FACULTEIT INGENIEURSWETENSCHAPPEN
EN ARCHITECTUUR

DEPARTMENT OF INFORMATION TECHNOLOGY
PHOTONICS RESEARCH GROUP

SILICON PHOTONICS

Dries Van Thourhout / 24 October 2018 / SPICE workshop Mainz

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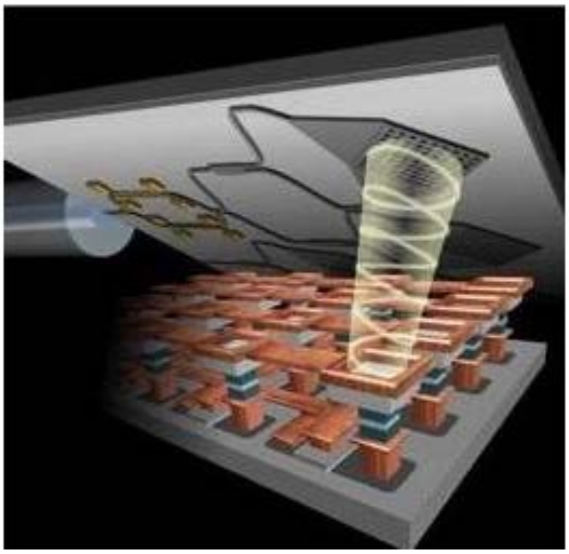
Spice

EU H2020 FET-OPEN Project

Objective: developing a **spintronic-photonic IC platform** to create world class ultra fast and low power memory and sensor designs

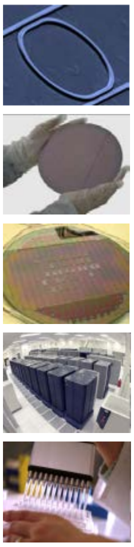
Silicon Photonics !

Need:
- Distribution of optical signals (passives)
- Switching of optical signals
- Coupling of optical signals



Coordinator: **Martijn Heck** (Aarhus)
Partners: Aarhus, IMEC, Spintec, Nijmegen, Quantum Wise

PHOTONICS RESEARCH GROUP



Research Group of Ghent University

- Faculty of Engineering and Architecture
- Department of Information Technology (INTEC)
- Associated laboratory of IMEC
- Member of the Center for Nano- & Biophotonics (NB photonics)

Technology Research

- Photonic Integration: Systems on a chip
- On silicon: "Silicon Photonics"
- Enhanced with new materials: III-V, ferro-electrics, graphene, …

Applications

- High-speed telecom and datacom
- Sensing for life sciences: visible and Mid-IR
- Optical information processing

9 Professors
16 postdocs
50 PhD students
10 support staff

20+ nationalities
6 ERC grants
4 spin-off companies
50 journal papers/year
Class 100 clean rooms

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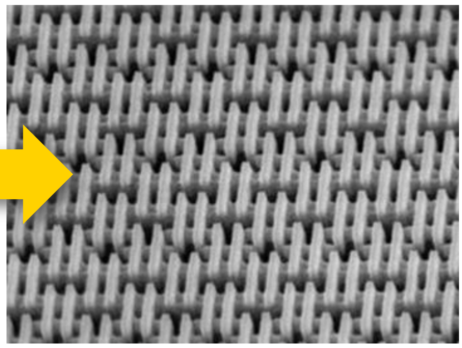
WHY INTEGRATED PHOTONICS ?

- In electronics: integration leads to miniaturization, higher performance, cost savings, robustness

IBM, mark 1

5 tons of components
can multiply in 1 sec



Modern TSMC-chip (7nm)

Several billion transistors
billions of multiplications per sec
(from TSMC.com)

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WHY NOT INTEGRATED PHOTONICS ?

Electronics ⟷ **Photonics**

Electronics

- Single building block:
  - Transistor
- Single material:
  - Silicon
- Relaxed processing requirements
  - Digital devices
  - High yield
- Massive economies of scale
- Common roadmap

Photonics

- Many building blocks
  - Laser, Modulator, Detector Filter
- Many technologies and materials
  - Laser : III-V semiconductors
  - Modulator : LiNbO3
  - Filter : Glass, Polymers
- High processing requirements
  - Analog devices
  - Low Yield
- No economies of scale advantage
- Many faction pushing own solution

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CAN "SILICON PHOTONICS" OVERCOME THIS BOTTLENECK ?

- Single material platform
  - Silicon transparent at telecom wavelengths
  - Very high contrast : compact circuits
  - Detectors (germanium), Modulators (pn-junction)
  - Wafer level testing
- Reuse installed equipment base
  - Use best equipment available
  - Without the capital expense …
  - Possibility to ramp up to high volumes
- Some standardization and roadmapping ongoing

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THE PAST 5-10 YEARS: STUNNING INDUSTRIAL DEVELOPMENT IN SILICON PHOTONICS FOR TELECOM AND DATACOM

- active optical cables (eg PSM4: 4x28 Gb/s on parallel fibers)
- WDM transceivers (eg 4 WDM channels x 25 Gb/s on single fiber)
- coherent receiver (eg 100 Gb/s PM-QPSK)
- fiber-to-the-home bidirectional transceiver (eg 12 x 2.5 Gb/s)
- monolithic receiver (eg 16x20Gb/s)
- 40Gb/s, 50Gb/s and 100 Gb/s Ethernet (future: 400Gb/s)
- …

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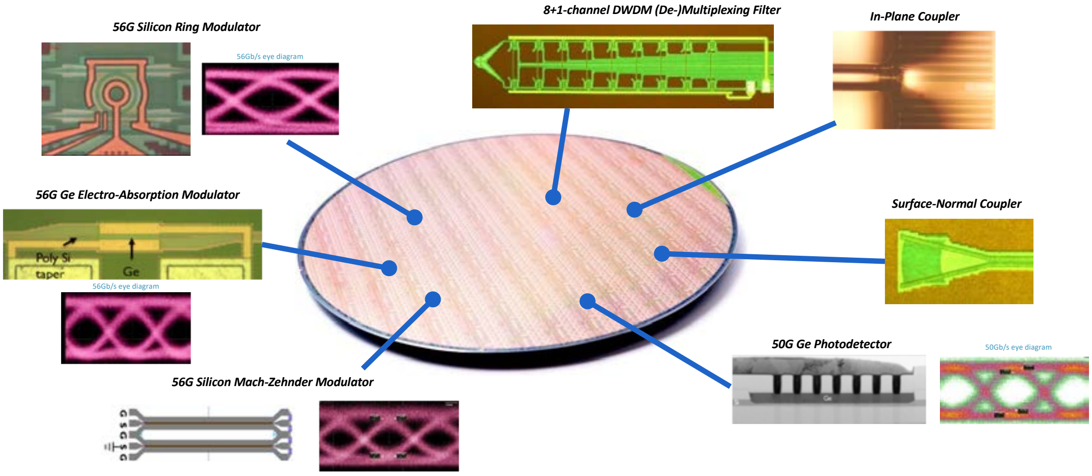
IMEC SILICON PHOTONICS PLATFORM

FULLY INTEGRATED 8X50G DWDM SI PHOTONICS TECHNOLOGY



Co-integration of the various building blocks in a single platform (O-band, C-band)

Today available on 200mm wafer size, coming soon on 300mm

95% compatible with CMOS130 in commercial foundries

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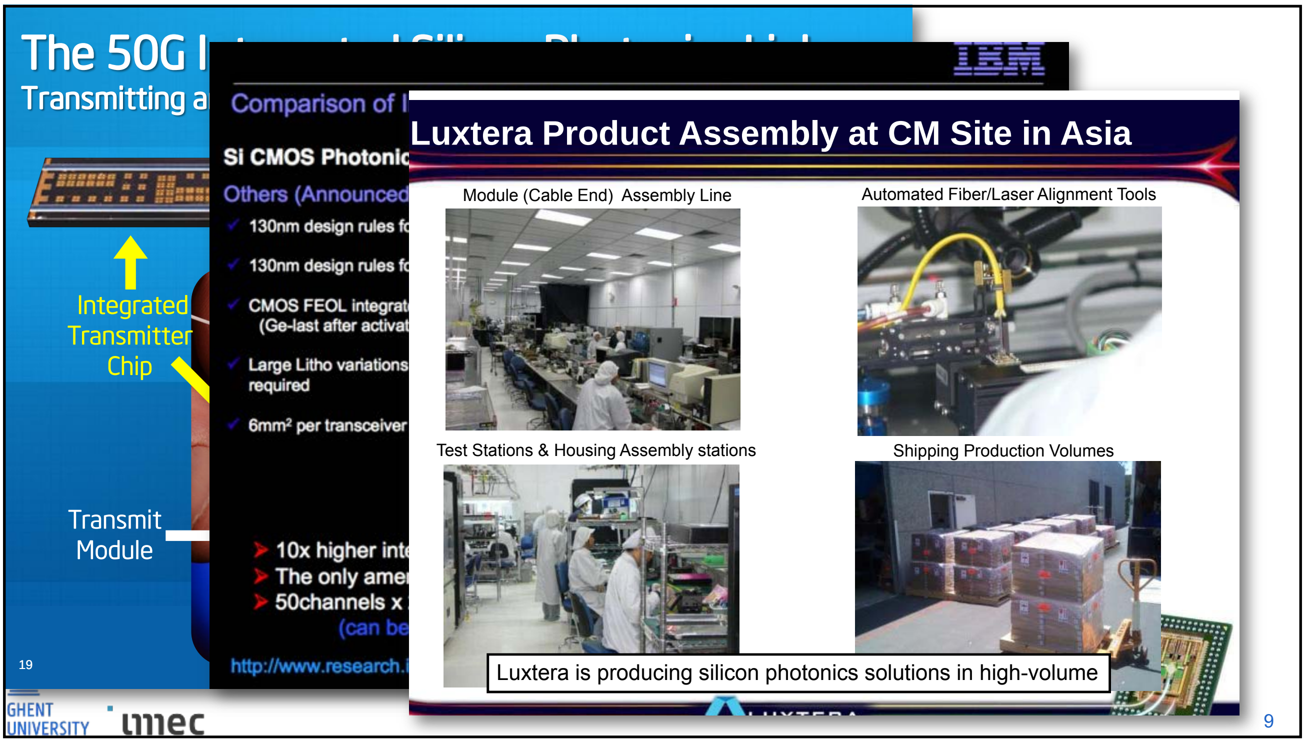
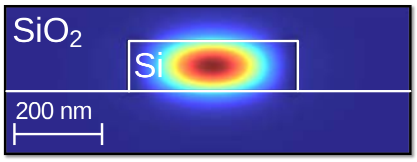
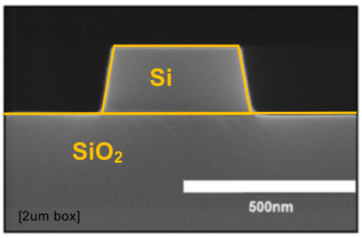
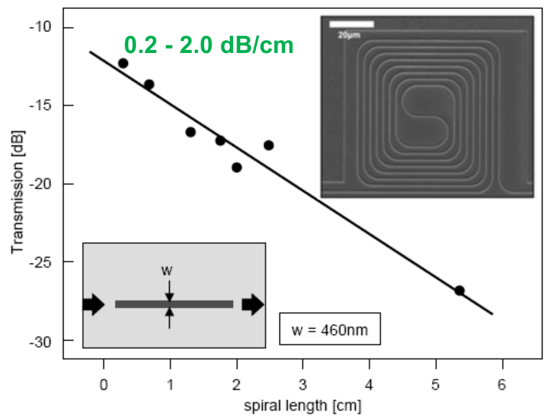


STRAIGHT WAVEGUIDE

- Our standard waveguide: 450nm x 220nm Si
- Fabricated using 193nm DUV lithography
- In standard pilot line, on 200mm or 300mm wafer
- Starting from SOI or amorphous silicon







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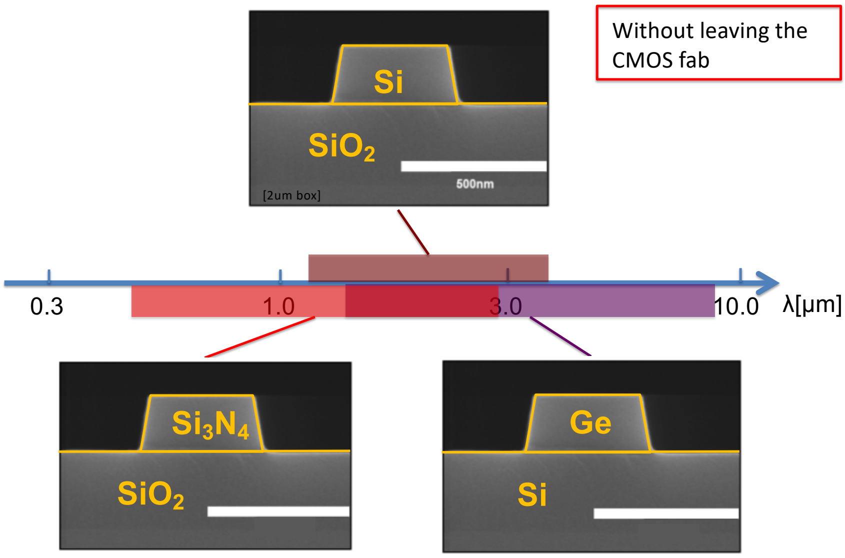
Bogaerts e.a. , JSTQE 16, 33-44 (2010)

SILICON PHOTONICS: EXTENDING THE WAVELENGTH RANGE



Without leaving the CMOS fab

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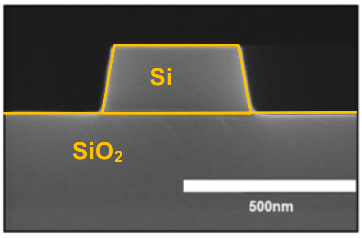
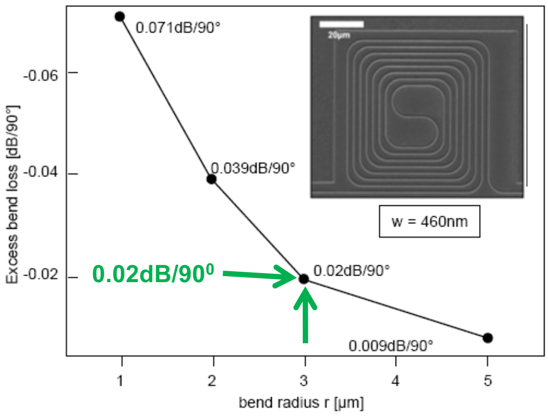
BEND WAVEGUIDE

S.K. Selvaraja, JLT 27, p.4070 (2009)
Y. A. Vlasov and S. J. McNab, Optics Express, p. 1622 (2004)

- Our standard waveguide: 450nm x 220nm Si
- Fabricated using 193nm DUV lithography
- In standard pilot line, on 200mm wafer
- Starting from SOI or amorphous silicon



- In agreement with FDTD calculations
- Offset straight-bend might improve performance (?)



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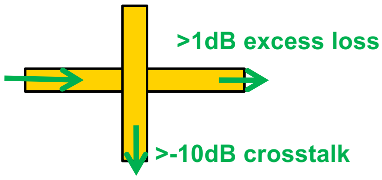
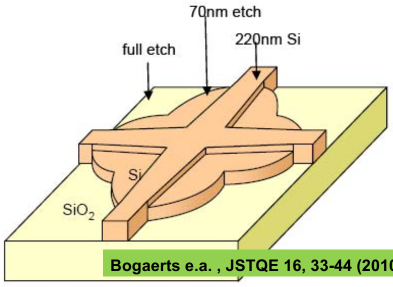
CROSSINGS

Standard Crossing

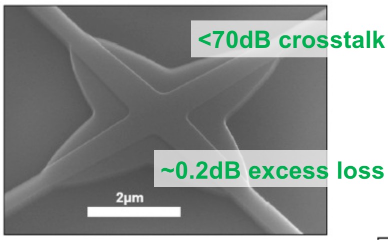


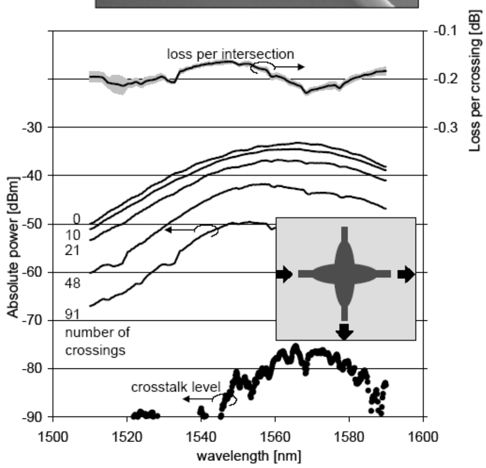
Not practical !

Improved version



Bogaerts e.a. , JSTQE 16, 33-44 (2010)





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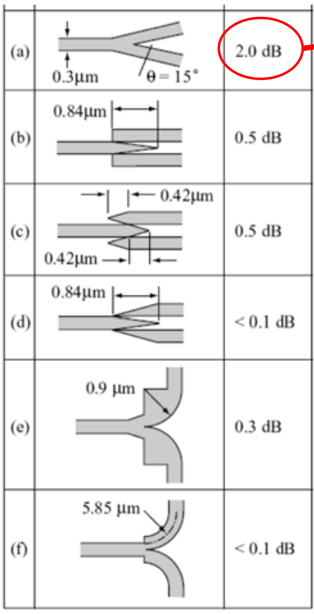
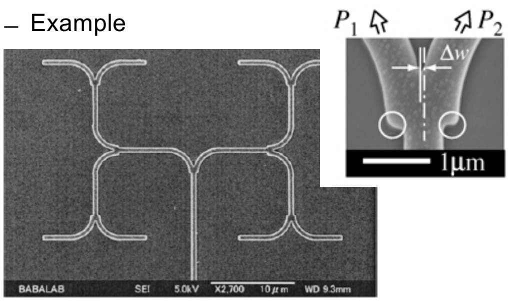
THE Y-JUNCTION



Large **losses** for standard Y-junction
Need **improved** design !!!

– Example



– Experiment: 0.3dB excess loss
– Some imbalance due to opt. prox. effects

Sakai e.a., IEICE Trans E85-C 1033 (2002)

Fukazawa e.a. Jpn JAP 41, p L1461 (2002)

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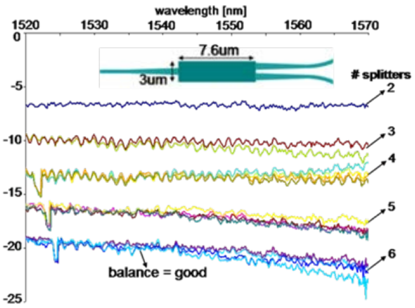
Other

MULTI-MODE INTERFEROMETER (MMI)

Standard MMI splitter

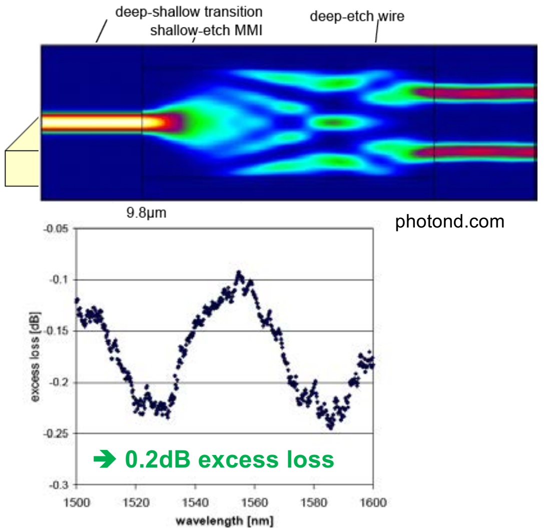


➔ 0.3dB excess loss

Bogaerts e.a. , JSTQE 16, 33-44 (2010)

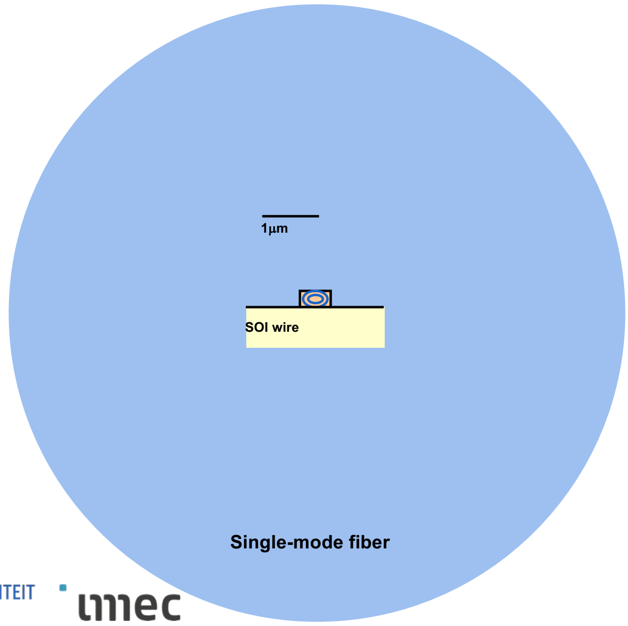
IME A*STAR paper, PTL (2013)

Improved version



➔ 0.2dB excess loss

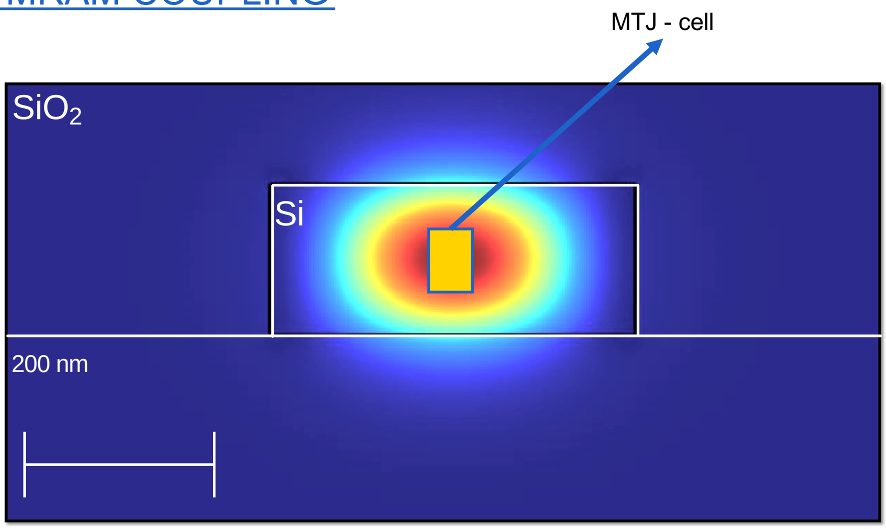
FIBER - CHIP COUPLING



We would like

- Low loss
- Broadband
- High coupling tolerance
- No facet reflections
- Waferscale testability
- Easy to fabricate
- A solution for the polarization problem

CHIP - MRAM COUPLING



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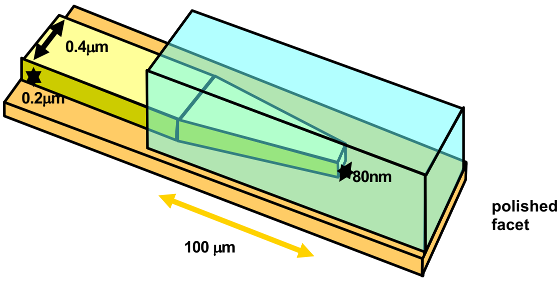
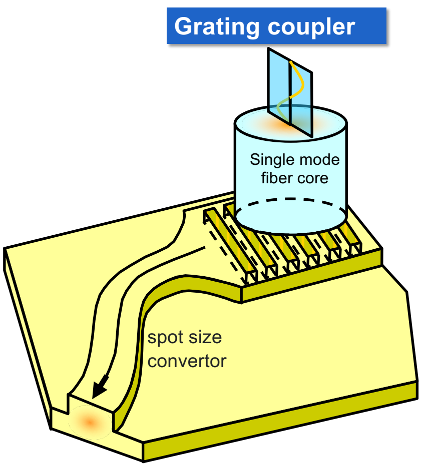
FIBER CHIP COUPLING: TWO WIDELY USED SOLUTIONS





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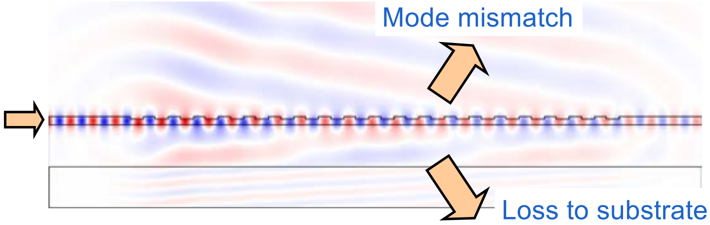
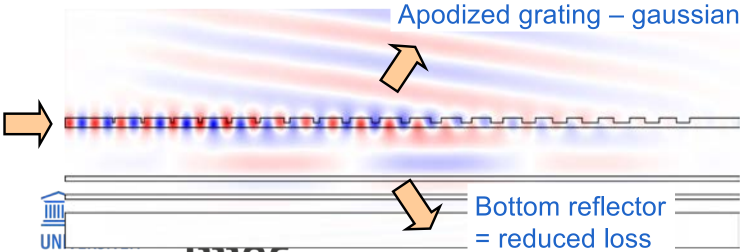
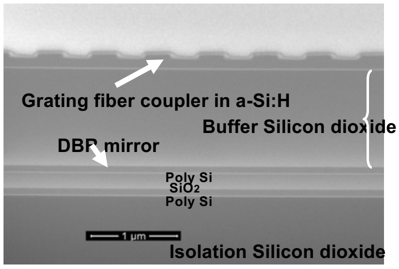
GRATING COUPLER – OPERATING PRINCIPLE

– Standard coupler (33% efficiency)



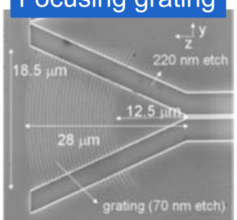
– Improved coupler (>90% efficiency)





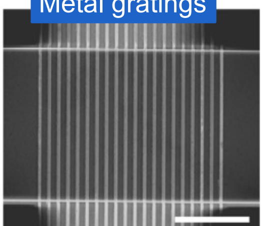
GRATING ZOO

Focusing grating



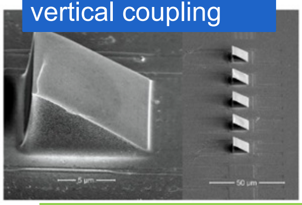
F. Van Laere, PTL 19, p. 1919 (2006)

Metal gratings



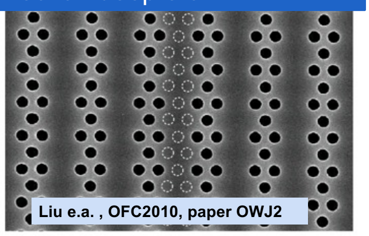
Scheerlinck, APL 92 p.031104 (2008)

Polymer wedge for vertical coupling



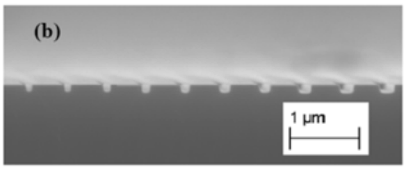
Schrauwen e.a.Phot. West, 7218, , p.72180B (2009)

Photonic crystal grating for low reflection deep etch



Liu e.a. , OFC2010, paper OWJ2

Apodized grating



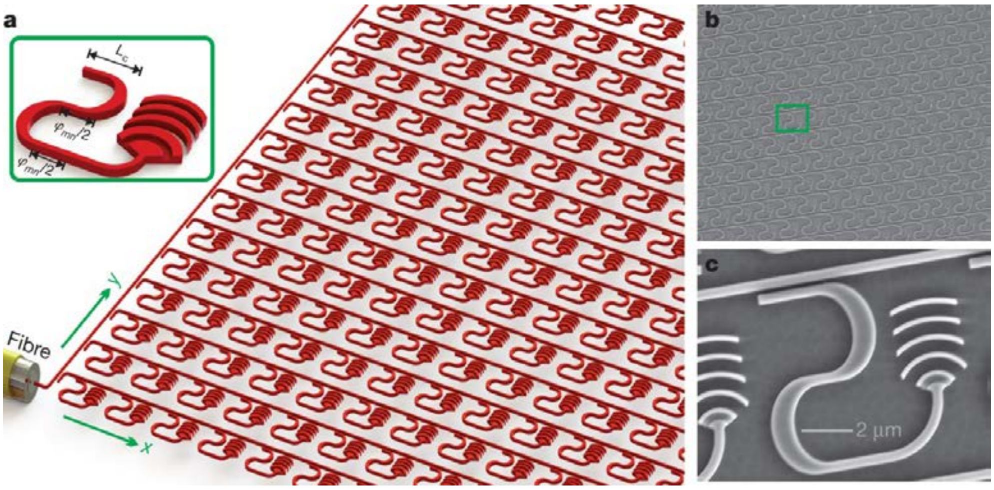
Tang e.a. , OFC2010, paper OWJ6

Large-scale nanophotonic phased array

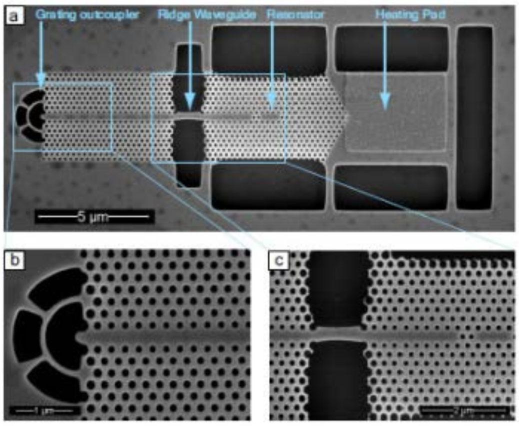
Jie Sun, Erman Timurdogan, Ami Yaacobi, Ehsan Shah Hosseini & Michael R. Watts

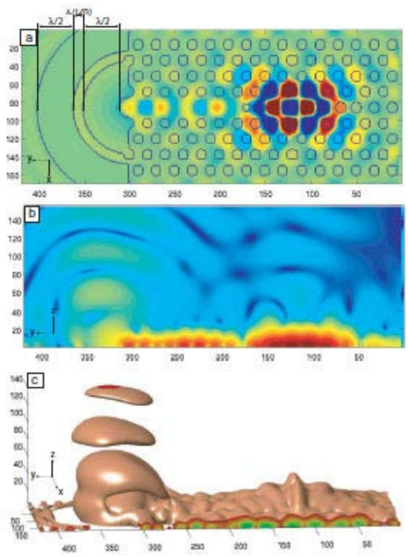
Affiliations | Contributions | Corresponding author

Nature **493**, 195–199 (10 January 2013) | doi:10.1038/nature11727
Received 02 August 2012 | Accepted 29 October 2012 | Published online 09 January 2013



MINIMIZING THE OUTPUT COUPLER





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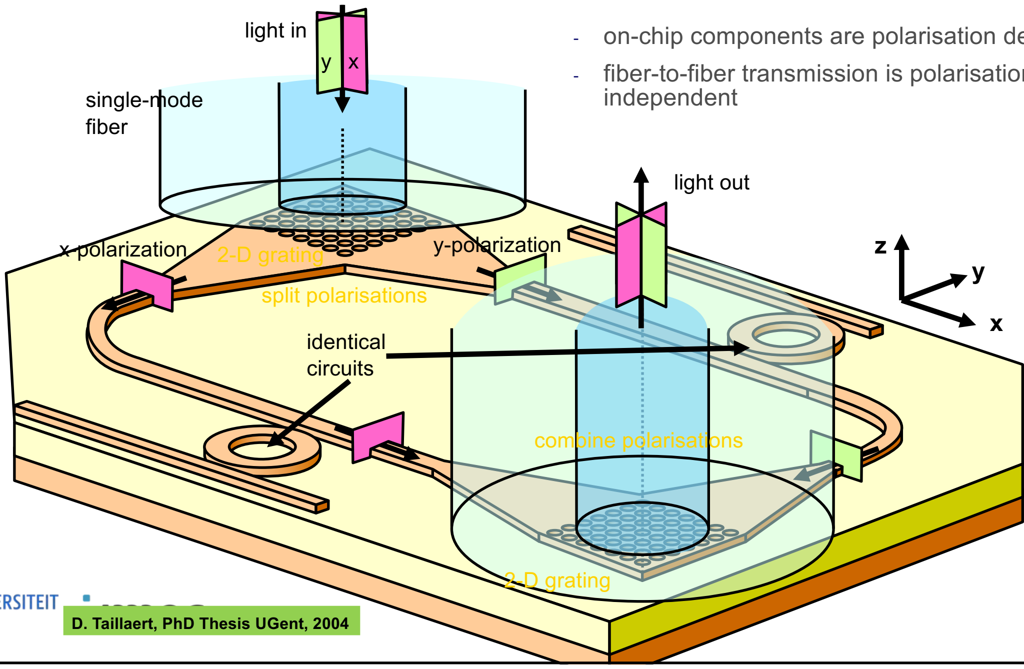
Andrei Faraon e.a., Optics Express 2008 (Stanford)

POLARISATION DIVERSITY CIRCUIT

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



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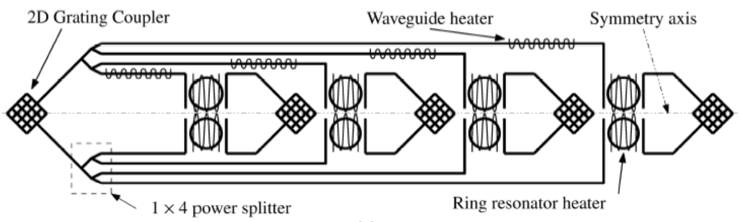
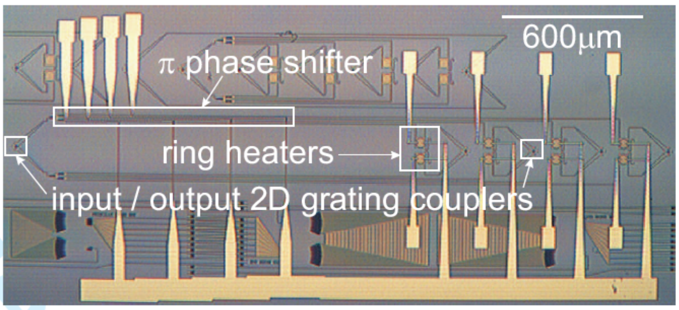
D. Taillaert, PhD Thesis UGent, 2004

2D-GRATING COUPLERS ALLOW CONTROL OF POLARIZATION





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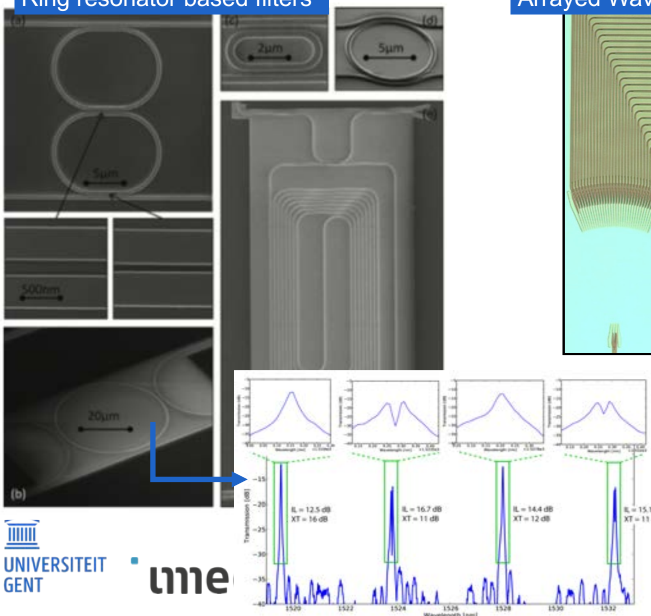
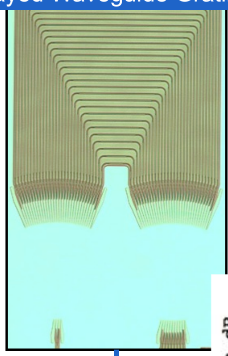
See Halir e.a. , OFC 2010, paper OWJ1

LARGE FAMILY OF PASSIVE DEVICES

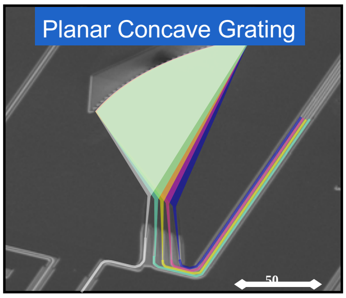
Ring resonator based filters

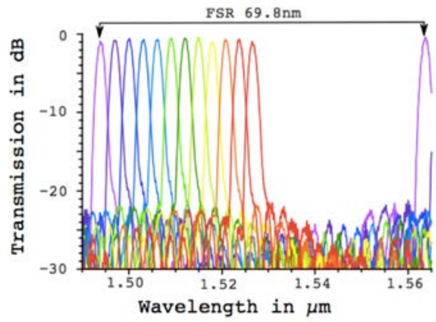


Arrayed Waveguide Grating



Planar Concave Grating





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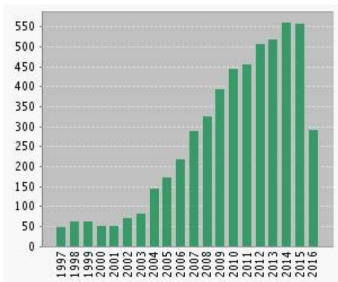
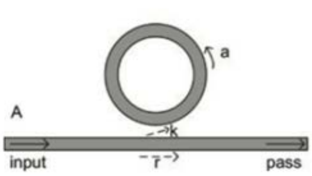
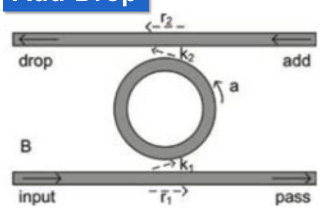
RING RESONATORS



All-Pass



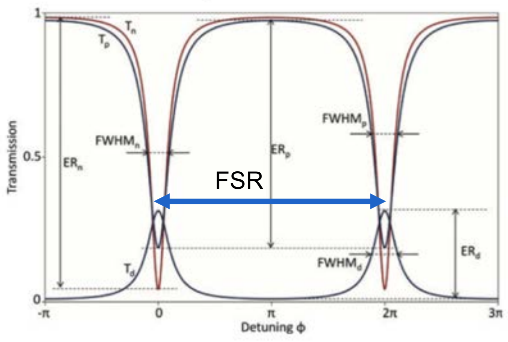
Add-Drop



Main characteristics

- Resonance wavelength
- Free Spectral Range (Periodicity)
- Quality Factor Q (Q=λ/Δλ)
- Finesse
- Loss …

Q=1E3 → Δλ=1.5nm
Q=1E6 → Δλ=1.5pm



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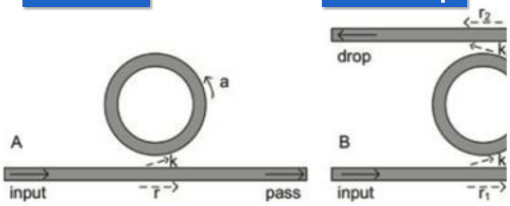
Bogaerts e.a., LPR 2012
Li e.a., LPR 2016

RING RESONATORS

All-Pass

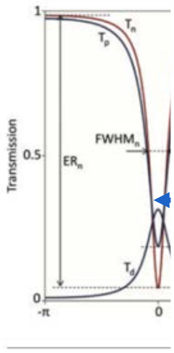
Add-Drop

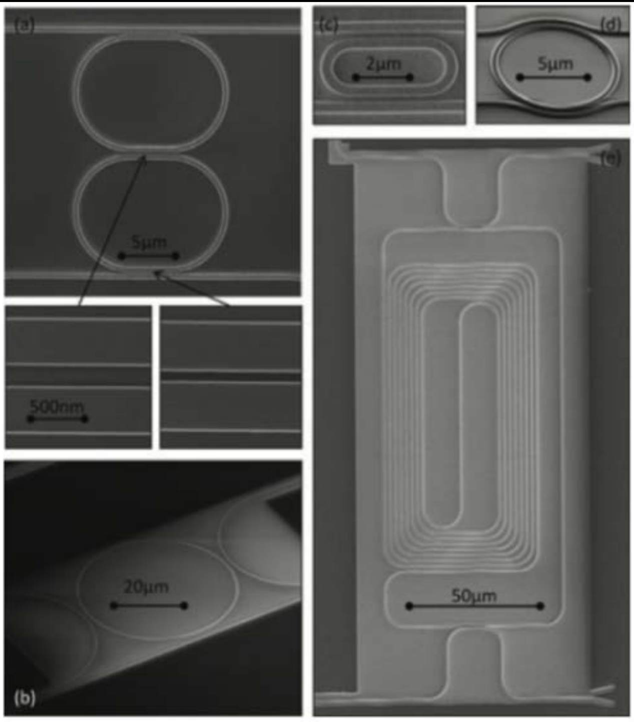


Main characteristics

- Resonance wavelength
- Free Spectral Range (Periodicity)
- Quality Factor Q ($Q=\lambda/\Delta\lambda$)
- Finesse
- Loss …

Q=1E3 → $\Delta\lambda$=1.5nm
Q=1E6 → $\Delta\lambda$=1.5pm





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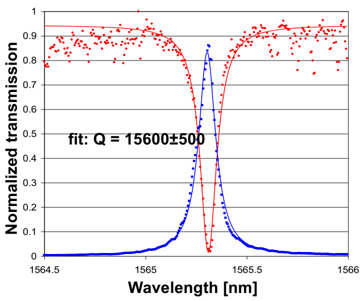
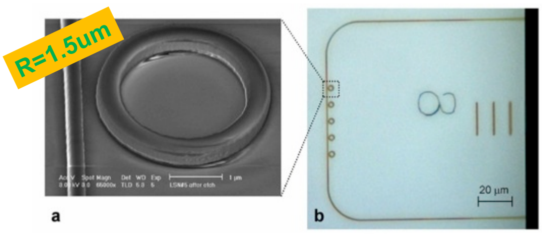
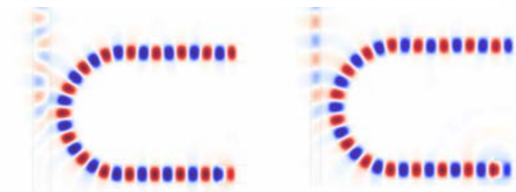
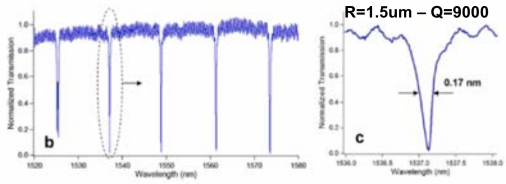
RING RESONATORS









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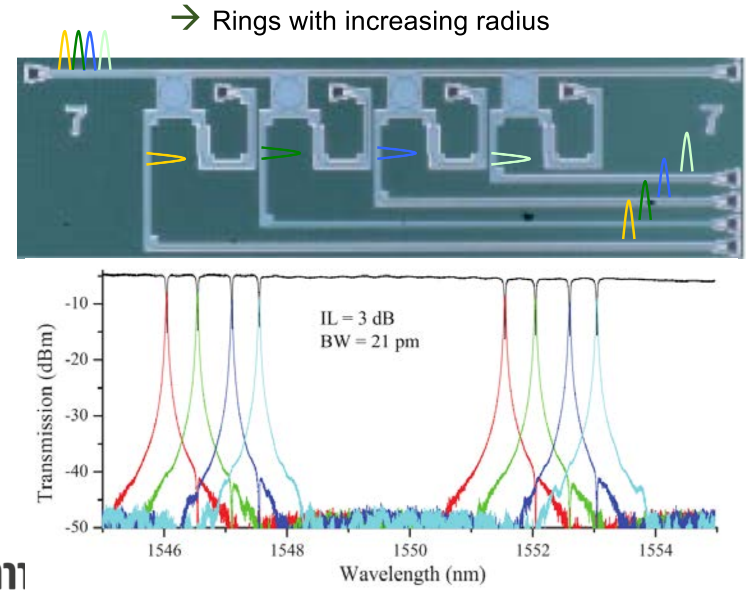
Bogaerts e.a. , JSTQE 16, 33-44 (2010)

Xu e.a. , OE 16, pp 4309 (2008)

THE RING RESONATOR AS WAVELENGTH DEMULTIPLEXER

→ Rings with increasing radius



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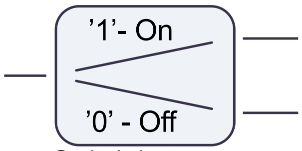
SI PHOTONICS PLATFORM – SWITCHING TECHNOLOGIES



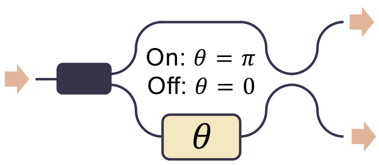
Switch between two output ports

θ Optical phase shift

$$\Delta\theta = (2\pi/\lambda)\Delta n L$$

Refractive index change required!!

MZI-based switch

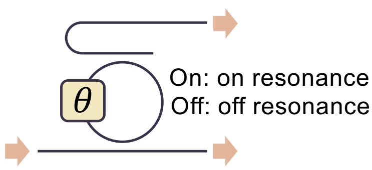


+ Bandwidth (10s of nm)
- Efficiency (~mW)

J. Van Campenhout, OpEx 17, p23793 (2009)

A. Ribeiro, OpEx 25, p29779 (2017)

Ring-resonator-based switch



+ Efficiency (~μW)
- Bandwidth (<1 nm)

Q. Xu, OpEx 15, p430 (2007)

N. Sherwood-Droz, OpEx 16, p15915 (2008)

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SI PHOTONICS PLATFORM – REFRACTIVE INDEX CHANGE

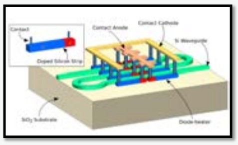
Electro-Optic effect

$$\Delta n_{\mathrm{LiNbO_3}}/E = 100\ \mathrm{pm/V}$$
$$\Delta n_{\mathrm{strained\text{-}Si}}/E = 15\ \mathrm{pm/V}$$

$LiNbO_3$ - Yes
Silicon - No
(unless strained)

Thermo-Optic effect

$$\Delta n_{\mathrm{Si}}/T = 1.86 \times 10^{-4}\ \mathrm{K}^{-1}$$

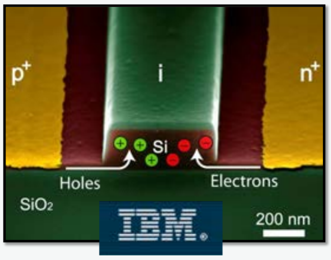


Large in Silicon (2 x $LiNbO_3$)
-> but slow (~100 µs)

Plasma-Dispersion effect

$$\Delta n_{\mathrm{Si}}(N) = -8.8 \times 10^{-22} N - 8.5 \times 10^{-18} N^{0.8}$$
$$\alpha(N) = (8.5 \times 10^{-18} + 6 \times 10^{-18}) N$$

Carrier injection or
Carrier depletion



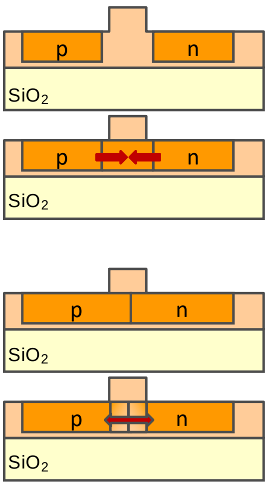
CARRIER INJECTION TECHNOLOGY - CONCEPT

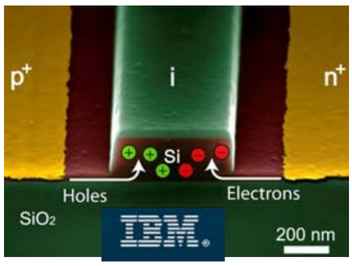
Carrier injection

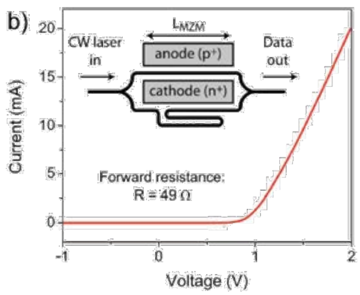
- p-i-n diode in forward bias
- Inject carriers into waveguides
- Strong effect (many carriers)
- Moderate fast effect (~1 GHz)

Carrier depletion

- p-n diode in reverse bias
- Extract carriers from waveguides
- Weaker effect
- Fast effect (>40 GHz)

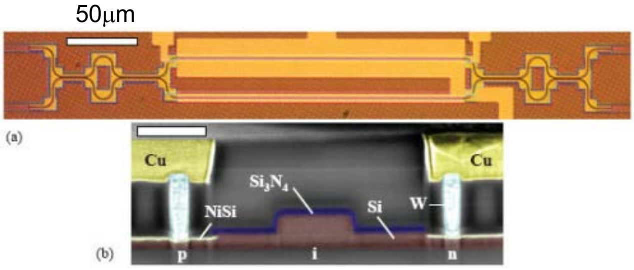


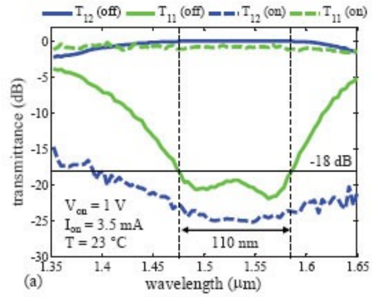




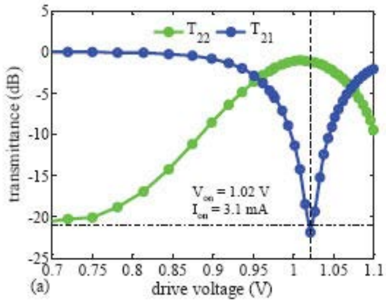
W. Green, OpEx 15, p17106 (2007)

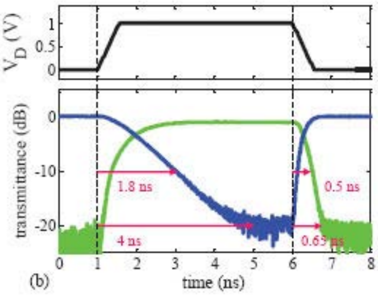
A TYPICAL MACH-ZEHNDER PIN SWITCH





J. Van Campenhout, OpEx 17, p23793 (2009)





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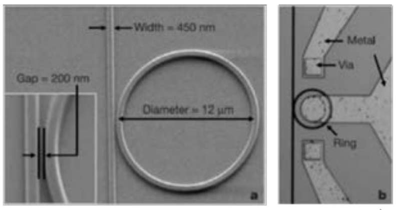
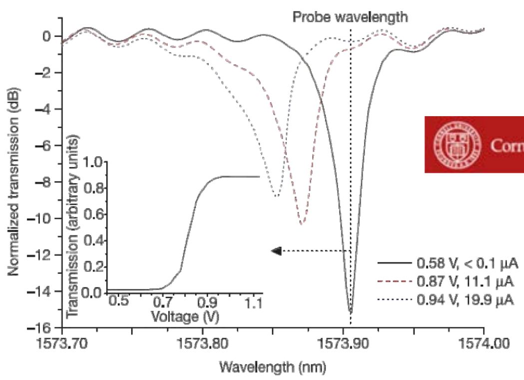
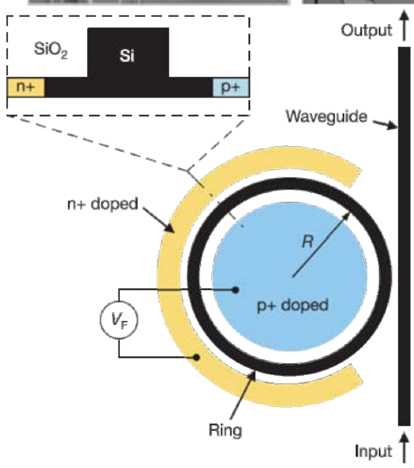
INJECTION MODULATOR (RING)

- Use resonator to enhance effects
- Speed ~2GB/s
- With pre-emphasis: >20GB/s





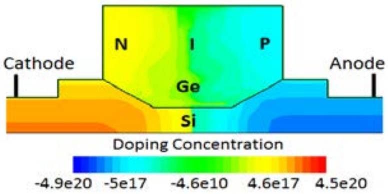


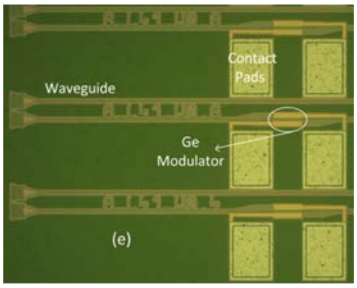
Q. Xu et al, nature 435(19), p03569 (2005)

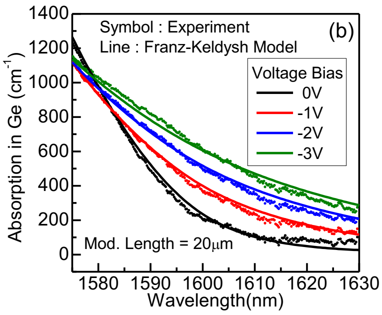
GeSi Franz Keldysh ELECTRO-ABSORPTION MODULATOR

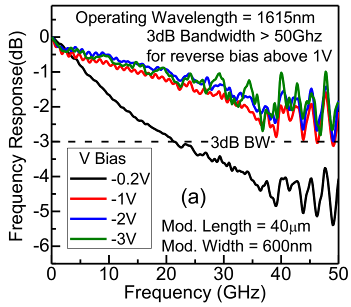
Advantages

- Uses existing Ge-detector technology
- Compact, optical BW > 35nm
- 3dB BW > 40GHz









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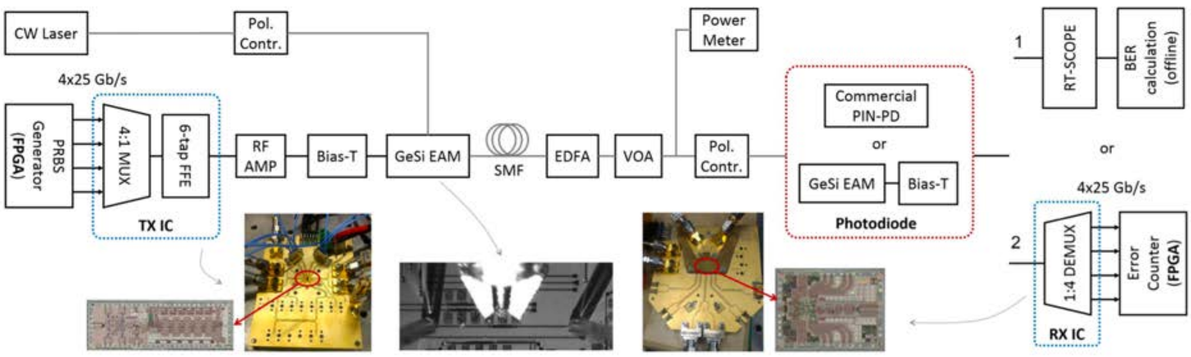
Gupta, S., et al. 50GHz Ge Waveguide Electro-Absorption Modulator Integrated in a 220nm SOI Photonics Platform. In *Optical Fiber Communication Conference* (Vol. 1, pp. 5–7) 2015.

RESEARCH ULTRA-HIGH-SPEED COMMUNICATION

ELECTRONIC-PHOTONIC CO-INTEGRATION

– Co-design and co-integration of electronic ICs and photonic ICs for advanced TxRx (100G per wavelength & polarization)



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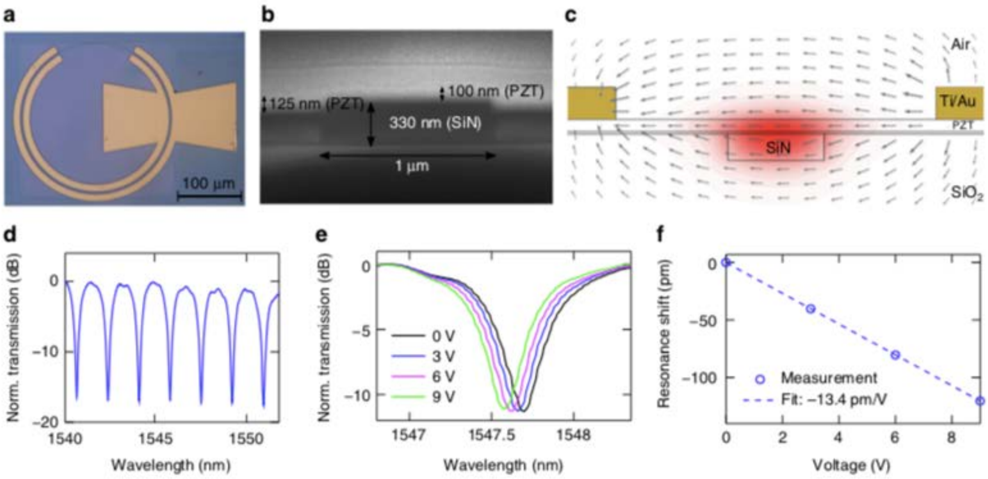
IDLab INTERNET & DATA LAB

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-05846-6 OPEN

Nanophotonic Pockels modulators on a silicon nitride platform



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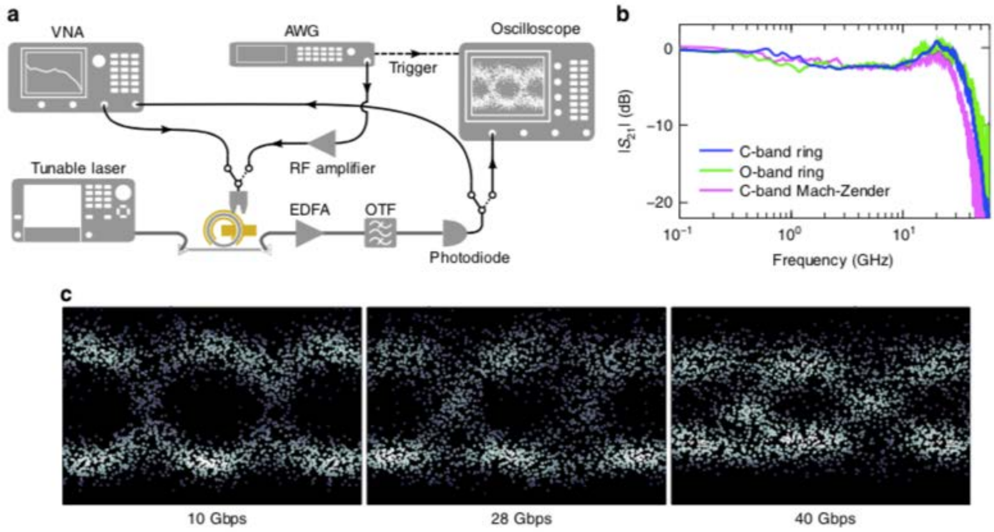
PZT ON SILICON NITRIDE

$V_\pi L$ = 3.2 V.cm - α ≈ 1 dB cm^{-1} – BW = 33GHz



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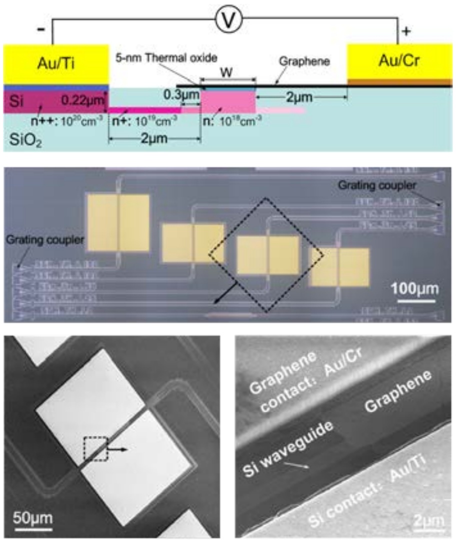
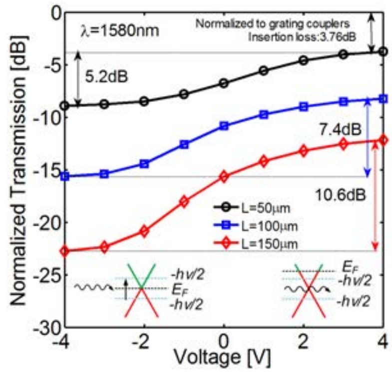
GRAPHENE MODULATOR FABRICATION



IEDM 2014, Y. Hu et al.



- Extinction Ratio (ER) and Insertion Loss (IL) scale with device length
- Best trade-off for 50μm device
- Neutrality point shifted to -4 Volt
- Stable up to at least 50C

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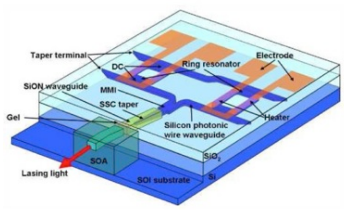
LASERS FOR SILICON PHOTONICS ?

- Silicon has indirect bandgap: no light emission
- Need direct bandgap III-V semiconductors !

Integration ??

- Option 1: Off-chip laser
  - Most mature solution
  - Compatible with high temperature operation
  - Limited flexibility, not scalable, coupling loss
- Option 2: Flip-Chip
  - Prefabricated, pretested laser diode
  - Mature
  - Limited flexibility, limited scalability



Song e.a. OE 17, 14063-14068 (2009).

Luxtera "Lamp"

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LASERS FOR SILICON PHOTONICS: MANY OPTIONS

- Option 3: Wafer bonding (heterogeneous integration)
  - Rapidly maturing
  - Very versatile (different materials, different device structures ...)

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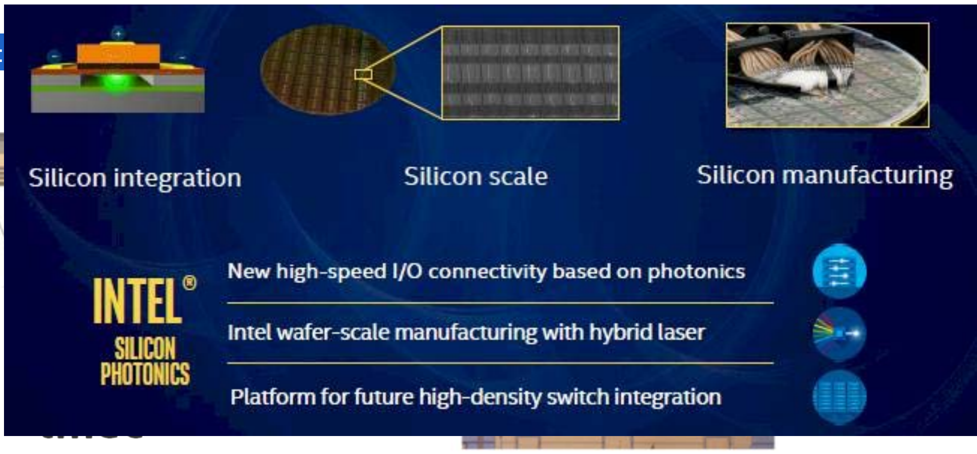
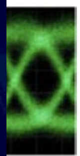


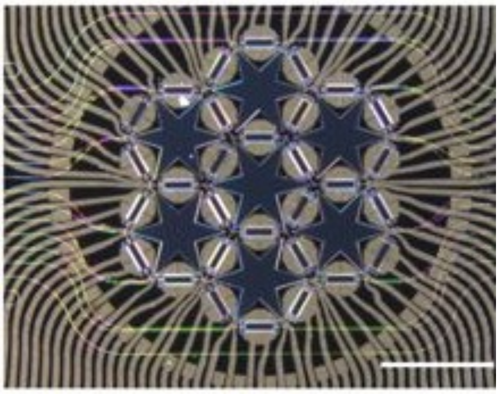


ye

'28 (UGent)

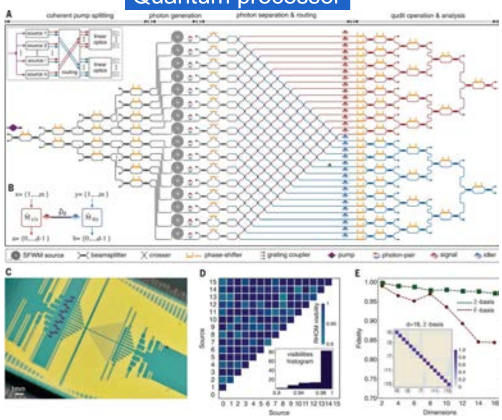
TOWARDS LARGER DEGREE OF INTEGRATION

Reconfigurable circuit for microwave photonics



D. Perez, Nat. Comm. 8 (2017)
(Valencia)

Quantum processor



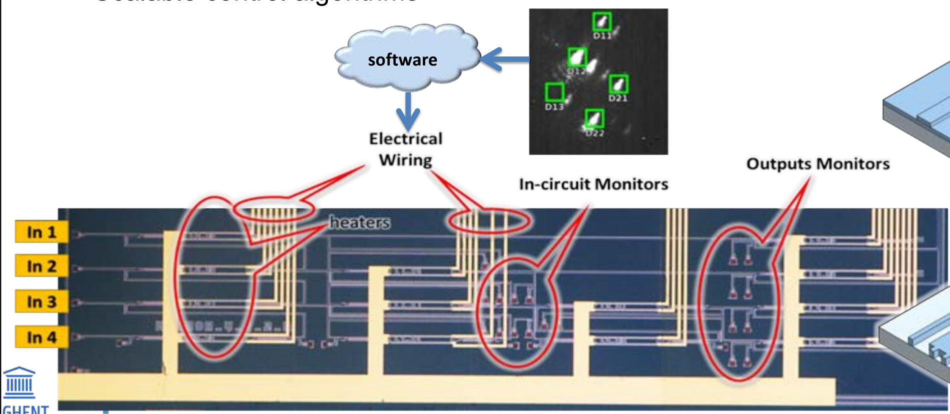
J. Wang et al., Science (2018)
(Glasgow et al)

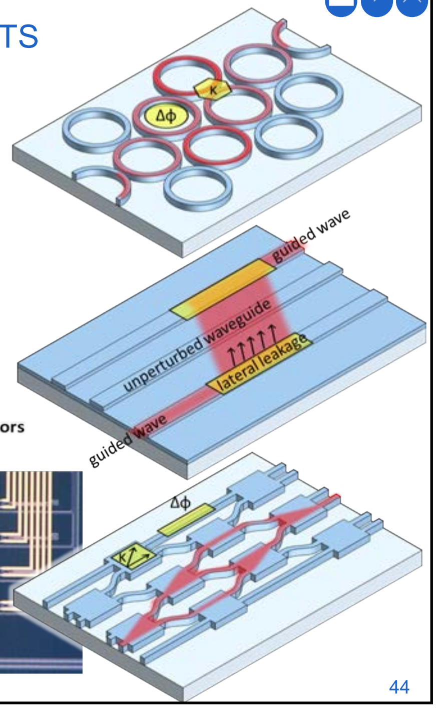
RESEARCH INFORMATION PROCESSING & COMPUTING

PROGRAMMABLE PHOTONIC INTEGRATED CIRCUITS

Develop general-purpose photonic ICs

- Mesh topologies (MZI, rings, lateral leakage)
- Distributed phase tuners and power monitors
- Scalable control algorithms





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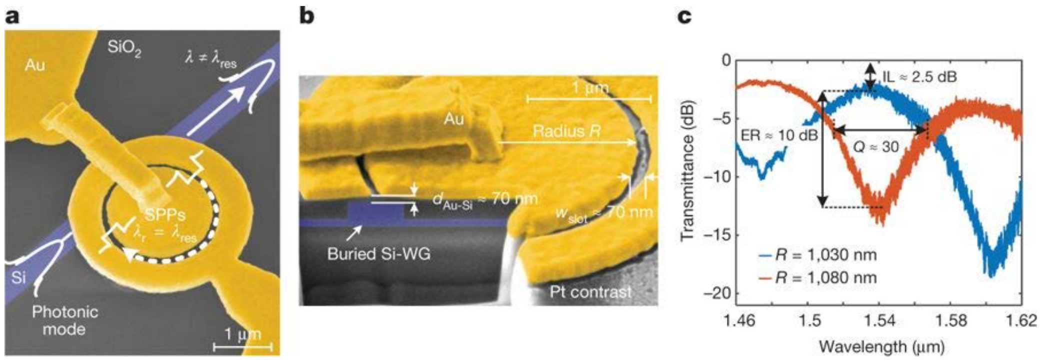
PLASMONICS FOR SCALING DOWN BUILDING BLOCKS ?



Leuthold group, Nature, 556: 483-486 (ETHZ)

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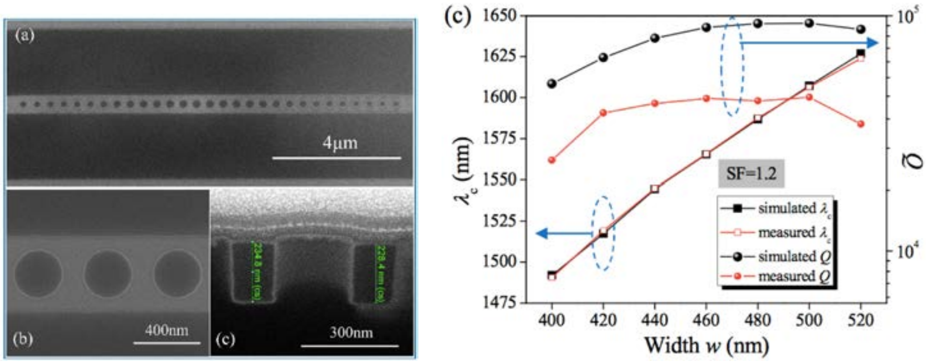
PHOTONIC CRYSTAL DEVICES



Photonic wire cavities fabricated using 300mm immersion litho

- Oxide cladding
- Very good match simulaton vs. design, on-par with state-of-art ebeam (Q > 1E6)
- Very good uniformity over wafer
- Starting point for active devices (e.g. slow light modulators, switches …)

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Xie e.a, JLT 2014

SILICON PHOTONICS – SUMMARY

- Silicon Photonics rapidly maturing:
  - All basic building blocks developed
  - Widely available from commercial foundries and through multi-project wafer services
- Current research focusses on:
  - Integration with new materials for enhancing functionality
  - Exploiting large scale integration for new applications
- Perfect match with EU-FET SPICE objectives !

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GROUP

ACKNOWLEDGMENTS – ALL GROUP MEMBERS

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