Polarization Splitting Rotator (PSR) based on Sub-Wavelength Grating (SWG) waveguides

Oscar Yun Wang
Dr. Lukas Chrostowski

Ref.
Outline – Polarization splitter rotators

• Design polarization splitting rotator based on sub-wavelength grating (SWG) waveguides.
  • introduction to SWG waveguides
  • introduction to polarization splitting rotators
  • using the effective medium theory to simulate a polarization rotating directional coupler,
  • calculating the band-structure diagrams of SWG waveguides,
  • verifying our design using 3D-FDTD,
  • designing the experiment,
  • creating a layout.
Sub-Wavelength Grating (SWG)
Silicon Photonics

Dr. Lukas Chrostowski
Sub-wavelength grating materials

• No diffraction in gratings when the period is << wavelength.
• First observed in nature in moths – C. G. Bernhard, Endeavour 26, p. 79, 1967
  • graded index
  • used in Canon lenses as an AR coating
Sub-wavelength grating materials

• What can you do with them?

• The optical response of the material becomes the weighted average of the original materials.

• Analogous to Pulse-Width Modulation in electrical engineering

• Can create arbitrary index of refraction values by digital modulation (in the mask layout) rather than analog modulation (e.g., varying the material composition, like in graded index fibres)

• Extra degree of freedom in PIC design
Sub-wavelength grating materials

• What can you do with them?
  • Graded index
    • lens
    • anti-reflection
  • Anisotropic materials
  • Mirrors
  • Waveguides
  • Edge couplers
  • Grating couplers
  • Waveguide crossing
  • MMI
  • Directional couplers

• Ring resonators
• Sensors
• Filters (e.g., Bragg gratings)
• ...

• Lots of publications in the field.
SWG Edge Coupler

- Mode profile of a large $\Delta n$ vs. small $\Delta n$ waveguide.
- Can engineer a gradual (adiabatic) change from a large $\Delta n$ high-contrast (high-confinement) silicon photonic waveguide, to a low-contrast (low confinement) SWG waveguide, that is well matched to the optical fibre.
- ~ 90% efficiency

P. Cheben et al., US Patent 7,680,371
Metamaterial converter for coupling to cleaved standard fiber

- Coupler embedded in suspended oxide membrane for isolation to Si handle
- First use of hybrid waveguide transition in Cheben et al., Optics Lett. 2010
Optical measurements of metamaterial converter performance

O-band converter response

<table>
<thead>
<tr>
<th>Wavelength (um)</th>
<th>Loss to fiber (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.26</td>
<td>-1.3 dB</td>
</tr>
<tr>
<td>1.28</td>
<td>0.8 dB</td>
</tr>
<tr>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td>1.32</td>
<td></td>
</tr>
<tr>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td>1.36</td>
<td></td>
</tr>
</tbody>
</table>

1.31 um measurement with water immersion (n~1.31)

<table>
<thead>
<tr>
<th>Chip ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max in polarization</td>
<td>-1.1 dB</td>
<td>-1.2 dB</td>
<td>-1.1 dB</td>
<td>-2.4 dB</td>
<td>-1.9 dB</td>
</tr>
<tr>
<td>Min in polarization</td>
<td>-1.4 dB</td>
<td>-1.5 dB</td>
<td>-1.4 dB</td>
<td>-2.6 dB</td>
<td>-2.1 dB</td>
</tr>
<tr>
<td>Position on wafer</td>
<td>random</td>
<td>random</td>
<td>random</td>
<td>edge</td>
<td>edge</td>
</tr>
</tbody>
</table>

Measurement setup

- Manual assembly to V-grooves, no active alignment (OFC’15, Th3F.3).
- Spread on single wafer: -1.1 dB to -2.6 dB
- V-groove variability expected to dominate spread in this early production tools implementation
Parallelized fiber assembly: automated assembly results

- Sliding base enables fiber butting on coupler with pure vertical pick-tip movement.
- Coupler in suspended membrane with undercut filled with adhesive at assembly.

Cross-section of an assembly, all 12 fibers seated.

Side-view polished cross-section.
Focusing Sub-Wavelength Grating Coupler – Lines

Ref: Y. Wang, “Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonics circuits”, OE, 2014
SWG Waveguides

• Light propagation in a periodic medium:
  • $\Lambda < \lambda/2$: The sub-wavelength zone. Diffraction is suppressed. The periodic structure supports a true lossless mode in this case. The waveguide behaves like conventional waveguide. This is in analogy to the electron distribution in periodic potentials (semiconductor).
  • $\Lambda \sim \lambda/2$: The wavelength range corresponding to the photonic bandgap where the propagation constant becomes complex and Bragg reflections occur.
  • $\Lambda > \lambda/2$: Radiation out of the waveguide. The propagation loss is determined by reflection and diffraction at the segment boundaries due to the high index contrast.

• SWG waveguides are attractive as they allow to tailor propagation properties – mode shape and dispersion – by varying the duty cycle, $\eta$, period, $\Lambda$, the waveguide width, $w$, and the waveguide thickness, $h$.

• Invented at the National Research Council of Canada (NRC).
Propagation: SWG waveguide

- Propagation just like in a regular waveguide, except the field profile is periodic
- Field enhancement in the gaps, just like in slot waveguides

SWG Ring Sensors

- Evanescent field sensors, with improved sensitivity ~ 400 - 490 nm / RIU

Polarization Splitting Rotator (PSR)

Oscar Yun Wang
Dr. Lukas Chrostowski

Ref.
Textbook:
L. Chrostowski,
M. Hochberg,
Outline

• What is a polarization splitter rotator (PSR) ?
• How does it work?
• State-of-the-art
• Remaining Issues?
• Why we need sub-wavelength gratings?
• How to design a PSR with SWG?
  • Based on paper from Carleton, NRC, Malaga:
• What can be improved?
What is a PSR? — Motivation

- Due to the high index contrast of the SOI platform, components are polarization dependent (dispersion, loss), which makes it inconvenient to integrate with other polarization insensitive systems, such as optical fibre networks;

- PSRs are fundamental building blocks in polarization diversity systems [1] and polarization multiplexing devices [2];

- The required components are polarization splitters and polarization rotators:
  - a PSR combines the two functionalities

![Diagram](image)

How Does It Work?

DC-based PSR

Fig. 1 Schematic of the cross section of a PSR based on directional coupler. [1]

- Phase match condition:

\[ n_{eff}^{1,TM} = n_{eff}^{2,TE} \]

The widths of the two waveguides are adjusted so that the effective index of the fundamental quasi-TM mode in waveguide 1 is equal to that of the fundamental quasi-TE mode in waveguide 2.

Numerous PSR implementations


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Remaining Issues

• DC-based PSR: sensitive to fabrication errors, strict constraints on waveguide width and coupler length. The coupling wavelength shifts with a rate of about 15 nm/nm with respect to the variation of the waveguide width;

• MMI-based PSR: complex structure: includes a mode-evolution taper, a Y-junction, a phase shifter and an MMI.

• Mode-evolution PSR: large size (~500 um): including a bi-level taper and a adiabatic coupler;

• Ideally, we need a PSR with high conversion coefficient, large extinction ratio, compact size, and low insertion loss.

Why we need sub-wavelength gratings?

The two waveguides of the conventional DC-based PSR have the same material index, therefore, the mode effective indices changes with different slopes, which leads to high sensitivity to fabrication errors. The coupling wavelength shifts with a rate of about 15 nm/nm with respect to the variation of w1.

The SWG approach allows the two waveguides in the DC to have different material indices. By doing so, the mode effective indices of both waveguides change equally when the waveguide width fluctuates, therefore maintaining the phase-matching condition.

Fig.2 Effective indices of the fundamental modes of (a) the silicon wire waveguide A and (b) the SWG waveguide B with different equivalent refractive indices \( n_B \) 3.476, 2.525, 2.4, and 2.3, as a function of the waveguide widths \( W_A \) and \( W_B \). Red circles represent the phase-matching condition where the width \( W_A \) is set to 450 nm. [1]

Principles

Fig. 1. Schematics of the polarization splitter and rotator based on an asymmetric directional coupler with a subwavelength grating (SWG) waveguide. (a) Top view, (b) 3D view, and (c) with the SWG waveguide represented as an equivalent wire waveguide with an engineered refractive index $n_B$. [1]

How Does It Work?

- What is a polarization splitter rotator (PSR)?
- How does it work?
- Why do we need sub-wavelength gratings (SWG) in a PSR?
- How to design a PSR with SWG?

Fig. 4. Wavelength dependence of the polarization splitter and rotator, calculated by 3D-FDTD simulations. (a) TE mode insertion loss and TM-TE polarization conversion loss; (b) polarization crosstalks $X_{TE}$ and $X_{TM}$. Waveguide parameters: $W_A = 450 \text{ nm}$, $H = 220 \text{ nm}$, $W_B = 685 \text{ nm}$, $\eta = 0.5$, $D = 100 \text{ nm}$, and $L = 25 \mu\text{m}$.
How Does It Work?

- What is a polarization splitter rotator (PSR)?
- How does it work?
- Why do we need sub-wavelength gratings (SWG) in a PSR?
- How to design a PSR with SWG?

Fig. 5. Dependence of the TM-TM polarization conversion loss (PCL) on the width variation ($\delta W$) of both the wire waveguide $A$ and the SWG waveguide $B$ (a) for $n_B = 3.476, 2.525, 2.4$, and $2.3$ (duty ratios $\eta = 1, 0.6, 0.5$, and $0.4$), as calculated by the EME method; (b) confirmation by the 3D-FDTD method for $\eta = 0.5$. 

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How to design a PSR with SWG?

- Step 1: Choose the geometry of the regular waveguide (WG width, WG height), and calculate the mode effective indices as a function of waveguide width;

- Step 2: Calculate the mode effective index as a function of waveguide width for SWG waveguide with various refractive index, $n_B$, of the SWG waveguide;

- Step 3: Design a SWG waveguide with an equivalent refractive index to $n_B$;

- Step 4: Design a taper to connect the SWG waveguide to the regular waveguide;

- Step 5: 3D FDTD simulation for the whole structure.

Fig. 1. Schematics of the polarization splitter and rotator based on an asymmetric directional coupler with a subwavelength grating (SWG) waveguide. (a) Top view, (b) 3D view, and (c) with the SWG waveguide represented as an equivalent wire waveguide with an engineered refractive index $n_B$. [1]

Step 1: WG geometry and mode effective index

- In Mode Solution, run WG_mode.lsf;
- run sweep_width.lsf;

![Mode distribution of the fundamental TE (TE0) mode in a strip waveguide with 220nm Si thickness and 450 nm width.](image1)

![Effective indices of the fundamental TE & TM mode as a function of waveguide width for a strip waveguide with a silicon thickness of 220nm.](image2)

The effective index of the fundamental TM0 mode for a 450 nm waveguide width is 1.545, indicated by the dash line. It is close to a linear relation between the effective index and the waveguide for the TM mode with a slope of 0.74/um.
Step 2: Choose $n$ for the SWG waveguide

- In this step, we use refractive index to approximate the SWG waveguide;
- We are trying to come up with a SWG waveguide in which the TE0 mode meet the phase match condition with the TM0 of the strip waveguide;
- We also want the slope of the SWG waveguide to be close to that of the TM0 mode in the strip waveguide

In Mode Solution, run sweep_index_width.lsf

Fig. Effective indices of the TE0 mode as a function of waveguide width for SWG waveguides with various refractive index.

From the above graph we can see that the TE0 mode of a SWG waveguide with $n=2.4$, width=685nm meet the phase match condition with the TM0 in the strip waveguide, and they have similar slope, which is the key to make fabrication insensitive design.
Step 3: Design SWG waveguide with required $n$

- Using 3D-FDTD with Bloch boundary conditions to calculate the band structure of SWG waveguide and determine the SWG waveguide period and fill factor;
Step 4: Design a SWG taper

- SWG taper connecting the SWG waveguide to a strip waveguide can be designed following the method shown[1];
- open SWG_taper.fsp

![Diagram of SWG taper design](image)

Fig. 3. Top view of the 3D FDTD simulation layout for a Si wire waveguide with a SWG crossing using bridging segments to reduce taper loss, where $b = 100$ is the bridging segment length and $w_1 = 400$, $w_2 = 100$ nm are the start and end widths of the bridging segments.

Step 5: 3D simulation for the whole structure

- The final step is to simulate the whole structure in 3D FDTD to confirm the final design.
- The gap between the two waveguide was 100nm;
- Coupling length used in the simulation was 25um.

- The reported polarization conversion loss (PCL) was 0.13dB, and To maintain a low polarization conversion loss with PCL better than -1 dB at the central wavelength of 1550 nm, it is required δW≤+/-40nm.
- The PCL of the draft design was 1.2 dB. Extra loss came from the taper design (50 um vs. 3 um), and the highlighted region (50 um S_bend vs. 3 um S_bend).

Fig. Input TE0 in the strip waveguide, power at the output of the through port and cross port.

Fig. Input TM0 in the strip waveguide, power at the output of the through port and cross port.
Experimental results

• Test the same device twice
  • TE input
  • TM input
• Use Y-Branches to combine/split
  • But introduces reflections and Fabry-Perot cavities.
Experimental results – TM input

![Graph showing experimental results for TM input with two lines: TM-TE (Cross) and TM-TM (Through).]
Experimental results – TE input

![Graph showing experimental results with TE-TE (Through) and TE-TE (Cross) comparison.](image-url)
What can be improved?

- The polarization conversion loss need to be reduced
  - better SWG taper, S_bend with larger radius;
- The bandwidth need to be enlarged
  - overlay with another set of SWG?
Tutorial on SWG Waveguide analysis using Effective Medium Theory using Lumerical MODE’s eigensolver

Lukas Chrostowski
James Pond
SWG Waveguide – Approximation using Effective Medium Theory

- Replace 3D periodic waveguide structure with an equivalent 2D uniform waveguide
- Volumetric weighted average of the sub-wavelength materials’ index of refractions

SWG Waveguide analysis using Effective Medium Theory using Lumerical MODE’s eigensolver

- Geometry:
  - SiO2 BOX 3 µm
  - SiO2 cladding 2 µm
  - waveguide 220 thick, 500 nm wide
    - $n = 3.47$ (solid silicon), or
    - $n = 2.45$ (SWG 50% Si / SiO2)
- 2D Eigensolver
  - 6 µm span in both dimensions
- Run simulations
- Plot settings for mode profile:
  - Energy density
  - Log scale
  - “Plot in New Window”
  - Settings | Set Color Bar Limits
- Min = -10
- Max = -20
- Frequency analysis
  - Track selected mode
  - start/stop 1.55 µm
  - # points = 1
  - # test modes = 1
  - detailed dispersion calculation
  - run “Frequency Sweep”
  - look in “Frequency Plot” | group index
- Repeat calculations twice:
  - solid silicon
  - SWG EMT
Oxide Geometry

\[ \begin{align*}
X &= \text{waveguide length} \\
Y &= \text{oxide width} \\
Z &= \text{oxide thickness}
\end{align*} \]
Waveguide Geometry

X = waveguide length

Y = waveguide width

Z = waveguide thickness

Solid waveguide

SWG waveguide
Simulation – Eigenmode solver

- Eigenmode Solver
- Variational FDTD Solver
- EME Solver
- Mesh

[Image of software interface with options for name, background index, solver type, and mesh settings]

- Name: FDE
- Background index: 1
- Solver type: 2D X normal
Run

- **frequency (THz)**: 193.414
- **wavelength (μm)**: 1.55
- **number of trial modes**: 4
- **search**: near n
- **use max index**: checked
  - **n**: 3.47
- **bent waveguide**: unchecked
  - **bend radius (μm)**
  - **bend orientation (degrees)**

[Button] Calculate Modes
Run – Eigensolver Analysis
Run – Eigensolver Analysis
Frequency Analysis tab

- Set Calculation Parameters

- Track selected mode
- Start frequency (THz): 193.414
- Stop frequency (THz): 193.414
- Start wavelength (μm): 1.55
- Stop wavelength (μm): 1.55
- Number of points: 1
- Number of test modes: 1
- Effective index

- Detailed dispersion calculation
- Store mode profiles while tracking
  - Bent waveguide

- Bend radius (μm)
- Bend orientation (degrees)

- Restore Last Settings
- Frequency Sweep

- Modal analysis
- Frequency analysis
- Overlap analysis

- Mode plot
  - Frequency plot
  - Group index
  - Linear scale
  - Log scale
  - Frequency
  - Wavelength

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Results

• $n_{\text{eff}} = 2.44$
• $n_g = 4.04$
  • Note: we neglected material dispersion
    ($n_g = 4.18$ with Si dispersion)
• $n_{\text{eff}} = 1.58$
• $n_g = 2.21$
  • Note: we neglected material dispersion; and approx. using EMT
Conclusions about Effective Medium Theory approach:

- This technique works well only if you are use that the wavelength is very large compared to the structure’s period. You need to be sure you are far away from the Bragg resonance.

- Good for estimating things like:
  - effective index
  - mode size
  - mode overlap with an optical fibre
  - estimating evanescent sensor’s sensitivity
Tutorial on SWG Waveguide analysis using 3D-FDTD with Bloch boundary conditions and dispersion diagrams

James Pond
Lukas Chrostowski
SWG Waveguide – Analysis using 3D FDTD and Bloch Boundaries

- 3D FDTD (time domain) simulations of a unit cell
- Band diagram: sweep simulations for different wave vectors (k) and find the frequency supported (f)
- Calculate $n_{\text{eff}}$, $n_g$.

- Top-view of the unit cell:

```
3.47 1.44 3.47 1.44 1.44 3.47 1.44 3.47 1.44 3.47 1.44 3.47 1.44
1.44
```
Bandstructure can be simulated with FDTD

Bandgap at $k = 0.5$
We are operating in the SW regime

In this region, the SWG behaves like a waveguide.

What we need is to get the effective index and group index.
Correct neff and ng

Introduce a pitch (for example $a=300\text{nm}$)

Beta = $k_0*\text{neff} = 2*pi/\lambda\times1.452$

Expressed in units of $2*pi/a$ we have

Beta = $1.452*a/\lambda = 1.452*300\text{nm}/1550\text{nm}=0.28$

- As long as beta $< 0.5$ we are operating below the bandgap

Perform a frequency sweep from Beta = 0.28 to 0.38

We must be cautious as we are close to cutoff!

Simulation region must be quite large

- Fine mesh only required near waveguide
Configure the SWG waveguide

Duty cycle, pitch (period), width 1, width 2

![Diagram showing waveguide configuration parameters]
Set frequency range to study

Configure the y-axis (frequency) range for band diagram:

range = 150 to 240 THz
Setup bandstructure sweep
Source settings

- **Override global source settings**
  - Set frequency/wavelength
  - Set time domain

**Set frequency/wavelength**
- **Frequency**
  - Min/max
  - Frequency start (THz): 150
  - Frequency stop (THz): 250

**Set time domain**
- **Source type**: Broadband source
- **Frequency (THz)**: 200
- **Pulsed length (fs)**: 7.95229
- **Offset (fs)**: 22.5473
- **Bandwidth (THz)**: 100

**Advanced options**
- Eliminate discontinuities
- Optimize for short pulse
Run bandstructure sweep
Analyze results

Run script file analyze_bandstructure.lsf
It will create the following results...
Image of bandstructure, log scale
Plot of $w$ vs $\beta$

The extracted 5 points of data are fit to a $4^{th}$ order polynomial.

The fitted data is resampled at high resolution.
Plot of $n_{\text{eff}}$ and $n_g$ vs lambda

• Effective Index, $n_{\text{eff}}$.
  - ~ 1.65

• Group index, $n_g$.
  - ~ 2.7

\[ n_{\text{eff}} = \frac{c}{v_{\text{phase}}} , \quad v_{\text{phase}} = \frac{\omega}{\beta} \]

\[ n_g = \frac{c}{v_{\text{group}}} , \quad v_{\text{group}} = \frac{d\omega}{d\beta} \]
Plot of wavelength vs k
Exercises

Repeat with

- Finer FDTD mesh
  - Set grid accuracy slider to 2 or 3
  - Use the mesh override for waveguide
    - Reduce mesh size around waveguide by factor of 2 (dy=dz=10nm)
- Increase simulation time from 500fs to 1000fs
- Increase number of sweep point of bandstructure to 10
- Include the Silicon substrate below the 3 µm BOX

- Make sure that your results are accurate
  - **Perform convergence tests.**

Extract the 3D Bloch mode profile at 1550nm

SWG Waveguide – Analysis using 3D FDTD and Bloch Boundaries

- time – improves the spectral resolution of the dispersion diagram. Longer times needed to resolve the two solutions near the bandgap. For SWG waveguides, we don’t need high resolution, hence we can do a fast simulation (e.g., 500 fs).
SWG Waveguide – Exercises

• Create a map of $n_{\text{eff}}$, $n_g$, versus parameters of interest:
  • duty cycle
  • period
  • width 1
  • width 2

• e.g., find $n_{\text{eff}}$ vs. width2, and use it to develop an SWG edge coupler.
**Lightline, cut-off**

- When you have an oxide cladding (below and above), the SWG core index is always greater than the cladding. So there is no cut-off.
- If you have air, or water, the SWG index can be lower than the BOX lower cladding.
- The lightline:
  - The waveguide is cutoff for all points of the curve above the lightline because light simply leaks into the substrate
Lightline, cut-off

- Oxide
- Air cladding (or water) for sensors
- more challenging to design
Lightline, cut-off

- Oxide

SWG in Oxide

SWG in Air
FDTD for Band Structures

• One advantage of using FDTD for bandstructure calculations is that you can easily calculate the bandstructure for dispersive media.
  • Dispersion for both:
    • Silicon dispersion, and the waveguide mode group index
    • Whether or not you are cutoff because the substrate index is also changing with wavelength (i.e., the lightline is not perfectly straight).
  • You can tell you are cutoff just by watching the autoshutoff value of the FDTD simulation (approaches 0 when cut-off).
Configure the materials
Results – dispersion

• For pitch = 0.3, duty = 0.5, w1 = 0.5, w2 = 0
  • with dispersive silicon & oxide materials
    Mesh accuracy 2, disabled mesh override
    • neff at 1550 = 1.64695
    • ng at 1550 = 2.6879

• with dispersive silicon & oxide materials
  Mesh accuracy 3, enabled mesh override
  • neff at 1550 = 1.64922
  • ng at 1550 = 2.70196

• with constant index materials
  Mesh accuracy 3, enabled mesh override
  • neff at 1550 = 1.6493
  • ng at 1550 = 2.64047 (3-5% error)

• In a strip waveguide, neglecting material dispersion results in larger group index errors.