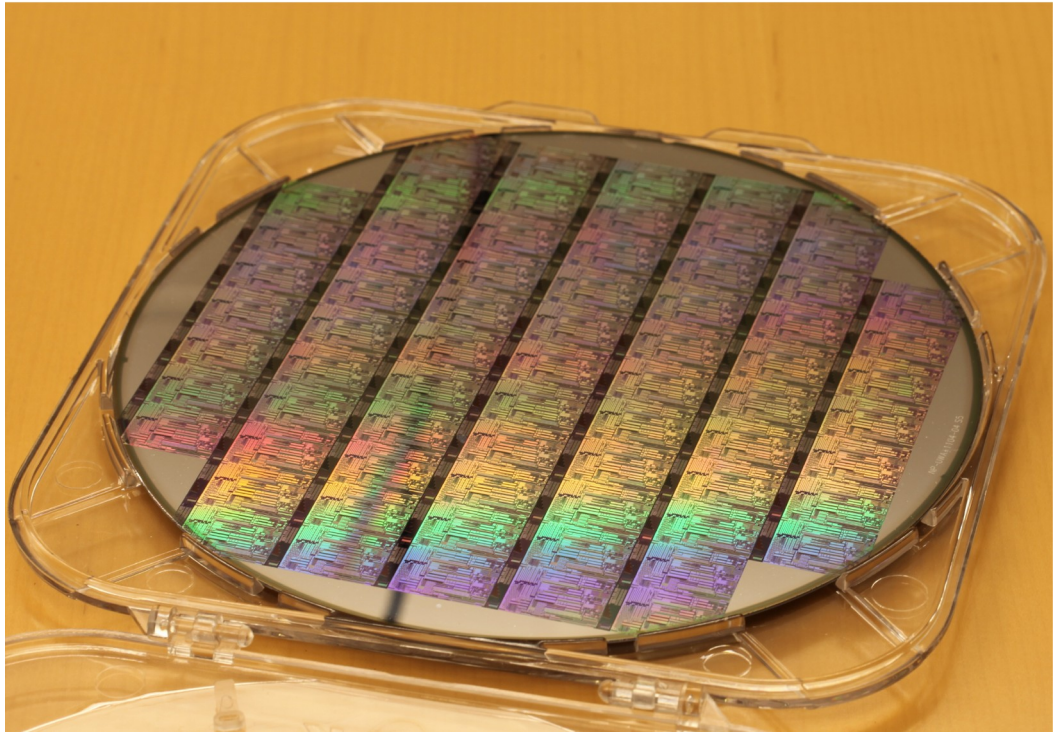
PAUL SCHERRER INSTITUT

Silicon Photonics

an introduction



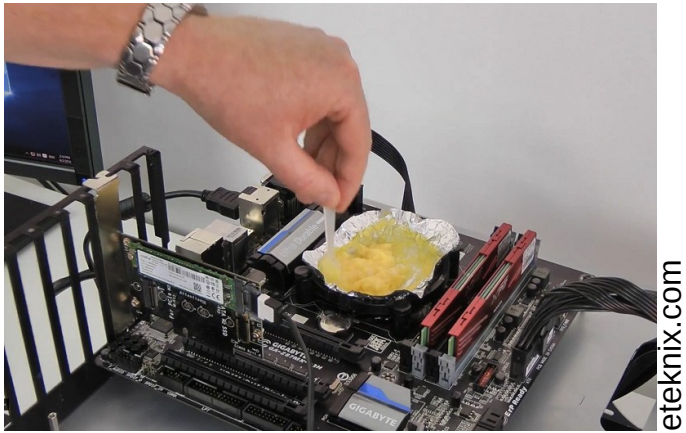
Aliakbar Ebrahimi

Paul Scherrer Institut

LTP Seminar
2020-11-23

Silicon Photonics

- Data transfer
  - Bottleneck in microelectronics
  - High power dissipation
  - Limited transfer rate
- Silicon photonics:
  - generate, guide, detect, modulate and manipulate light in a silicon chip
  - A young filed: started in early 2000s
  - At a stage similar to microelectronics in 1970s
  - Major advantage: existing silicon foundries
  - **Already commercial!**
  - Much more applications than just data transfer



eteknix.com

servethehome.com

Silicon Photonics - Industry

- Intel - 100 Gb/s PSM4 QSFP28 optical transceiver
- IBM – Watson, Zurich, Bromont
- Mellanox, acquisition of Kotura
- Huawei, and Caliopa
- TeraXion, now Ciena - coherent receiver
- Cisco, acquisition of Lightwire and CoreOptics - CPAK 100-Gbps pluggable transceiver
- LuxMux - oil & gas industry
- Lumerical Solutions Inc
- Mentor Graphics
- Genalyte – medical

Foundries:

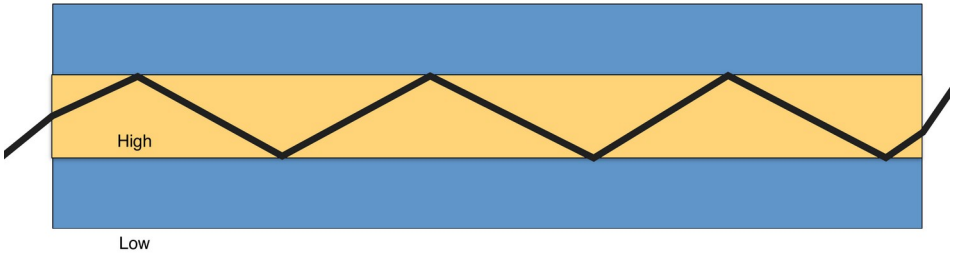
- IME, Singapore
- imec, Belgium
- LETI, France
- IHP, Germany
- VTT, Finland
- AIM Photonics, USA
- Global Foundries, USA

Multi-project wafer Services:

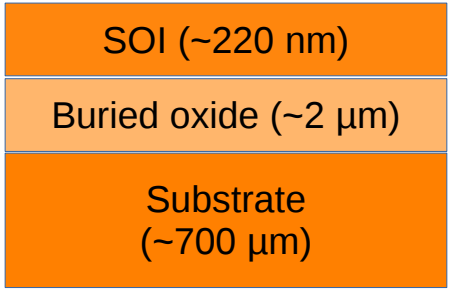
- Europractice
- ePIXfab
- CMC Microsystems
- MOSIS

Waveguide: Basic Building Block

- Waveguide
  - Guide the light by Total Internal Reflection (TIR)
  - Core should have a higher index of refraction n than the cladding



- Silicon On Insulator (SOI)
  - SOI wafer used in CMOS electronics
  - Can be used for optical confinement



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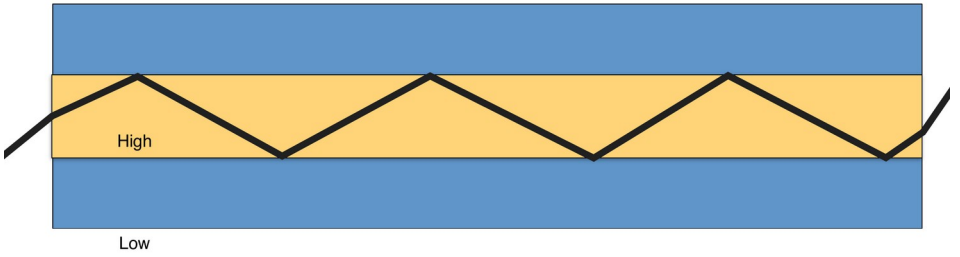

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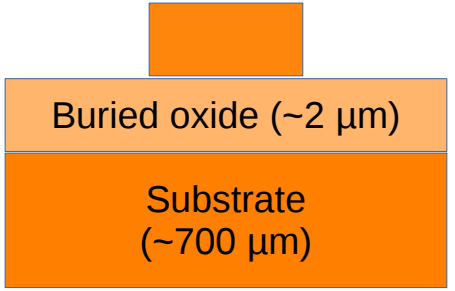

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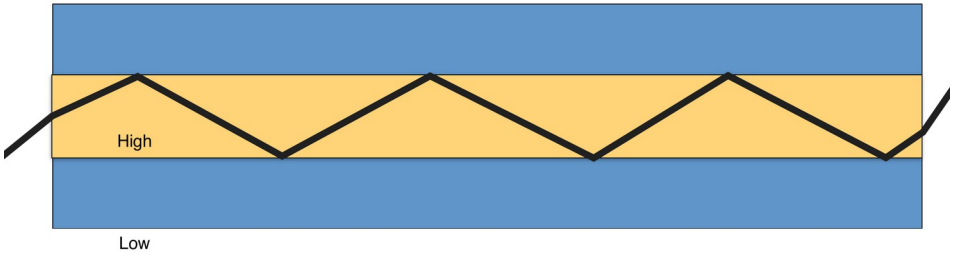

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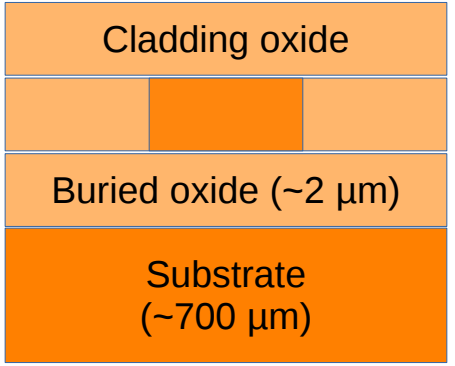
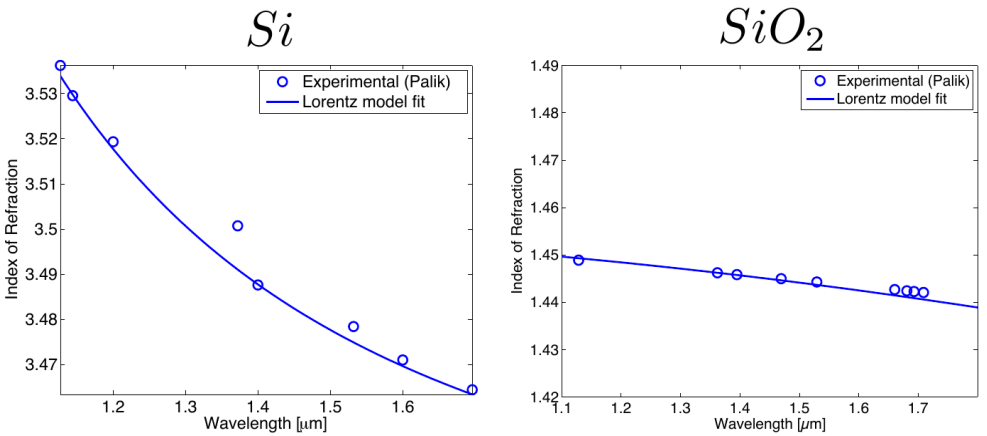


Materials in Silicon Photonics

- Silicon On Insulator (SOI)
  - Buried Oxide: SiO_2
  - Crystalline silicon: Si
- Alternative: SiN
  - Visible, near IR
- n is temperature and wavelength dependent

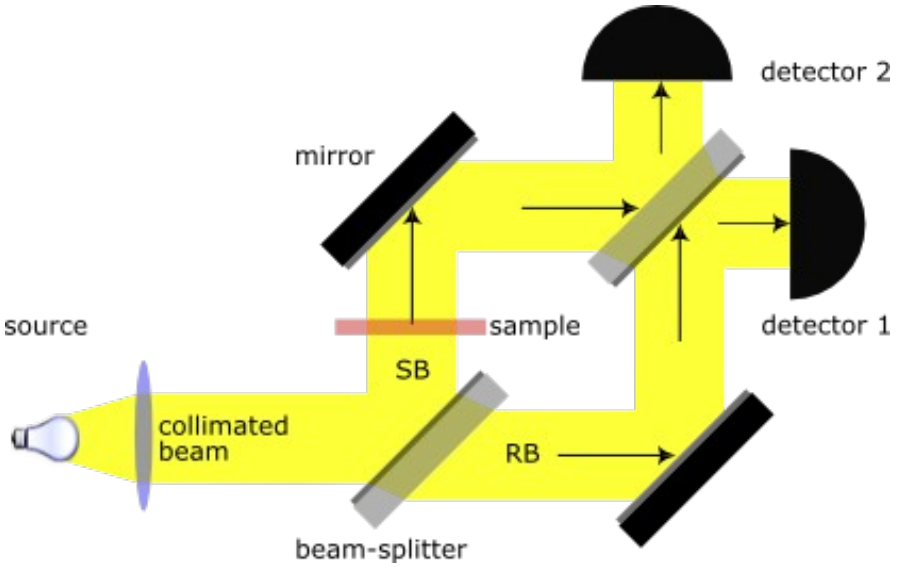


- Data points from “Handbook of Optical Constants of Solids”, E. D. Palik, 1998

		Si	SiO_2
Index	n	3.47	1.44
Wavelength dependance	$dn/d\lambda$	$-7.6 \cdot 10^{-5}/nm$	$-1.2 \cdot 10^{-5}/nm$
Temperature dependance	dn/dT	$1.87 \cdot 10^{-4} K^{-1}$	$8.5 \cdot 10^{-6} K^{-1}$

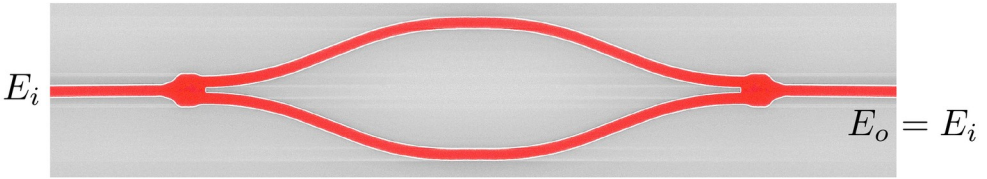
Mach-Zehnder Interferometer (MZI)

- Proposed by Ludwig Zehnder in 1891, refined by Ludwig Mach in 1892
- A device used to determine the relative phase shift of two beams split from the same source
- In absence of a sample, no light gets to detector 2
- Can be fabricated in silicon



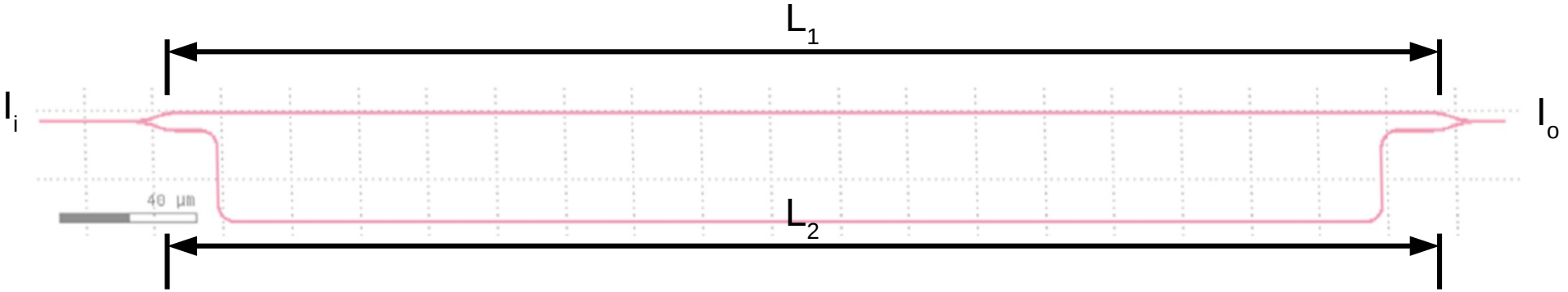
MZI in Silicon

- Basic components
  - Waveguide
  - Splitter / combiner: Y-branch
  - Input/output coupling
- Sinusoidal varying output
  - Period: Free Spectral Range (FSR)

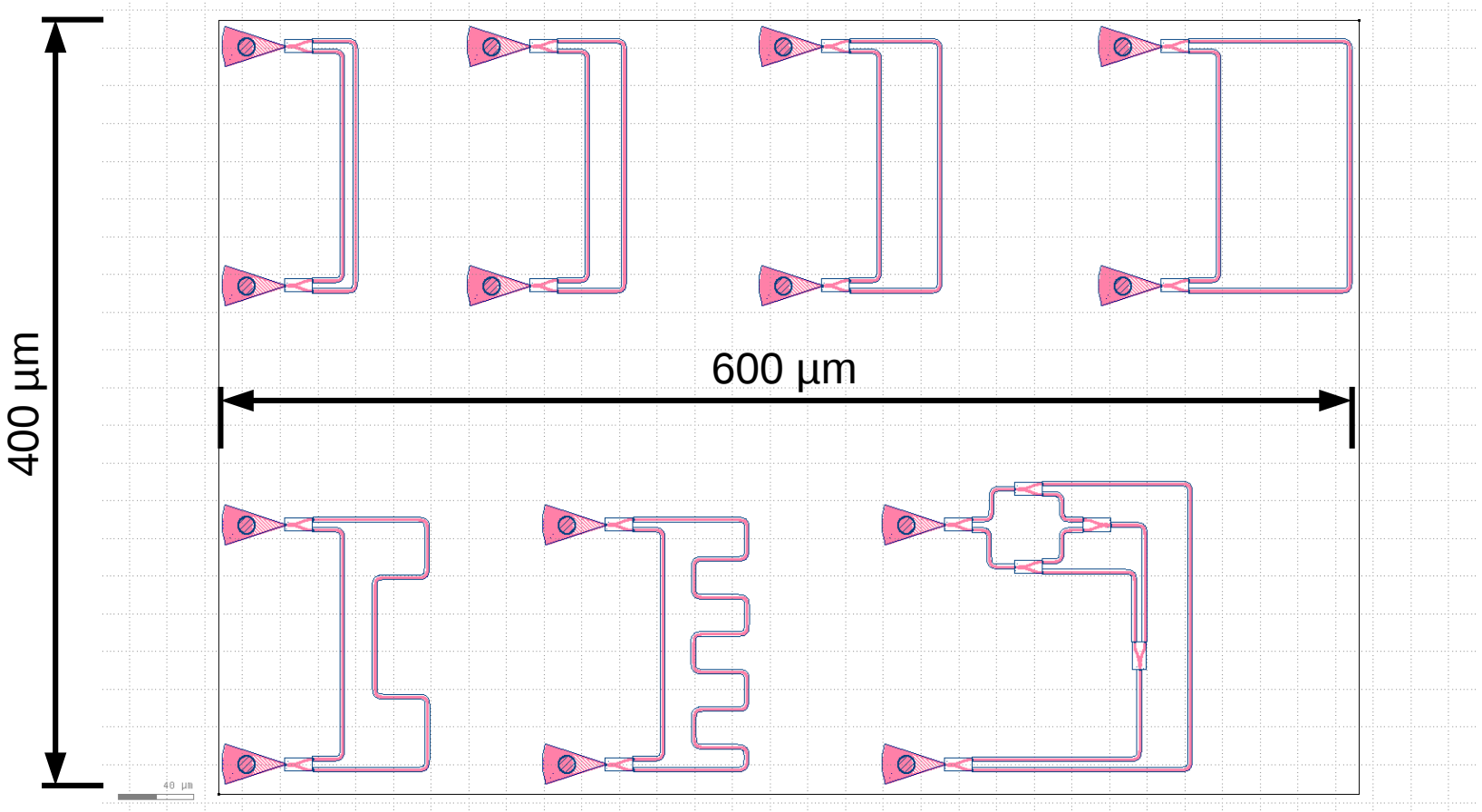


$$I_o = \frac{I_i}{2}\left[1+\cos\left(\beta_1 L_1 - \beta_2 L_2\right)\right]$$

$$\beta = \frac{2\pi n}{\lambda} \qquad FSR = \frac{\lambda^2}{n_g \Delta L}$$

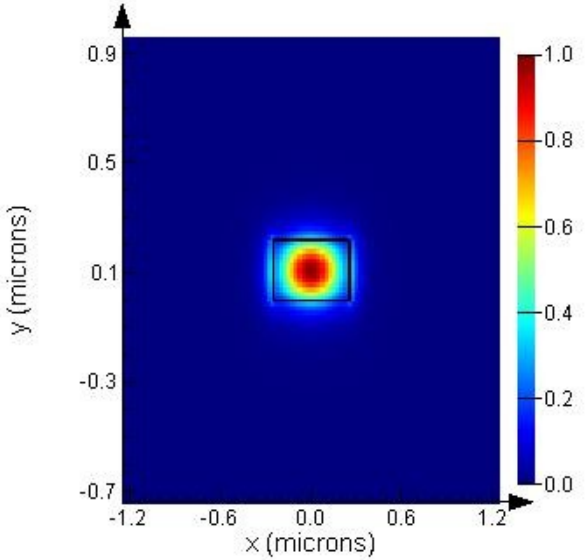


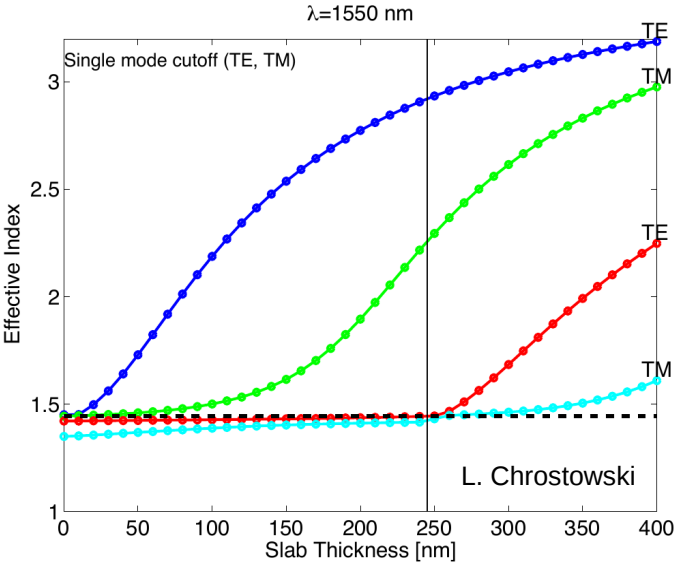
Test Structures in Chip Layout



Waveguide

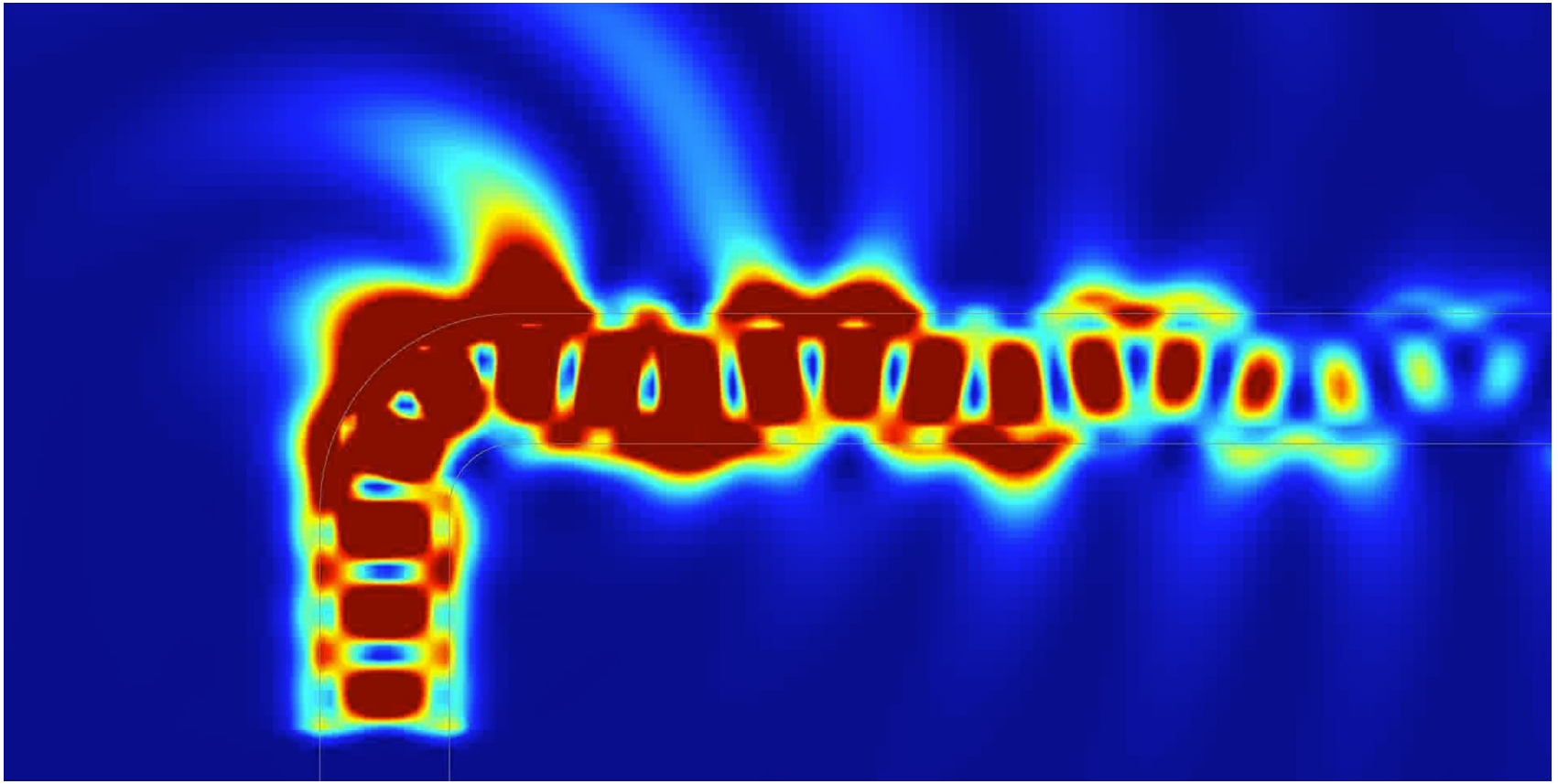
- Waveguides
  - Slab waveguide
  - Single mode
  - Width: 500 nm
  - Height: 220 nm
  - Wavelength: 1550 nm





- Simulated using Lumerical MODE

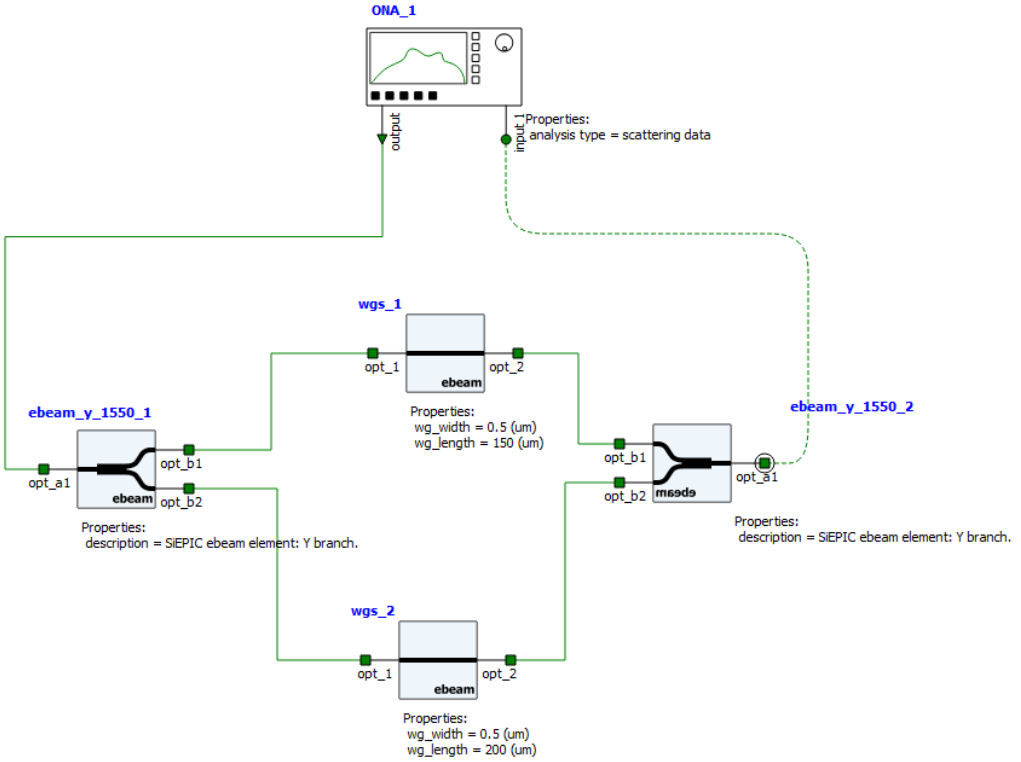
Challenge: Bent Waveguides



L. Chrostowski

Photonic Circuit Simulation

- Using Lumerical INTERCONNECT
- MZI with ΔL = 50 µm
- Wavelength 1.55 µm
- Using realistic models for components



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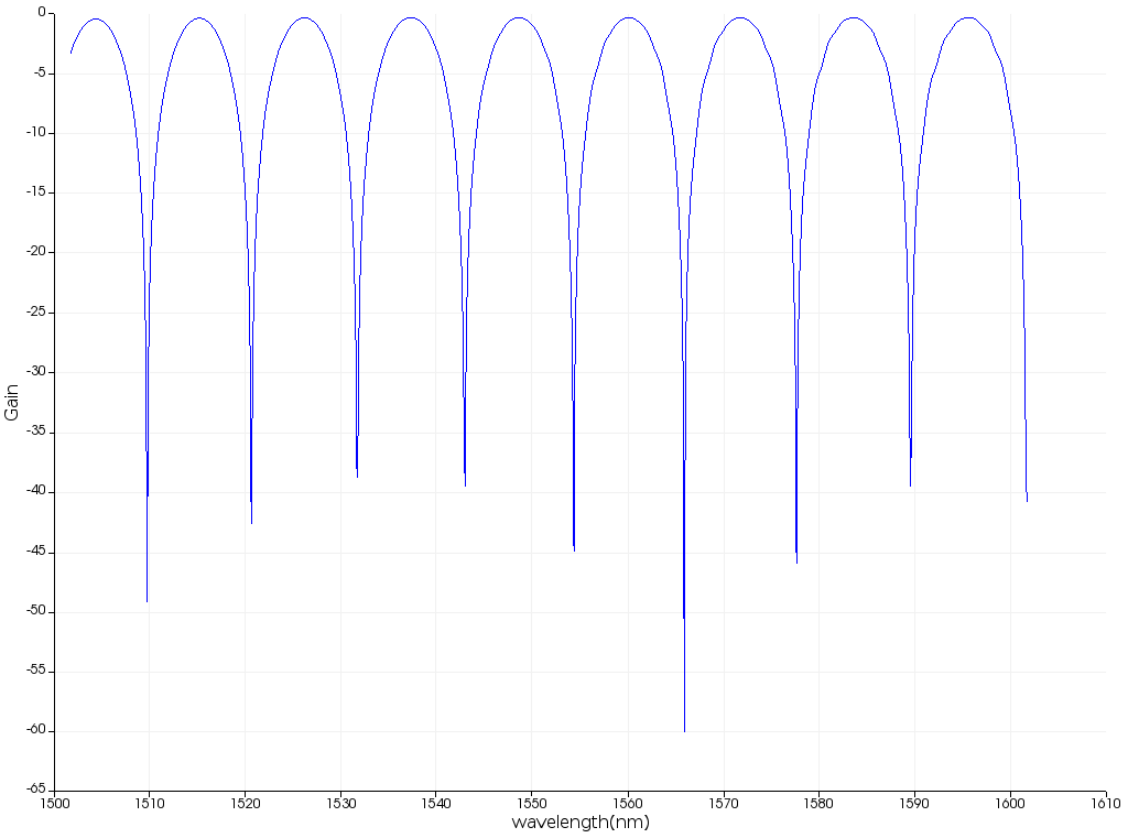


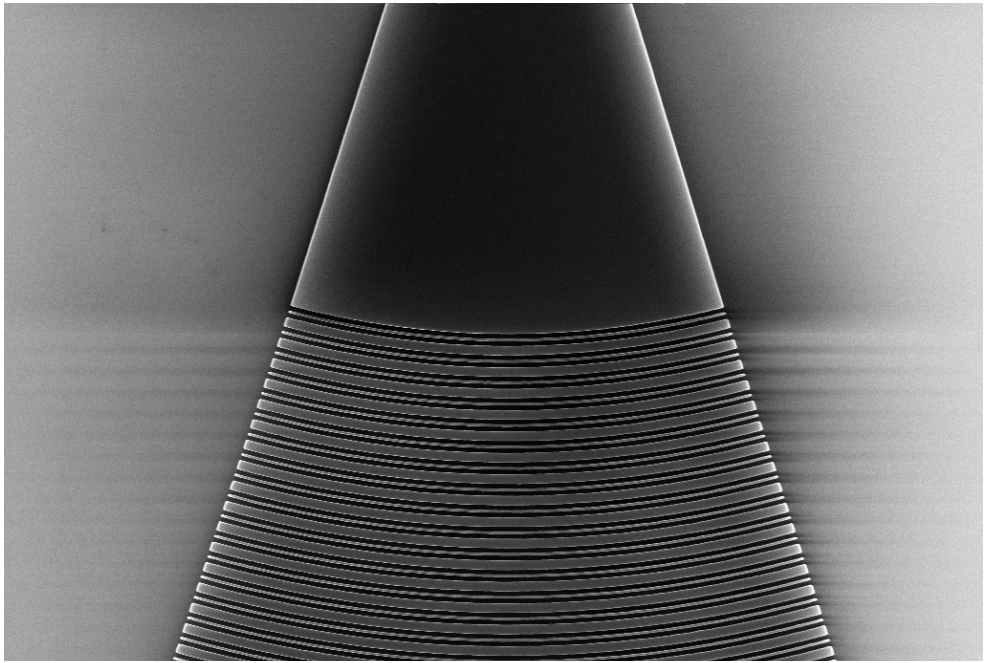
Fabrication

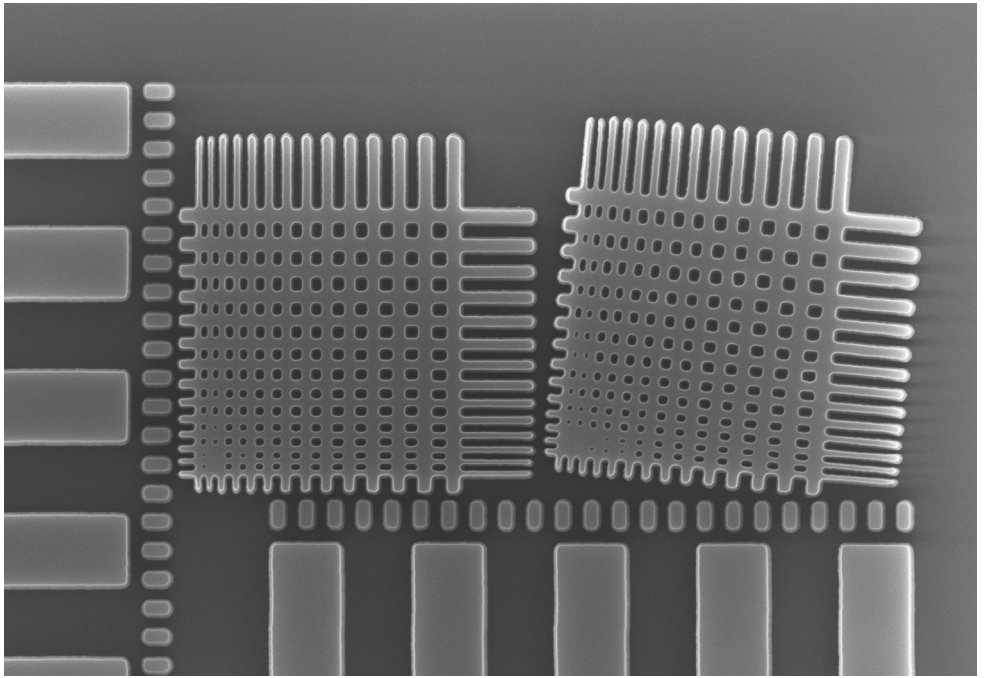
- Electron beam lithography
  - Nano-scale structures
  - Transferring a computer pattern to a resist coated surface
  - Using steerable focused electron beam (<3 nm)
- No mask needed: “direct write”
  - No mask cost / time
  - Pattern variation on a single wafer/mask
  - Variable exposure dose
- Serial process: exposure time depends on amount of area to be exposed!

JBX-6300FS Electron Beam Lithography System

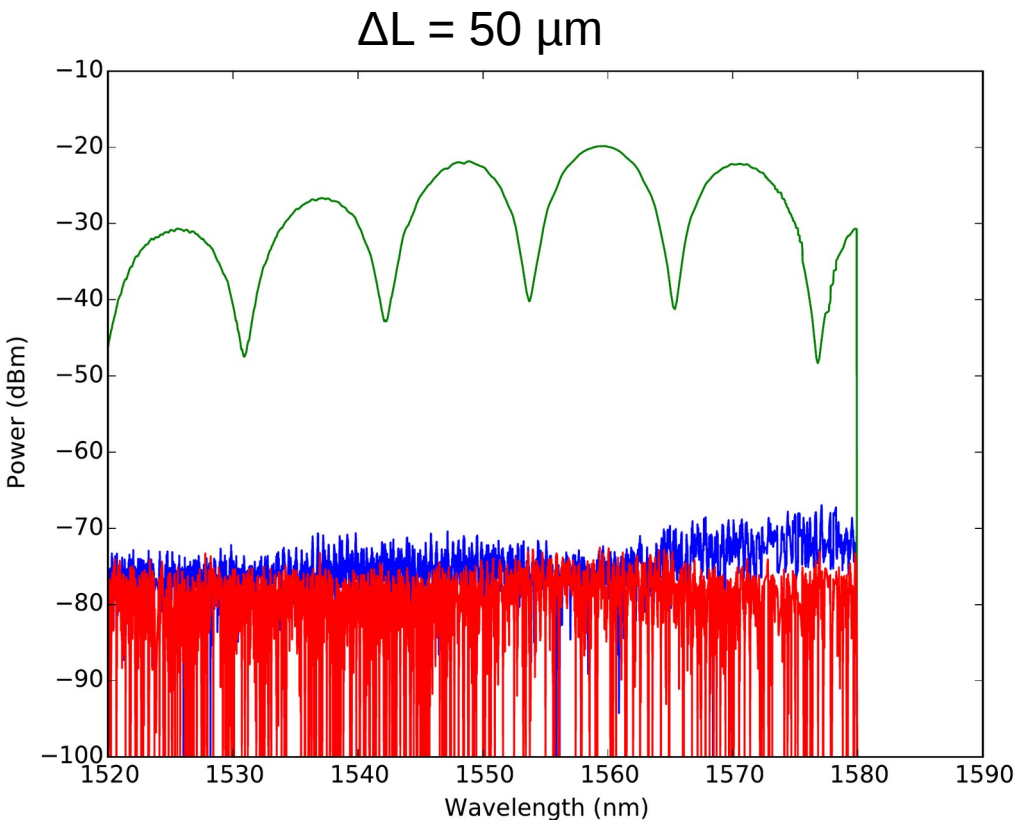
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	GDS file upload; pattern processing	chip prep; spin resist; EBL writing	etching	SEM imaging	dicing, FedEx shipping	

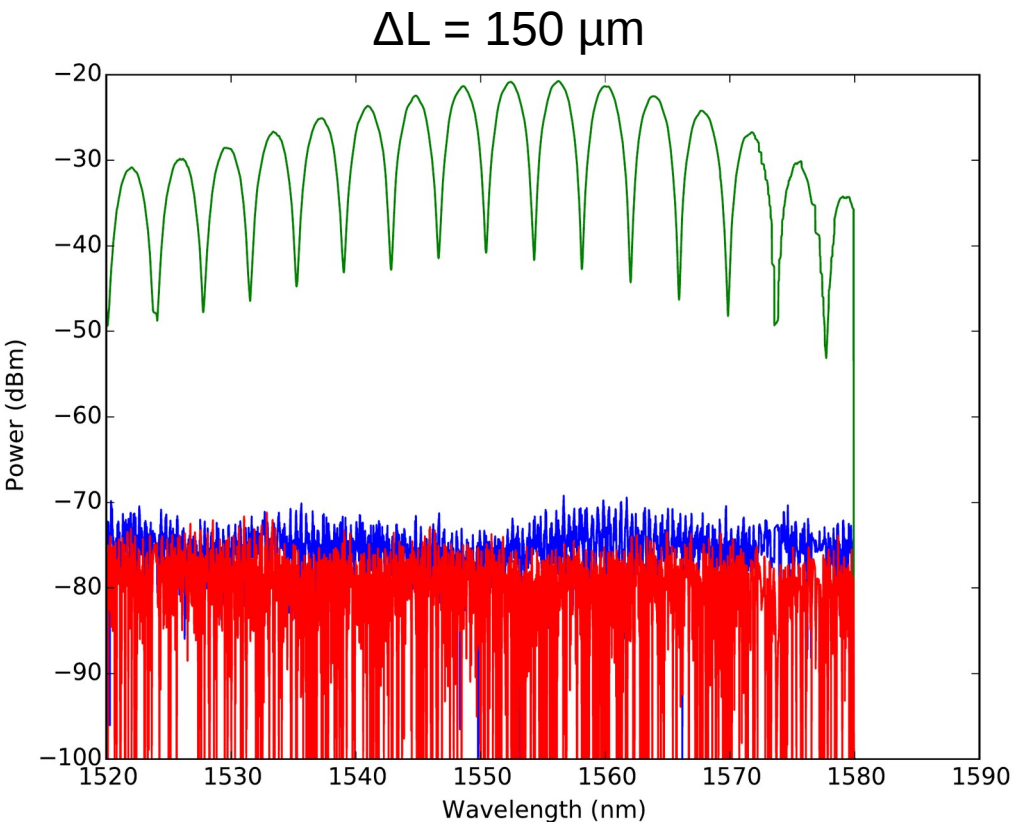
Devices Fabricated - SEM Images





Imbalanced MZI





MZI – An Application

Thermo-Optic Switch

Ref: P. Sun, R. M. Reano, "Submilliwatt thermo-optic switches using free-standing silicon-on-insulator strip waveguides", Optics Express, Vol. 18 Issue 8, pp. 8406-8411 (2010)

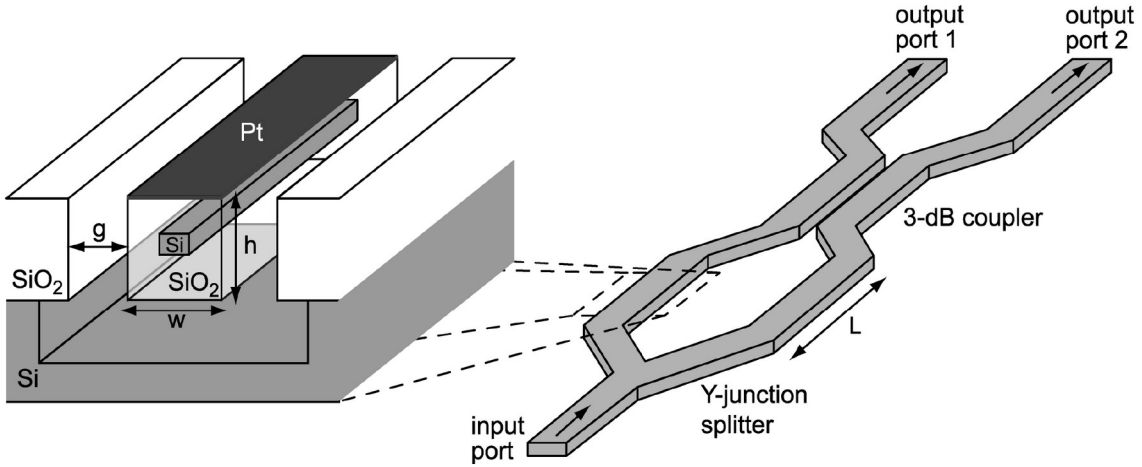
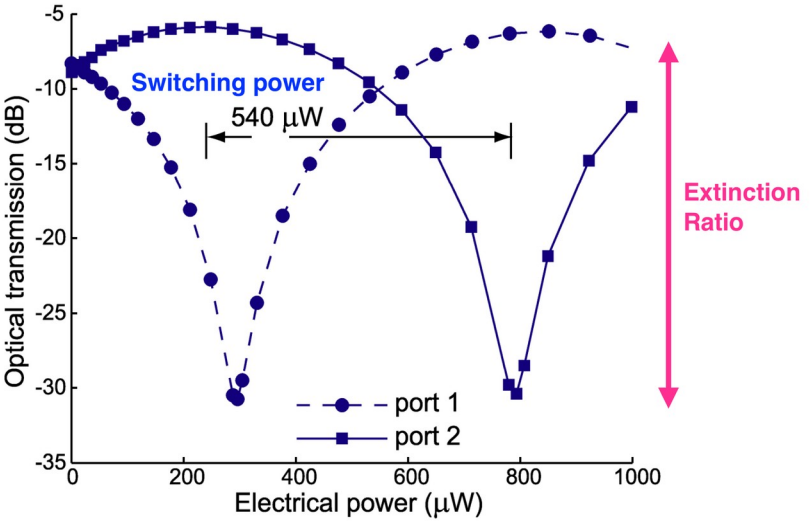
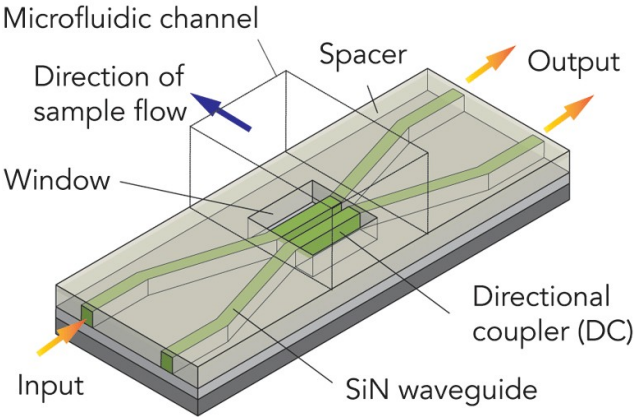


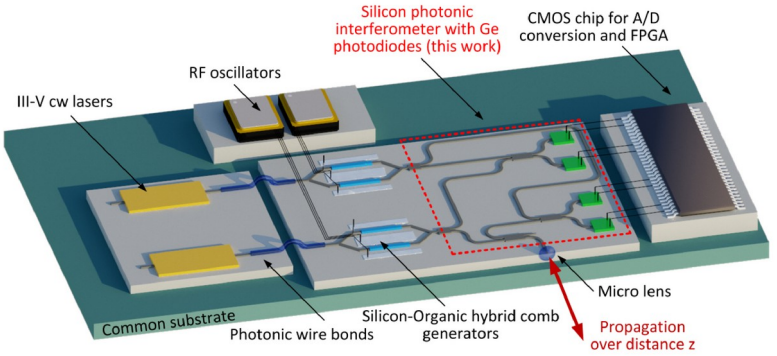
Fig. 1. Schematic of the MZI thermo-optic switch with free-standing SOI waveguides; the interferometer arms consist of silicon strip waveguides embedded in silicon dioxide which are released from the silicon substrate. Platinum heaters are deposited on top of the released arms. The silicon waveguide core cross-sectional width and height are 450 nm and 250 nm, respectively. The cladding width w is 2.9 µm, the cladding height h is 2.1 µm, and the gap g is 4.5 µm. The interferometer arm length L is 100 µm.



Further Applications

- Physical sensors
  - Temperature, Pressure, acceleration, strain, ...
- Chemical Sensors
  - CO2, methane, … sensors
- Biochemical Sensor
- Integrated Lab-on-a-chip
- Radiation sensors?

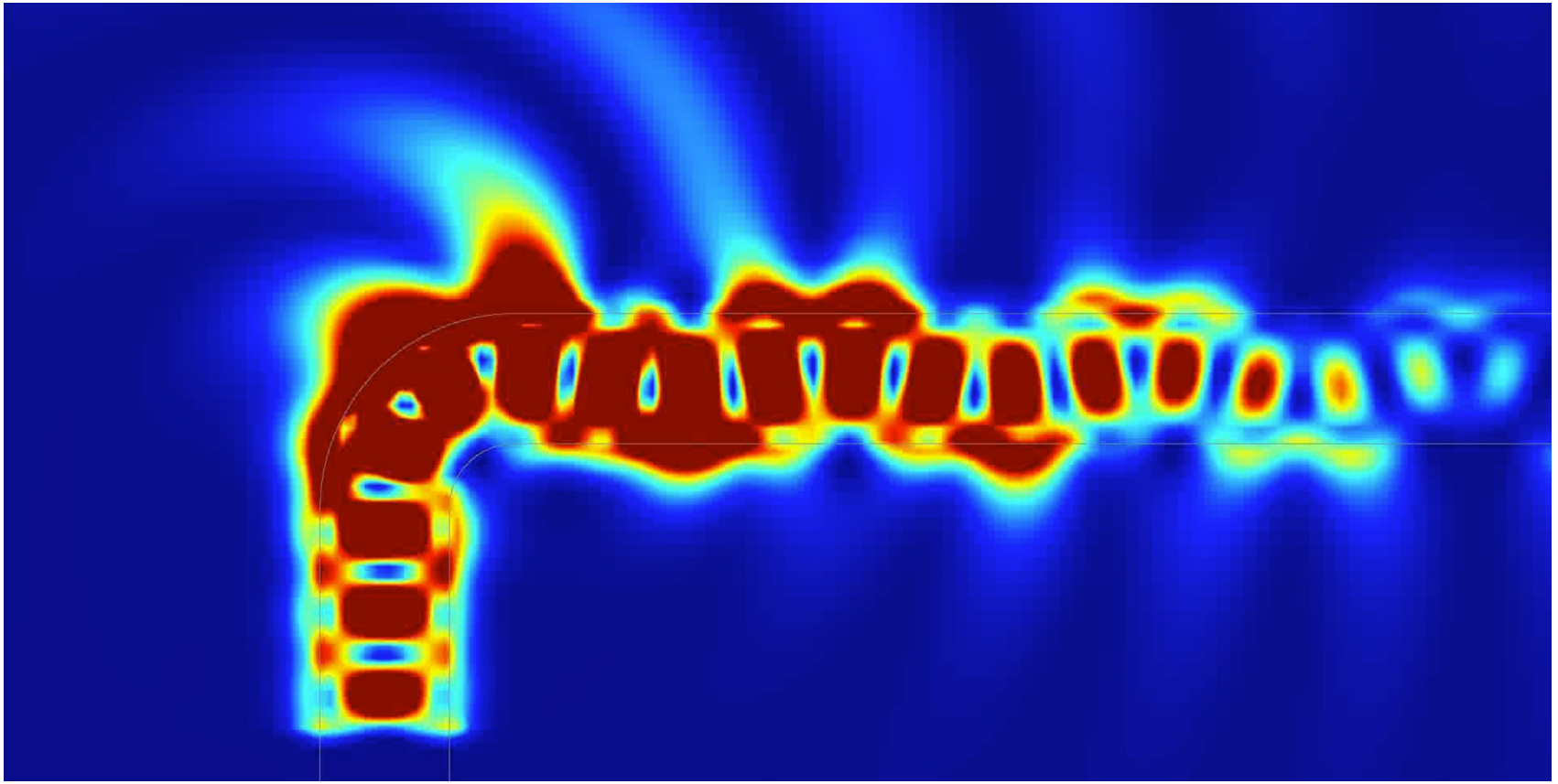




Summary

- Silicon photonics is currently and active an progressive research field
- Started to address the demand for higher communication and processing speed
- Photonic circuits finding ever increasing in other applications such as physics, chemical and biological sensing
- A passive Mach-Zhender Interferometer has been designed, developed and tested.
- Next step is to implement the MZI in active designs such as modulators and sensors

Challenge: Bent Waveguides



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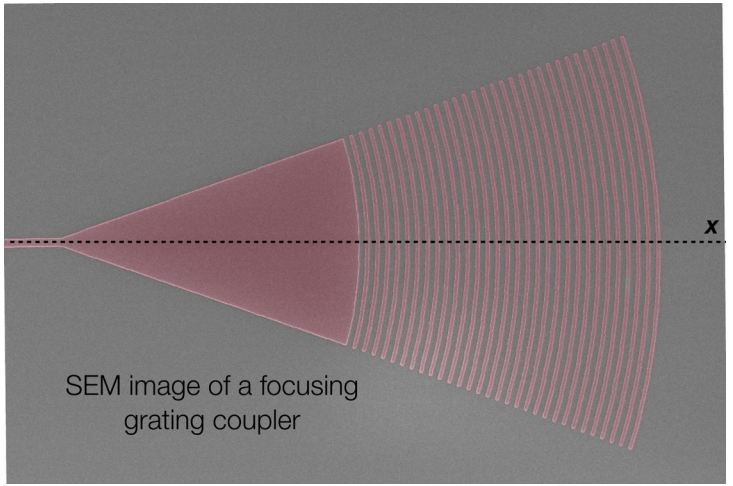
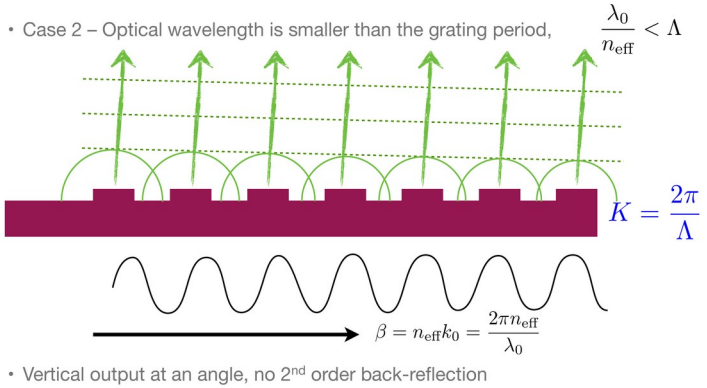
Challenge: Input / Output



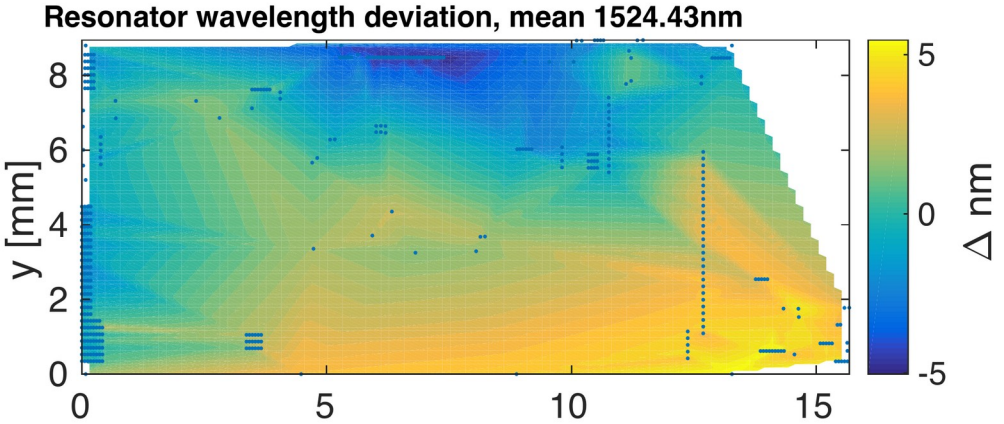


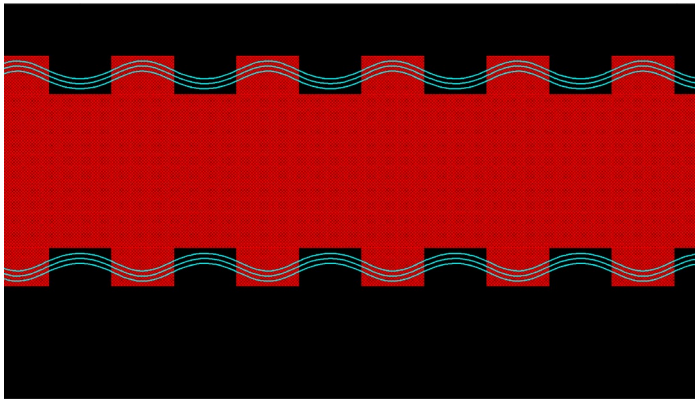
Silicon photonic
strip waveguide
500 x 220 nm

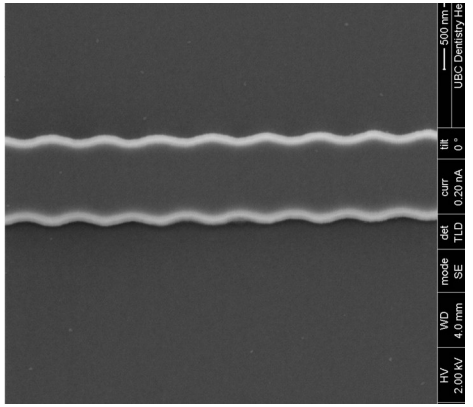
Single Mode Fibre
9 µm diameter core

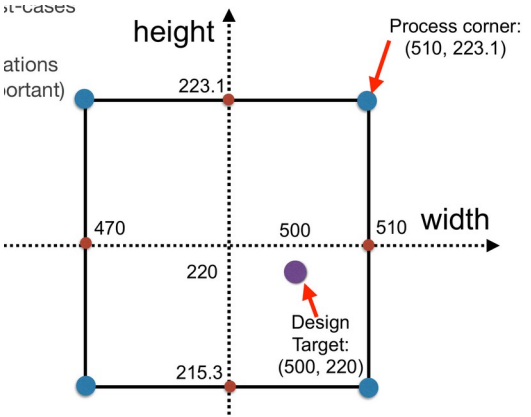
Fabrication Challenges

- Variability of
  - Silicon thickness
  - Feature size
  - Measurements
- Smoothing due to lithography









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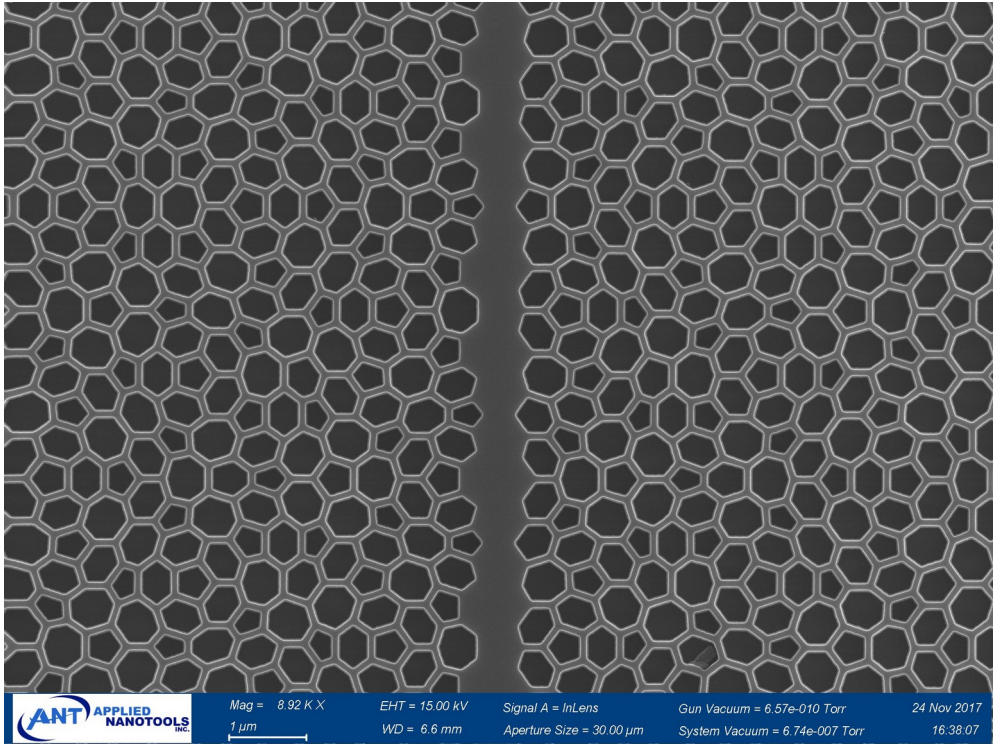

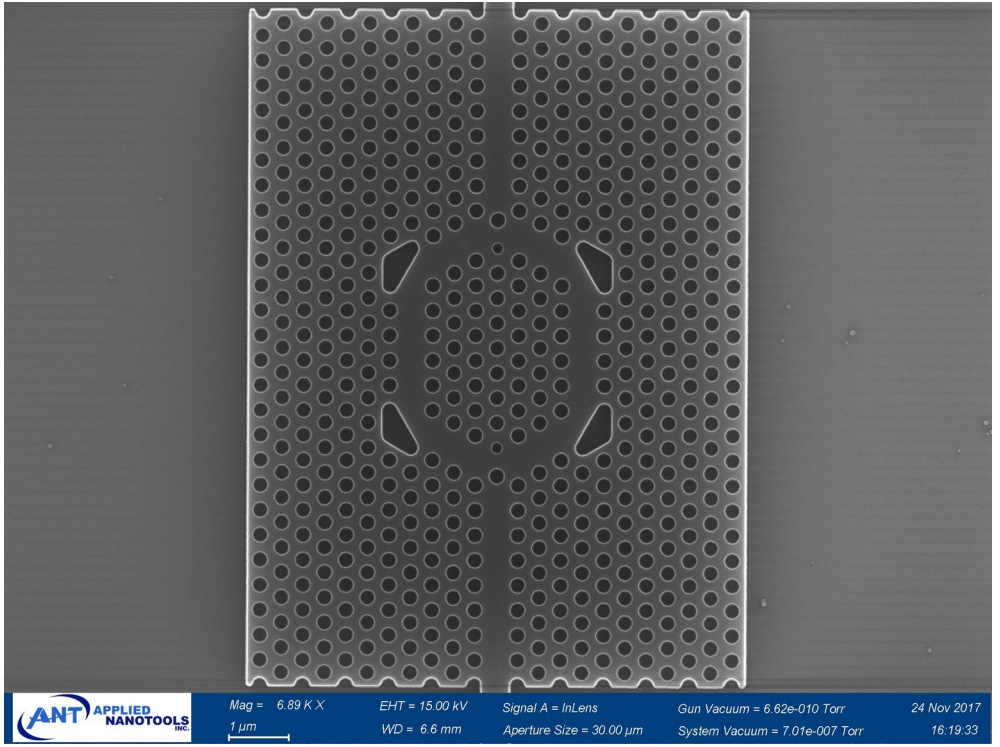

F. Y. Gardes, D. J. Thomson, N. G. Emerson, and G. T. Reed, "40 Gb/s silicon photonics modulator for TE and TM polarisations," Opt. Express 19, 11804-11814 (2011)