SiEPIC – Silicon Photonics – Fabrication via Electron Beam Lithography at UW – Example Devices and Circuits

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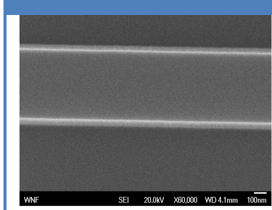
Example devices and circuits

A list of publications via the University of Washington EBeam lithography is available at the following link: https://ebeam.mff.uw.edu/ebeamweb/news/news/pubs.html
The mask layout (GDS) is available for the examples below.

Strip Waveguides – 400 nm



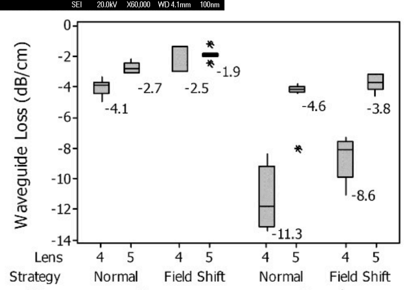


FIG. 10. Box plot of waveguide loss using 4th and 5th lens writing modes, normal and field shift writing, for linear and curved waveguides.

Description: Fully-etched strip waveguides. Typical width of 400 nm.

Performance:

- SiEPIC & UBC researchers typically use 500 nm for TE and TM.
- In paper, 400 nm was used. A variety of write methods were explored which have trade-off of write-time vs. loss.

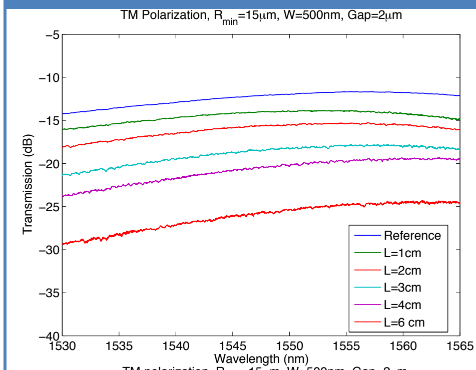
Design tools & methodology:

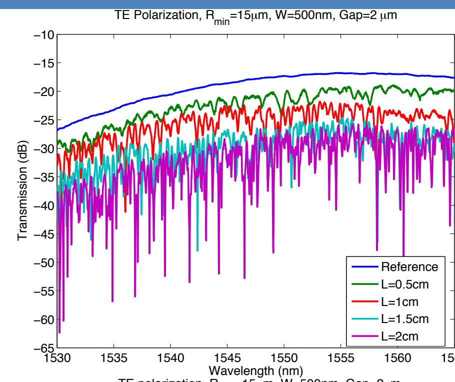
- Cut-back method for determining loss

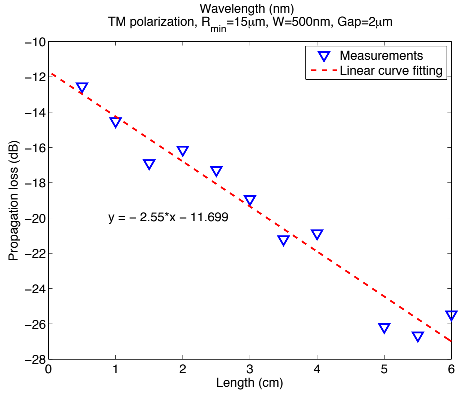
Reference: R. Bojko, et al., JVSTB, 2011, http://dx.doi.org/10.1116/1.3653266

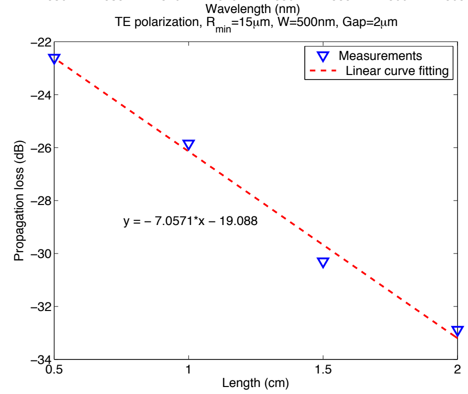
Files: Waveguides/J. Vac. Sci. Technol. B 2011 Bojko.pdf

Strip Waveguides – Spiral – 500 nm, TE and TM









Description:

- Fully-etched strip waveguides. Width of 500 nm.
- SiEPIC & UBC researchers typically use 500 nm for TE and TM.
- SiEPIC runs use 4th Lens, 2-pass field shift writing, with default 6 nm shot pitch, 8 nA beam current.

Performance:

- TE – 7 dB/cm
- TM – 2.6 dB/cm
- September 2014.

Focusing sub-wavelength grating couplers

Summary table

Coupler type	Publication	Details
Uniform	Yun Wang, et al., "Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonic circuits", Optics Express, 08/2014	• Fully-etched fiber-waveguide grating couplers with sub-wavelength gratings. • TE – 4.1 dB loss, 30.6 nm 1-dB bandwidth, XXº incident angle • TM – 3.7 dB loss, 47.5 nm 1-dB bandwidth, XXº incident angle • Repeatable results
Apodized	Yun Wang, et al., "Apodized focusing fully etched sub-wavelength grating couplers". Photonics Journal, 2015	• Reduced insertion loss. • TE – 3.2 dB loss, 36 nm 1-dB bandwidth, -24 dB back reflections, -31º incident angle • TM – 3.3 dB loss, 37 nm 1-dB bandwidth, -21 dB back reflections, 10º incident angle • Less repeatable results
Broadband	Yun Wang, et al., "Design of Broadband Sub-Wavelength Grating Couplers with Low Back Reflection", Optics Letters, 9/2015	• Increased bandwidth, but slightly lower coupling efficiency • TE – X dB loss, X nm 1-dB bandwidth, XXº incident angle • TM – X dB loss, X nm 1-dB bandwidth, XXº incident angle • Small Fabry-Perot ripples 0.08 dB due to the low reflections (-23 dB) • Repeatable results

Uniform

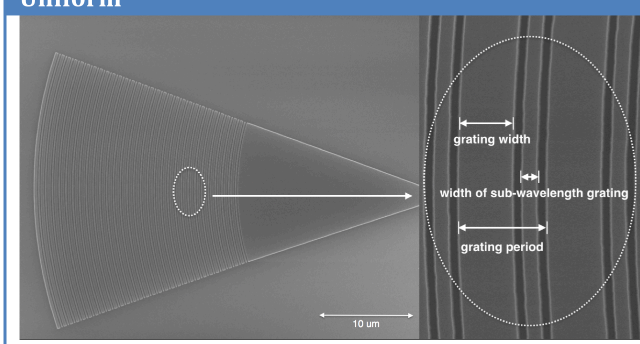


Fig.1 SEM of op view of the sub-wavelength grating coupler

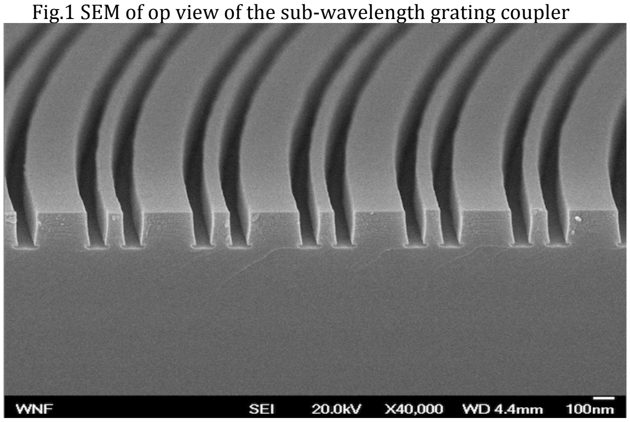


Fig.2 SEM of side view of the sub-wavelength grating coupler

Description: Fully-etched fiber-waveguide grating couplers with sub-wavelength gratings showing high coupling efficiency as well as low back reflections for both transverse electric (TE) and transverse magnetic (TM) modes. EBeam fabrication cost is reduced by ~2-3X when eliminating the shallow etch.

Incremental Fabrication Cost: $0.02 each on Layer 1.

Performance:

- TE – 4.1 dB loss, 30.6 nm 1-dB bandwidth
- TM – 3.7 dB loss, 47.5 nm 1-dB bandwidth

Design tools & methodology:

- 2D & 3D FDTD (Lumerical Solutions)
- Scripted mask layout (Mentor Graphics Pyxis)

Number of fabrication iterations

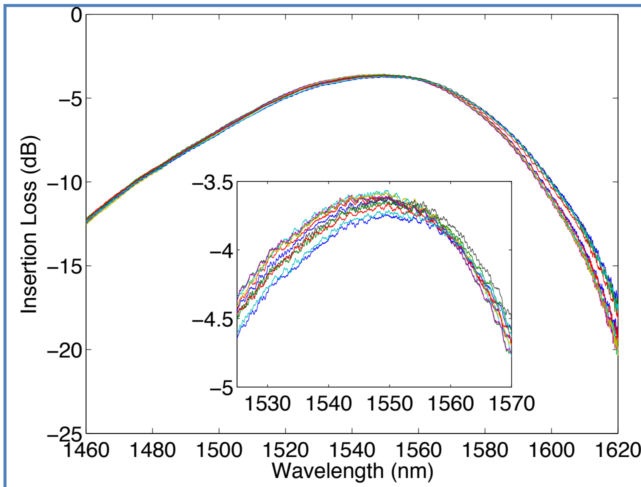


Fig.3 Measured spectra of 11 identical sub-wavelength grating couplers

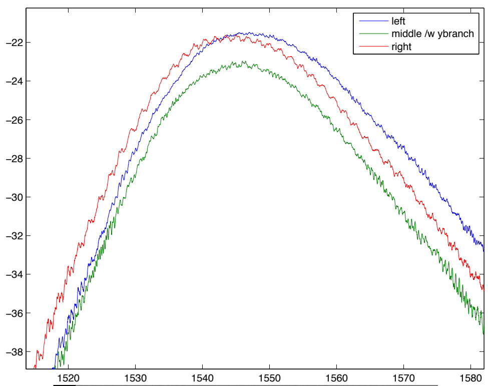
(separate runs) to get to published results: 6

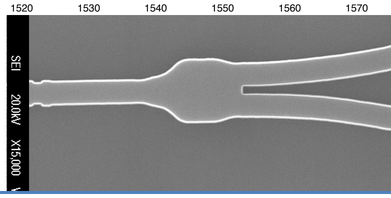
Number of variations fabricated: 100+

Reference: Yun Wang, et al., "Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonic circuits", Optics Express, vol. 22, no. 17: OSA, pp. 20652-20662, 08/2014, http://dx.doi.org/10.1364/OE.22.020652

Files:
SubGC/ TE1550_SubGC_neg31_oxide.gds
TM1550_SubGC_10degree_oxide.gds
2014_IPC_SubGC.pdf

Y Branch – 3 dB splitter





Description: 50/50% splitter. Useful for splitting light, Mach-Zehner Interferometers, etc. The layout parameters for the device were taken from the journal paper below, and implemented in EBeam lithography.

Performance:

- Excess loss < 1 dB.

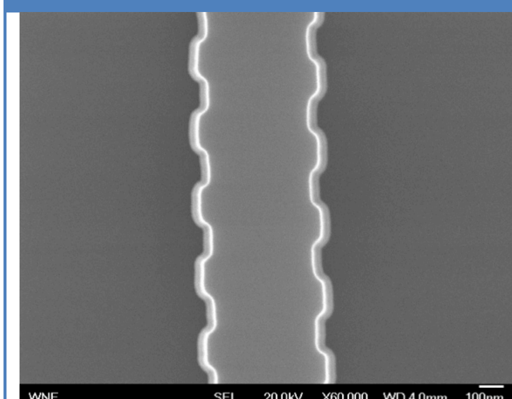
Design tools & methodology:

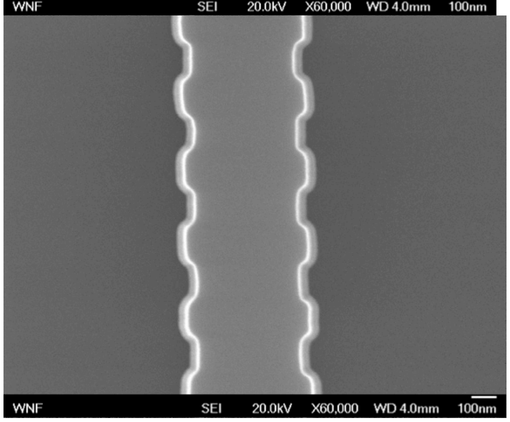
- FDTD (Lumerical FDTD Solutions)

Reference: Y Zhang, et al., "A compact and low loss Y-junction for submicron silicon waveguide", Opt. Express, 21/1, pp. 1310-1316 (2013) http://dx.doi.org/10.1364/OE.21.001310

Files: YBranch/YBranch_Compact.GDS

Waveguide Bragg grating





Description: Uniform waveguide Bragg gratings, 1st order, TE polarization. This design provides a simple method of varying the grating strength (kappa). This allows for apodization.

Performance:

- Kappa ranging from ~0 to 140,000 m^{-1}, for a fixed ΔW = 50 nm, with misalignment technique
- Measured with air cladding; expect reduced kappa with oxide cladding.

Design tools & methodology:

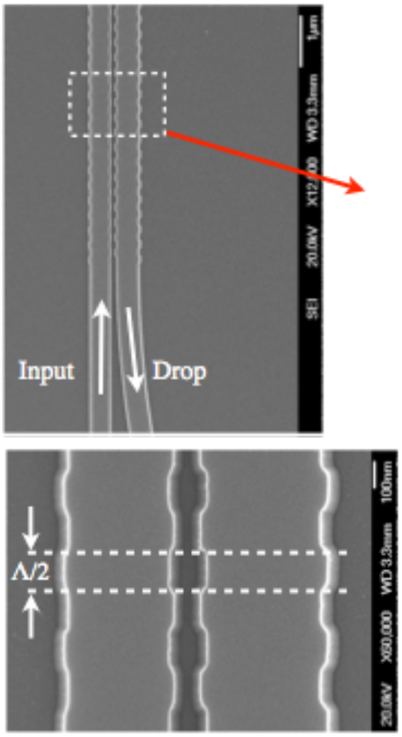
- Hand-drawn layout (kLayout)
- Post-fabrication modeling using Eigenmode (Lumerical MODE Solutions) 3D-FDTD (Lumerical FDTD Solutions)

Number of fabrication iterations (separate runs) to get to published results: 1
Number of variations fabricated: 10

Reference: Xu Wang, et al., "Precise control of the coupling coefficient through destructive interference in silicon waveguide Bragg gratings", Optics Letters, vol. 39, issue 19, pp. 5519-5522, 10/2014
http://dx.doi.org/10.1364/OL.39.005519

Files: Bragg/lukasc_BraggShift.GDS, ol-39-19-5519.pdf

Grating-assisted contra-directional couplers



Description: Uniform and apodized add-drop filters without an FSR, using Bragg-grating assisted contra-directional couplers. (De-)Multiplexers can be implemented by cascading multiple of such devices.

Performance:

- Bandwidth ranging from sub-nanometer to 10+ nm depending on the coupler gap and grating design.
- Sidelobe suppression: 10 to 20 dB using Gaussian apodization
- 4-channel CWDM (de-)multiplexer: flat-top responses, 1-dB bandwidth of 8 to 12 nm, crosstalk of -20 dB (Ref: CLEO 2013)

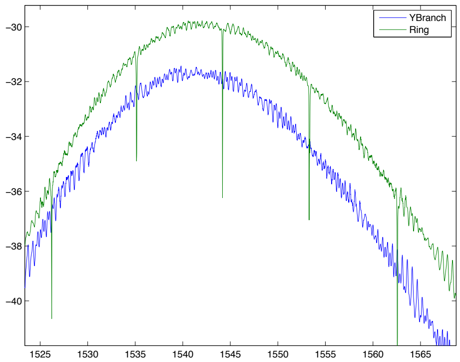
Design tools & methodology:

- Eigenmode (Lumerical MODE Solutions)
- Scripted mask layout (Mentor Graphics Pyxis)

Number of fabrication iterations (separate runs) to get to published results: 3
Number of variations fabricated: 4

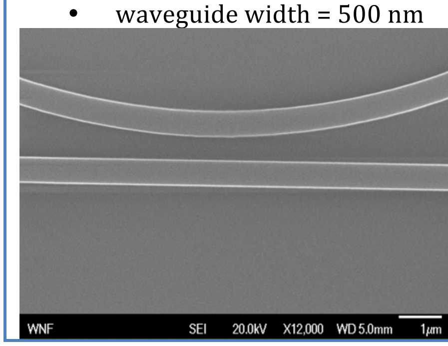
References: W. Shi, el al., "Silicon CWDM Demultiplexers Using Contra-Directional Couplers," in CLEO: 2013, Optical Society of America, paper CTu3F.5. http://dx.doi.org/10.1364/CLEO_SI.2013.CTu3F.5
W. Shi, et al., "Ultra-compact, flat-top demultiplexer using anti-reflection contra-directional couplers for CWDM networks on silicon," Opt. Express 21, 6733-6738 (2013). http://dx.doi.org/10.1364/OE.21.006733
W. Shi, et al., “Silicon photonic grating-assisted, contra-directional couplers” Optics Express, Vol 21, No 6, p. 6733, 2013, http://dx.doi.org/10.1364/OE.21.003633

Ring Resonator



Ring resonator parameters:

- R = 10 µm
- gap = 200 nm
- waveguide width = 500 nm



Description: Ring resonator. Useful for filters, sensors, etc. Also useful to extract fabrication non-uniformity

Performance:

- Found that for EBeam process with existing wafer stock, the wavelength variation for resonators across the chip was +/- 3 nm. Grating coupler insertion loss varied by +/- 1.5 dB.
- Un-optimized ring: Line-width = 40 pm; Extinction Ratio = 6 dB

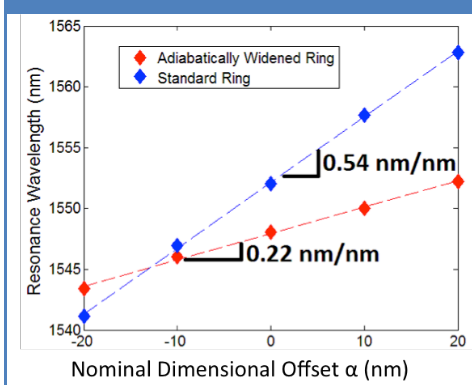
Design tools & methodology:

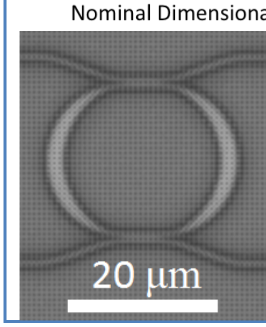
- Eigenmode (Lumerical MODE Solutions)
- Scripted mask layout (Mentor Graphics Pyxis)

Reference: L. Chrostowski, et al., "Impact of Fabrication Non-Uniformity on Chip-Scale Silicon Photonic Integrated Circuits", Optical Fiber Conference, 2014
http://dx.doi.org/10.1364/OFC.2014.Th2A.37

Files: Ring/2014_OFC_lukasc.pdf
Ring_OFC2014.gds

Ring Resonator – Adiabatic





Description: Ring resonator with reduced sensitive to fabrication variations.

Performance:

- 2.5X reduction in width sensitivity of resonance wavelength shift.

Design tools & methodology:

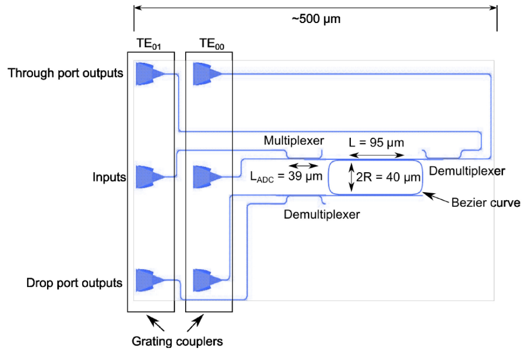
- Eigenmode (Lumerical MODE Solutions)

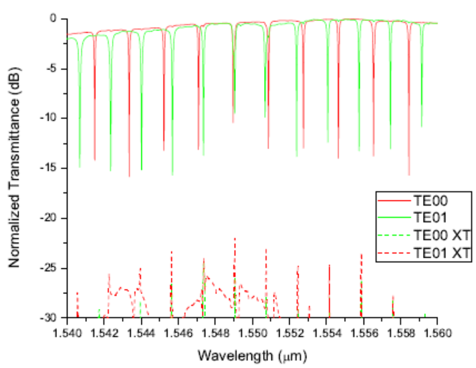
Reference: Jared C. Mikkelsen, et al., “Improving the dimensional tolerance of microrings with adiabatically widened bends”
http://dx.doi.org/10.1364/CLEO_SI.2013.CM1F.5

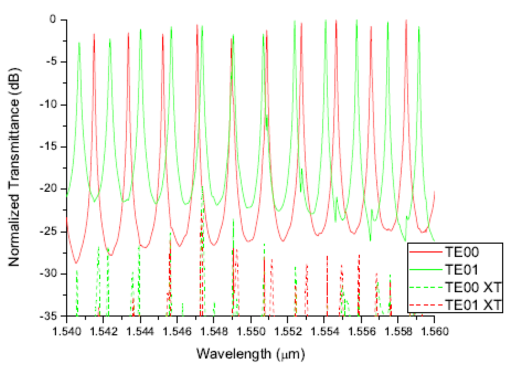
Files: Ring2/ CLEO_SI-2013-CM1F.5.pdf
JoycePoon_group.gds
JoycePoon_group_Slides.pdf

Mode Division Multiplexing

Multimode ring resonator filters







Description: We designed and fabricated a two-mode SOI ring resonator for MDM systems. By optimizing the device parameters, we have ensured that each mode is treated equally within the ring. Using adiabatic Bezier curves in the ring bends, our ring demonstrated a signal-to-crosstalk ratio above 18 dB for both modes at the through and drop ports. We conclude that the ring resonator has the potential for filtering and switching for MDM systems on SOI.

Performance:

Property	TE_{00}	TE_{01}
Through port loss (exp.)	12 dB	15 dB
Drop port loss (exp.)	15 dB	19 dB
Minimum SXR at the through port (exp.)	24 dB	22 dB
Minimum SXR at the drop port (exp.)	18 dB	23 dB
Through port extinction ratio (exp.)	13 dB	12 dB
Drop port extinction ratio (exp.)	25 dB	20 dB
FSR (simulated)	1.896 nm	1.692 nm
FSR (exp.)	1.90 nm	1.68 nm
Q (exp.)	22 000	26 000

Design tools & methodology:

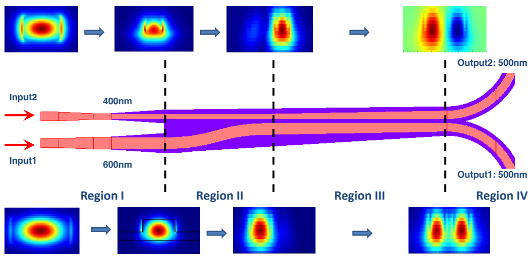
- 3D FDTD (Lumerical Solutions)
- 3D EME (FIMMWAVE)
- Scripted mask layout (Mentor Graphics Pyxis)

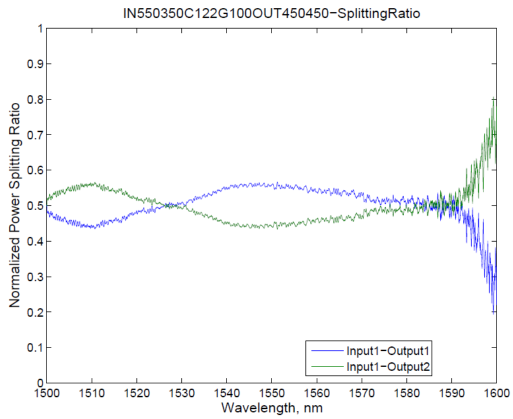
Number of fabrication iterations (separate runs) to get to published results: 1
Number of variations fabricated: 60

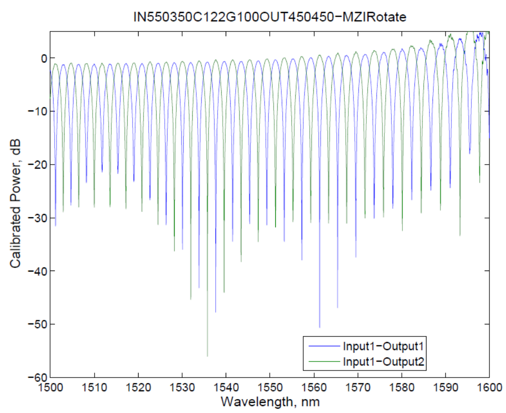
Reference: Bryce A. Dorin and Winnie N. Ye, "Two-mode division multiplexing in a silicon-on-insulator ring resonator," Opt. Express **22**, 4547-4558 (2014) http://dx.doi.org/10.1364/OE.22.004547

Files: Mode_Division_Mux/BDorin.gds

2×2 Adiabatic 3-dB Coupler







Description: 50/50% 2×2 broadband adiabatic 3-dB couplers/splitters. Two 3-dB couplers can be used to make an unbalanced Mach-Zehnder Interferometer (MZI), showing a large extinction ratio. The advantage of this device compared to the Y-Branch is that it has 2x2 ports, thus the MZI has two outputs; compared to the directional coupler, it is less wavelength sensitive.

Performance:

- TE or TM polarization operation
- They seem to work better for rib waveguides. For strip waveguides, the gap was reduced to increase the interaction.
- Splitting ratio was extracted from the unbalanced MZI spectra.
- Excess loss negligible

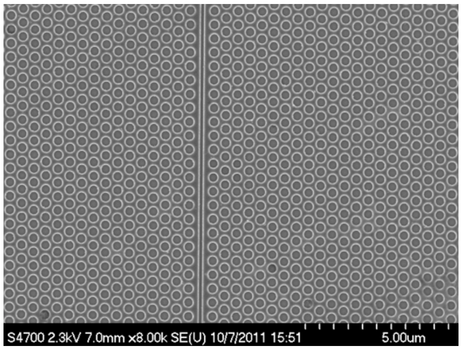
Design tools & methodology:

- 3D-FDTD (Lumerical FDTD Solutions) and eigenmode expansion propagator (MODE Solutions)

Reference: Han Yun, et al., "**2×2 Adiabatic 3-dB Coupler on Silicon-on-Insulator Rib Waveguides**", *Proc. SPIE, Photonics North 2013*, vol. 8915, pp. 89150V, 06/2013 http://dx.doi.org/10.1117/12.2037968

Files: Adiabatic_3dB_Coupler/*
TE (In550350C100G100OUT450450)
TM (In550350C122G100OUT450450)

Photonic crystal slot-microcavity



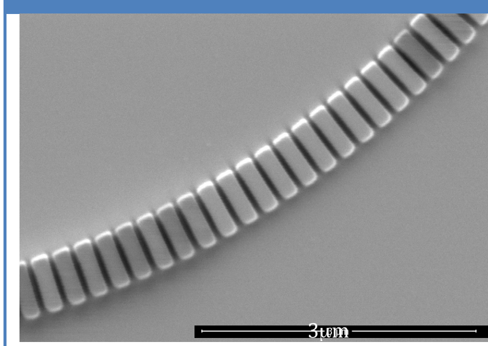
Description: We report the fabrication and characterization of a silicon-based photonic integrated circuit consisting of a photonic crystal slot-cavity, waveguides, and grating couplers, designed as a robust, easy-to-use device for enhancing light-matter interactions at a precise location inside a fluidic medium, while minimizing fabrication complexity. Measured Q values in excess of 7500 for circuits immersed in hexane and operating near 1.5 μm are obtained, in good agreement with simulations. The detection limit for changes in solvent refractive index unit (RIU) for these structures, which have not been optimized, is 2.3×10−5 RIU.

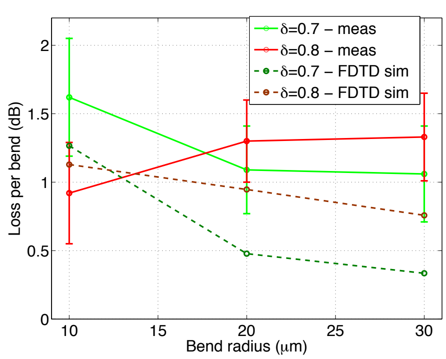
Design tools & methodology:

- 3D-FDTD (Lumerical FDTD Solutions)
- Scripted mask layout (Mentor Graphics Pyxis)

Reference: S. H. Mirsadeghi, et al., "Photonic crystal slot-microcavity circuit implemented in silicon-on-insulator: High Q operation in solvent without undercutting", APL 102, 131115 (2013) http://dx.doi.org/10.1063/1.4799963

SWG (sub-wavelength gratings) – Bends





Description: Waveguide core is based on fully etched silicon blocks, repeated periodically, no upper cladding. Possibility of tailoring waveguide refractive index and optical properties by changing sub-wavelength gratings' parameters.

Performance:

- Bend loss (for 90º bend, TE polarization) is in the range 0.8-1.6 dB

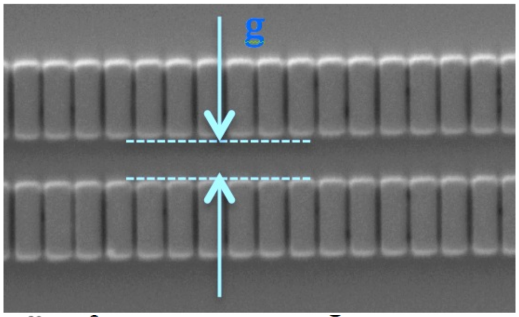
Design tools & methodology:

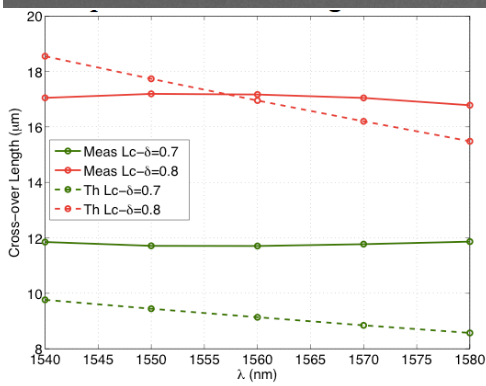
- MODE (Lumerical) + equivalent refractive index method
- 3D-FDTD (Lumerical FDTD Solutions)
- Scripted mask layout (Pyxis)

Number of fabrication iterations (separate runs) to get to published results: 2-3
Number of variations fabricated: ~50

Reference: Valentina Donzella et al. "Sub-wavelength grating components for integrated optics applications on SOI chips," Optics Express, 22(17), 21037-21050 (2014) http://dx.doi.org/10.1364/OE.22.021037
Files: SWG/ oxide_cladding_NOT_TESTED/*.gds

SWG (sub-wavelength gratings) – Directional Coupler





Description: Waveguide core is based on fully etched silicon blocks, repeated periodically, no upper cladding.
The SWG-based directional coupler has lower sensitivity to changes of central wavelength and to fabrication errors; furthermore, it introduces improvements in terms of wavelength flatness.

Performance:

- Flat wavelength response on a wavelength span of more than 40 nm (TE and TM modes).

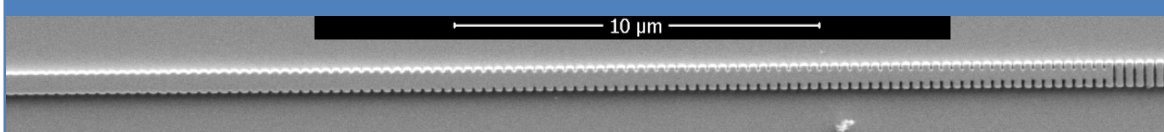
Design tools & methodology:

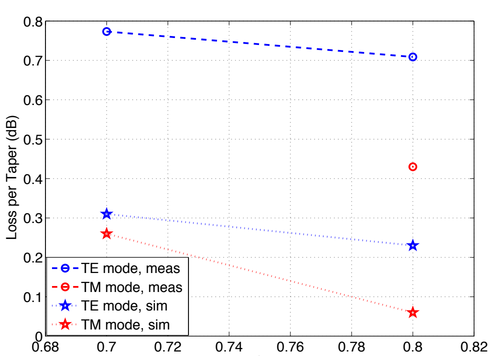
- MODE (Lumerical) + equivalent refractive index method
- 3D-FDTD (Lumerical FDTD Solutions)
- Scripted mask layout (Pyxis)

Number of fabrication iterations (separate runs) to get to published results: 2
Number of variations fabricated: ~100

Reference:
V. Donzella et al. "Compact and broad band directional coupler for sub-wavelength grating SOI components", IEEE Photonics Conference (IPC), 2014, ThF1.3, to be presented;
File: SWG/IPC_SWG_DC_2014.pdf
SWG/air_cladding/*.gds

SWG-to-strip waveguide taper





Description: Converter to/from SWG-based waveguides and strip waveguides (TE and TM polarized light). Measurements have been performed with no upper cladding.

Performance:

- Taper Loss in the range 0.4-0.8 dB
- Taper length is 30 μm

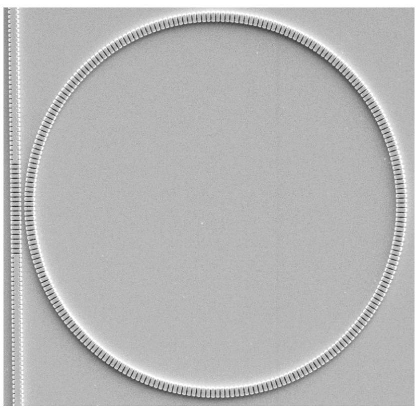
Design tools & methodology:

- MODE (Lumerical) + equivalent refractive index method
- 3D-FDTD (Lumerical FDTD Solutions)
- Scripted mask layout (Pyxis)

Number of fabrication iterations (separate runs) to get to published results: 2
Number of variations fabricated: ~20

Reference:
Valentina Donzella et al. "Sub-wavelength grating components for integrated optics applications on SOI chips," Optics Express, 22(17), 21037-21050 (2014) http://dx.doi.org/10.1364/OE.22.021037
Files: SWG/oxide_cladding_NOT_TESTED/*.gds

SWG (sub-wavelength gratings) – Ring Resonator



Description: SWG-based point coupled ring resonator.

Performance:
- Q factor in the range of 1,000 to 6,000

Design tools & methodology:
- MODE (Lumerical) + equivalent refractive index method
- 3D-FDTD (Lumerical FDTD Solutions)
- Scripted mask layout (Pyxis)

Number of fabrication iterations (separate runs) to get to published results: 2
Number of variations fabricated: ~100

Reference:
Valentina Donzella et al., "Design and fabrication of SOI micro-ring resonators based on sub-wavelength grating waveguides", (Submitted).