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.
• 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!
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
- Complicated design layout can be achieved in RSoft
- No single simulation tool can solve the complex problem
- Combined tools have to be used for different elements


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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

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


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 $\approx 49.3\%$
1x2 Power Splitter

Comparison between MMI and Y-branch

- Symmetric input

- Asymmetric input

- Power/Phase Sensitivity study to layout offsets

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

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

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

$\theta=5^\circ$
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**
  - Thermal solver
  - Electrode
  - Si-wire
  - SiO₂
  - Si-substrate

- **Thermal conductivity**

Tip: For better convergence, exclude air in computational window

- **RSOsoft Multiphysics Solver settings**
Thermal-Optical Phase Shifter

Thermal-Optics

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, $\lambda$ wavelength,
  - $L$ device length
- Device length to achieve $\pi$ phase shift:
  
  \[ L_{\pi} = \frac{\lambda}{2\Delta N_{eff}} \]
Thermal-Optical Phase Shifter

Phase Arrays – Thermal-Optic Solver

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

Temperature Rise $\Delta T$ (°K)

Index Change $\Delta n$
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

\[ \Delta T = 50^\circ \]
\[ \Delta T = 0^\circ \]

\[ \phi \approx 15^\circ \]

\[ \psi = \sin^{-1} \left( \frac{2\pi \Delta \phi}{\lambda} \right) = 15^\circ \]

D=2µm
Thermal-Optical Phase Shifter

Phase Arrays – Push-Pull

- Two triangle heaters shift phase in both directions

\[ \Delta T_1 = 50^\circ \quad \Delta T_2 = 0^\circ \]

- Index change \( \Delta T \)

- Edge emitting far-fields at different biases
Emitting Grating

Working mechanism

• Same working mechanism as grating fiber coupler

\[
\sin \theta = N_{eff} - \frac{\lambda}{\Lambda}
\]

• Emitting angle: \( \sin \theta = N_{eff} - \frac{\lambda}{\Lambda} \)
Emitting Gratings

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

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

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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

![Graph showing transmission power against etching depth](image-url)
Width Emitting Grating

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

Width function: \[ W(Z) = W_0 + \Delta W f(Z) \]
Taper function: \[ f(Z) = B + (1 - B)Z^P \]

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

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
    – $\Delta W=0.1382$
  – About 15% power emitted into the air
  – Where does the rest of the power go? See next slide
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

- 1st order diffraction angle
  \[ -\beta_1 = \sin^{-1}\left(\frac{\lambda_0}{D}\right) \]
  \[ -\beta_1 = 90^\circ \text{ @ } D=\lambda_0 \]

- 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!
  - \(\Delta\delta \sim 18^\circ\) for \(\lambda=1.5\sim1.6\mu m\)

- Simulation results agree well with theory
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

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. Metalic 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.

Thank You