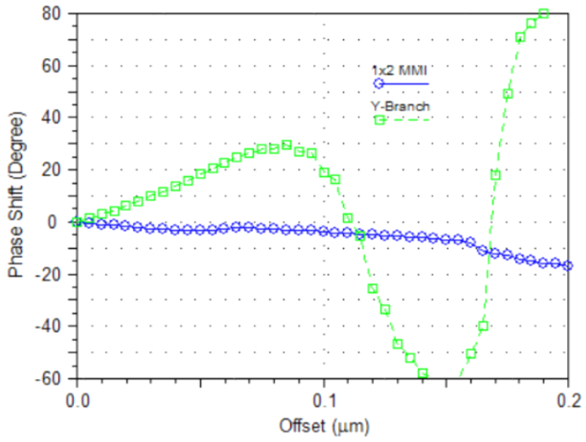


- Power/Phase Sensitivity study to layout offsets

Power



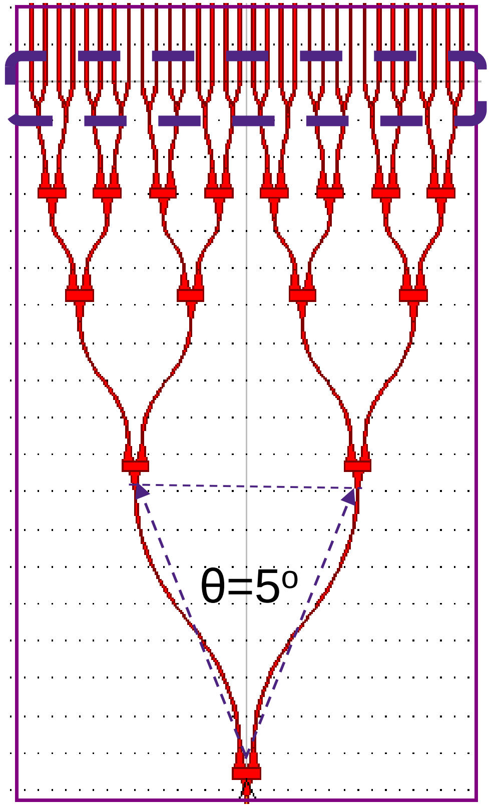
Phase



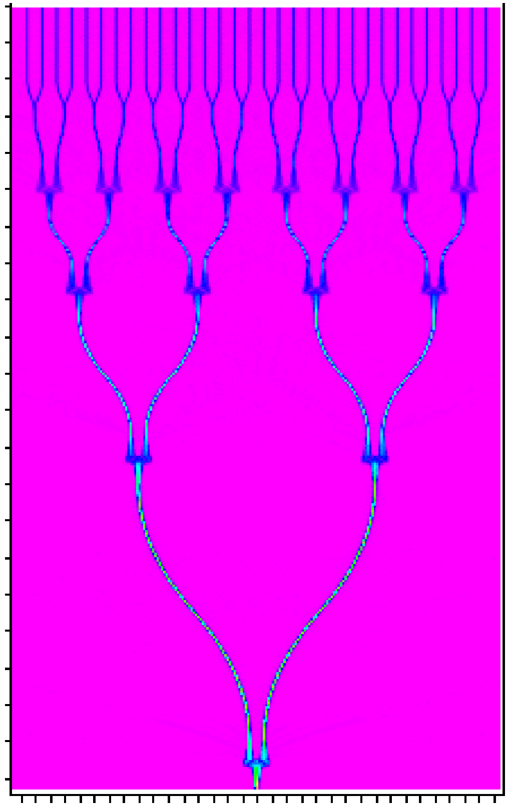
Result: MMI is more tolerant and robust than Y-branch to asymmetric input, which is inevitable due to the S-bends

# 1x32 Power Splitter

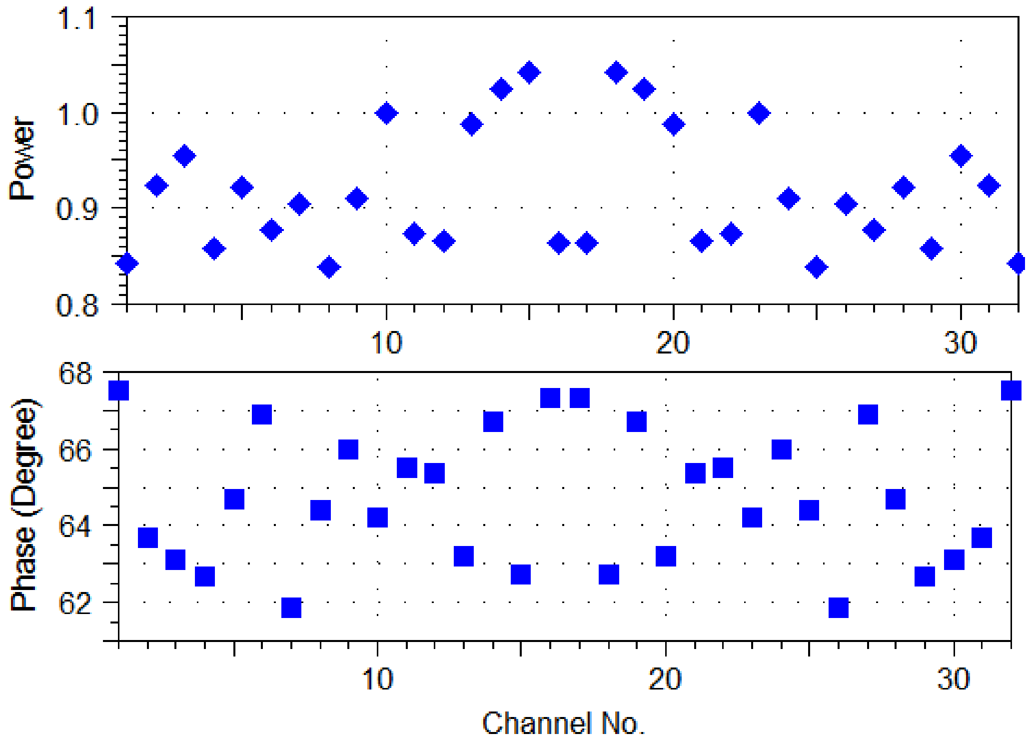
Cascaded 1x2 splitters



BeamPROP simulation



Monitored power and phase



Y-branch splitters are used in the last stage, MMI is too big to fit

**Some uniformity is observed because of the asymmetric input from S-bends**

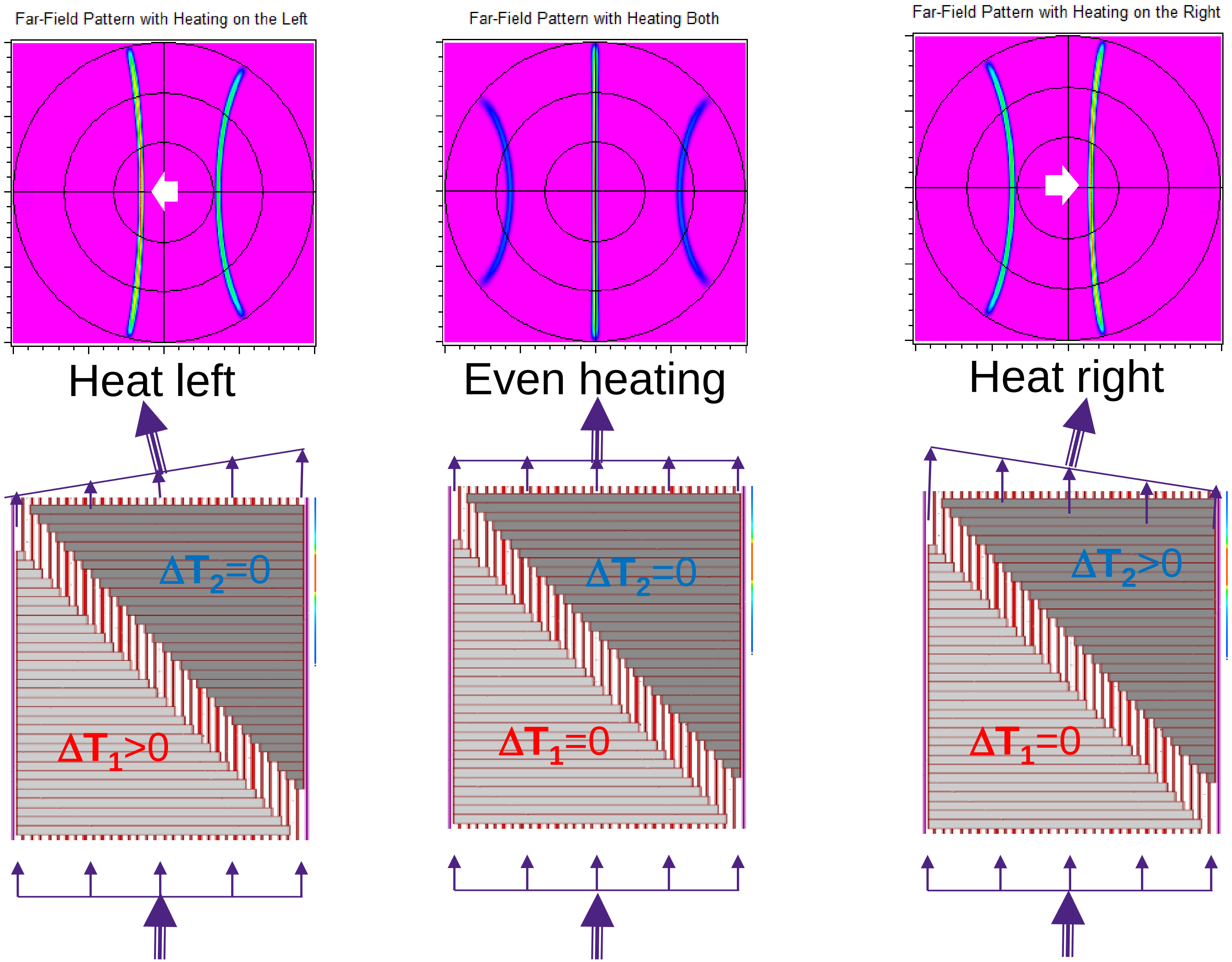
# Thermal-Optical Phase Shifter

*Working mechanism*

- Silicon is a thermally sensitive material with thermal-optical coefficient:

$$\frac{dn}{dT}0.00024$$

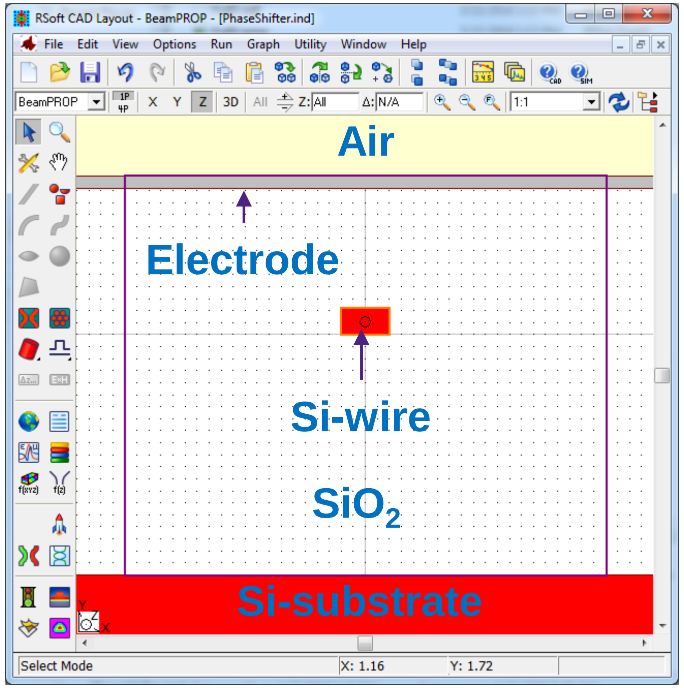
- Heating the waveguide array unequally creates phase delays among each other
- Because of the phase delay, the emerging light will be steered to one side



# Thermal-Optical Phase Shifter

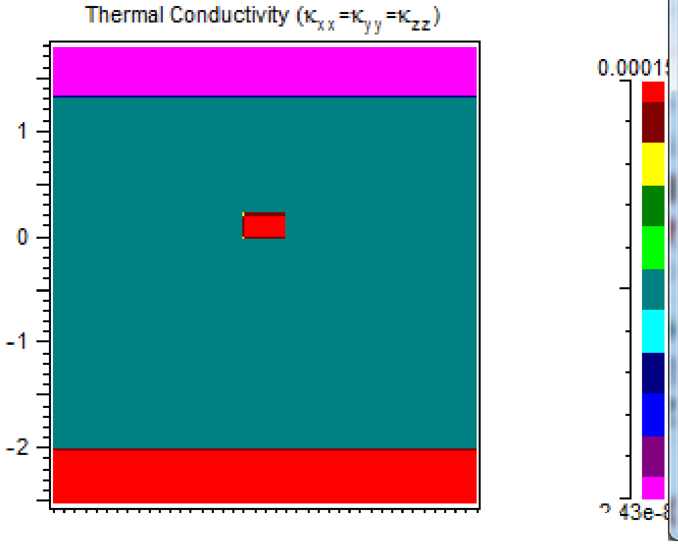
*Thermal solver*

- Configuration

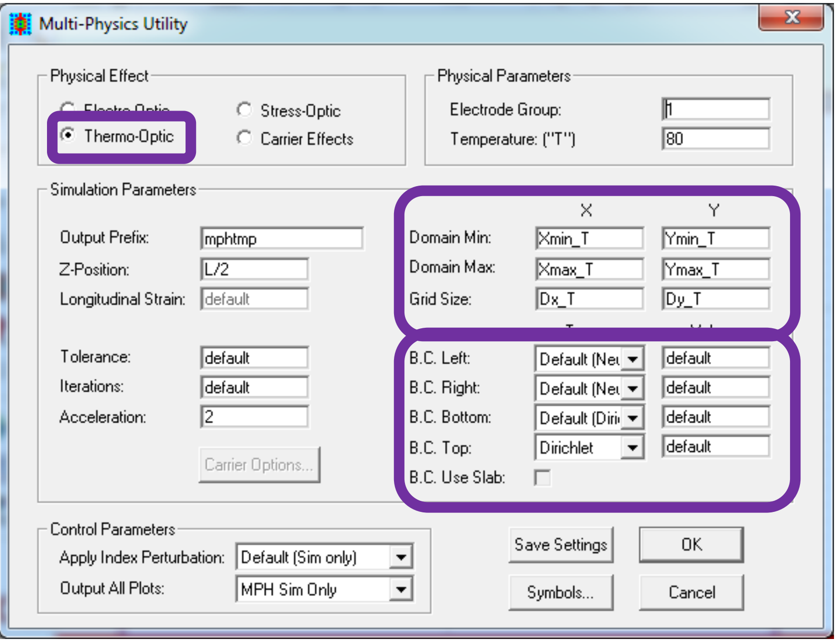


Tip: For better convergence, exclude air in computational window

- Thermal conductivity



- RSoft Multiphysics Solver settings



Multi-Physics Utility

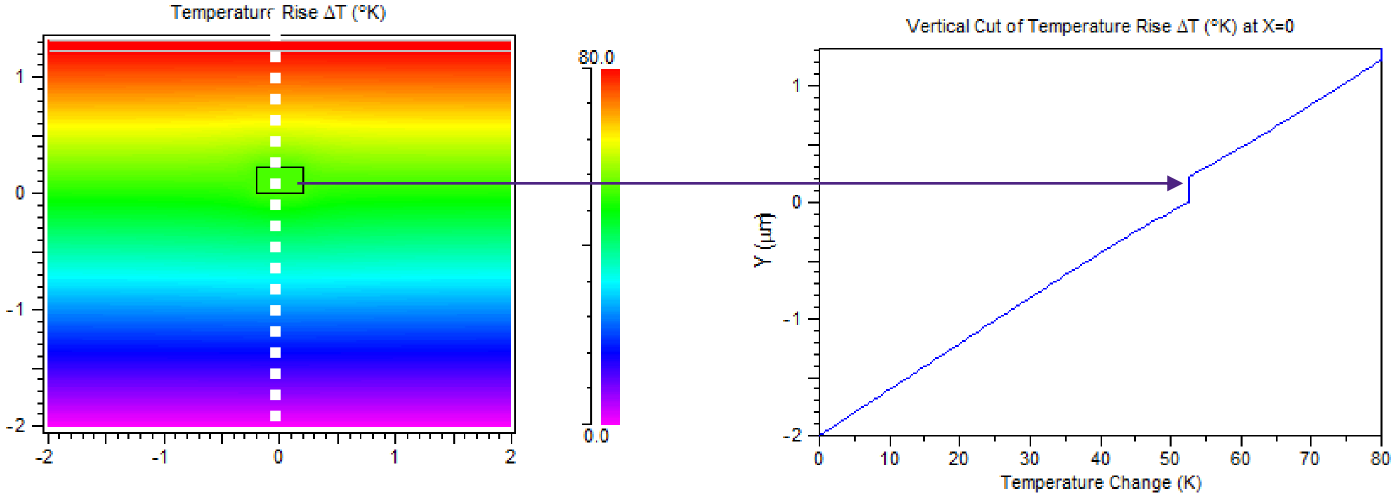
Physical Effect
○ Electro-Optic
● Thermo-Optic
○ Stress-Optic
○ Carrier Effects

Physical Parameters
Electrode Group: 1
Temperature: ("T") 80

Simulation Parameters
Output Prefix: mphtmp
Z-Position: L/2
Longitudinal Strain: default
Tolerance: default
Iterations: default
Acceleration: 2

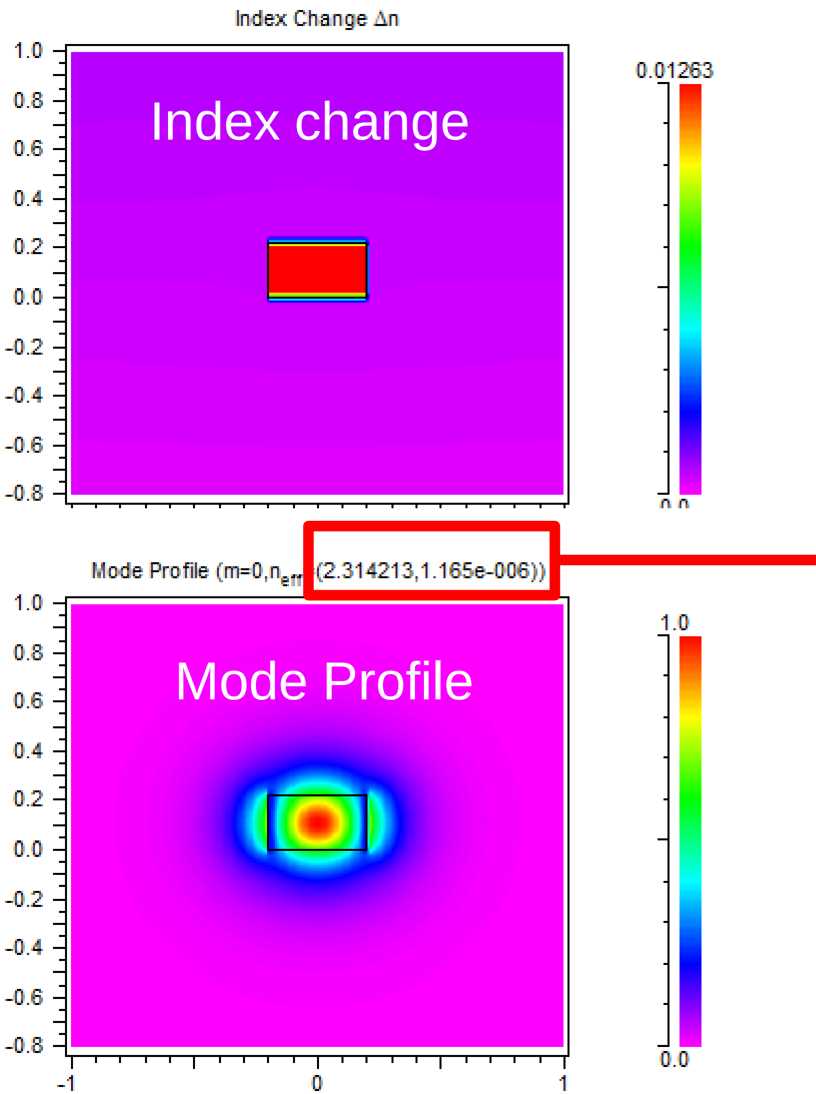
| | X | Y |
|---|---|---|
| Domain Min: | Xmin_T | Ymin_T |
| Domain Max: | Xmax_T | Ymax_T |
| Grid Size: | Dx_T | Dy_T |
| B.C. Left: | Default (Ne | default |
| B.C. Right: | Default (Ne | default |
| B.C. Bottom: | Default (Diri | default |
| B.C. Top: | Dirichlet | default |
| B.C. Use Slab: | ☐ | |

Control Parameters
Apply Index Perturbation: Default (Sim only)
Output All Plots: MPH Sim Only

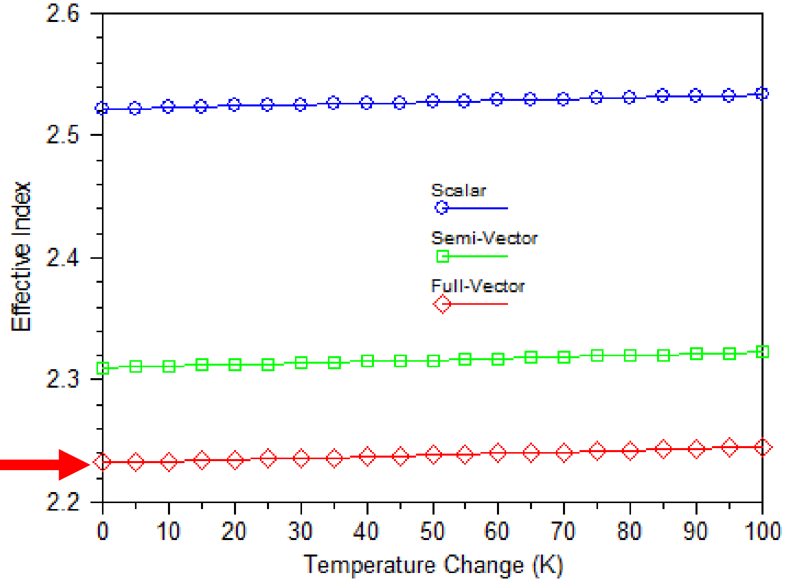


# Thermal-Optical Phase Shifter

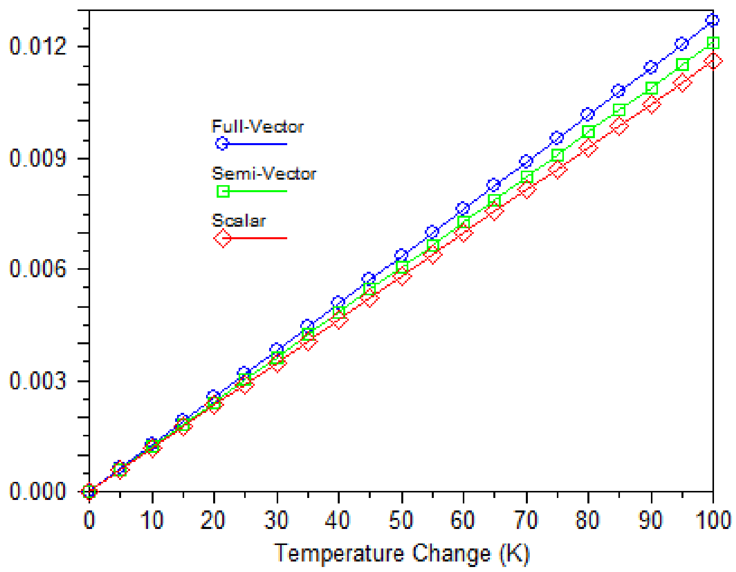
*Thermal-Optics*



Effective index



Change in effective index



**Summary:**

- Effective index of propagation mode is different based on scalar, semi-vector, or full-vector mode calculation
- The index change vs temperature is similar for three cases
- Semi-vector or even scalar mode propagation can be used for efficient and reliable calculation

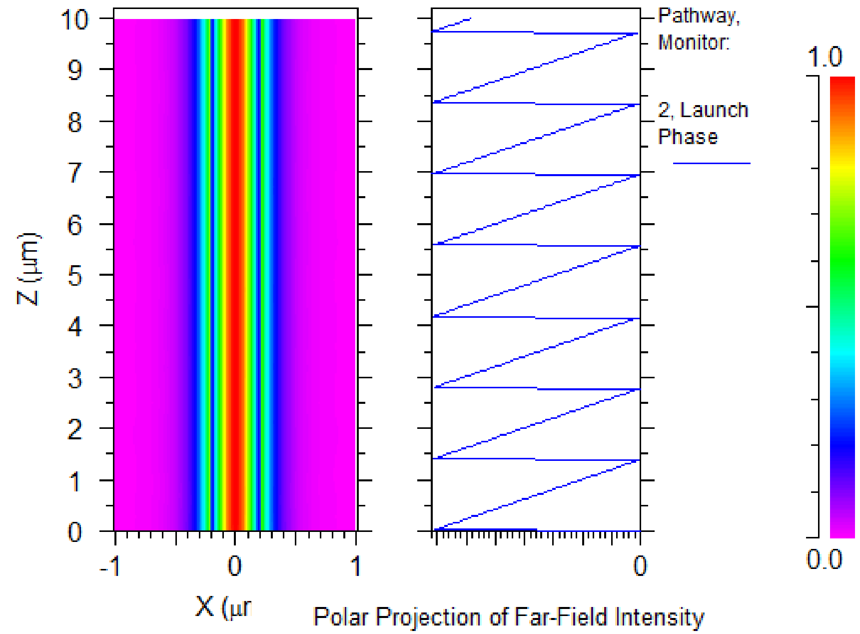
# Thermal-Optical Phase Shifter

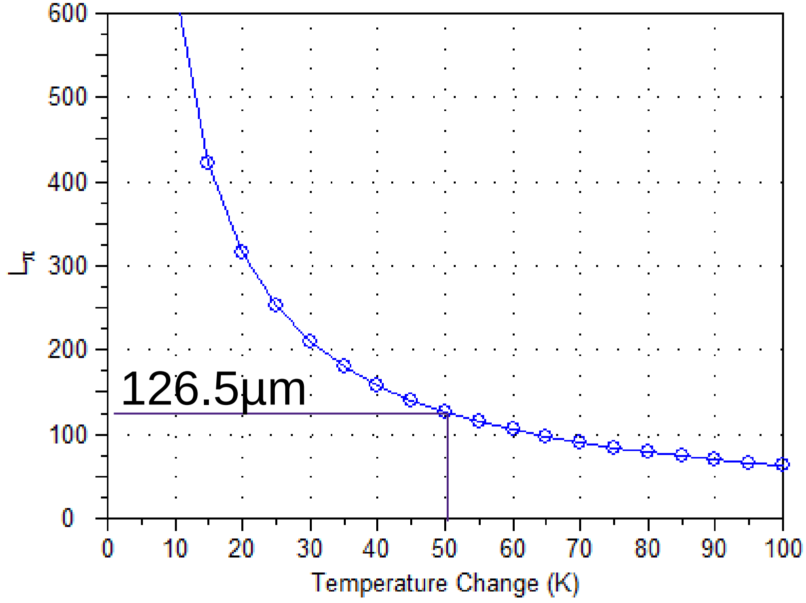
*Optical propagation*

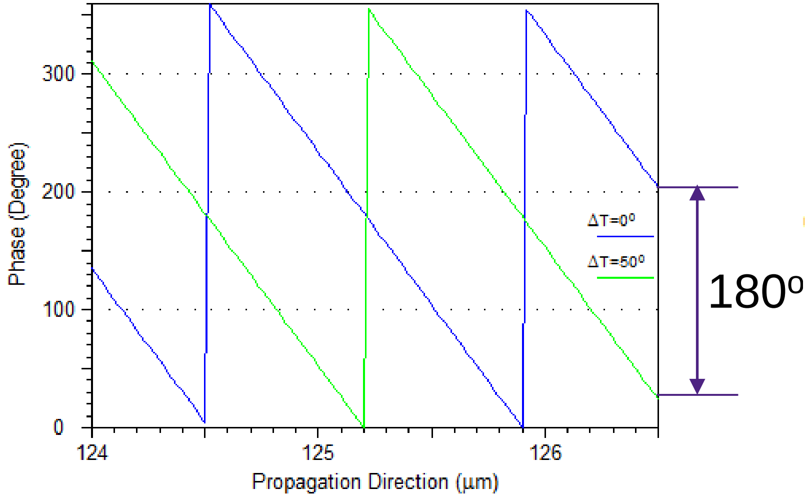
- Phase shift: $\Delta\Phi = \Delta N_{eff}\,\frac{2\pi}{\lambda}\,L$
  - $\Delta N_{eff}$ effective index change, λ wavelength,
  - L device length
- Device length to acheve π phase shift:

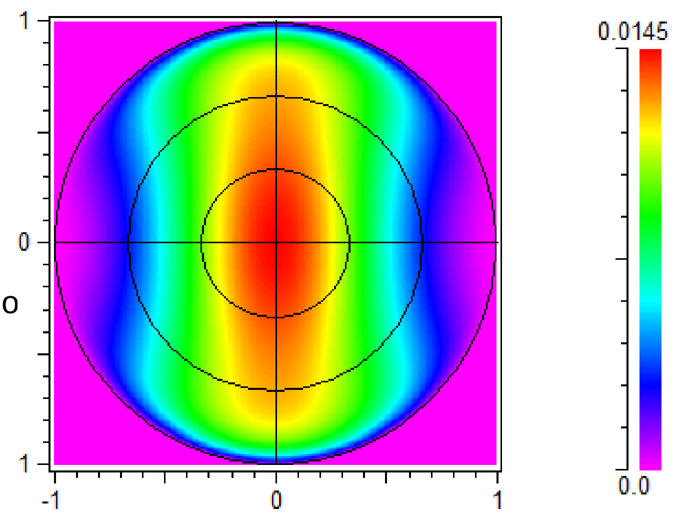
$$L_\pi = \frac{\lambda}{2\Delta N_{eff}}$$

- BeamPROP simulation





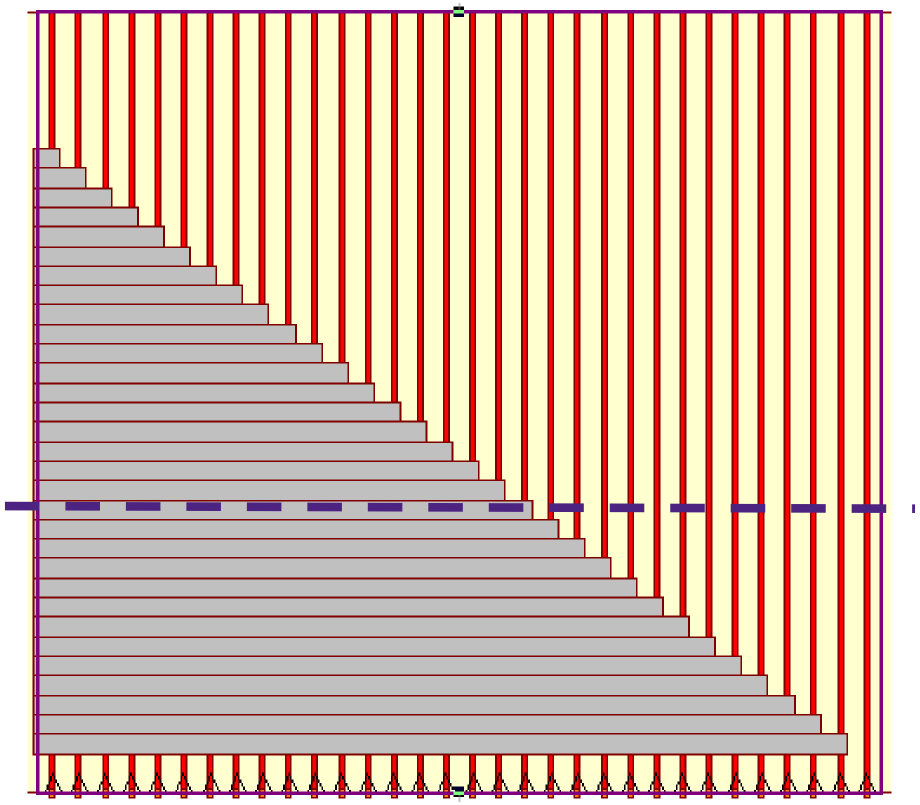




# Thermal-Optical Phase Shifter

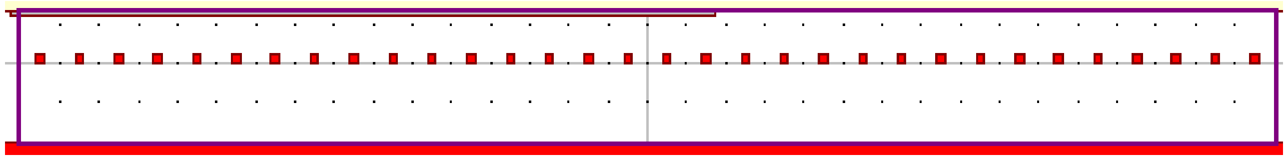
*Phase Arrays – Thermal-Optic Solver*

Top view

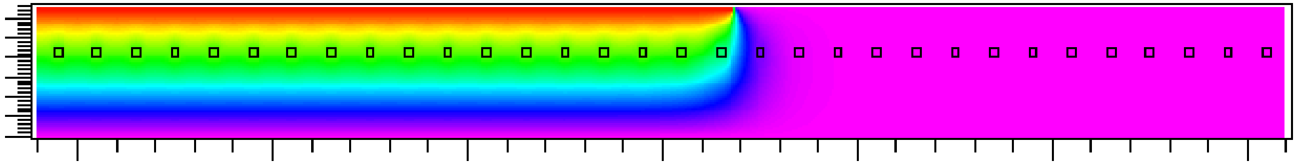


- Triangle-shaped heaters give different phase shifts for different waveguides

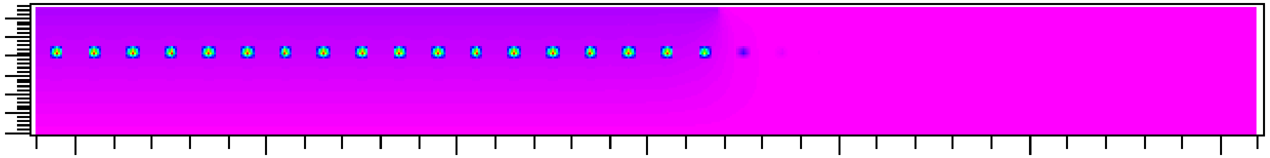
Cross-section view



Temperature Rise ΔT (°K)



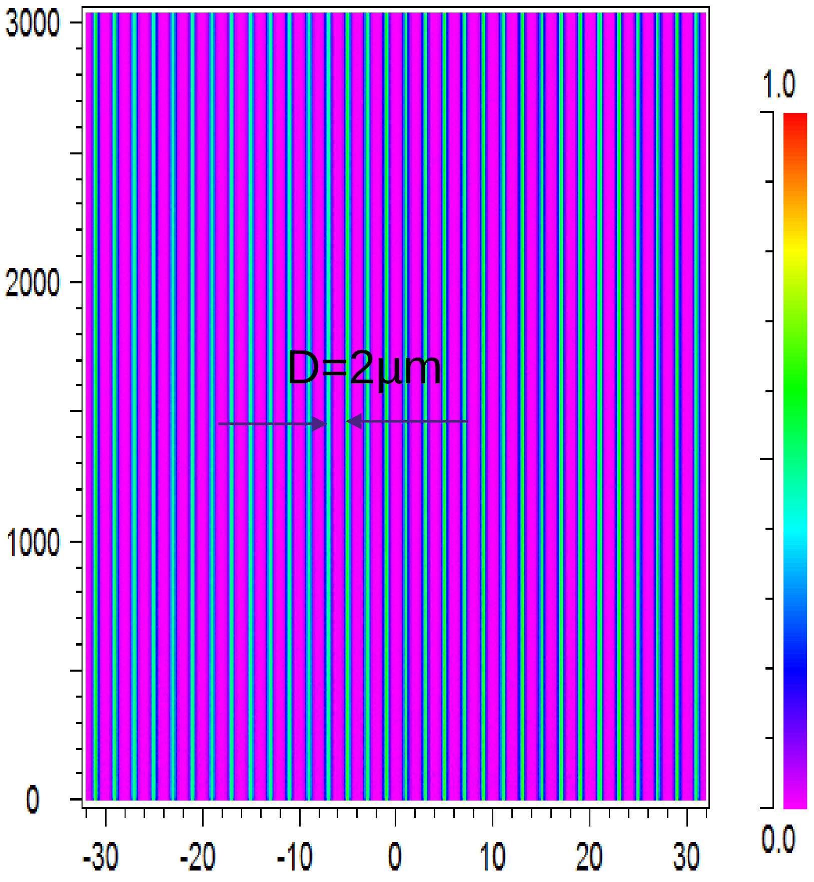
Index Change Δn



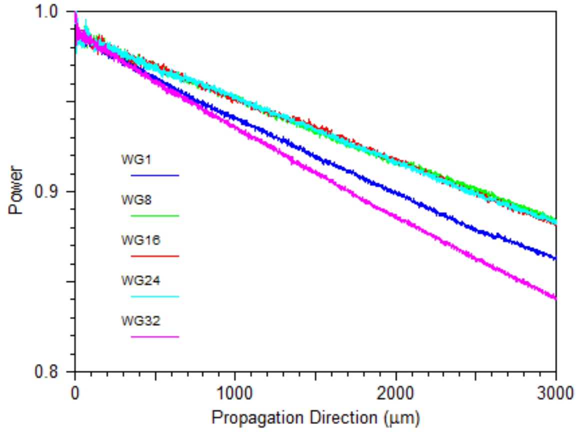
# Thermal-Optical Phase Shifter

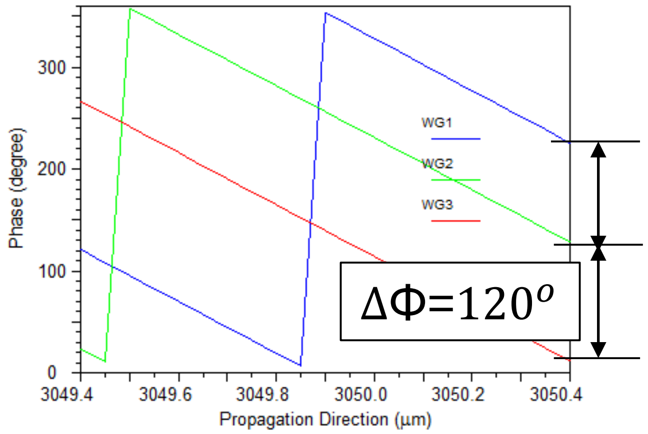
*Phase Arrays – Optical Simulation*

- BeamPROP traces beam input from each waveguide

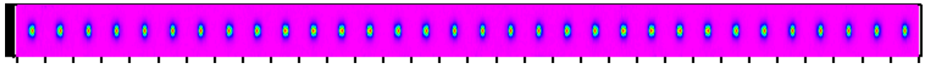


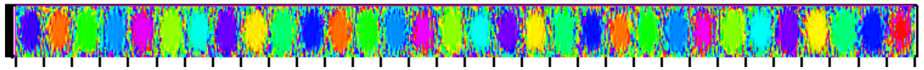
- Both power and phase of each waveguide are monitored



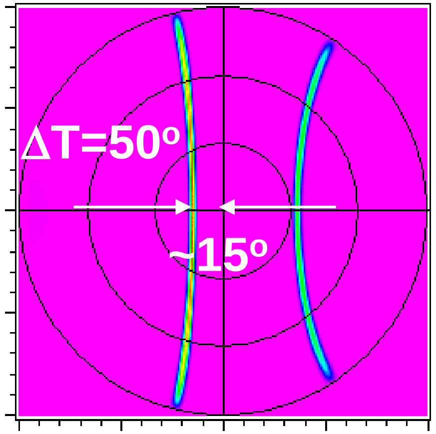


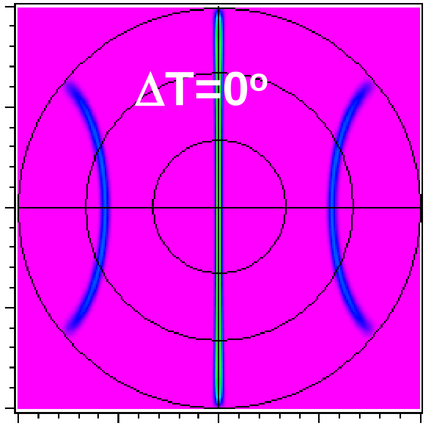
- Both amplitude and phase can be recorded at the end of the waveguides


Field Profile at the End


Phase Profile at the End

- Far-field from edge can be calculated


Far-Field Pattern with Thermal Turning

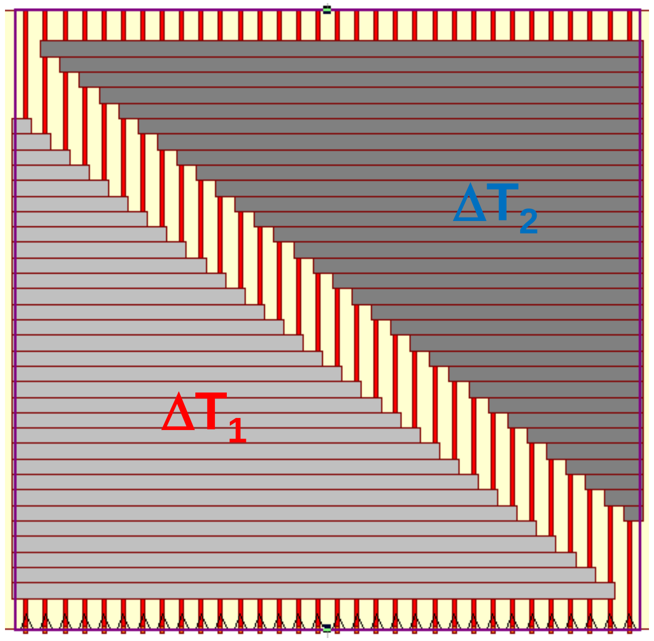

Far-Field Pattern without Thermal Turning

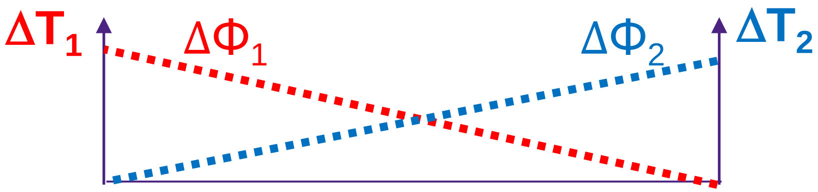
$$\psi = sin^{-1}\left(\frac{2\pi\Delta\varphi}{\lambda}\right) = 15^{o}$$

# Thermal-Optical Phase Shifter

*Phase Arrays – Push-Pull*

- Two triangle heaters shift phase in both directions





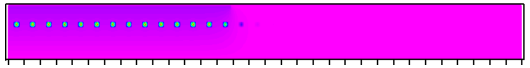
$\Delta T_1=50^{o}$ $\Delta T_2=0^{o}$

$\Delta T_1=\Delta T_2$

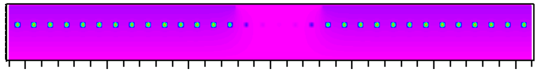
$\Delta T_1=0^{o}$ $\Delta T_2=50^{o}$

- Index change **ΔT**

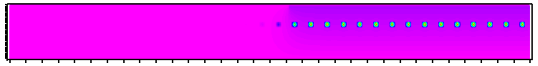
Index Change Δn



Index Change Δn

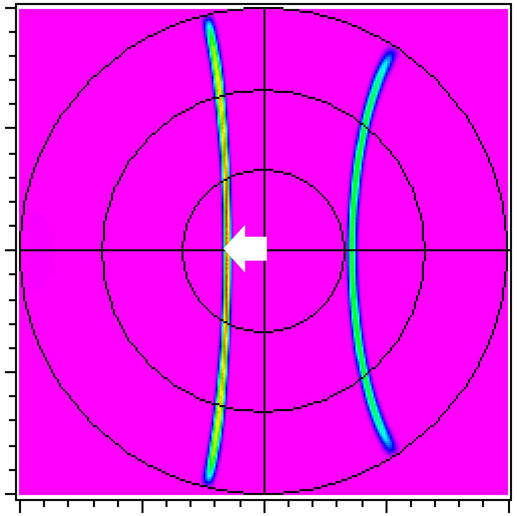


Index Change Δn

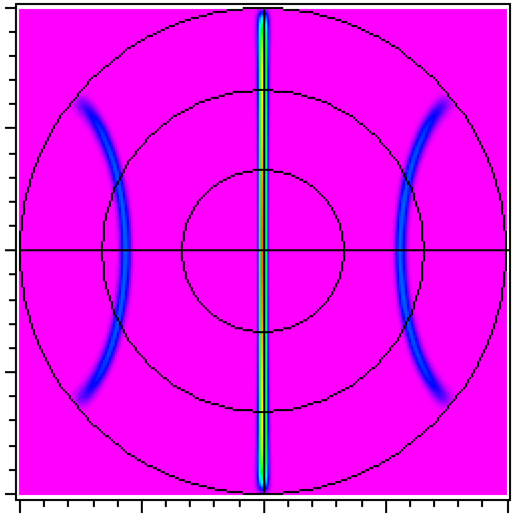


- Edge emitting far-fields at different biases

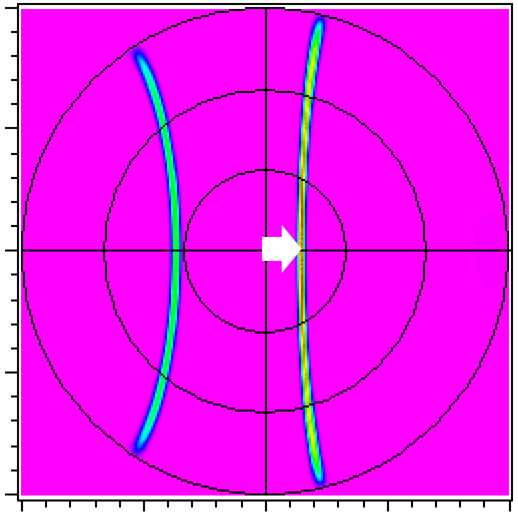
Far-Field Pattern with Heating on the Left



Far-Field Pattern with Heating Both



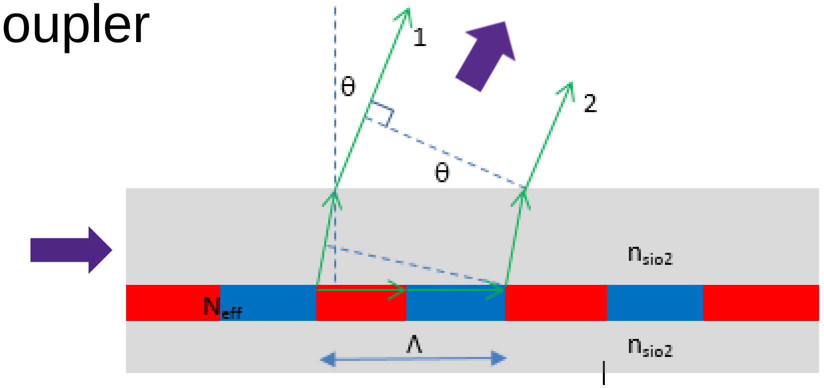
Far-Field Pattern with Heating on the Right



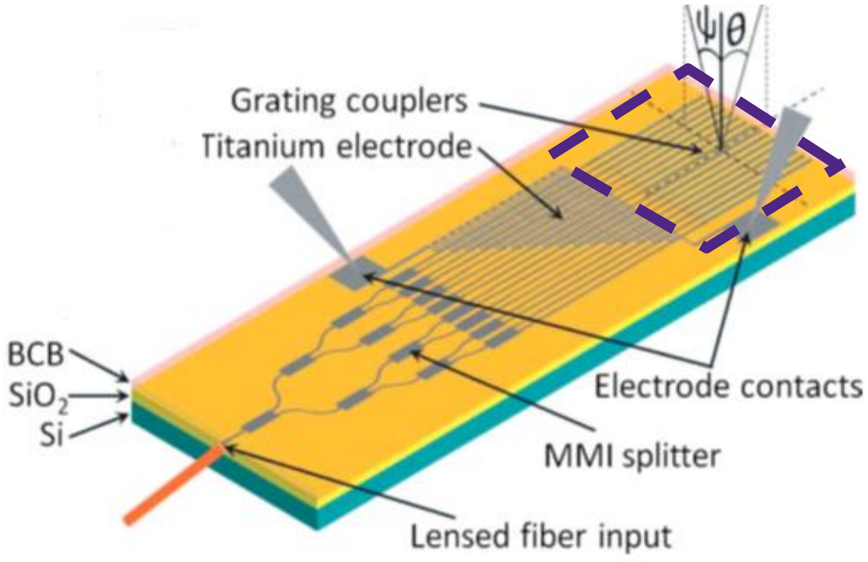
# Emitting Grating

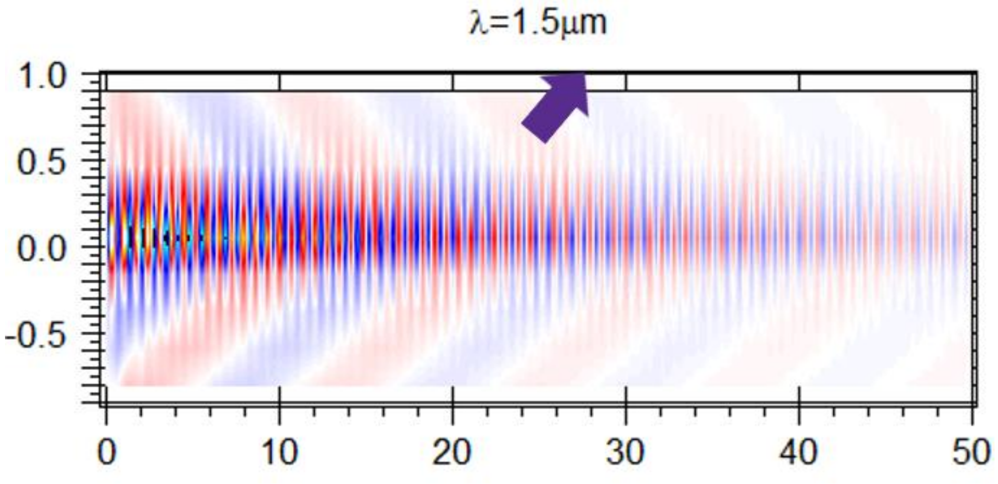
*Working mechanism*

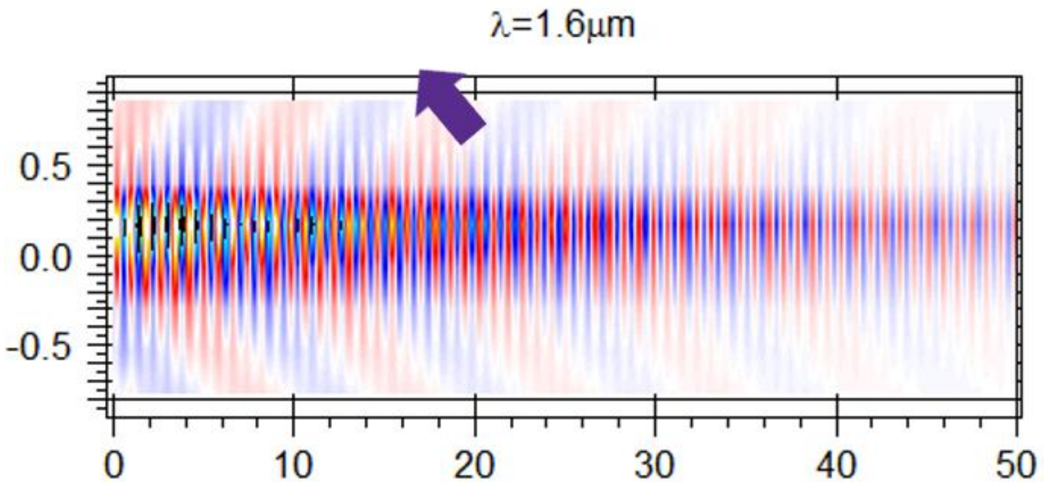
- Same working mechanism as grating fiber coupler



- Emitting angle: $\sin\theta = N_{eff} - \dfrac{\lambda}{\Lambda}$



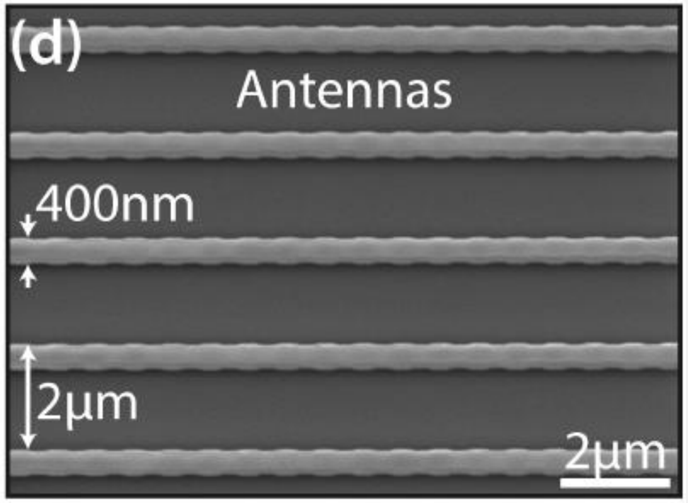




# Emitting Gratings

- Width Gratings
  - Easy process, one-step etching
  - Easy to apodize to emit light evenly

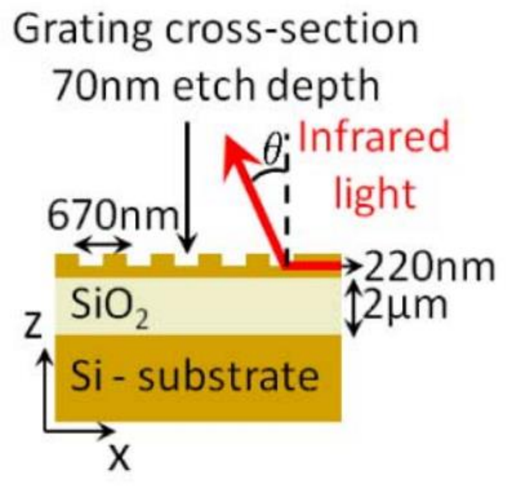
**MIT**



Poulton, Christopher V., et al. "Optical phased array with small spot size, high steering range and grouped cascaded phase shifters." *Integrated Photonics Research, Silicon and Nanophotonics*. Optical Society of America, 2016.

- Shallow Gratings
  - Complex process, two-step etching
  - Difficult to apodize

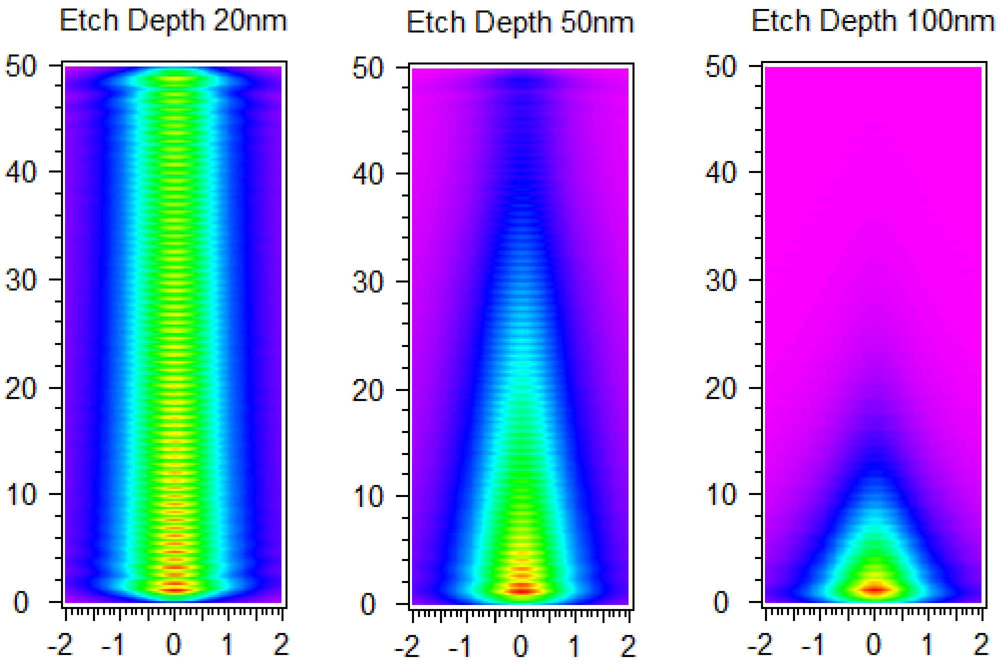
**Ghent**



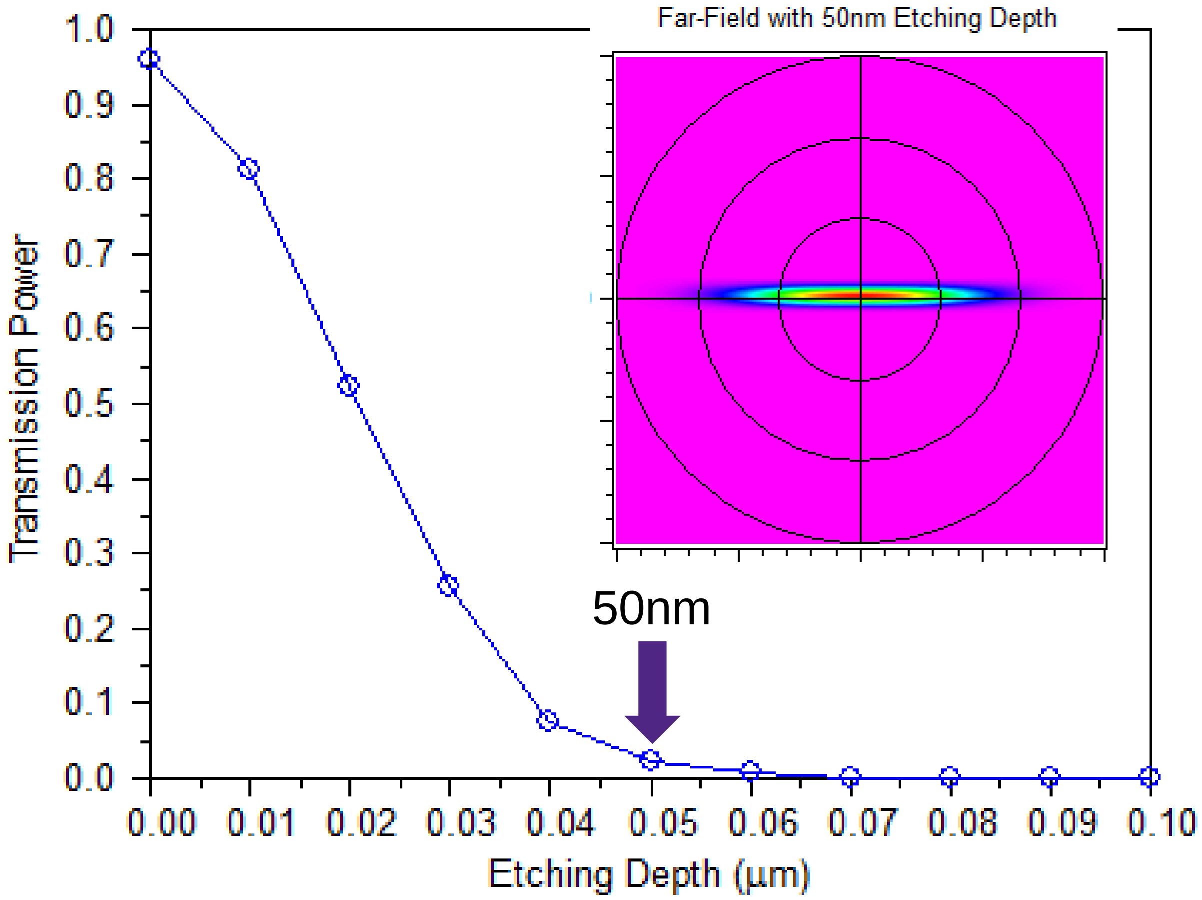
Van Acoleyen, Karel, Wim Bogaerts, and Roel Baets. "Two-dimensional dispersive off-chip beam scanner fabricated on silicon-on-insulator." *IEEE photonics technology letters* 23.17 (2011): 1270-1272.

# Etched Emitting Grating

- Apodization is difficult for etched grating
  - Emittance is always stronger at waveguide beginning
  - The best designs should have even power emission, with nearly all power emitted out by the end of the waveguide

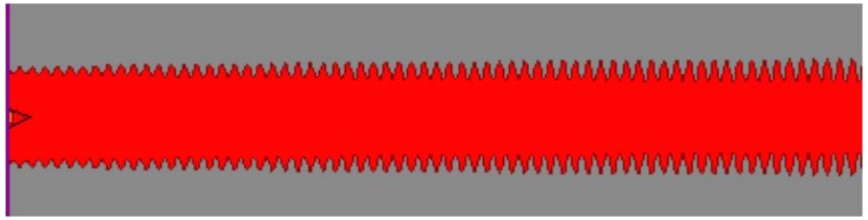


- MOST scan of etching depth



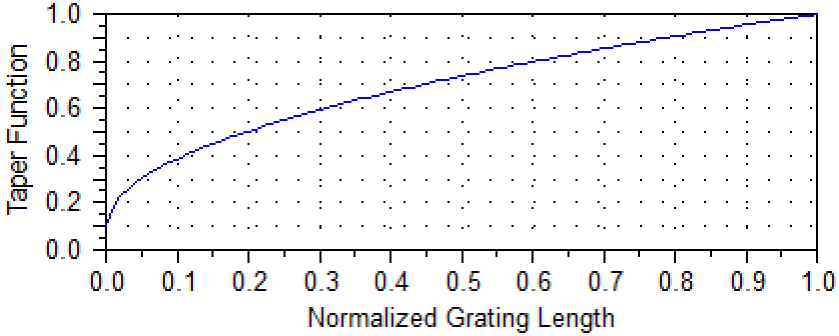
# Width Emitting Grating

- Apodized grating can be used to emit light evenly and completely

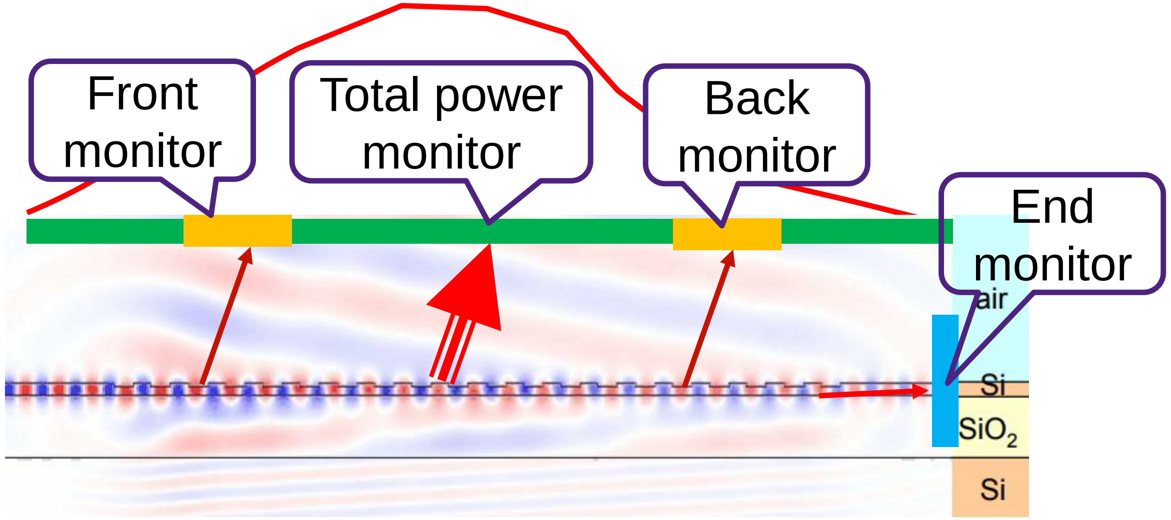


Width function: $W(Z) = W_0 + \nabla W f(Z)$

Taper function: $f(Z) = B + (1 - B)Z^P$



- Parameters to be optimized
  - ΔW, B, & P
- Design Targets:
  - Maximize the emitted power
  - Minimize transmission through waveguide
  - Emitted power as uniform as possible



Front monitor

Total power monitor

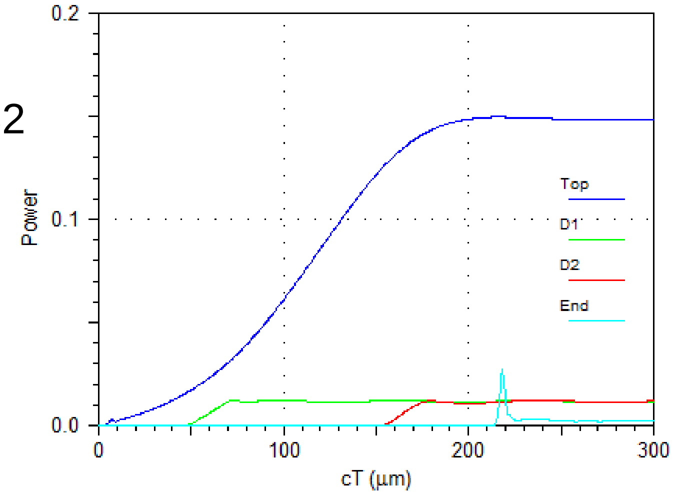
Back monitor

End monitor

**Target function:** $f = P_E - P_T + |P_F - P_B|100$

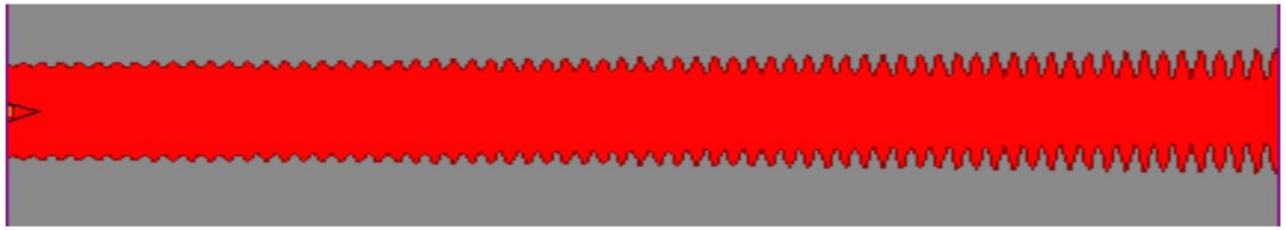
# MOST Optimization

- Optimization results
  - The 1st optimized result was obtain after ~24 hours
  - Better results can be obtained with longer runs
  - Optimized parameters
    - B=0.1305
    - P=1.4108
    - ΔW=0.1382

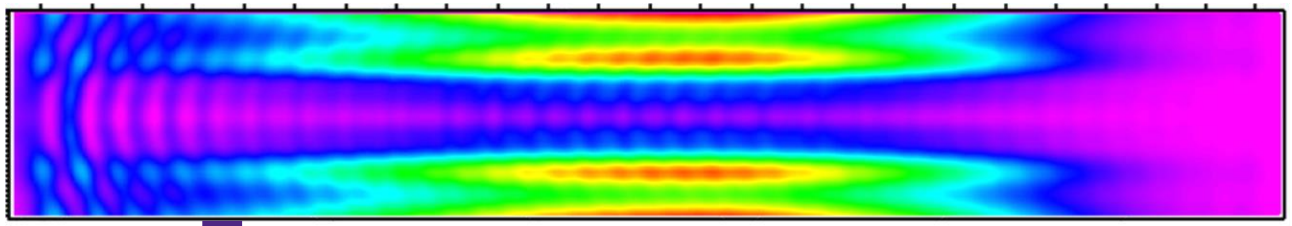


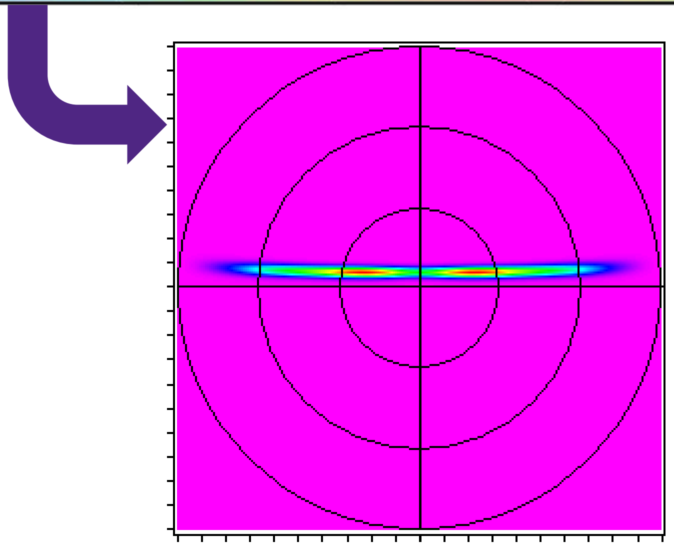
  - About 15% power emitted into the air
  - Where does the rest of the power go? See next slide

**Layout of the optimized gratings**



**Total near-field emitted from the optimized gratings**

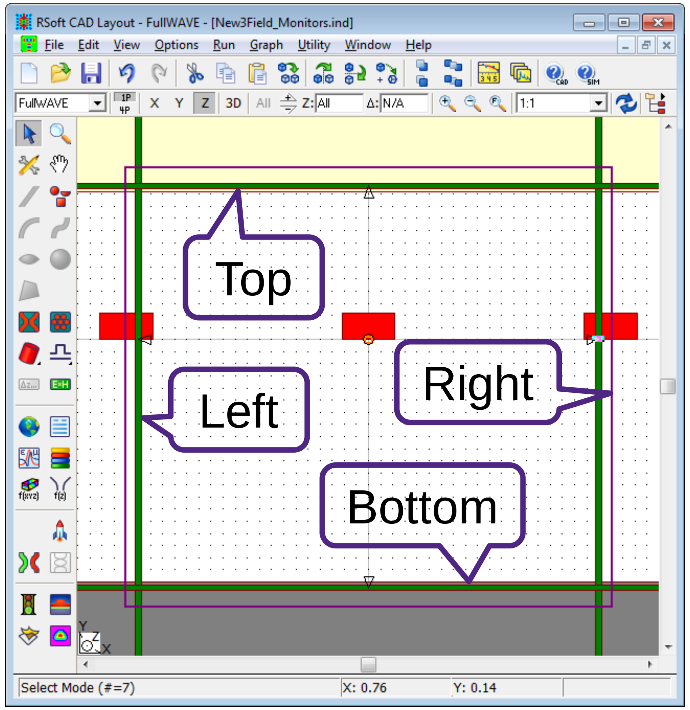




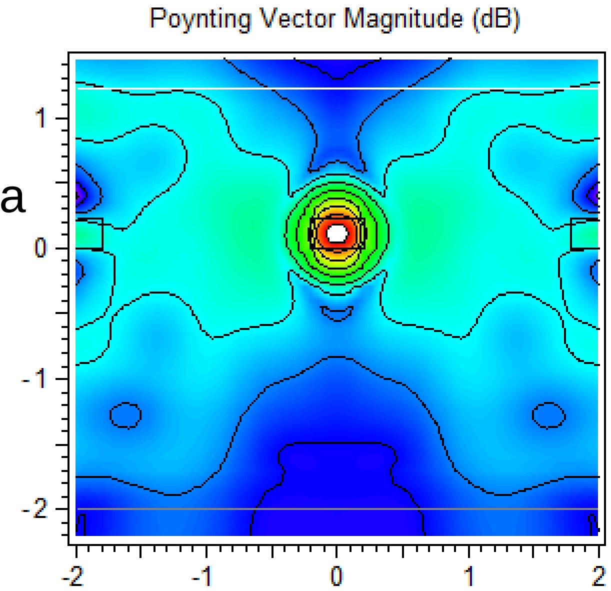
**Emitted Far-field**

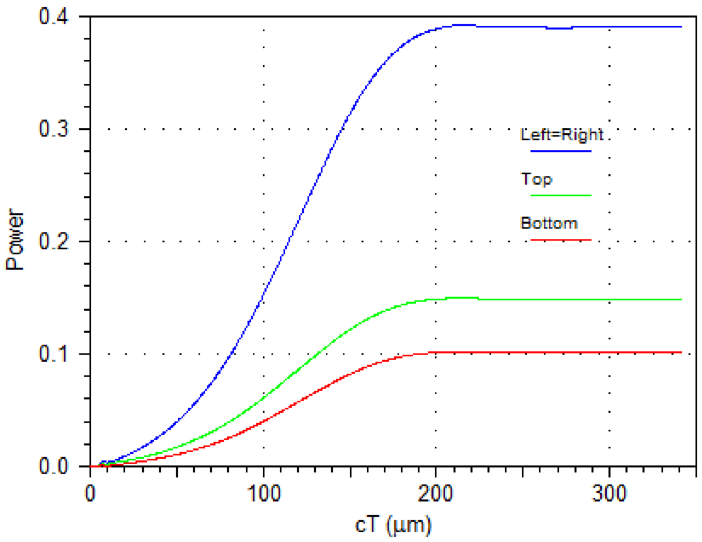
# Power Flow in Grating Coupler

- Four power monitors are placed at the boundaries to monitor the power flows
  - Top: power emitted into air
  - Bottom: power emitted into silicon substrate
  - Left and right: power trapped inside the silica layer



- Power flow



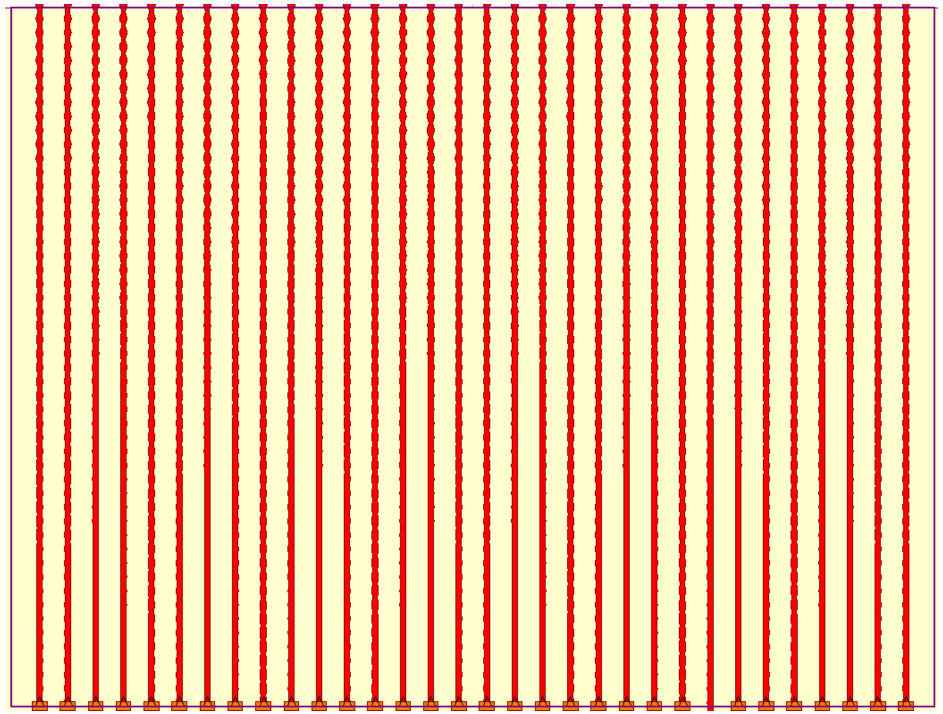


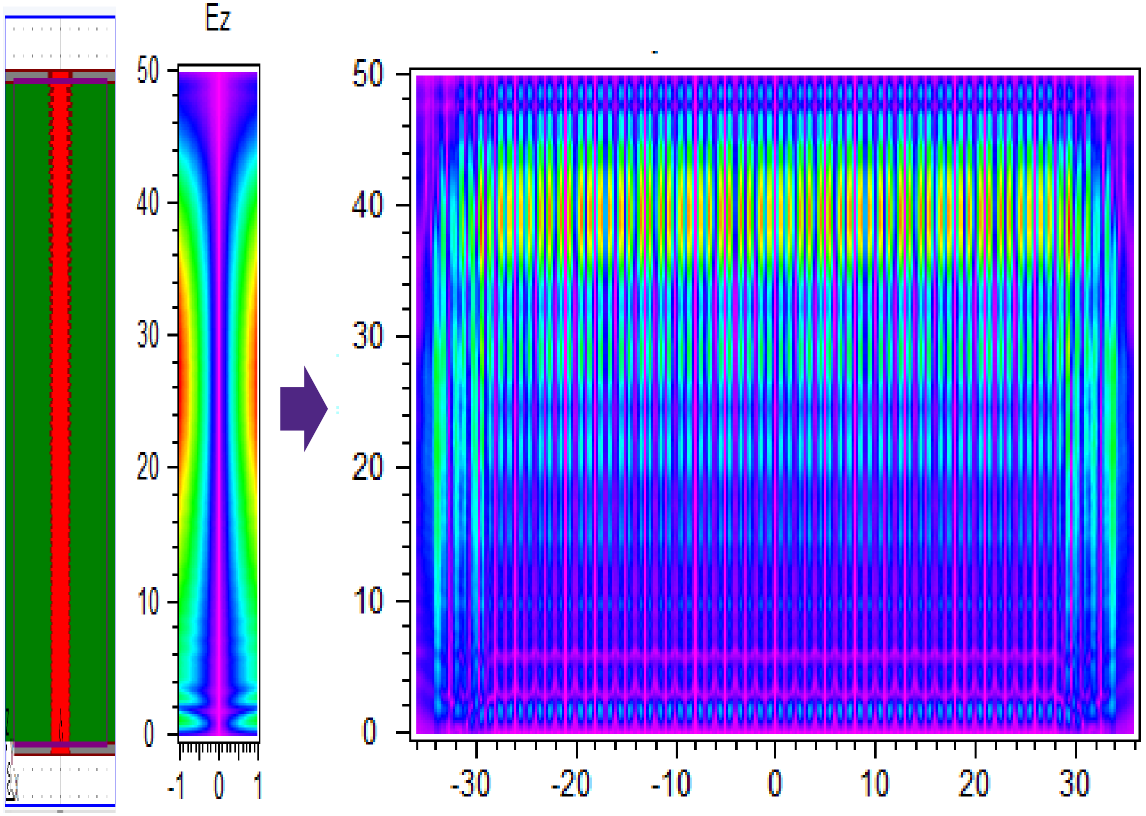
  - Most power is trapped inside silica layer
  - About 10% emitted into silicon substrate
  - Only about 15% power emitted into air
- How to increase the extraction efficiency?
  - Textured surface, bottom mirror, etc

# Multi-Channel Gratings

*Simulation Approaches*

- 32 channel grating is too big for FDTD
  - Requires >100GB RAM
  - Simulation would take several days at least
- Simulate one channel by FullWAVE
  - Combine 32 individual results, coherently
  - Simulation completed in ~1 hour

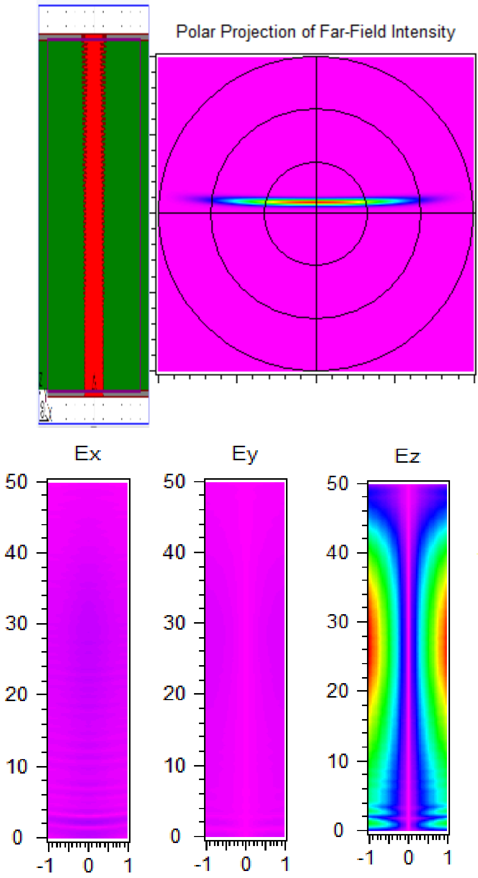




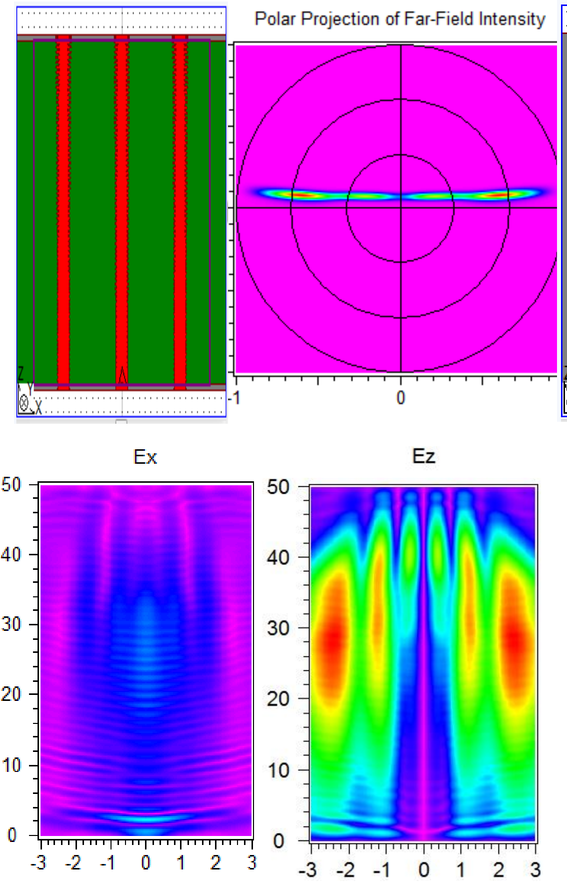
# FullWAVE Simulation for Single Input

*Convergence test*

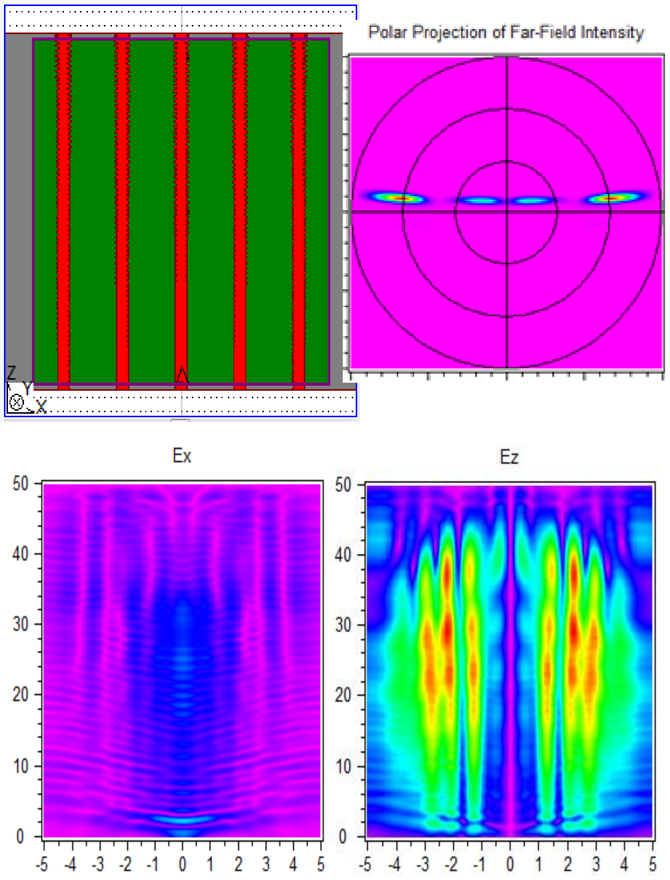
1 channel



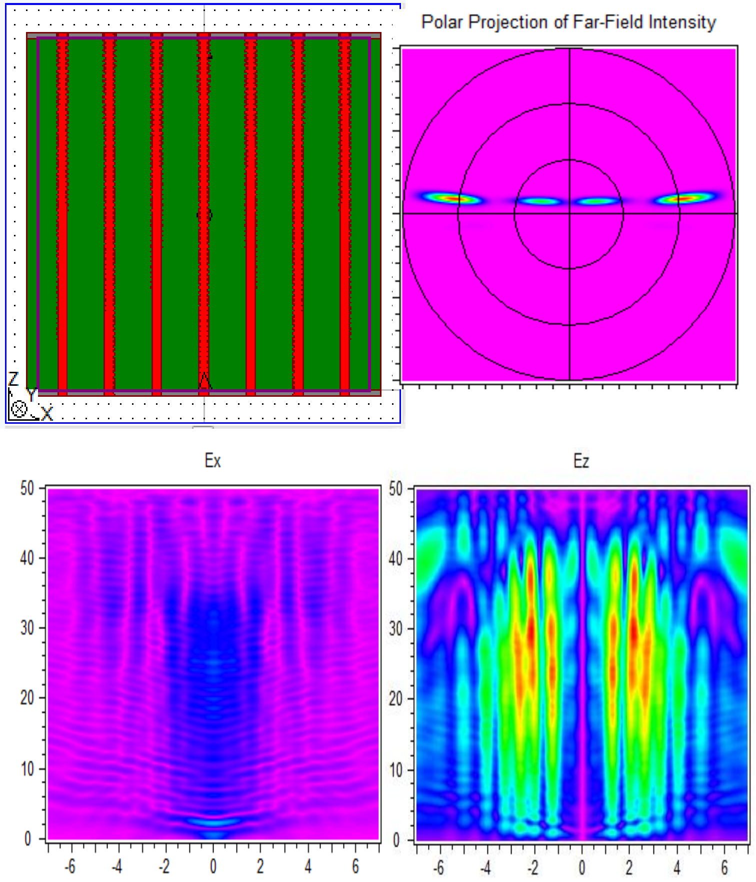
3 channels



5 channels



7 channels

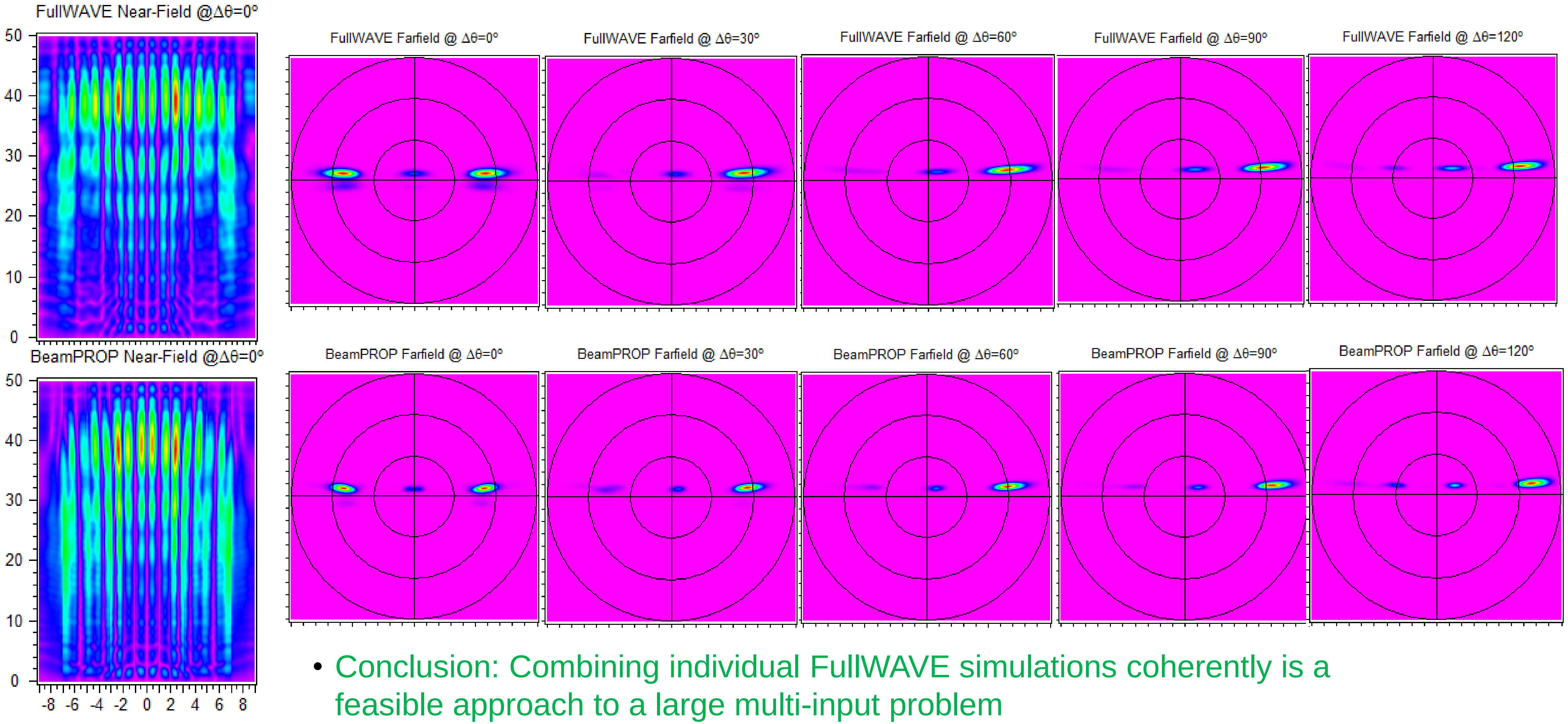


Ey component is weak and doesn’t contribute to the far-field

5 channels gives reasonable converged results

# Validation with 5 Inputs

*Comparison between FullWAVE and BeamPROP*



- Conclusion: Combining individual FullWAVE simulations coherently is a feasible approach to a large multi-input problem

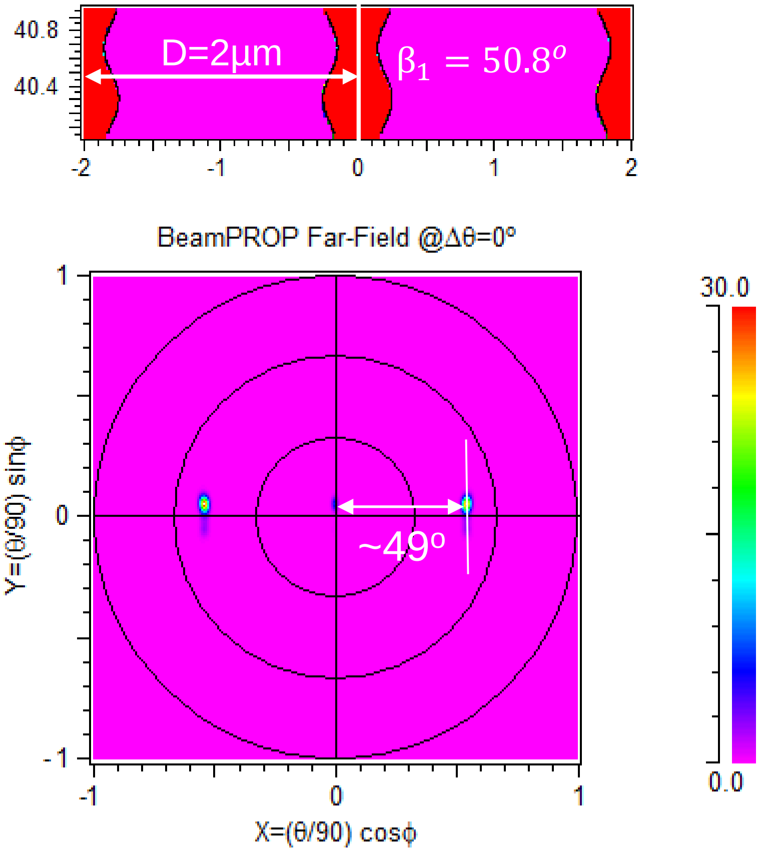
# Array Diffraction Gratings

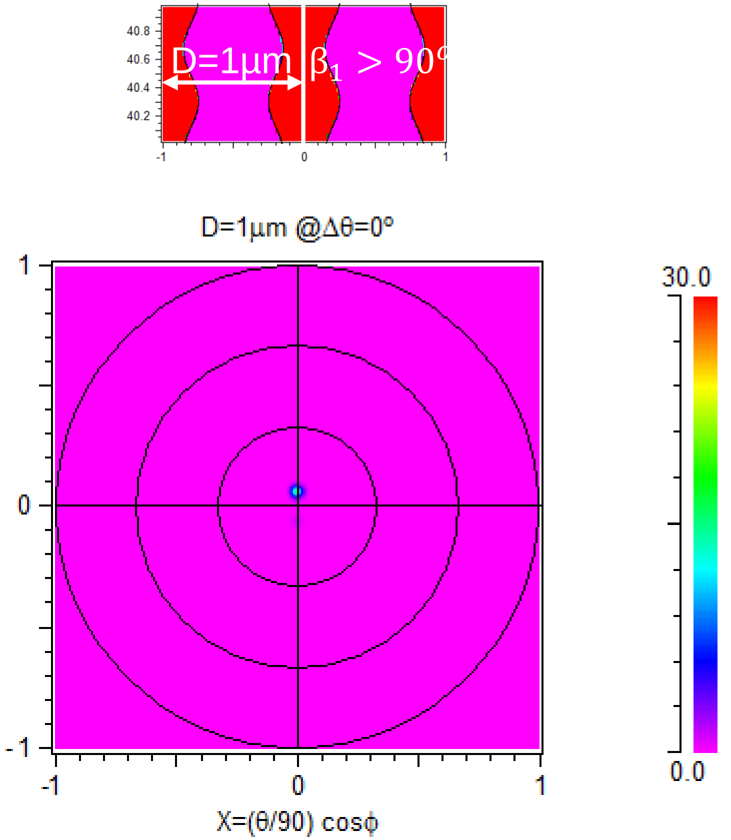
*High order diffraction*

- $1^{st}$ order diffraction angle
  - $\beta_1 = \sin^{-1}\left(\frac{\lambda_0}{D}\right)$
  - $\beta_1 = 90^o$ @ $D = \lambda_0$

- To suppress high-order diffraction, the channel spacing $D < \lambda_0$

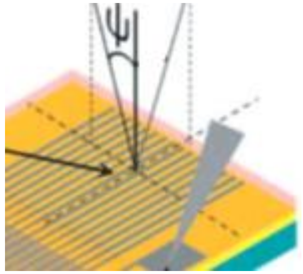
- Simulation results agree well with theory



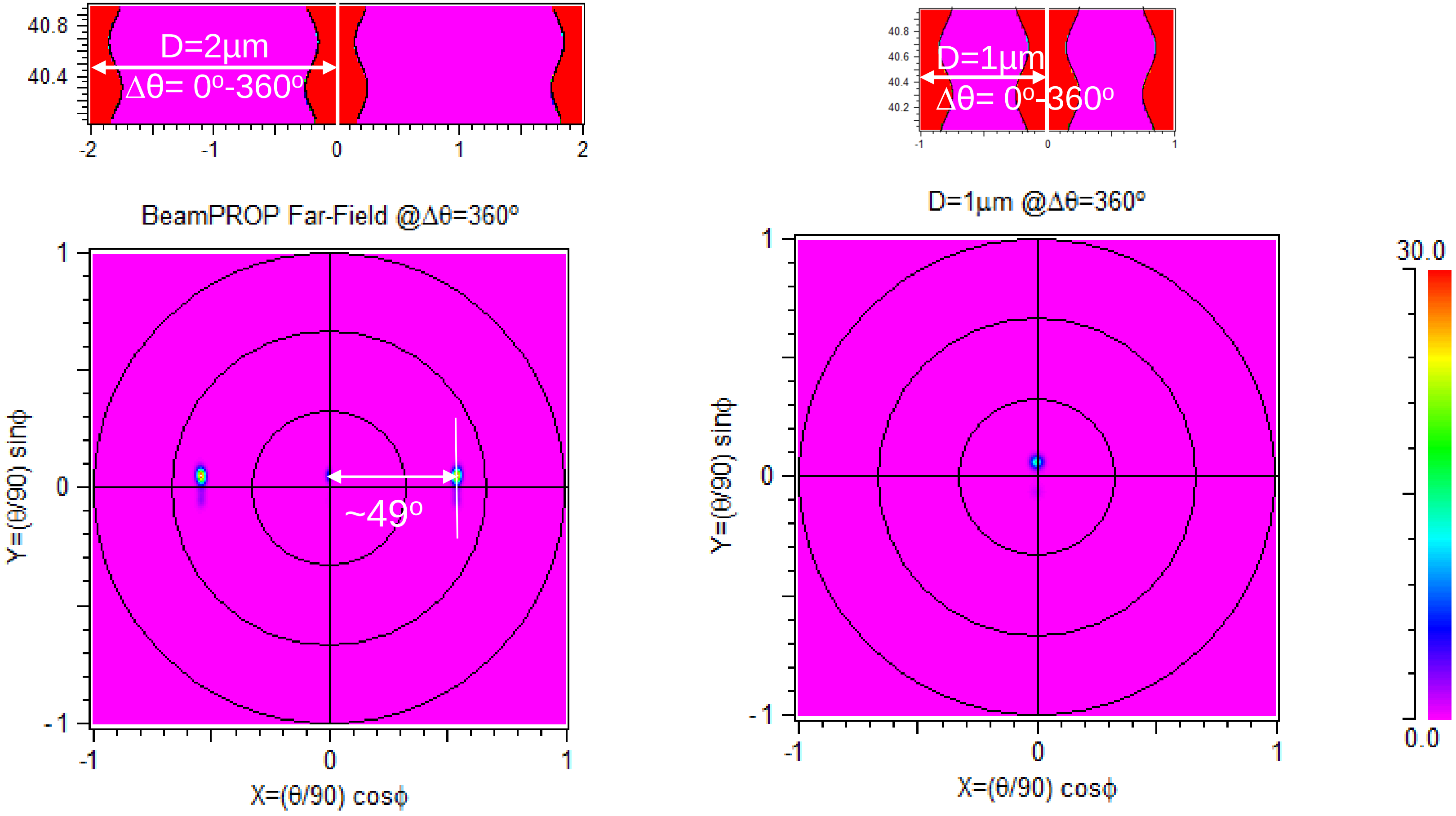


# Lateral Beam Steering

*Phase array tuning*

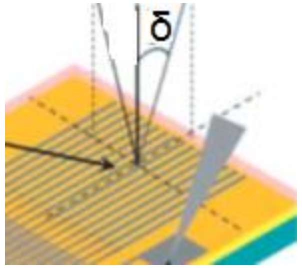


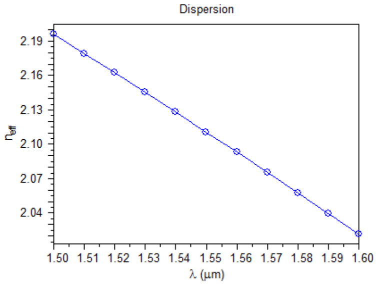
- Beam steering angle:
  - $\psi = \sin^{-1}\left(\frac{\lambda_0 \Delta\theta}{2\pi D}\right)$
  - $\psi_{max} = \sin^{-1}\left(\frac{\lambda_0}{D}\right) = \beta_1$
- Narrow channel spacing increases the tunability
- Simulation results agree well with theory



# Vertical Beam Steering

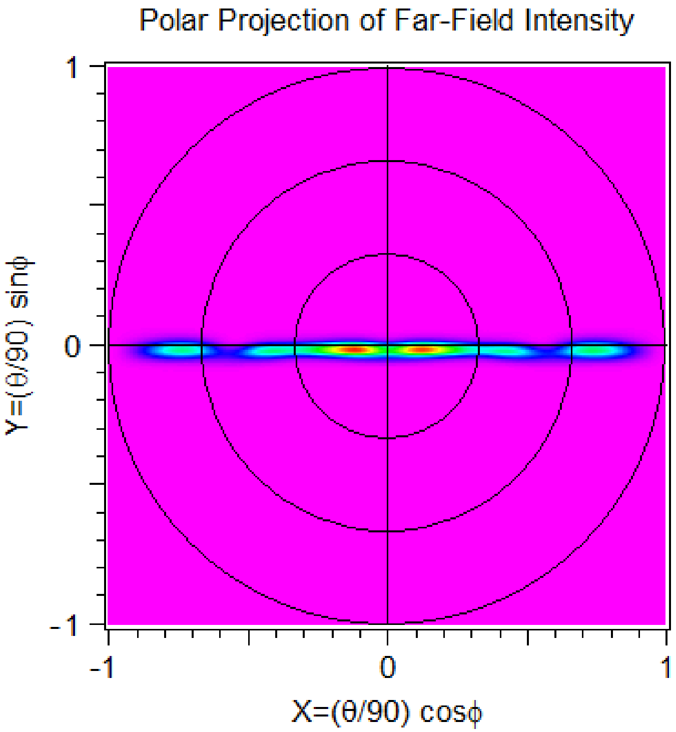
*Wavelength tuning*



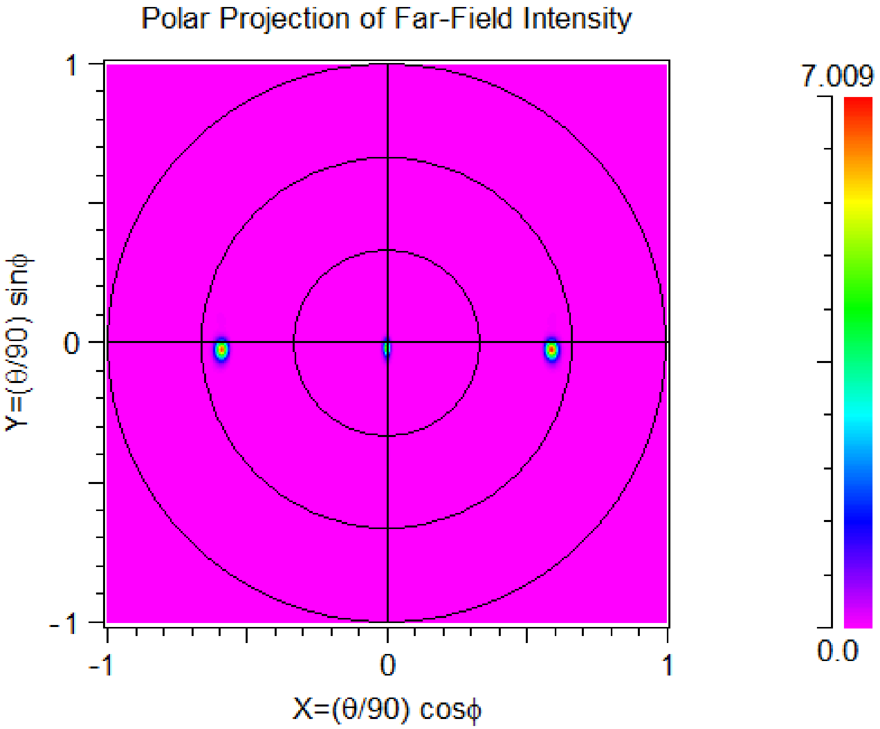


- Beam steering angle:
  - $\delta = \sin^{-1}\left(\frac{\Lambda n_{eff}-\lambda}{\Lambda}\right)$
  - $\Delta\delta = \Delta n_{eff} - \frac{\Delta\lambda}{\Lambda}$
    - Dispersion is important!
  - $\Delta\delta \sim 18^{o}$ for λ=1.5~1.6μm
- Simulation results agree well with theory

1-Channel



32-Channel



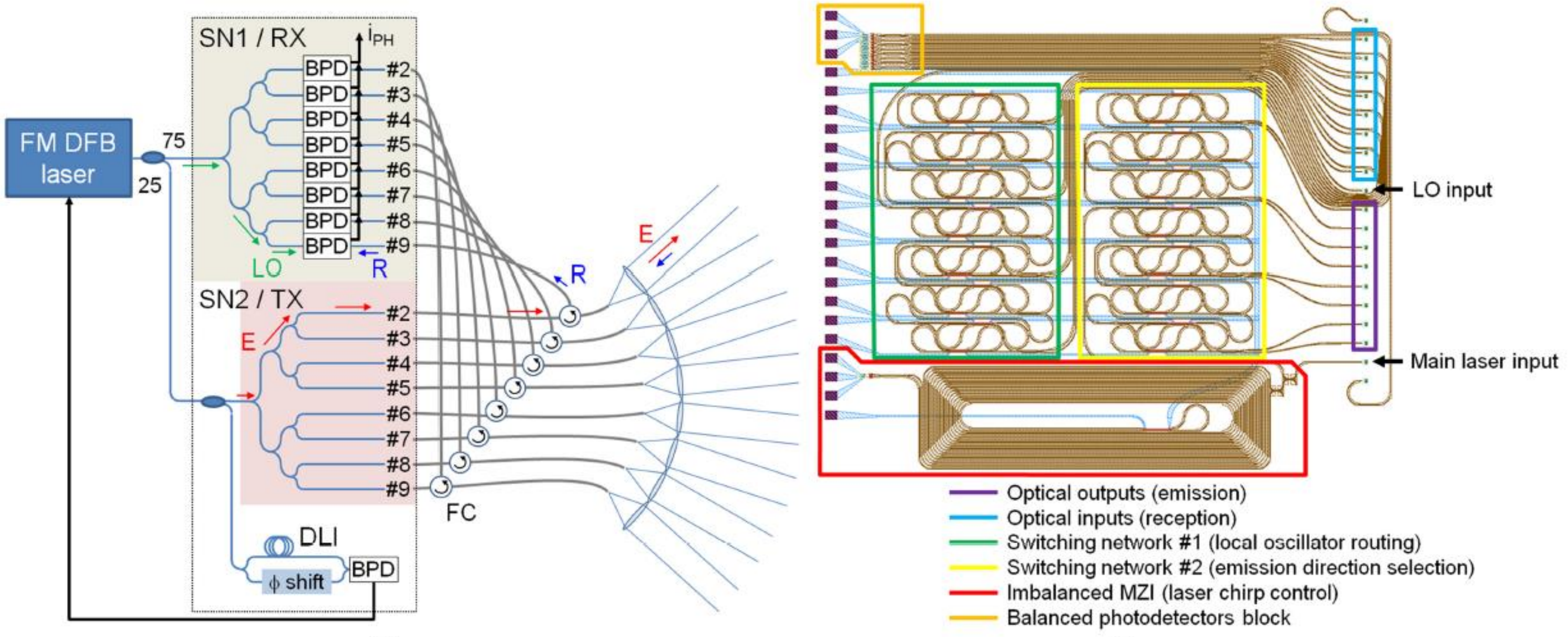
# Conclusions

- RSoft's tools can be used to optimize design of LIDAR on an integrated photonic chip
- The purpose of this presentation is to demonstrate how RSoft's tools can be used to optimize a LIDAR design, not to demonstrate a commercial LIDAR device
- Because of the complexity of the problem, there is no single tool can handle the whole device completely. It has to be decomposed into a number of key elements to be designed individually, using different tools where suitable.
- There are many design issues for designers to explore, such as
  - Maximizing output power
  - Improving uniformity of phase array
  - Investigating nonlinearity at high-power
  - etc.

# Recent LIDAR on-chip technology developments (Dec 2018)

*60m Range with 5mW*

- Edge output
- 8 Channels to 8 directions
- TX/RX integrated
- Limited by coherent length of the DFB laser
- No scan



(a) (b)

Fig. 1. (a) Architecture of the FMCW LiDAR system. The rectangle delimits the chip perimeter. Switches networks are highlighted in green (SN1) for the reception ports and red (SN2) for the emission ports. Emission channels are successively addressed and connected via optical fibered circulators (FC) to the corresponding Balanced PhotoDiodes (BPD) and the output collimator. The waveform calibration is achieved with the delay line interferometer (DLI). (b) Mask layout of the chip. Metallic pads (purple rectangles on the left) are electrically connected to the printed circuit board and fibers are attached to the grating couplers (blue rectangle on the right). Inset shows a picture of the device.

Martin, Aude, Delphin Dodane, Luc Leviandier, Daniel Dolfi, Alan Naughton, Peter O'brien, Thijs Spuesens et al. "Photonic integrated circuit based FMCW coherent LiDAR." *Journal of Lightwave Technology* (2018).

# Thank You