Si-EPIC Workshop:  
Silicon Nanophotonics Fabrication  
– Fibre Grating Couplers

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Outline

- Coupling light to chips using Fibre Grating Couplers (FGC, or GC).
- Grating coupler physics
- Tutorial on modelling
Grating Couplers

- Are used to couple light in/out of the chip via the top
  - similar to electrical “pads”
  - typically 10x10 um
  - can have hundreds per chip

Luxtera Inc.
Grating Fiber Coupler

single-mode fibre,

adiabatic taper (>150µm)

to integrated circuit

10µm wide waveguide

grating

TE
1-D grating coupler

Experimental results ($\lambda=630\text{nm}, \text{depth}=70\text{nm}$, TE pol.)

- 31% efficiency (5.1 dB coupling loss)
- 40 nm 1 dB bandwidth

Also acts as a broadband filter
2-D grating + polarization splitter

Fiber-to-waveguide interface for polarization independent photonic integrated circuit

- 2-D grating, 2 waveguides
- Couples each fiber polarization in its own waveguide
- In the waveguides the polarization is the same (TE)
- Patented
Polarisation Diversity Circuit

- on-chip components are polarisation dependent
- fiber-to-fiber transmission is polarisation independent

single-mode fiber

x-polarization

2-D grating

split polarisations

identical circuits

patented

2-D grating

combine polarisations

light in

y x

light out

x y z
Measurement
Semi-Automated Optical Probe Station – 2 fibres

- All-band Agilent tunable laser (180 nm span, 1460-1640 nm)
- 1220 nm tunable laser

Fig. 1: Sketch of the automated optical probe station mechanics.
Automated Probe Station – Fibre Array
Automated Probe Station – Fibre Array

- 127 µm fibre spacing
- 2 separate devices
FDTD Tutorial – Grating Couplers

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Grating Coupler – Operation

- Case 1 – Optical wavelength inside the grating matches its period,
  \[ \frac{\lambda_0}{n_{\text{eff}}} = \Lambda \]

- Vertical output (1st diffraction order), plus back-reflection (from 2nd diffraction order)

\[ K = \frac{2\pi}{\Lambda} \]

\[ \beta = n_{\text{eff}}k_0 = \frac{2\pi n_{\text{eff}}}{\lambda_0} \]
Grating Coupler – Operation – Detuned

- Case 2 – Optical wavelength is smaller than the grating period, \( \frac{\lambda_0}{n_{\text{eff}}} < \Lambda \)

\[ K = \frac{2\pi}{\Lambda} \]

- Vertical output at an angle, no 2\textsuperscript{nd} order back-reflection

\[ \beta = n_{\text{eff}}k_0 = \frac{2\pi n_{\text{eff}}}{\lambda_0} \]
Grating Coupler – Bragg Condition

\[ \theta = \sin^{-1} \left( \frac{k_x}{k_0} \right) \]

\[ n_1 = 1 \]

\[ k_0 = \frac{2\pi}{\lambda_0} \]

\[ k_x = \beta - mK \]

\[ \beta = n_{\text{eff}} k_0 = \frac{2\pi n_{\text{eff}}}{\lambda_0} \]

\[ 2K = 2 \frac{2\pi}{\Lambda} \]

\[ n_2 = n_{SiO_2} \]

[Diagram showing grating coupler with equations and grating conditions]
Gratings – Bragg condition

- Bragg condition – Grating’s scattering modifies the light’s wave-vector to be (in the direction of propagation, $x$):

$$k_x = \beta - mK = \beta - m\frac{2\pi}{\Lambda}$$

- Slab’s effective index in the region of the grating:
  - for 220 nm thick ~ 2.875
  - for 150 nm thick ~ 2.574

- Duty cycle is 50%, thus estimate average effective index to be 2.724

$$k_x = \beta - K = \frac{2\pi \cdot 2.724}{1.55 \mu m} - \frac{2\pi}{0.63 \mu m} = 11.04 - 9.97 = 1.069 \mu m^{-1}$$
Gratings – Bragg condition

• We know the free-space wave-vector:

\[ k_0 = \frac{2\pi}{\lambda_0} = 4.05 \mu m^{-1} \]

• Estimated diffracted angle is:

\[ \theta = \sin^{-1} \left( \frac{k_x}{k_0} \right) = \sin^{-1} \left( \frac{1.069}{4.05} \right) = 15.3^\circ \]
• Detuned second-order gratings: “A first generation of gratings was etched 40 to 50nm deep, with a 610 nm pitch and uniform 50% fill factor. These have a coupling efficiency of about 20% and a 60 nm 3 dB bandwidth [16] without index matching material between grating and fibre. The second generation of couplers used has a 70 nm etch depth, a 630 nm pitch and a higher coupling efficiency of up to 35% when cladded with oxide, with an almost 60 nm wide 3 dB bandwidth.” [Pieter Dumon thesis]
3.1 Introduction

In other words, the bandwidth will depend on the coupling strength of the grating.

3.1.3 Definitions

In this section, we will define the grating coupler problem and some terms used in the rest of this work. This section is needed because some terms have different meanings in different articles in the literature. The problem is sketched in Figure 3.3. The waveguide has a core $n = n_g$ and a top $n = n_t$ and bottom $n = n_b$ cladding. In general, there can be additional layers, such as a high index substrate, under the bottom cladding. The grating has an etch depth $ed$. The grating period is $\Lambda$ and the filling factor is $ff = \frac{w}{\Lambda}$. The filling factor is also called duty cycle. The axes and the angle $\theta$ are defined as in Figure 3.3.

When considering the coupler as an output coupler, the power in the waveguide will be exponentially decaying due to the presence of the grating (if there is no coupling between the forward and backward propagating guided mode):

$$P_{wg}(z) = P_{wg}(z=0) \exp(-2\gamma z)$$

$\gamma$ is the coupling strength or leakage factor of the grating. The inverse of the coupling strength is the coupling length $L_c = \frac{(2\gamma)^{-1}}{2\gamma}$.

When $\gamma$ is small, we talk about a weak grating, when $\gamma$ is large, the grating is strong. Equation 3.3 is only exact for weak detuned gratings. The

Source: Dirk Taillaert, PhD Thesis, IMEC
4.2.1 Vertical coupling

The case of vertical coupling ($\theta = 0^\circ$) is very interesting from a practical point of view. Vertical coupling can be achieved when the grating period $\Lambda$ equals the wavelength $\lambda$ divided by the refractive index. For a very shallow grating, this index is the effective index of the waveguide mode. As mentioned in chapter 3, this grating is called a second order grating. But for the grating coupler, the first order diffraction is used. The second order diffraction is reflecting back into the waveguide. To avoid any confusion, we will use the term coupler grating instead of second order grating in the rest of this work.

4.2.2 Almost vertical coupling

To avoid the reflection at the grating, we have to choose a working point away from the second order reflection peak. Either a shorter or longer wavelength can be chosen. As a result, light is coupled out not exactly vertical, but at a small angle $\theta$ with respect to the vertical direction. This grating is also called a detuned grating. Instead of changing the wavelength, the grating period can be changed. The grating can be negatively or positively detuned (figure 4.5). In a negatively detuned grating, the grating period is smaller ($K$ is larger) or the wavelength is longer ($\beta$ is smaller) compared to the case of vertical coupling. In a
Figure 4.8: Calculated coupling efficiency to fibre for an optimized uniform grating and near vertical coupling. \( \Lambda=630 \text{ nm}, \text{ ed}=70 \text{ nm}, \text{ ff}=0.5, \text{ N}=20, \)
Experimental Alignment Tolerances

Source: Dirk Taillaert, PhD Thesis, IMEC

Figure 6.9: Experimental alignment tolerances.
Resources - Grating Couplers

- Book chapter:
  - David J. Lockwood and Lorenzo Pavesi, "Silicon Photonics II – Components and Integration," 2011, Online PDF
    - Chapter 3 Interfacing Silicon Nanophotonic Integrated Circuits and Single-Mode Optical Fibers with Diffraction Gratings (IMEC)
  - Chrostowski and Hochberg, Silicon Photonics Design, Ch. “Optical I/O”

- Thesis:
  - Dirk Taillaert, PhD Thesis, IMEC

- Journal papers:
Grating Coupler Modelling

• Approach:
  
  1) Waveguide to air – 2D FDTD
     • Start with mode-source in the waveguide, measure output power in free-space
     • far-field, check angle
  
  2) Air to waveguide – 2D FDTD
     • Start from optical fibre – Gaussian mode – incident on grating. Measure power in the waveguide
     • use previous angle, vary position
     • Fibre mode – MFD 10.5
  
  3) optimize for 1550 nm
  
  4) validate design – 3D FDTD
IMEC Coupler

- Oxide 2 µm
- Cladding 2 µm – check?
- Silicon 0.22 µm
- Period 0.63 µm
- Fill 0.32 µm – (each tooth)
- Etch 70 nm (150 nm remaining)
- Oxide index 1.444
- Si index: 3.47 constant, vs. Palik data dispersive?
1) Output Grating Coupler simulation

- Launch a mode in the slab
- Monitor the output far-field pattern vs. angle (for a specific wavelength)
3D FDTD – Fibre Grating Coupler object
Setup

User properties

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>index_coating</td>
<td>Number</td>
<td>1.444</td>
</tr>
<tr>
<td>index_grating</td>
<td>Number</td>
<td>1.4</td>
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<tr>
<td>mat_coating</td>
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<td>h_grating</td>
<td>Length</td>
<td>0.22</td>
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<tr>
<td>fill</td>
<td>Length</td>
<td>0.32</td>
</tr>
<tr>
<td>period</td>
<td>Length</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Setup Script

```plaintext
49 Vc[9,1:2]=[fill/2-a, h_grating];
50 Vc[10,1:2]=[-fill/2+a, h_grating];
51 Vc[11,1:2]=[-fill/2,0];
52 Vc[12,1:2]=[-period/2,0];
53 for(i=-n_periods:0){
54   #add grating
55   addpoly;
56   set("name","post");
57   set("x",period*i);
58   set("y",0);
59   set("vertices",V);
60   set("material",mat_grating);
61   if(get("material")=='Object defined di {
62     set("index",index_grating); 
63   }
64   #add coating
65   if (add_coating) {
66     addpoly;
67     set("name", "coating");
```
Far field projection

- Peak angle is between 10-20° (wavelength dependant)
Total output power

- 1545 nm peak wavelength
- Power out 56%
e.g.,
2) Input Grating Coupler simulation

- Gaussian beam input (waist diameter 10.5 µm)
- Measure transmission spectrum into slab waveguide
- Sweeps: angle, position
Setup

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<tr>
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<td>movie1</td>
<td>MovieMonitor</td>
</tr>
<tr>
<td>coupled</td>
<td>DFTMonitor</td>
</tr>
<tr>
<td>source1</td>
<td>GaussianSource</td>
</tr>
<tr>
<td>backwards</td>
<td>DFTMonitor</td>
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<tr>
<td>above</td>
<td>DFTMonitor</td>
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<tr>
<td>below</td>
<td>DFTMonitor</td>
</tr>
<tr>
<td>2D</td>
<td>DFTMonitor</td>
</tr>
<tr>
<td>FDTD</td>
<td>FDTD</td>
</tr>
<tr>
<td>cladding</td>
<td>Rectangle</td>
</tr>
<tr>
<td>waveguide</td>
<td>Rectangle</td>
</tr>
<tr>
<td>SiO2</td>
<td>Rectangle</td>
</tr>
<tr>
<td>substrate</td>
<td>Rectangle</td>
</tr>
<tr>
<td>waveguide</td>
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</tr>
<tr>
<td>waveguide</td>
<td>Rectangle</td>
</tr>
<tr>
<td>GC</td>
<td>AnalysisGroup</td>
</tr>
</tbody>
</table>

Mesh type: auto non-uniform

Mesh accuracy:
- mesh accuracy: 2

Low accuracy and low memory requirements for fastest simulations.

Mesh refinement:
- mesh refinement: conformal

How do I choose?
Setup

FDTD 7:

FDTD 8:
Setup – Movie

- Move the movie monitor into simulation region.
- Setup script is automatically executed before simulation.

```plaintext
# update movie monitor to have same resolution as mesh.
1. select("FDTD"); m = get("mesh cells x");
2. select("movie1"); set("horizontal resolution", m);
3. 
```
Run

- Run simulation
- Run analysis script
  - “runanalysis;”
# Transmission at 1550 nm

\[ \lambda = \frac{c}{\text{getdata("coupled","f")}}; \]

\[ \text{Tspectrum} = \text{transmission("coupled")}; \]

\[ T_{1550} = \text{interp(Tspectrum,}\lambda,1550e-9); \]

# Spectrum

\[
\begin{align*}
\text{plot ( } \lambda, \text{Tspectrum,}\"\text{Wavelength},\"\text{Power Coupled}, \"\text{Grating coupler efficiency}\text{);}
\text{plot ( } \lambda, 10\times\log_{10}(\abs{\text{Tspectrum}}),\"\text{Wavelength},\"\text{Power Coupled}, \"\text{Grating coupler efficiency}\text{);}
\end{align*}
\]

setplot("x min", 1.5e-6); setplot("x max", 1.6e-6);
setplot("y min", -15); setplot("y max", 0);
setplot("y label", "Coupling, dB");

\[ \text{Tspectrum1} = \text{transmission("below")}; \]

\[ \text{plot ( } \lambda, 10\times\log_{10}(\abs{\text{Tspectrum1}}),\"\text{Wavelength},\"\text{Power Coupled}, \"\text{GC - into substrate}\text{);} \]

setplot("x min", 1.5e-6); setplot("x max", 1.6e-6);
setplot("y min", min(10\times\log_{10}(\abs{\text{Tspectrum1}}))-1); setplot("y max", 0);
setplot("y label", "dB");

\[ \text{Tspectrum1} = \text{transmission("above")}; \]

\[ \text{plot ( } \lambda, 10\times\log_{10}(\abs{\text{Tspectrum1}}),\"\text{Wavelength},\"\text{Power Coupled}, \"\text{GC - reflection}\text{);} \]

setplot("x min", 1.5e-6); setplot("x max", 1.6e-6);
setplot("y min", min(10\times\log_{10}(\abs{\text{Tspectrum1}}))-1); setplot("y max", 0);
setplot("y label", "dB");

\[ \text{Tspectrum1} = \text{transmission("backwards")}; \]

\[ \text{plot ( } \lambda, 10\times\log_{10}(\abs{\text{Tspectrum1}}),\"\text{Wavelength},\"\text{Power Coupled}, \"\text{GC - backwards, waveguide}\text{);} \]

setplot("x min", 1.5e-6); setplot("x max", 1.6e-6);
setplot("y min", min(10\times\log_{10}(\abs{\text{Tspectrum1}}))-1); setplot("y max", 0);
setplot("y label", "dB");

Simulation Results

Grating coupler efficiency

Power Coupled

Wavelength

Coupling, dB

Wavelength

Power Coupled

Wavelength
Where is the coupling loss from?
Optimization

- Optimize
  - the gaussian beam angle
  - the position of the beam
- Done either with optimization or with sweep
Sweep – Angle

Parameters:
- **Name**: sweep, angle
- **Ranges**: Number of points: 9

<table>
<thead>
<tr>
<th>Name</th>
<th>Parameter</th>
<th>Type</th>
<th>Start</th>
<th>Stop</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td>position</td>
<td>::model::source1::x</td>
<td>Length</td>
<td>10</td>
<td>10</td>
<td>microns</td>
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<tr>
<td>angle</td>
<td>::model::source1::angle</td>
<td>Number</td>
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<td>20</td>
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Results:

<table>
<thead>
<tr>
<th>Name</th>
<th>Result</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>power_1550</td>
<td>::model::coupled::Px</td>
<td></td>
</tr>
<tr>
<td>Tspectrum</td>
<td>::model::Tspectrum</td>
<td></td>
</tr>
<tr>
<td>T_1550</td>
<td>::model::T_1550</td>
<td></td>
</tr>
</tbody>
</table>

Optimization:
- sweep, position

Run button

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• After it is done, run the script to analyze all the data.

```matlab
# plot the results from an FDTD sweep on position.

angles = getsweepdata("sweep, angle", "angle");
lambda = c/getdata("coupled", "f");
NUM = length(angles);

T_data = getsweepdata("sweep, angle", "Tspectrum");
plot (lambda, T_data, "Wavelength", "Power Coupled", "Gaussian angles: "+num2str(angles(1)) + " to " + num2str(angles(NUM)));
legend (num2str(angles(1)));
setplot("y label", "Coupling");

plot (lambda, 10*log10(abs(T_data)), "Wavelength", "Power Coupled", "Gaussian angles: "+num2str(angles(1)) + " to " + num2str(angles(NUM)));
legend (num2str(angles(1)));
setplot("y min", -15);

setplot("y max", 0);
setplot("y label", "Coupling, dB");

T_1550 = getsweepdata("sweep, angle", "T_1550");
plot (angles, 10*log10(T_1550), "Angle", "Power @ 1550");
setplot("y label", "Coupling, dB");
setplot("x min", 1.5e-6);

matlabsave("GC_in_sweep,angle", T_data, angles, lambda);

```
Gaussian input – Angle

- Mesh accuracy = 2 (auto mesh, conformal)
- About 5-10 nm per degree tuning
Gaussian Input – Angle

- Mesh accuracy = 4 (auto mesh, conformal)
- 

![Graph showing Gaussian angles from 12 to 16 degrees with coupling dB on the y-axis and wavelength on the x-axis.](image)
Sweep – Position

Name: sweep, position

Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Parameter</th>
<th>Type</th>
<th>Start</th>
<th>Stop</th>
<th>Units</th>
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<tr>
<td>angle</td>
<td>::model::source1::angle</td>
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<td>16</td>
<td>16</td>
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<tr>
<td>position</td>
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<td>18</td>
<td>microns</td>
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Results

<table>
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<tr>
<th>Name</th>
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<tr>
<td>T_1550</td>
<td>::model::T_1550</td>
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<tr>
<td>T_spectrum</td>
<td>::model::T_spectrum</td>
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</tr>
</tbody>
</table>
Gaussian Input – Position

![Graphs showing Gaussian input positions]

- Coupling, dB vs Wavelength
- Coupling, dB vs Position
Sweep – Buried Oxide Thickness

- Sweep the oxide thickness
- Achieved by overlapping the oxide on top of the silicon substrate, and changing the y-min of the oxide.

![Graph showing the sweep of oxide thickness](image_url)
Oxide thickness – 2 µm

- Oscillations as a function of thickness are a result of constructive/destructive interference from the oxide layer.
Optimized

- 16° injection angle, optimized laterally: 10 µm
- peak is 1.547 nm
- -3.45 dB coupling efficiency

Grating coupler efficiency with 10 nm mesh-x

Grating coupler efficiency with auto-mesh, accuracy=4
Sweep – Mesh accuracy – Convergence test

**Parameters**

- **Name**: convergence
- **Ranges**: Number of points: 8
- **Parameters**:
  - mesh_accuracy
  - ::model::FDTD::mesh accuracy
  - Type: Number
  - Start: 1
  - Stop: 8

**Results**

- **Name**
  - T_1550
  - Tspectrum
  - T_max
  - lambda_max

- **Result**
  - ::model::T_1550
  - ::model::Tspectrum
  - ::model::T_max
  - ::model::lambda_max
Convergence Test

- Without Mesh Override
Convergence Test

- Using Mesh Override

- Conclusion: Slightly faster convergence
Sensitivity to “Accuracy”

- Using mesh overrides to ensure correctly-periodic mesh
- Error is < 10 nm, ~0.01 coupling error
Manual mesh

• Mesh override: 10 nm grid in the waveguide & grating
3D FDTD – Grating Coupler
3D FDTD – Grating Coupler

- Layout imported from GDS
- FDTD simulation region includes substrate and cladding:
  - \(-2.4 \, \mu m < z < 3.0 \, \mu m\)
- Gaussian beam input, above the oxide
  - Beam centre offset 5 \, \mu m from 1\textsuperscript{st} grating tooth.
- Power monitors:
  - in the taper (faster simulation time)
  - in the waveguide (include taper in the simulation, 2X longer)
GDS – Grating coupler IMEC
GDS Import

- GDS: TE_Curved_Grating_coupler_right
- Layer 52, Silicon, edit to be 220 nm
- Layer 75, Silicon, edit to be 150 nm
Mesh accuracy = 1
(several minutes)

Mesh accuracy = 2
(several tens minutes)
3D FDTD – Grating Coupler

- Core i7 ~$1000 linux

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Time</th>
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<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>00:15:40</td>
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<tr>
<td>3</td>
<td>00:47:00</td>
</tr>
<tr>
<td><strong>4</strong></td>
<td><strong>01:56:00</strong></td>
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<tr>
<td>5</td>
<td>03:46:00</td>
</tr>
<tr>
<td>6</td>
<td>07:27:00</td>
</tr>
</tbody>
</table>

Increasing accuracy:

```bash
> plot (c/linspace(c/1600,c/1500,100), pinch(getsweepdata("sweep, accuracy","coupled2"))),
```