Mid-Infrared Silicon Photonics

Goran Mashanovich

g.mashanovich@soton.ac.uk

A future manufacturing research hub

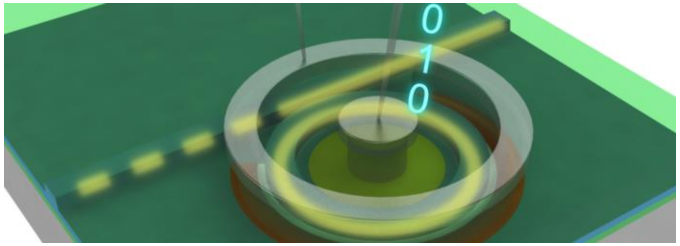
UNIVERSITY OF Southampton
The University Of Sheffield.

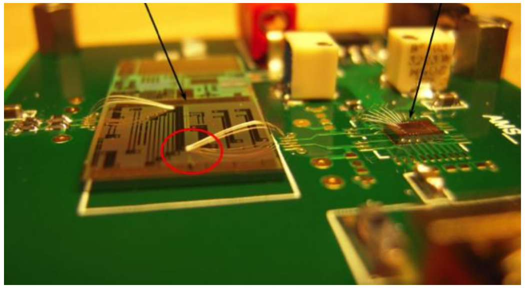
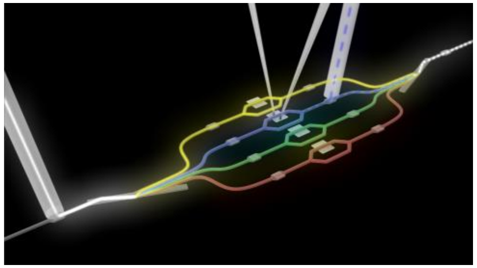
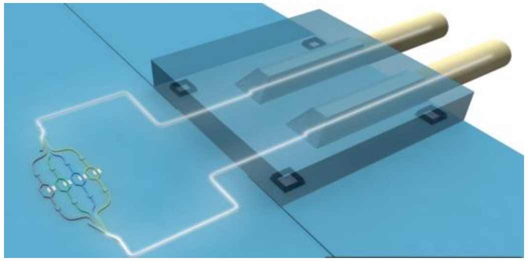
Outline

- Motivation
- Material Platforms
- Recent Results
- MIR Hub Activities

Southampton Si Photonics Group research

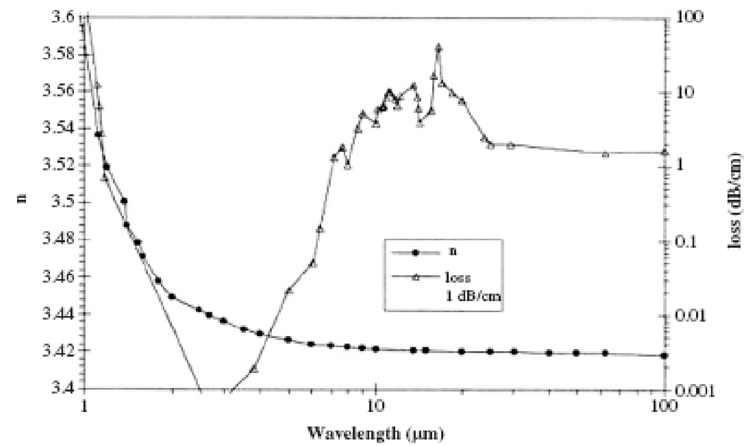
- Low loss waveguides
- Couplers, splitters, filters, interferometers, switches
- Novel (DE)MUX
- Optical modulators
- Optical detectors
- Photonic/electronic integration
- Packaging
- Wafer scale testing
- Fabrication, growth, new materials



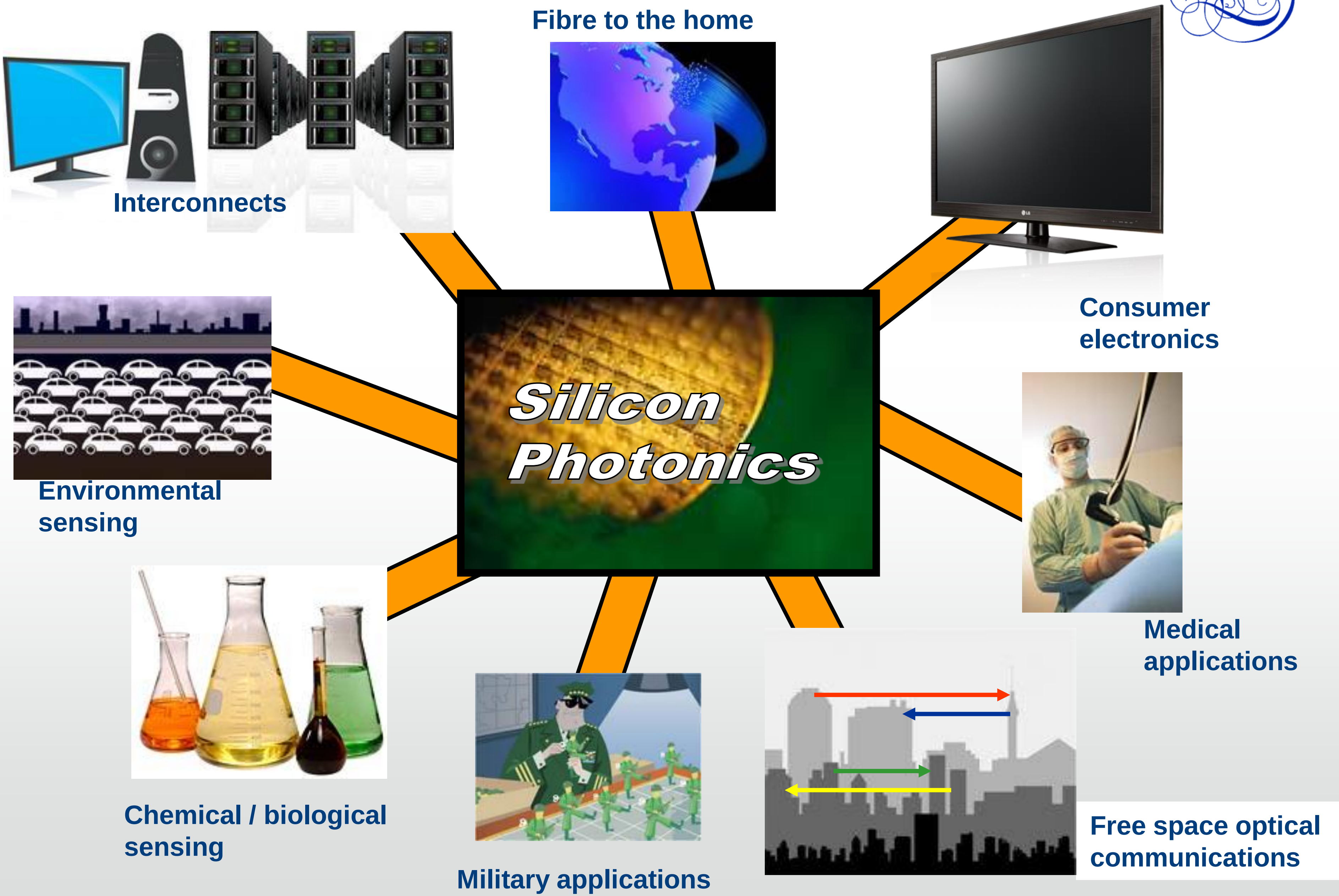




MIR Silicon Photonics?

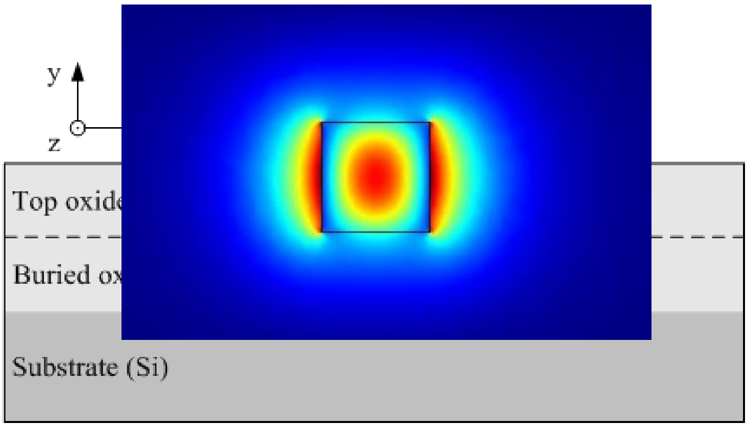
- Relatively new research field
- Si transparent from 1.1 to ~8 µm
- Ge transparent from 2 to ~14 µm
- Prospect of integrating electronics & photonics on the same substrate:
  - greater functionality
  - improved performance
  - cost reduction
- Mature processing derived from years of development in the electronics industry and in NIR Si photonics
- High refractive index contrast (compact components)
- Several important applications
- Low cost for mass markets



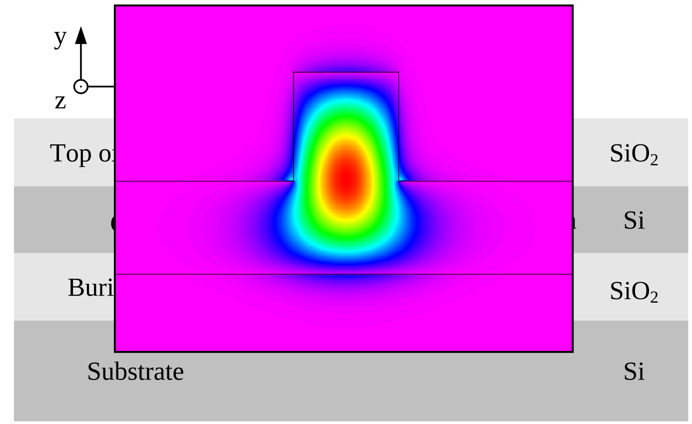
Silicon Photonics: Applications



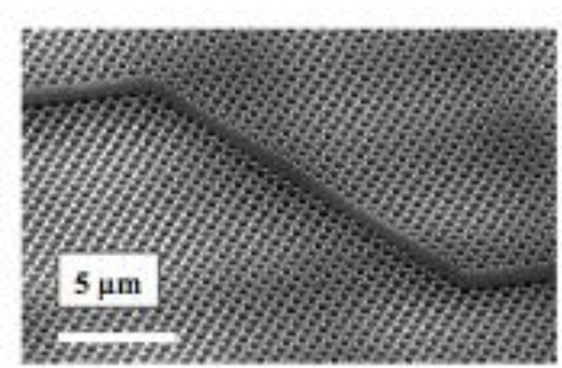
Popular optical waveguides in Si



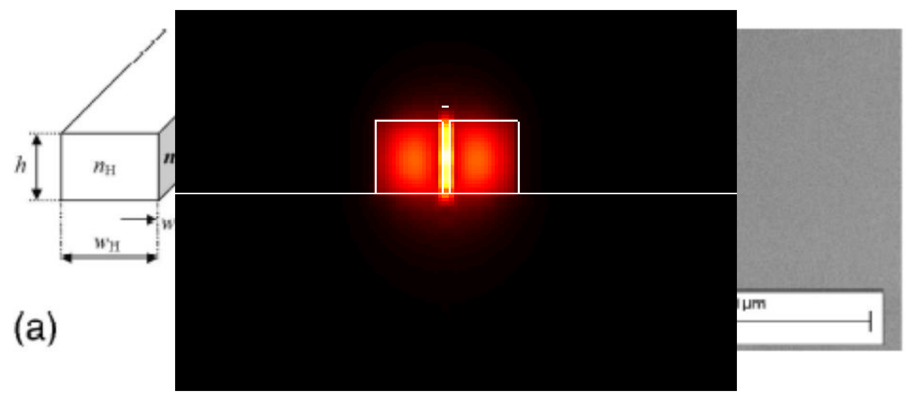
Strip waveguide / (nano) photonic wire (500 × 200 nm)



Rib waveguide
(400 nm – few microns)

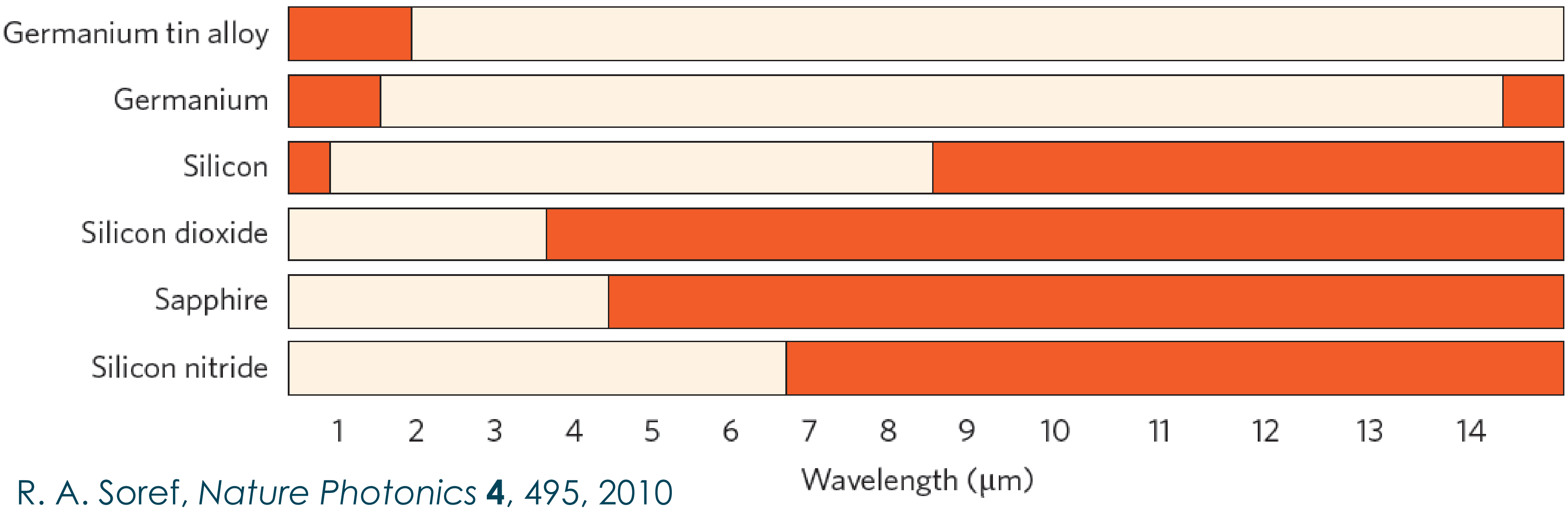


Photonic crystal

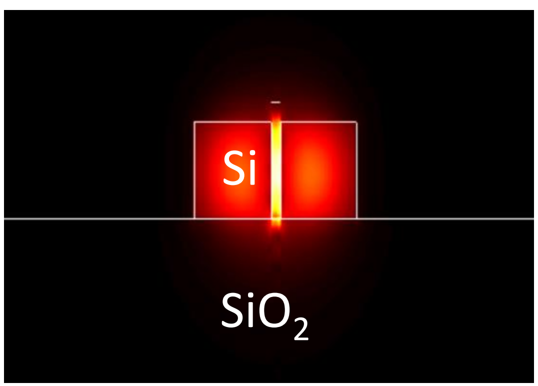


Slot waveguide

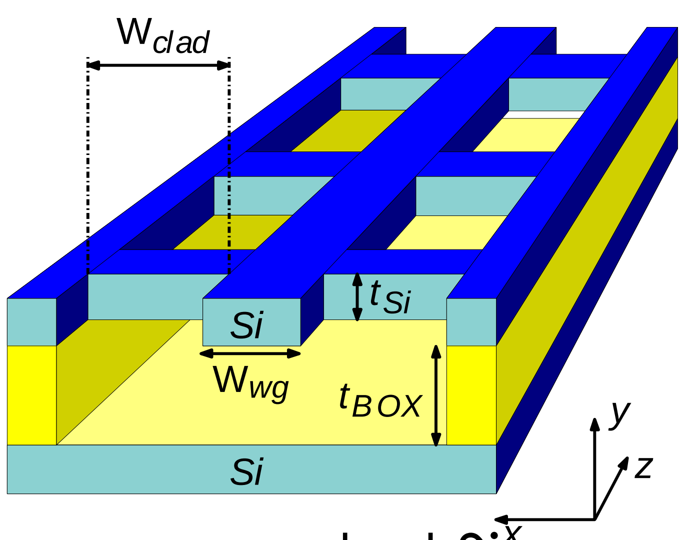
Group-IV mid-IR waveguide platforms



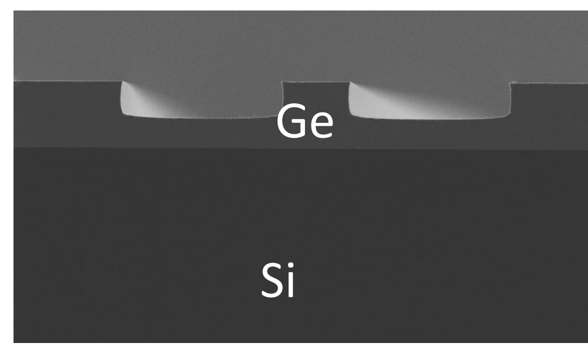
R. A. Soref, *Nature Photonics* **4**, 495, 2010



SOI



suspended Si



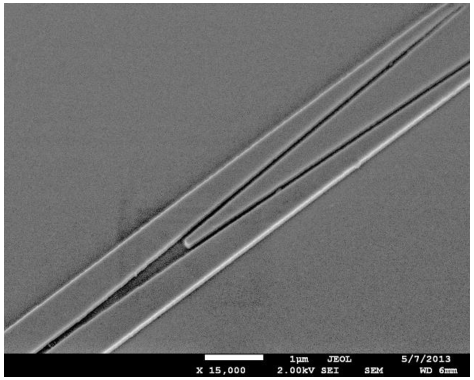
Ge-on-Si

Silicon-on-Insulator (SOI) platform

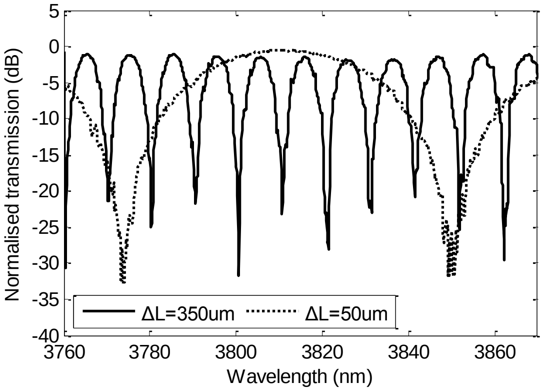
Strip waveguides:
H=500 nm, W=1.3 μm, 3 μm BOX,
e-beam lithography, ICP etching
Propagation loss at 3.74 μm: 1.3 dB/cm
MMIs: 0.15 dB/MMI
[G. Z. Mashanovich et al., *JSTQE* (2015)]

Slot waveguides:
1.4 dB/cm (H=500 nm, W_{tot} ~ 1.38 μm, W_{slot}=70-100nm)

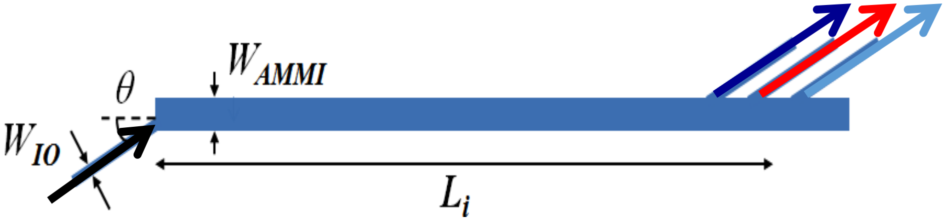
Transition loss 0.09dB/interface



[J. Soler Penades et al., *IEEE PTL* **27**, 1197 (2015)]

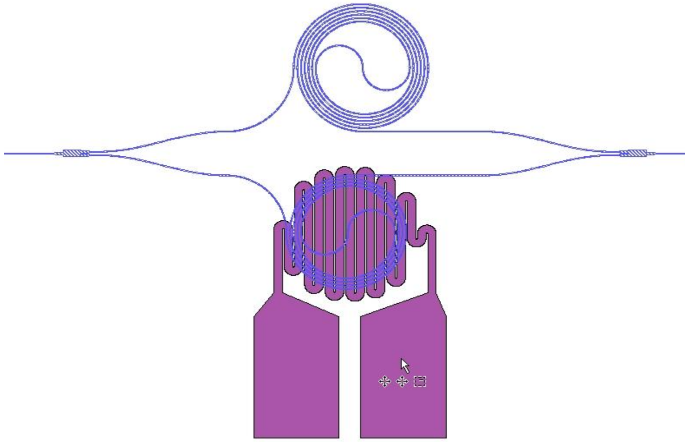


MZIs:
H = 400 or 500 nm
ΔL = 25-350 μm
ER = 25-35 dB
IL = 1-2 dB



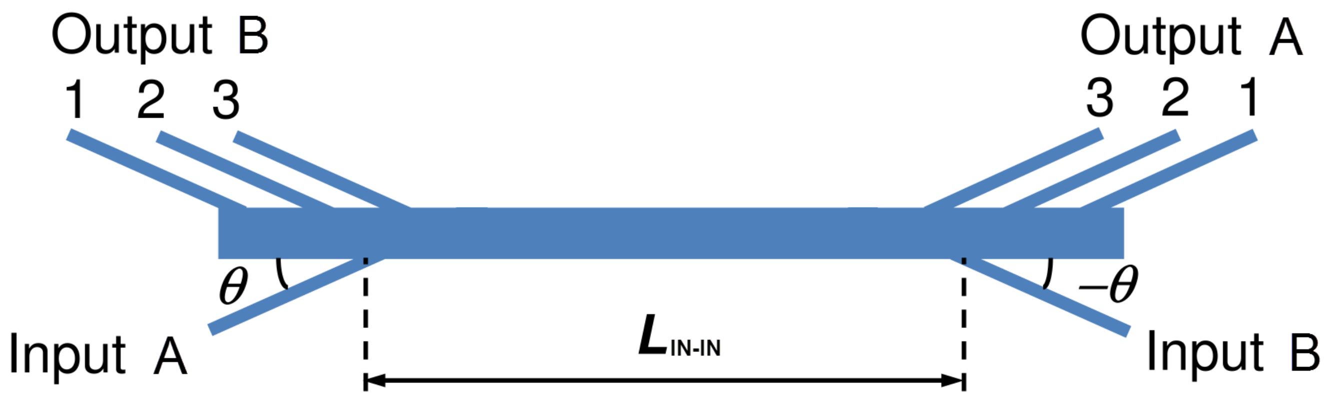
3- and 6-ch devices, IL: 2.5- dB, Cross talk: **<-**15dB

[Y. Hu et al., *Opt. Lett.* **39**, 1406 (2014)]



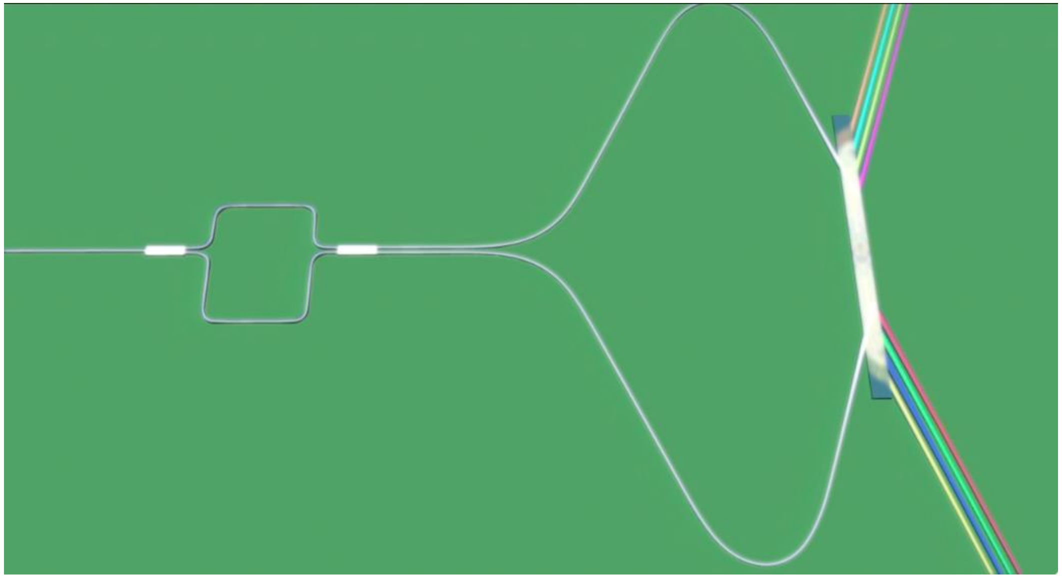
MIR modulator based on spiral waveguides
[M. Nedeljkovic et al., *IEEE PTL* **26**, 1352 (2014)]

Bidirectional AMMI (BAMMI)



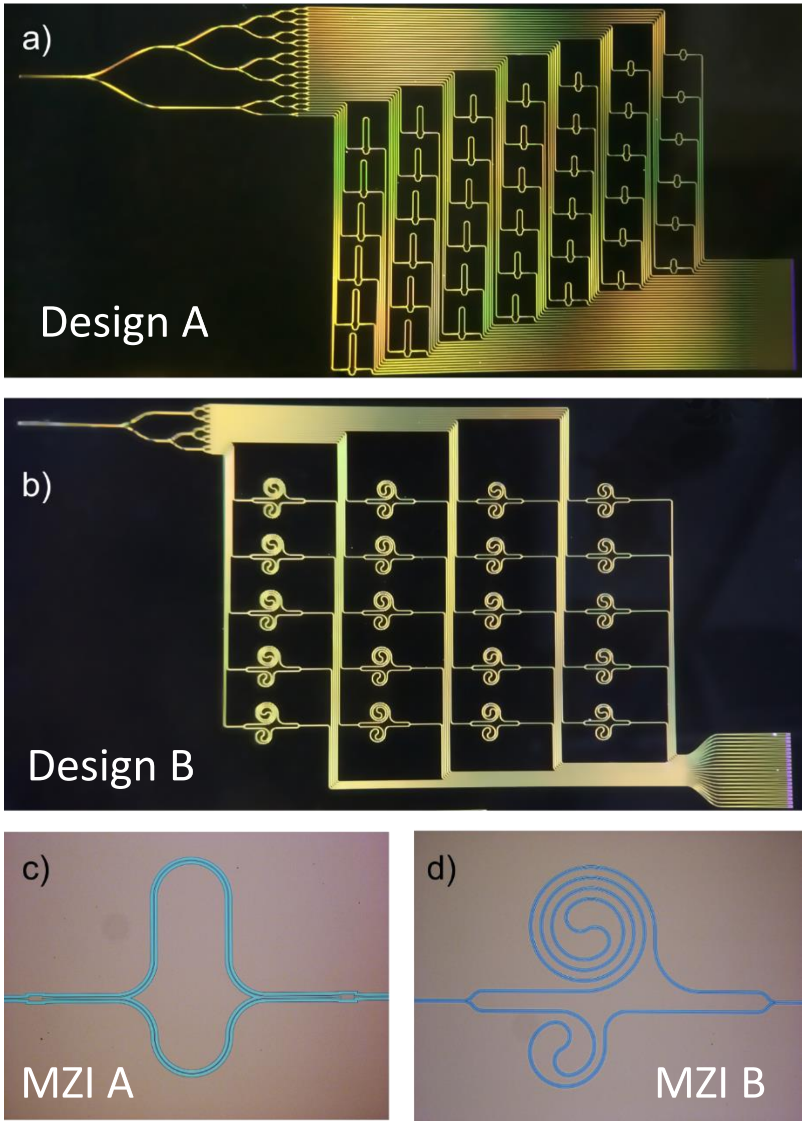
Symmetrical BAMMI: Same forward and backward channel groups (A and B)

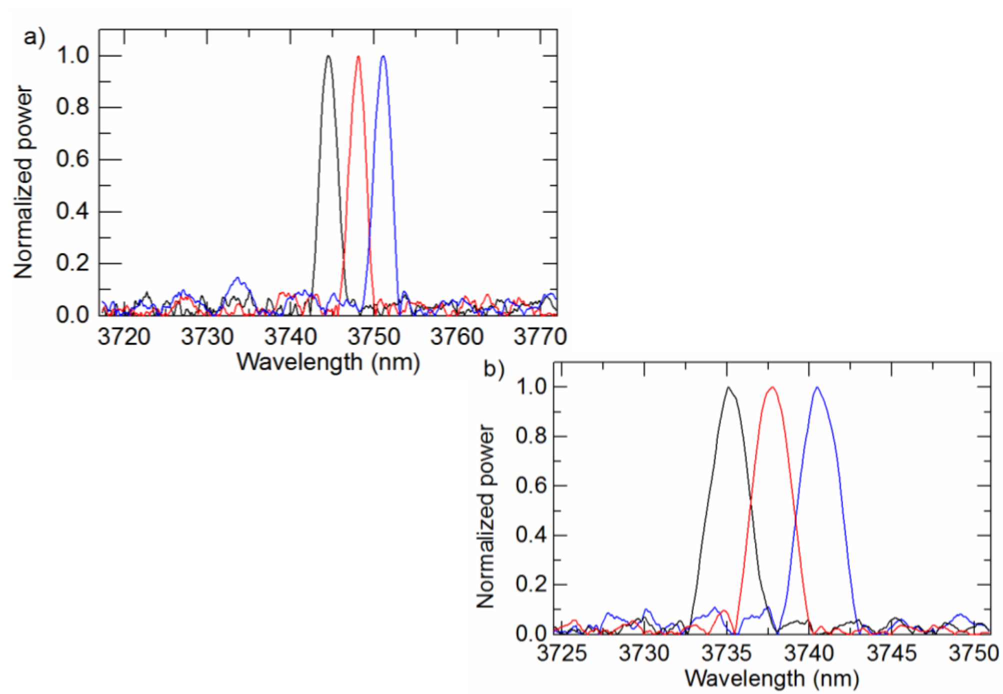
Asymmetrical BAMMI: Different forward and backward channel groups



SOI MIR FT spectrometer

- SOI device based on spatial heterodyne spectroscopy (SHS); 400nm SOI
- Array of 42 Mach-Zehnder interferometers, with linearly varying arm length differences
- Device is equivalent to a stationary Fourier Transform spectrometer. SHS enables a multi-aperture configuration





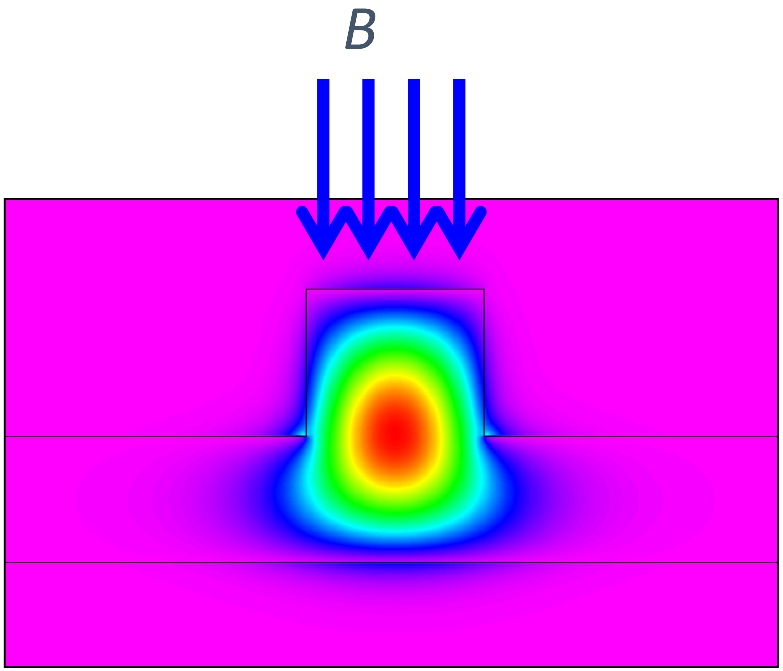
[M. Nedeljkovic et al. *IEEE PTL* 28, 528 (2016)]

A future manufacturing research hub

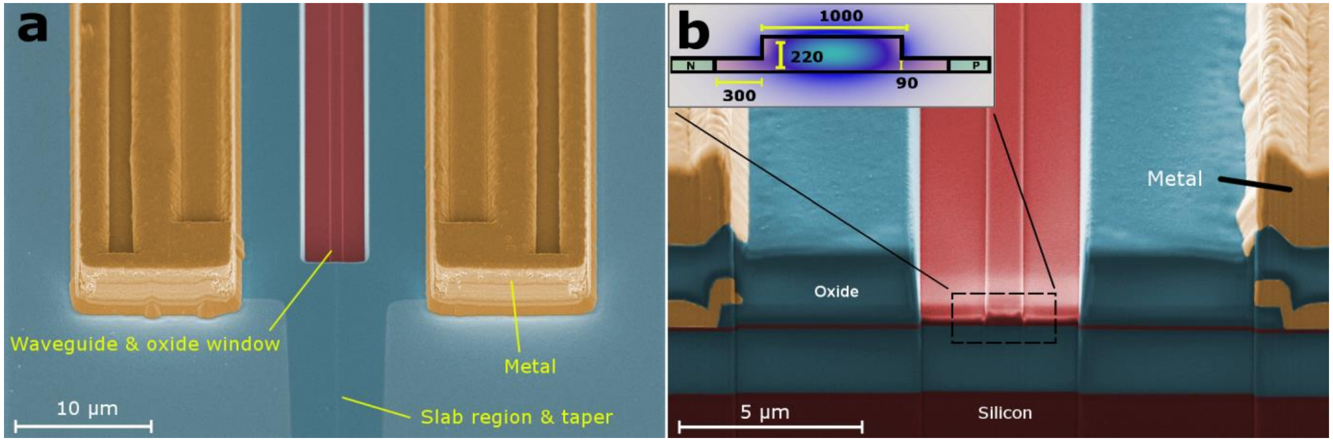
UNIVERSITY OF Southampton

The University Of Sheffield.

Detection via defect engineered structures



- Boron implant: 60keV, $10^{13}/cm^2$, introduced through etched oxide window
- Avalanche mode, reverse bias > 20V
- Max speed 28 Gb/s @ λ~2μm
- R = 0.3 A/W



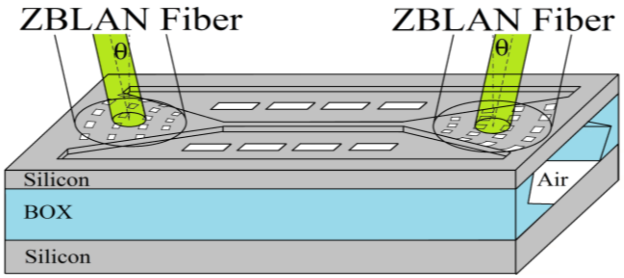
[J. J. Ackert et al., *Nat. Photon.* **9**, 393 (2015)]

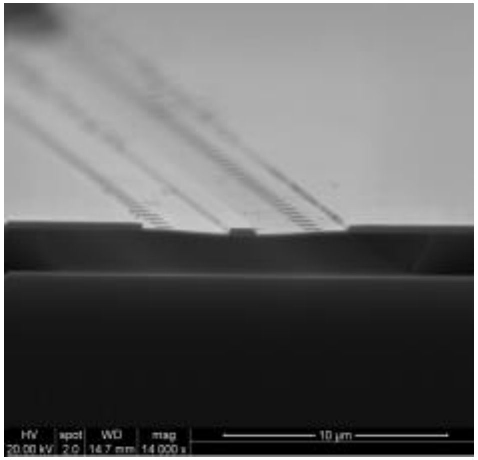
A future manufacturing research hub

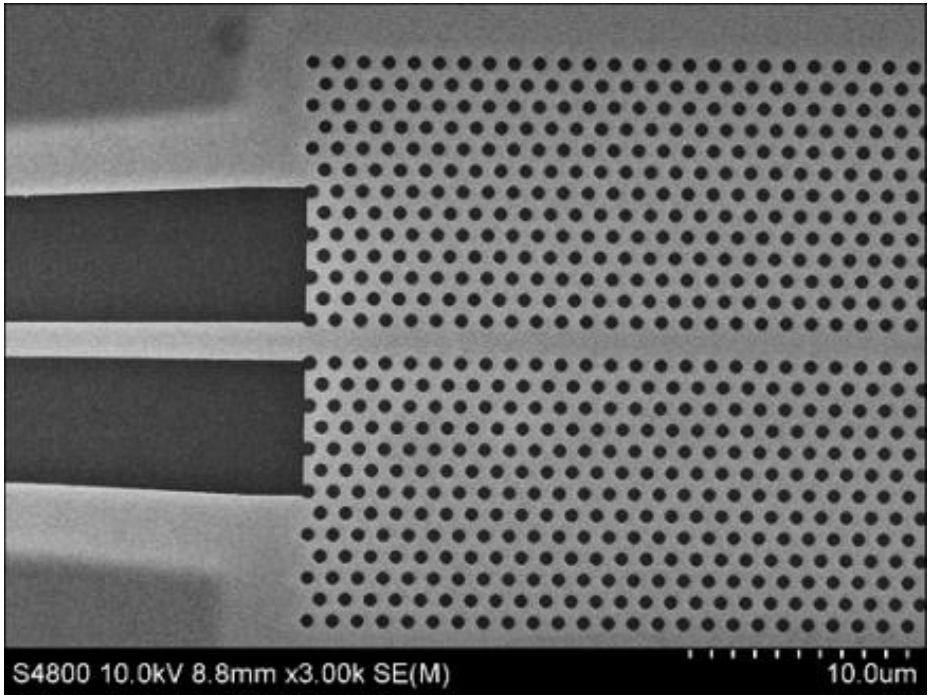
University of Southampton

The University Of Sheffield.

Suspended Membrane Waveguides – previous work







Loss=3dB/cm @2.75µm for H_1=340nm, H_2=2µm, H_3=240nm, W=1µm, W_1=2.5µm
[Z. Cheng et al., *IEEE Photon. J.* **4**, 2012]

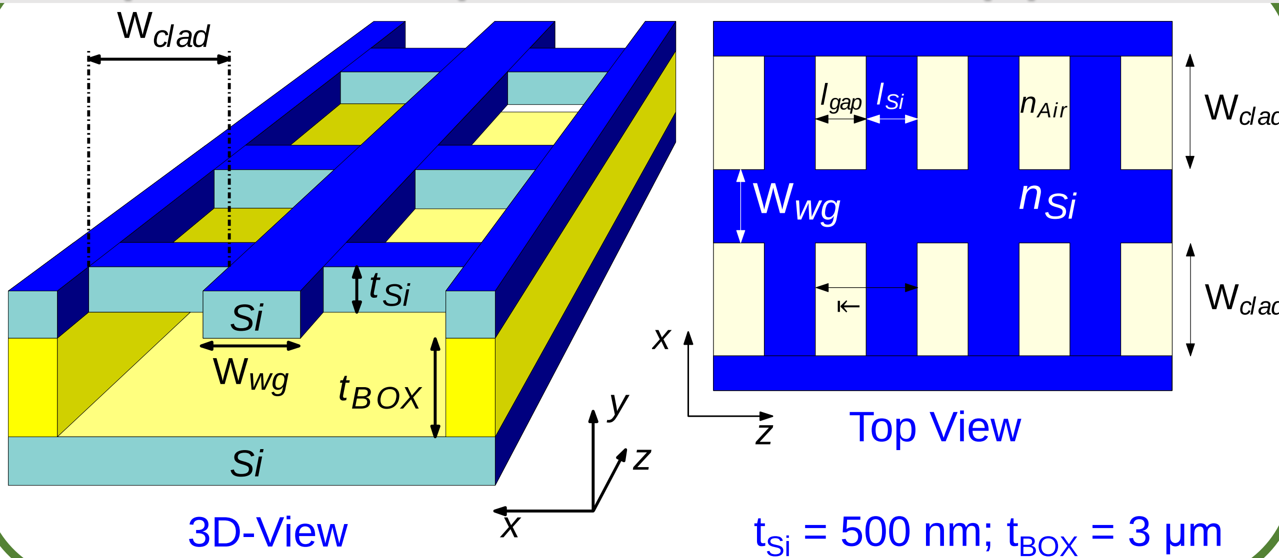
[C. Reimer et al., *Opt. Express* **20**, 29361 (2012)]

A future manufacturing research hub

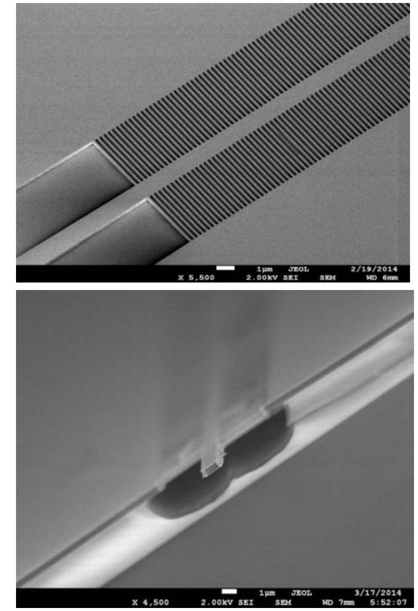
UNIVERSITY OF Southampton

The University Of Sheffield.

Suspended Si platform – new approach



t_{Si} = 500 nm; t_{BOX} = 3 µm



Waveguides: 3.5dB/cm @3.8µm
*[J. Soler Penades et al., Opt. Lett. **19**, 5661, 2014]*

Fabrication Constraints

- l_{gap} must allow the flow of hydrofluoric acid (HF)

Mechanical Constraints

- Support of the waveguide (W_{wg})
- Better robustness

Electromagnetic Constraints

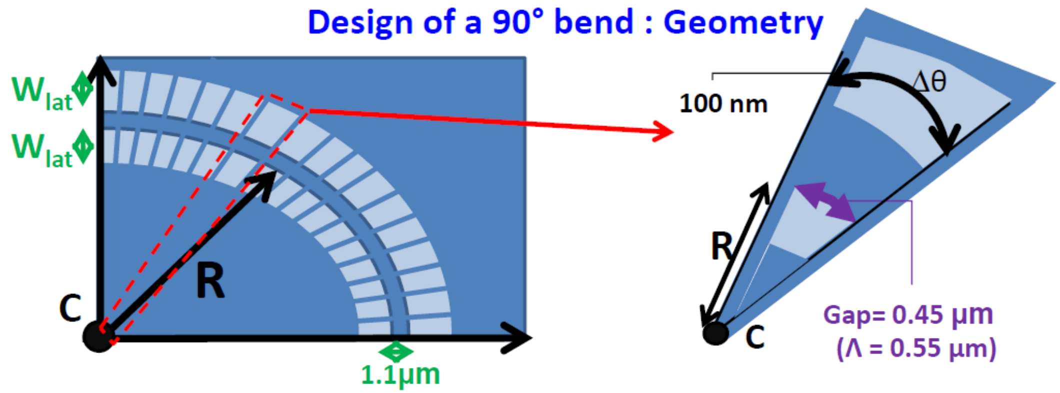
- Single-mode regime
- Operation in subwavelength regime
- Avoid lateral leakage

Floquet-Bloch mode calculations with Fourier Eigenmode Expansion Method (F-EEM)

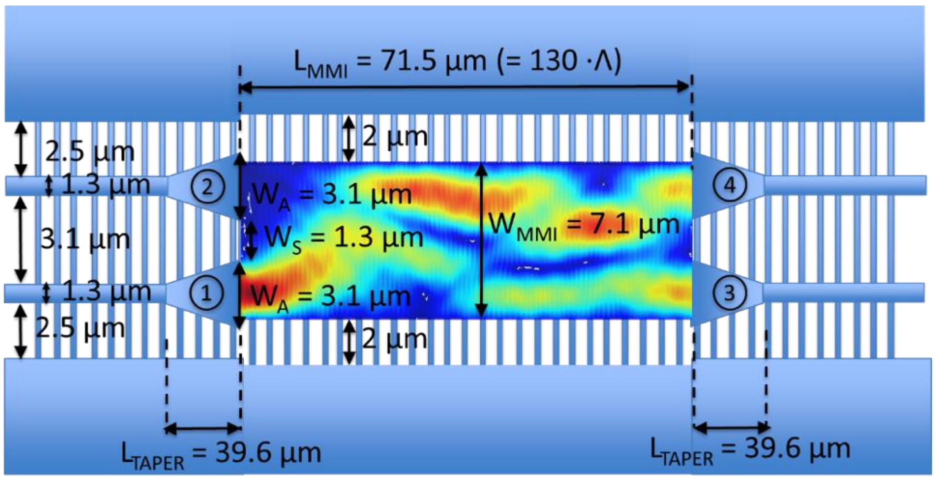
To suppress diffraction effects and reduce back-reflections:

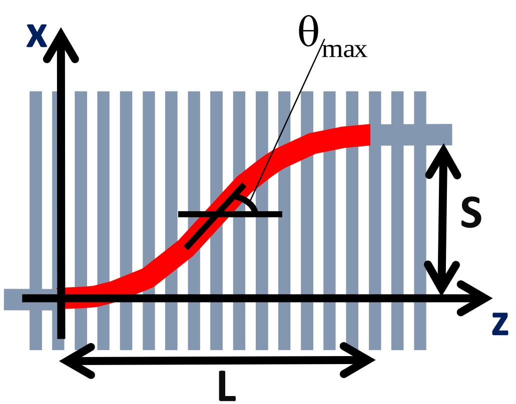
$\Lambda = l_{Si} + l_g < \Lambda_B = \lambda_0 / 2n_{FB}$

Design: MMIs, S-bends and 90° bands

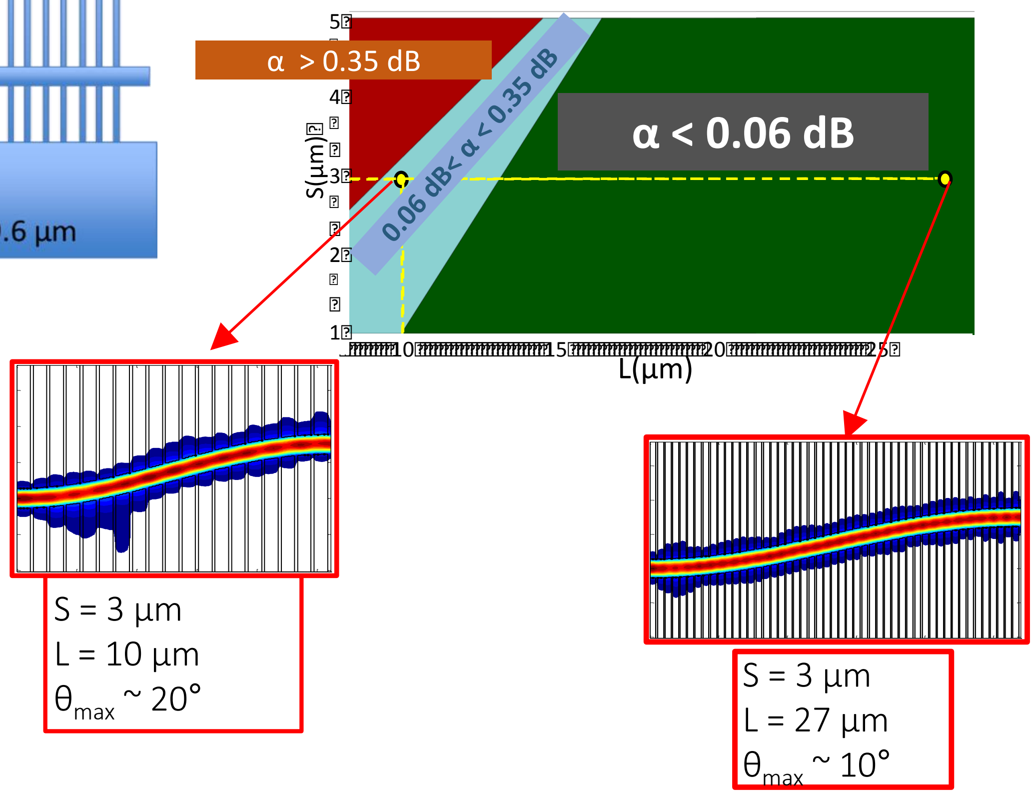


Radius must be R>15 µm for low loss operation





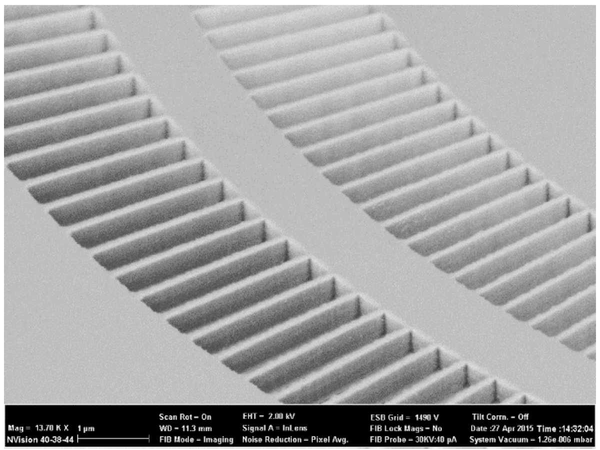
θ_{max} ≈ 10-20º for low losses



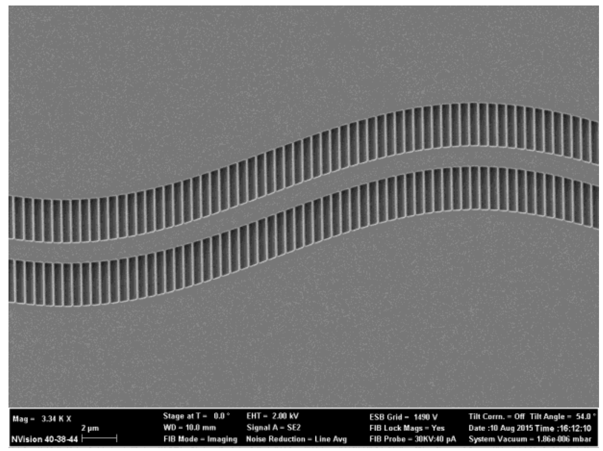
Fabricated devices

Waveguide loss: **0.82dB/cm** S-bend loss: **0.005dB/bend** 90° bend loss: **0.014dB/ben** MMI IL **<0.5dB**

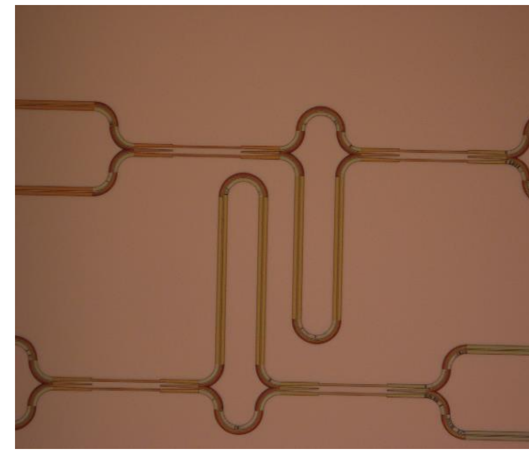
Bends:



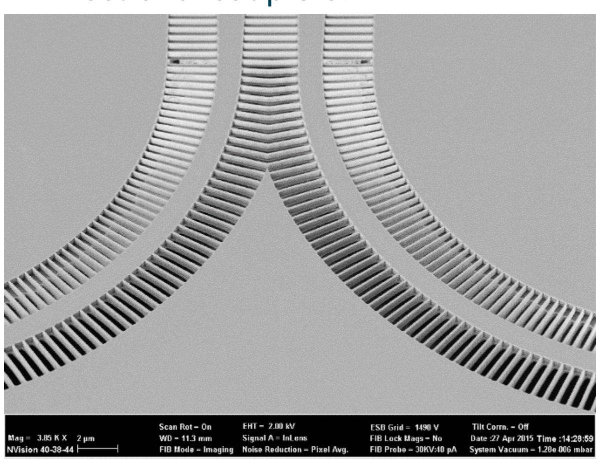
S-Bends:



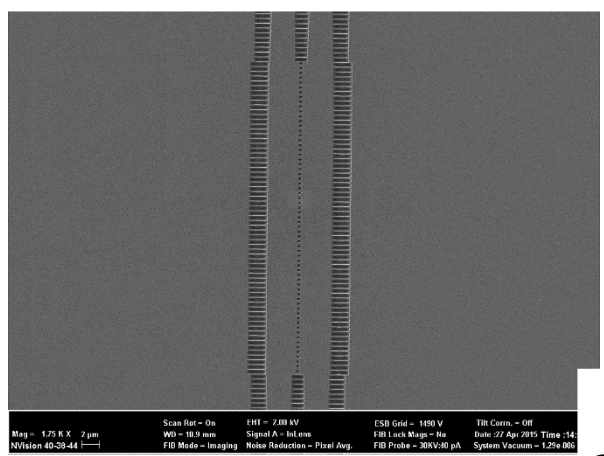
Mach-Zehnders:

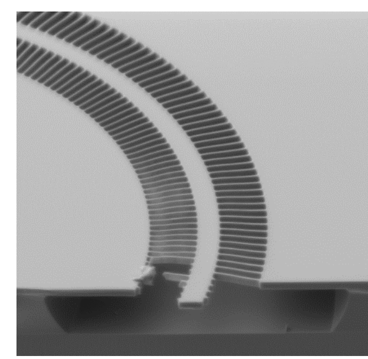


Directional couplers:



Multimode interferometers:



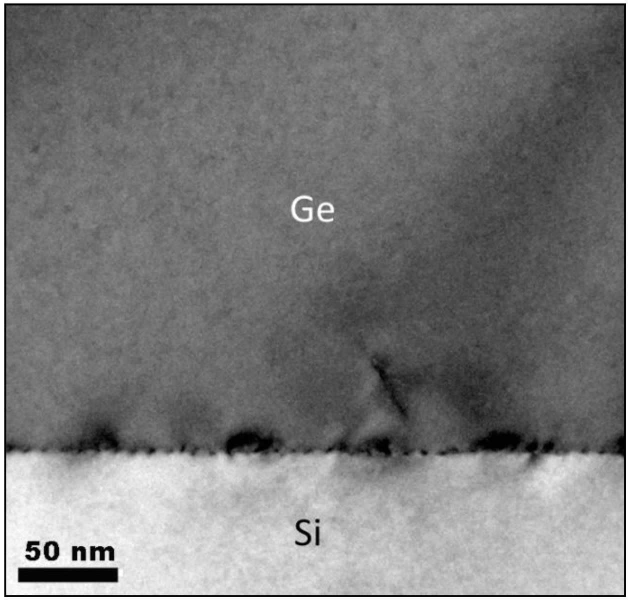


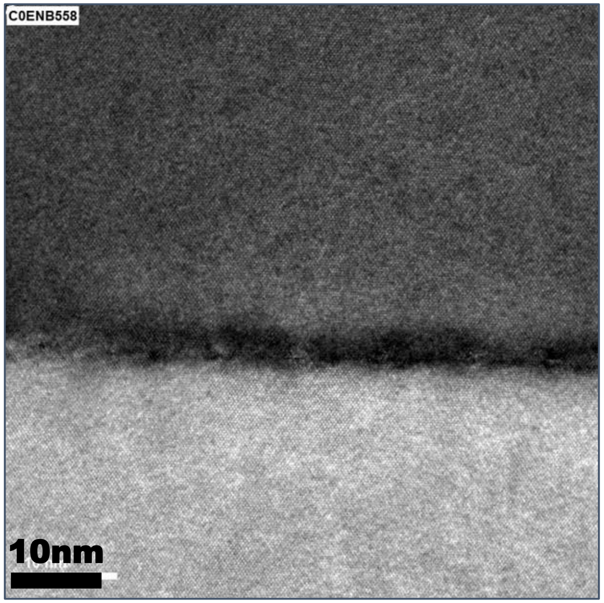
[J. Soler Penades *et al., Optics Express 2016 (in press)*]

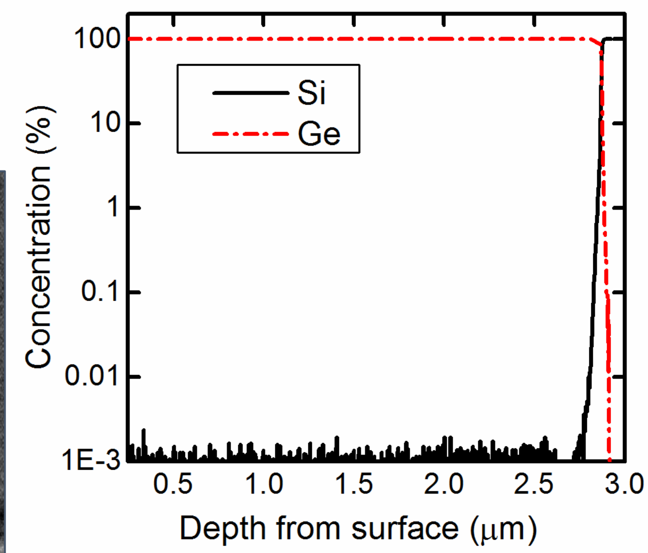
Ge-on-Si: material quality

- RPCVD Ge-on-Si
- 6" wafers with 2-3μm thick Ge layer
- TDD = 2×10^7 - 5×10^7 cm^{-2}

TEM images:

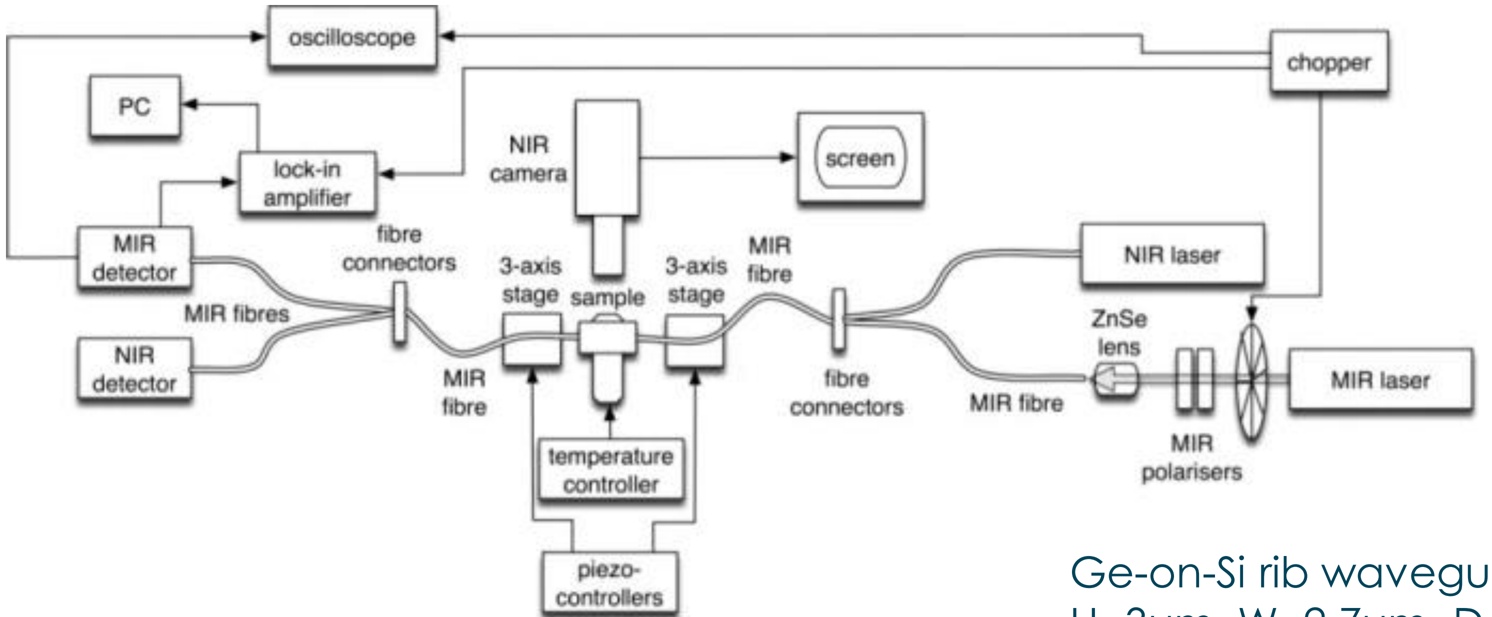




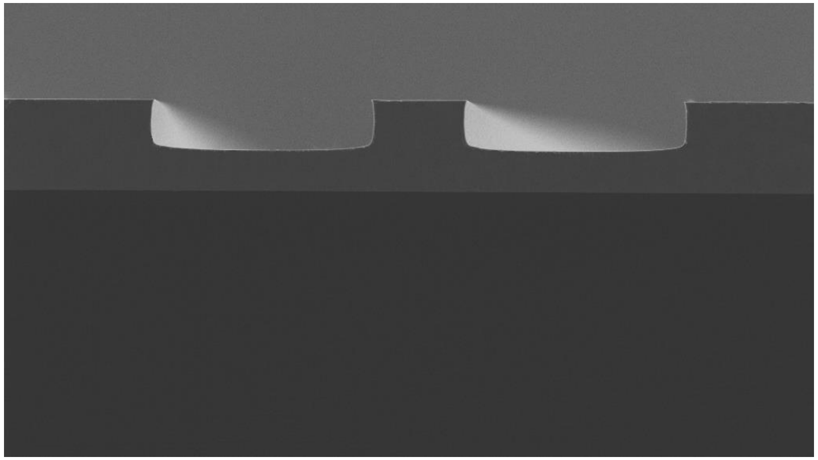


Negligible Si conc. >100nm away from interface

Ge-on-Si platform



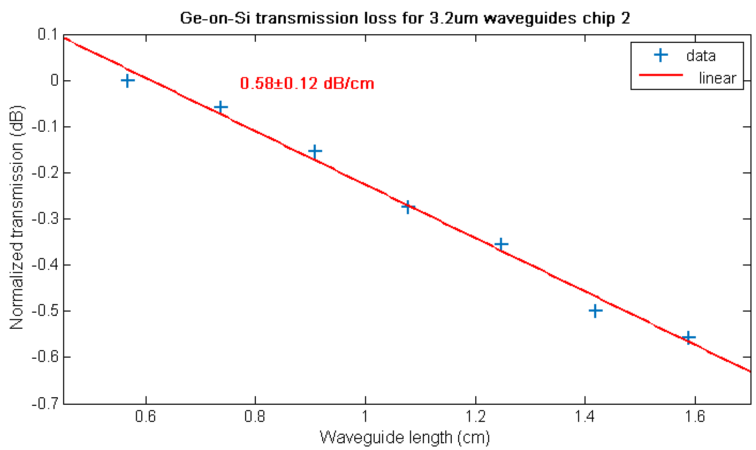
Ge-on-Si rib waveguides:
H=3μm, W=2.7μm, D=1.7μm



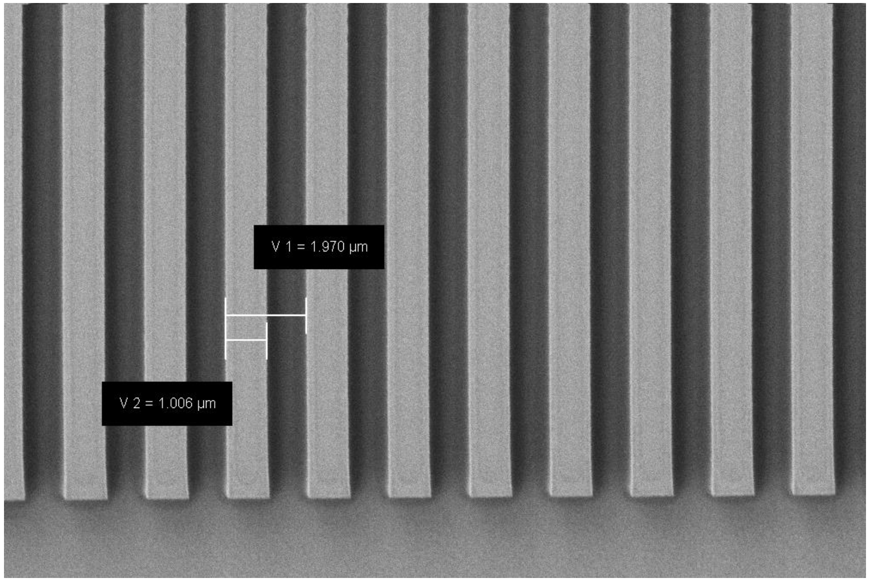
(a) Grating couplers used for couping light from mid-IR fibres to Ge waveguides
(b) Record low loss of **0.6 dB/cm** measured at 3.8μm using the cut-back method.
(c) MMIs: 0.2 dB/MMI
(d) MZIs: 20 dB extinction ratio

[M. Nedeljkovic et al., *IEEE PTL* **27**, 1040 (2015)]

Ge-on-Si passive devices

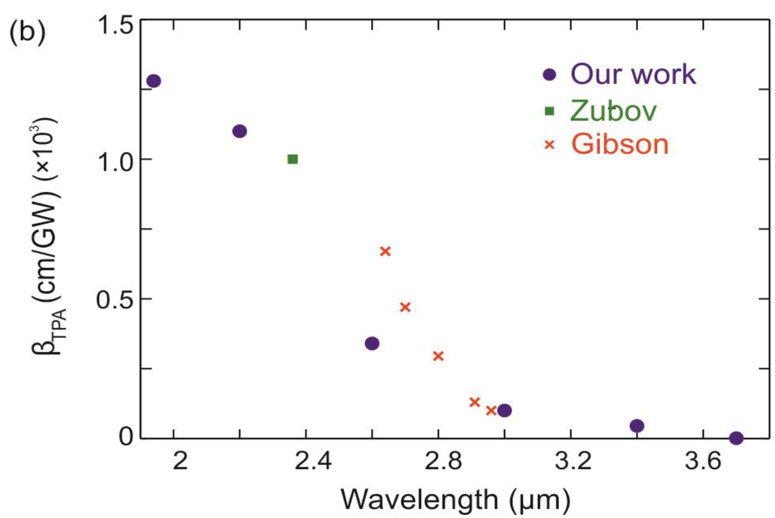


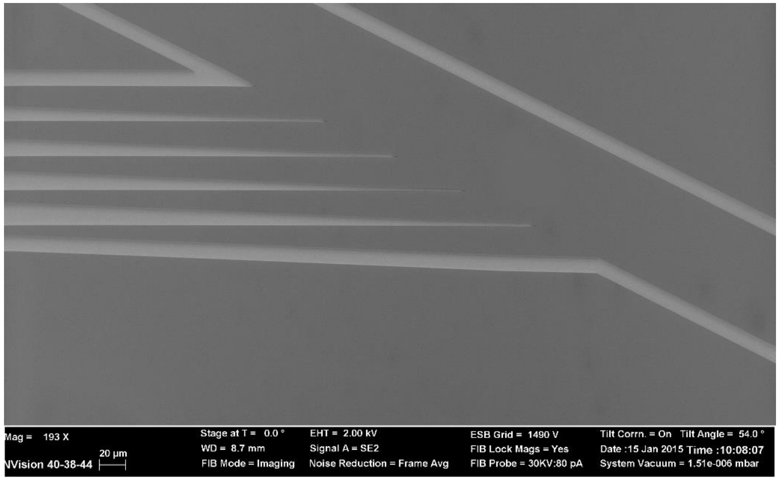
Waveguide propagation loss: **0.58±0.12 dB/cm**
[M. Nedeljkovic et al., *IEEE PTL* **27**, 1040 (2015)]



[C. Alonso-Ramos et al., *Optics Lett.* **41,** 4324 (2016)]

[J. Soler Penades et al., *CLEO Europe* 2015]





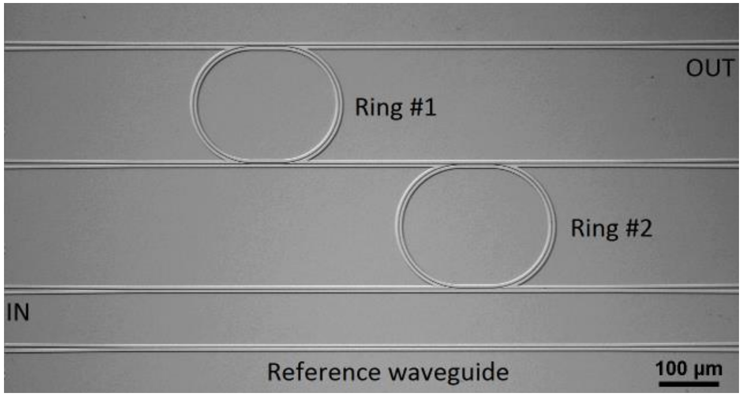
TPA measurements and high speed all optical modulation
[L. Shen *et al.*, *Opt. Lett.* **40**, 2213, 2015]

A future manufacturing research hub

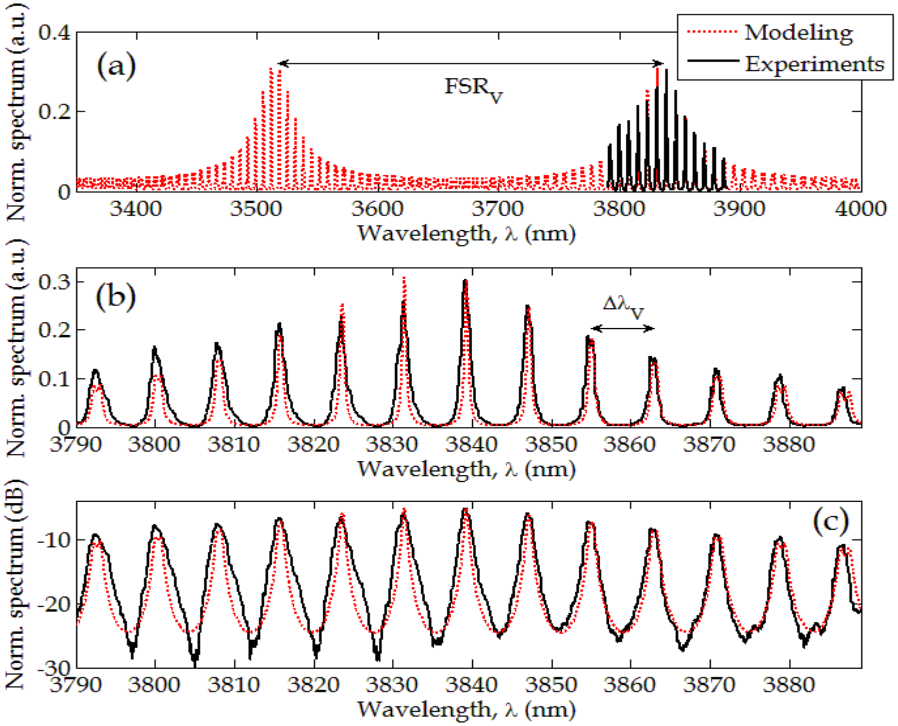
UNIVERSITY OF Southampton

The University Of Sheffield.

Ge-on-Si single and cascaded rings for sensing



[B. Troia et al., *Opt. Lett.* 41, 610 (2016)]



CORNERSTONE Project

EPSRC
Engineering and Physical Sciences Research Council

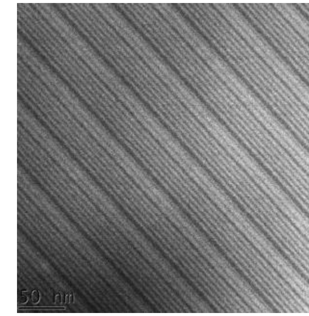
CORNERSTONE: CAPABILITY FOR OPTOELECTRONICS, METAMATERIALS, NANOTECHNOLOGY, AND SENSING

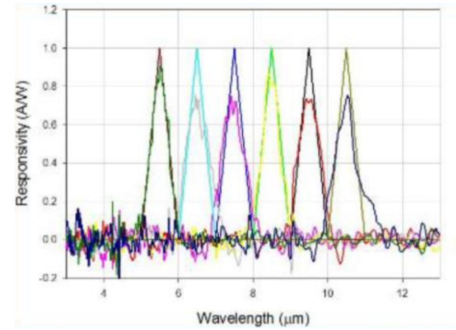
Goal: to establish Silicon Photonics Fabrication Capability that can support photonic research in UK and elsewhere

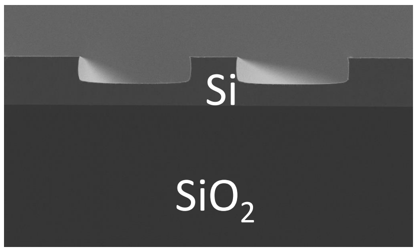
- Four-year project funded by EPSRC
- Three UK academic institutions involved as capability providers: University of Southampton, University of Glasgow, University of Surrey
- 9 UK universities involved as partners (service users): Bristol, Cardiff, Heriot-Watt, Leeds, Nottingham, St Andrews, Strathclyde, UCL, York

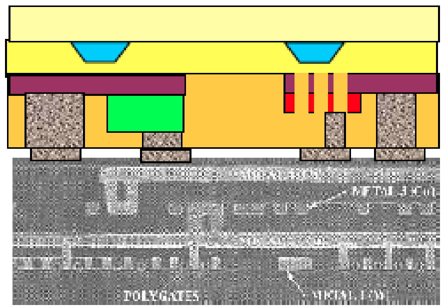
MIR Hub activities

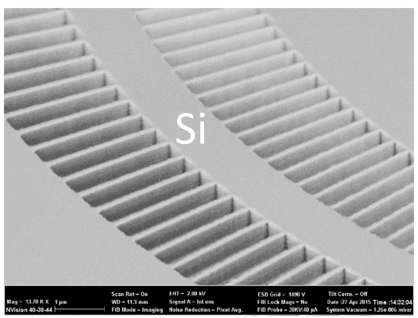
- Sources (ICLs, QCLs)
- Detectors (InGaAs, QCDs, DED)
- Integration

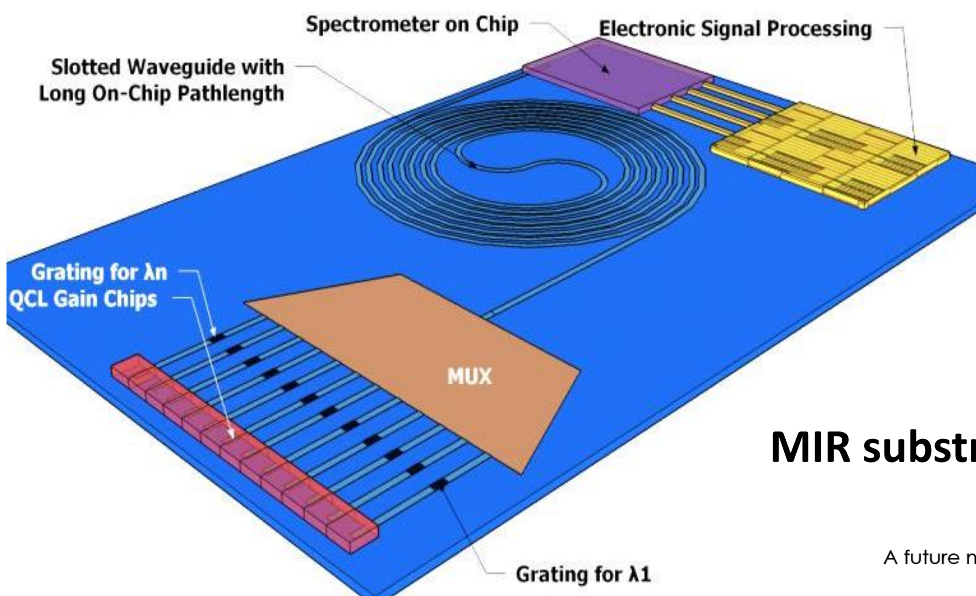


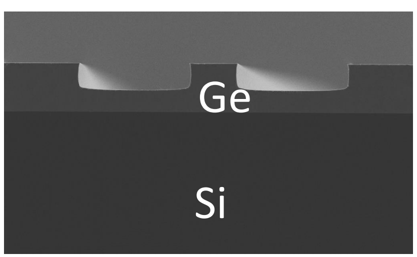












MIR substrates and fibres

The FUTURE PHOTONICS Hub
Advancing manufacturing of next-generation light technologies

EPSRC
Engineering and Physical Sciences Research Council

Goran Mashanovich

g.mashanovich@soton.ac.uk

A future manufacturing research hub

UNIVERSITY OF Southampton

The University Of Sheffield.