Integration of MEMS for Scalable Programmable Photonic Circuits

Niels Quack

COMMAD, Adelaide, 13 December 2022

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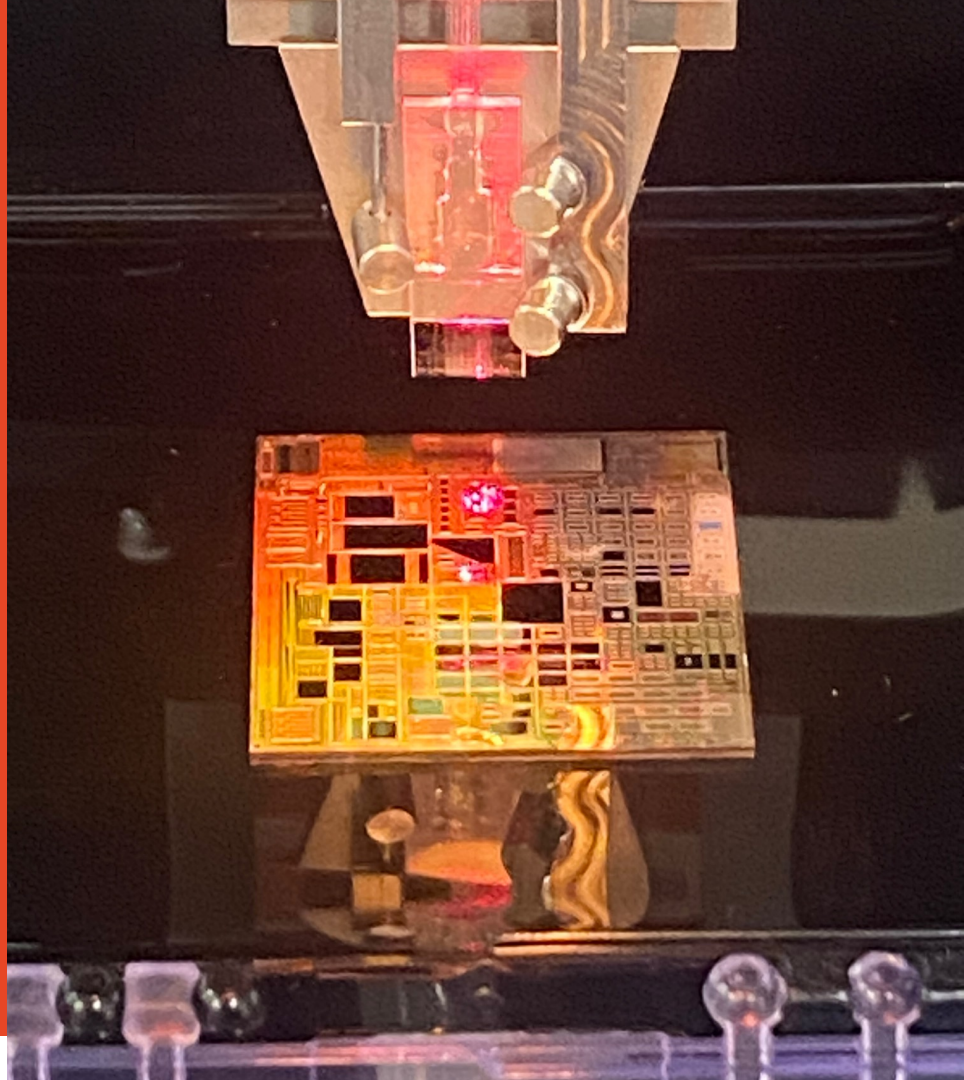
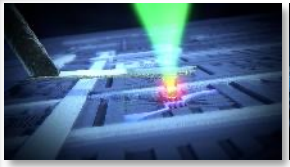
[1]EPFL, Switzerland, [2]KTH, Sweden, [3]IMEC, Belgium, [4]Tyndall National Institute, Ireland, [5]UGhent, Belgium, [6]The University of Sydney, Australia

THE UNIVERSITY OF SYDNEY



Outline

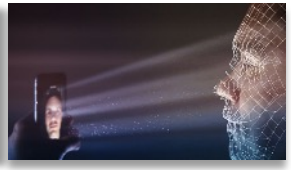
- **MEMS & Silicon Photonics**
- **Wafer-Scale Integration of MEMS in a Standard Silicon Photonics Platform**
  - MEMS Tunable Power Coupler / Photonic Switch
  - On-Chip MEMS Tunable Filter
- **Outlook & Conclusions**



Quantum Sensing & Computing

Photonic Accelerators

New Space

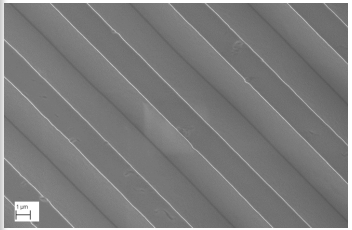


Imaging

Information & Communication Tech

Personalized Health

Research, Engineer & Build Enabling Solutions



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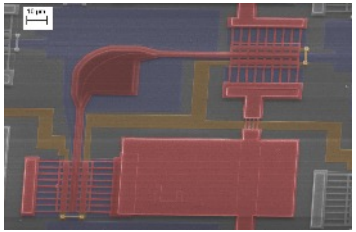
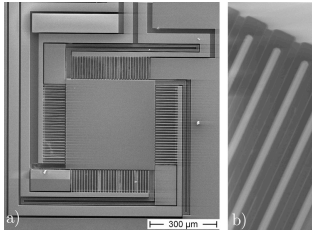
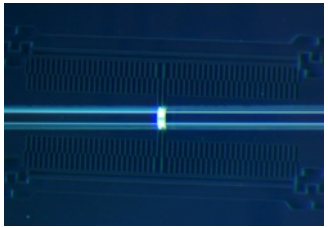


Photonic Integrated Circuits



Micromirrors



MEMS

Optical Switches

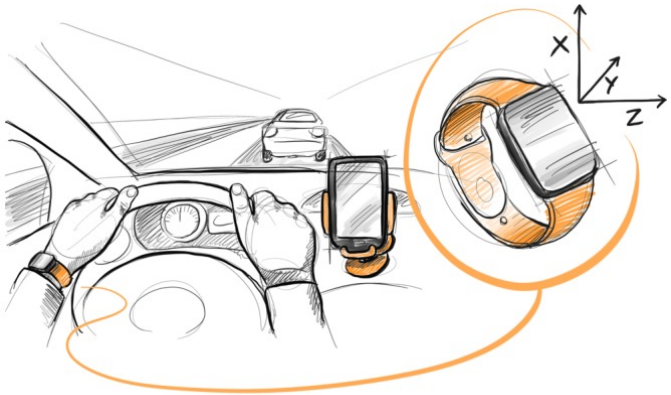
Photonic Micro- and Nanosystems

Nanofab & Materials Engineering

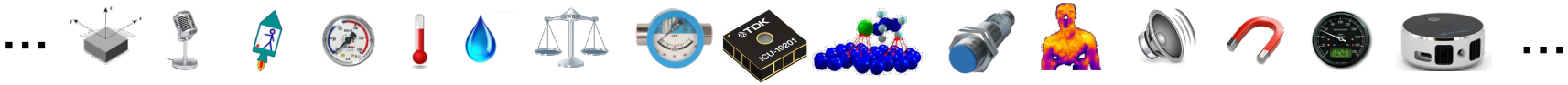
Physics at the Micro- & Nanoscale

System Level Integration

MEMS: Ubiquitous Miniaturized Sensors and Actuators



Sensors **Actuators**

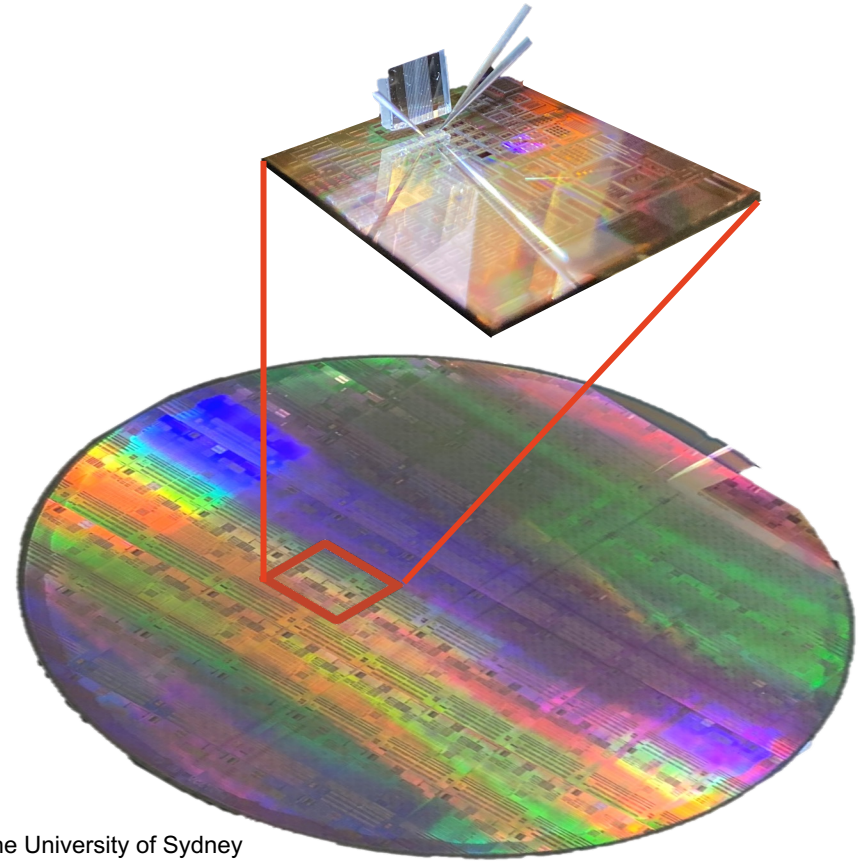


integration using **Micro/Nano Engineering** is the **only solution** for high performance, scalable, cost effective systems

Image: Thomas A. Cano Hald et al., AutomotiveUI 2018

Projector Image: InFocus

Silicon Photonics: Wafer Scale Photonic Integration of



- Waveguides (Low Loss)
- Photodiodes (> 50GHz)
- Modulators (> 50GHz)
- Detectors (> 50GHz)

- Filters, Resonators, Couplers…
- Nonlinear Functions…

- Integration with Electronics
- Interfaces to Optical Fibers/Source

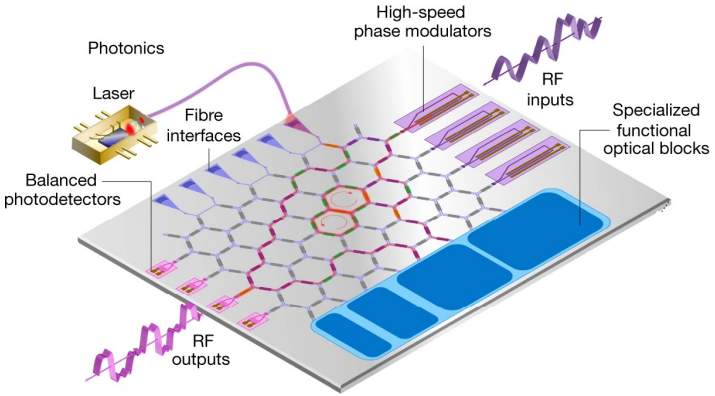
Silicon Photonics – Applications

today

Silicon Photonics 400G DR4 QSFP-DD Optical Transceiver (Intel)

Tele-/Datacom

tomorrow

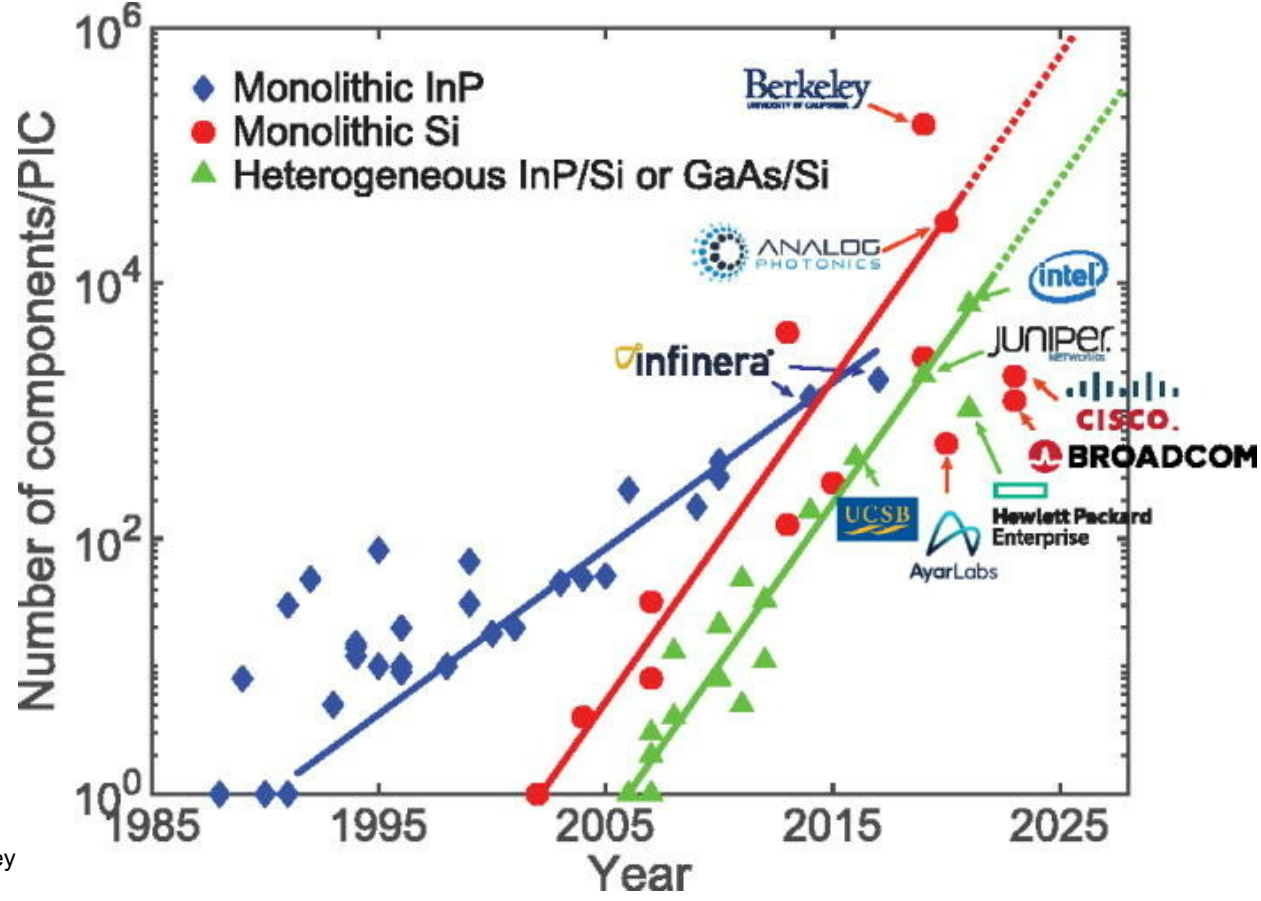


Programmable Photonic ICs [1]

AI, QIP, QKD, Quantum Sensors, Imaging, Biosensors, Switching…

[1] Bogaerts, W., et al. Nature 586, 207–216 (2020).

Photonic Integration and Scaling

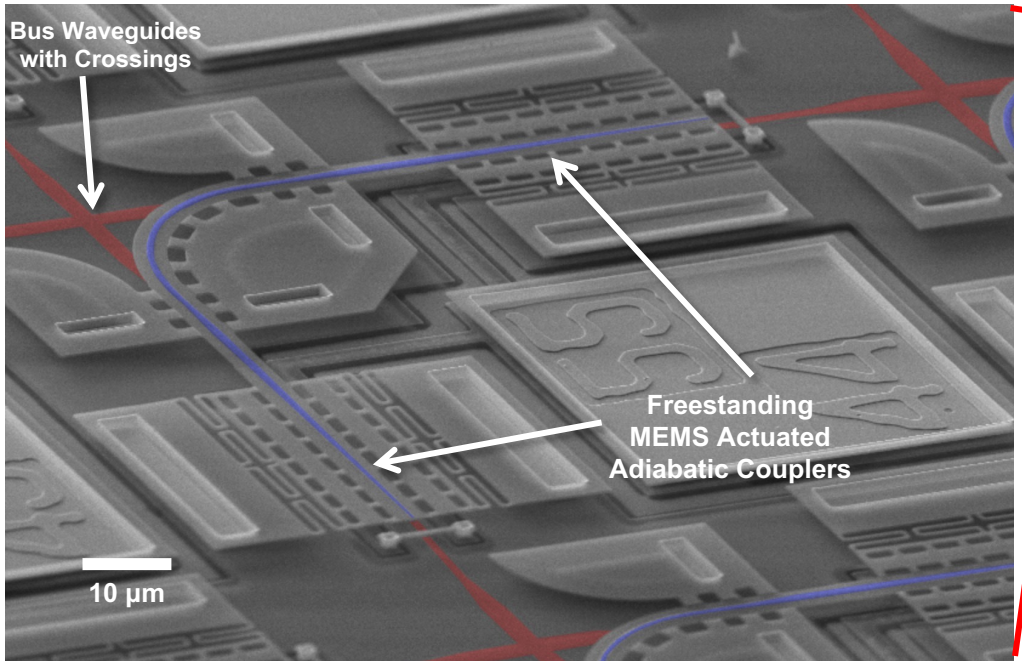


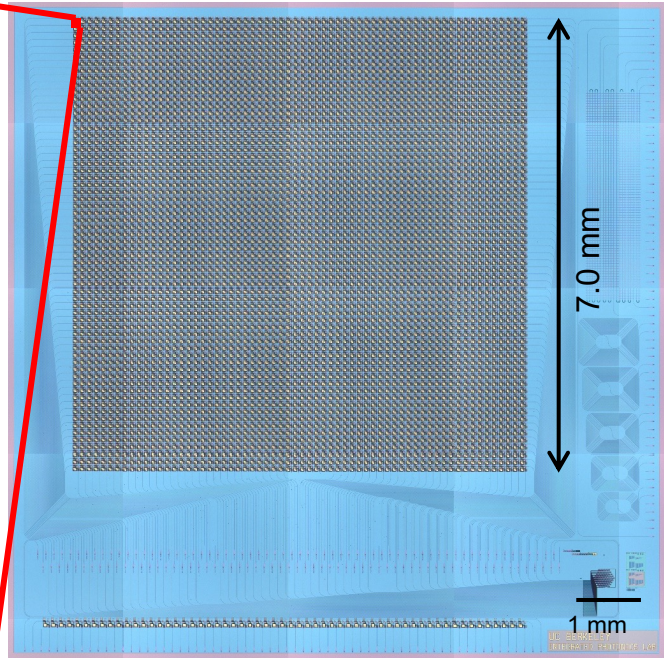
Margalit et al. 2021

64 x 64 Silicon Photonic MEMS Switch Matrix

Silicon Photonic MEMS Switch Unit Cell
110μm x 110μm

4096 Individual Silicon Photonic MEMS Switches





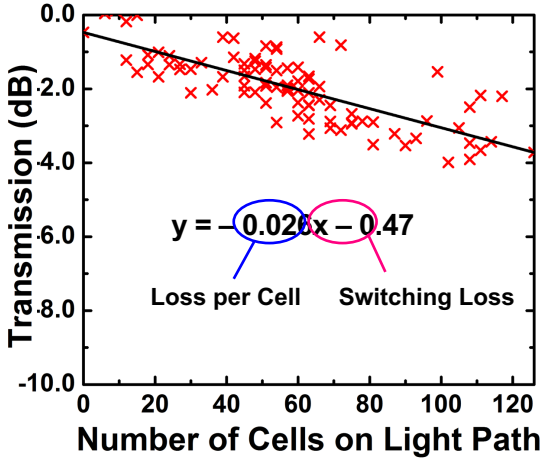
Seok, Quack, Han, Zhang, Muller, Wu, Optica, 2016

Kwong et al. CLEO 2018, SF1A.4 (128 x 128)

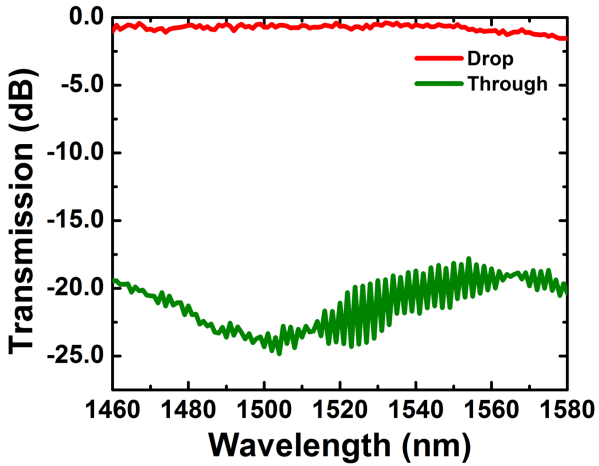
Seok et al. OFC 2019, (240 x 240)

Silicon Photonic MEMS Switch Performance

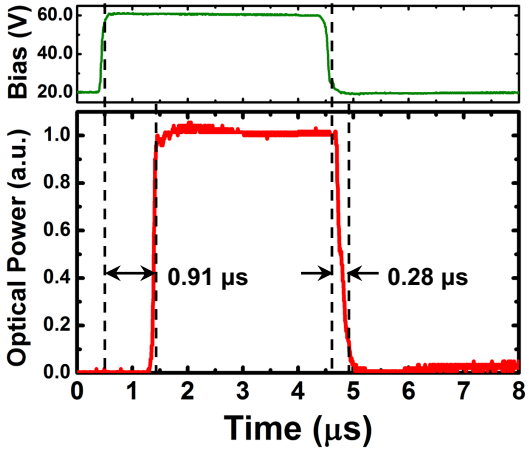
On-Chip Insertion Loss (Measurement)



Spectral Response (Measurement)



Temporal Response (Measurement)



Low Loss

Broadband

Fast

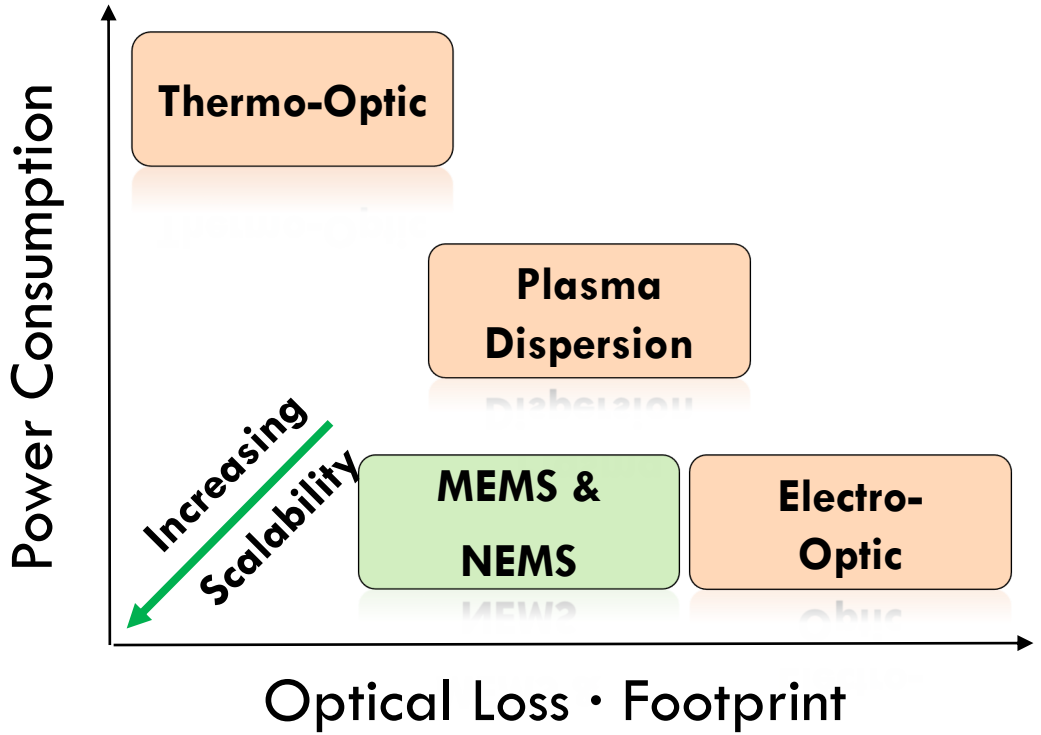
Seok, Quack, Han, Zhang, Muller, Wu, Optica, 2016

Scaling Photonic Integrated Circuits with MEMS

Device Requirements

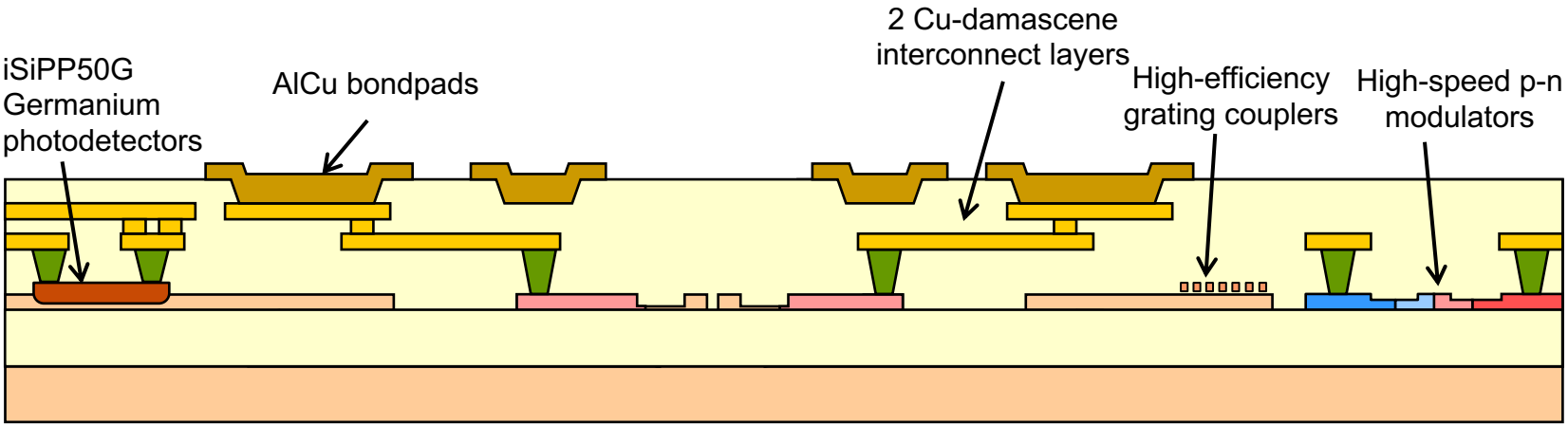
- ↓ Power Consumption
- ↓ Footprint
- ↓ Optical Loss
- ↓ Response Time
- ↑ Spectral Response

Physical Effects for Scalable PICs



Standardization of Silicon Photonic MEMS

– **Starting Point: IMEC's state-of-the-art iSiPP50G platform**



Bogaerts et al. *Silicon Photonics XV*. Vol. 11285.2020.

https://h2020morphic.eu/

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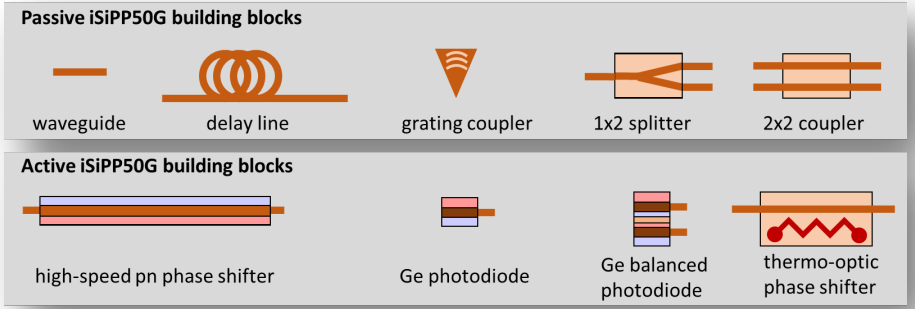

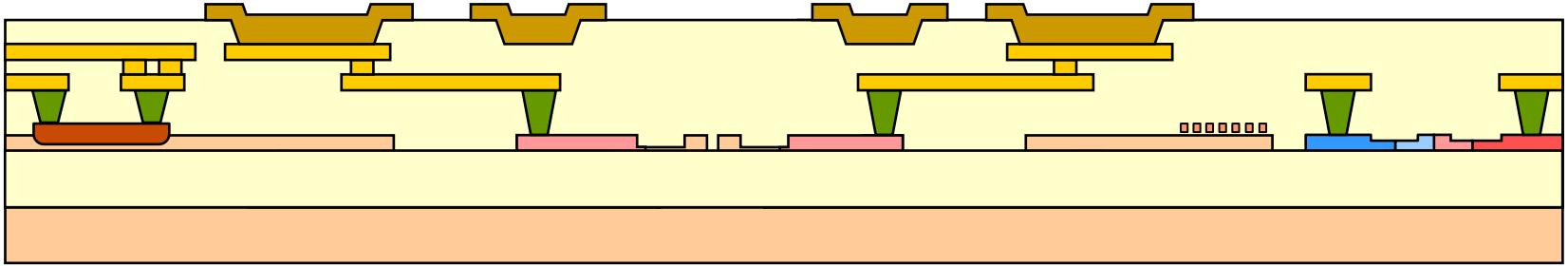

Bogaerts et al. *Silicon Photonics XV*. Vol. 11285.2020.

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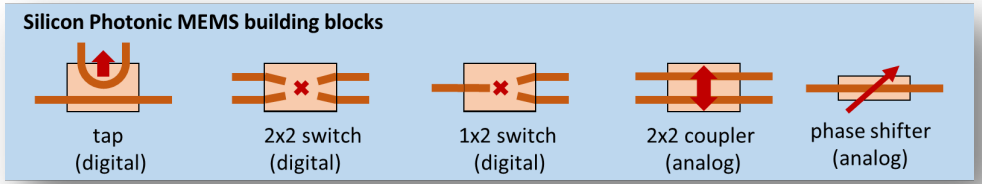
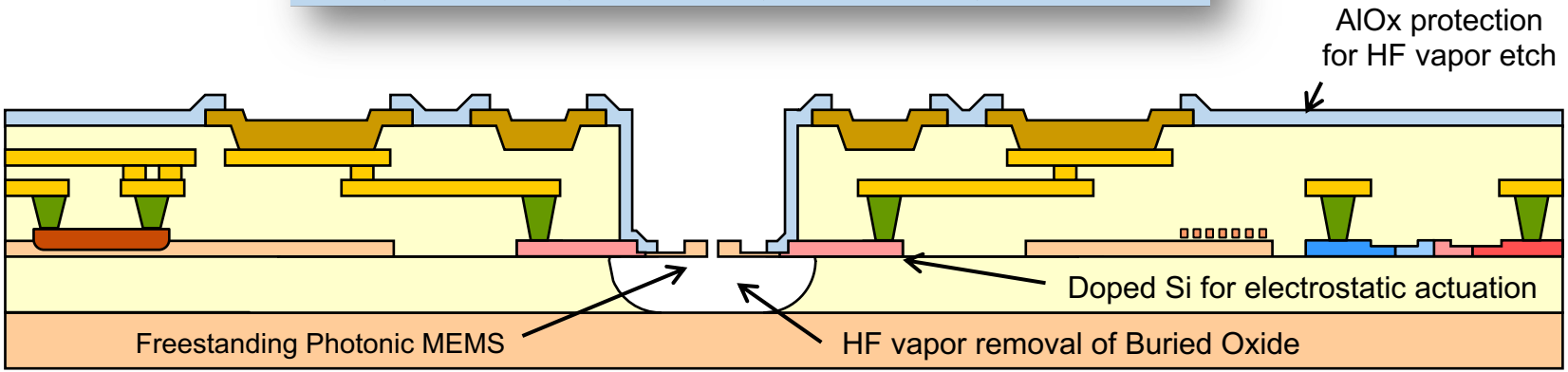
Standardization of Silicon Photonic MEMS

- Starting Point: IMEC's state-of-the-art iSiPP50G platform
- Add MEMS by custom Post-Processing





Bogaerts et al. *Silicon Photonics XV*. Vol. 11285.2020.

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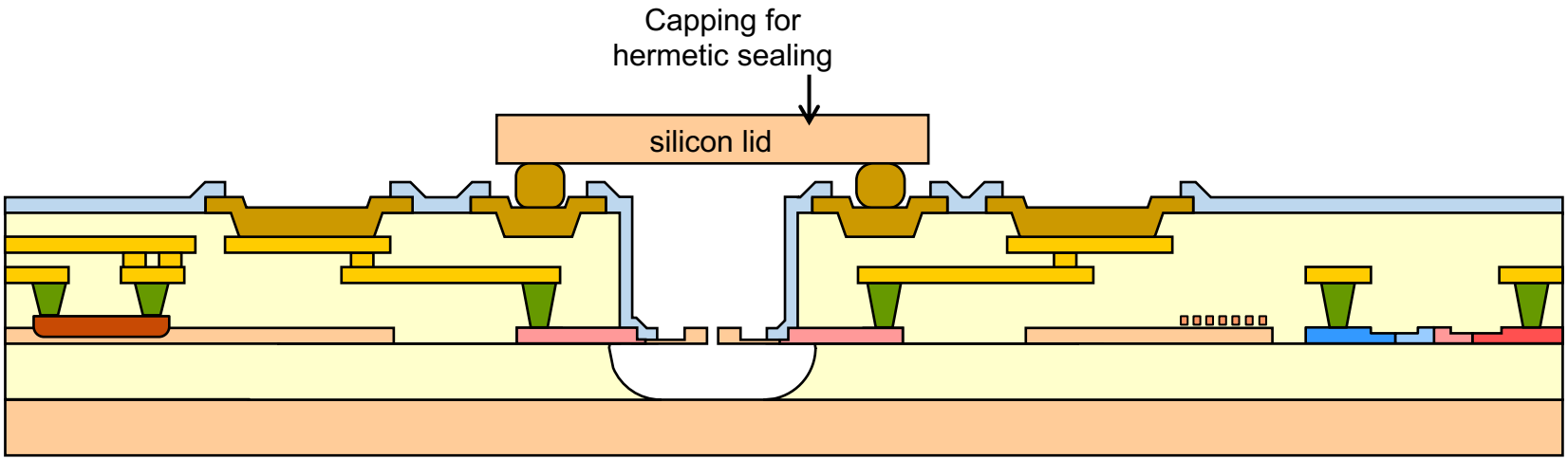
Standardization of Silicon Photonic MEMS

- Starting Point: IMEC's state-of-the-art iSiPP50G platform
- MEMS Release by custom Post-Processing
- Wafer Level Hermetic MEMS Sealing



Bogaerts et al. *Silicon Photonics XV*. Vol. 11285.2020.

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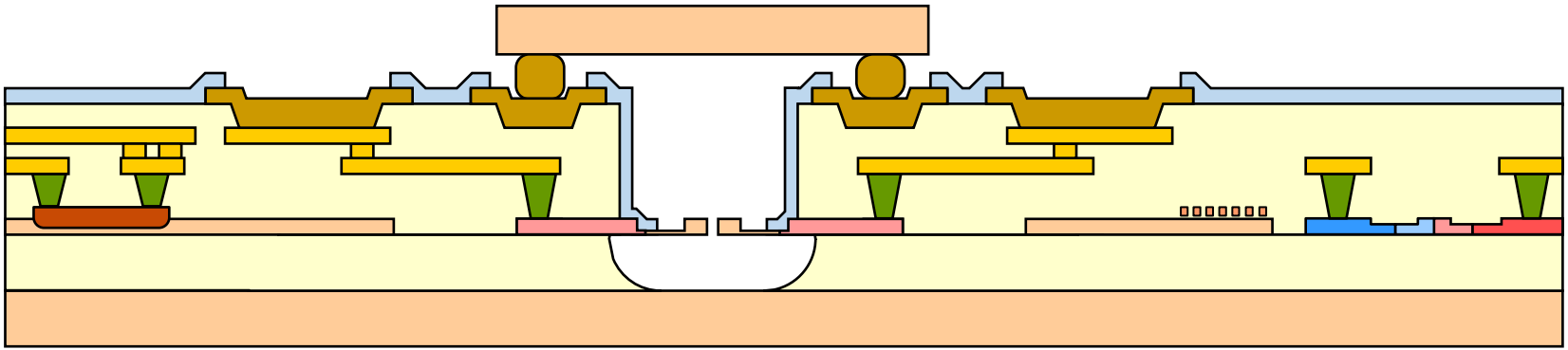
Standardization of Silicon Photonic MEMS

- Starting Point: IMEC's state-of-the-art iSiPP50G platform
- MEMS Release by custom Post-Processing
- Wafer Level Hermetic MEMS Sealing
- Robust Wafer Level Process - Challenges Addressed



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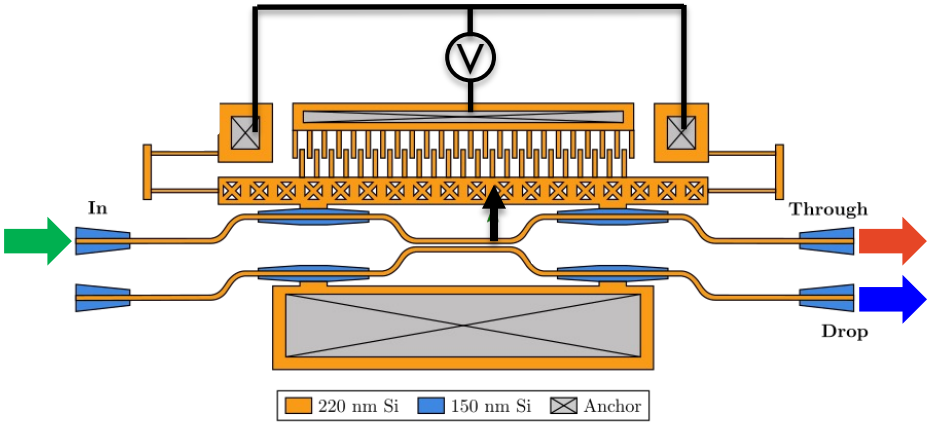
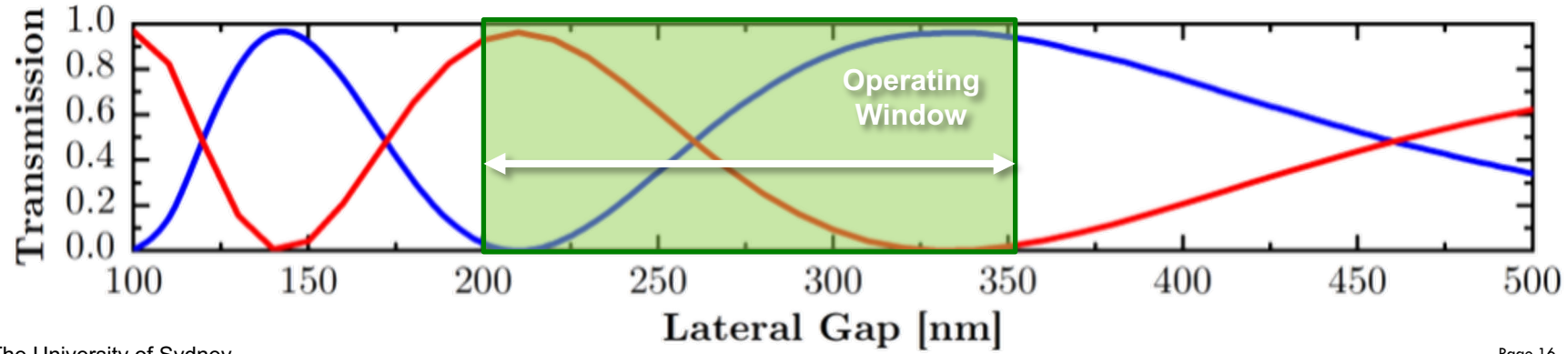
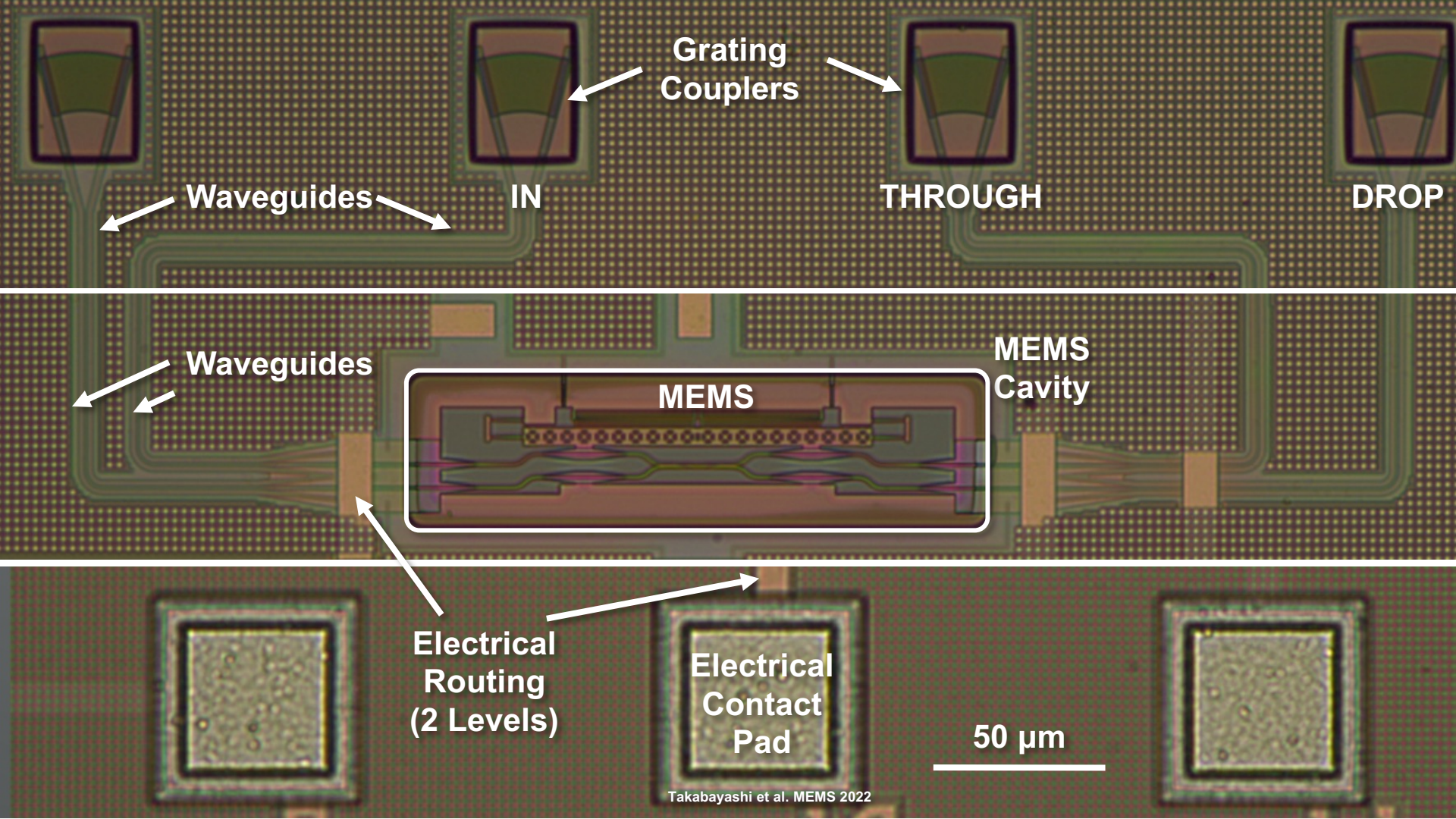
Compact Tunable Power Coupler

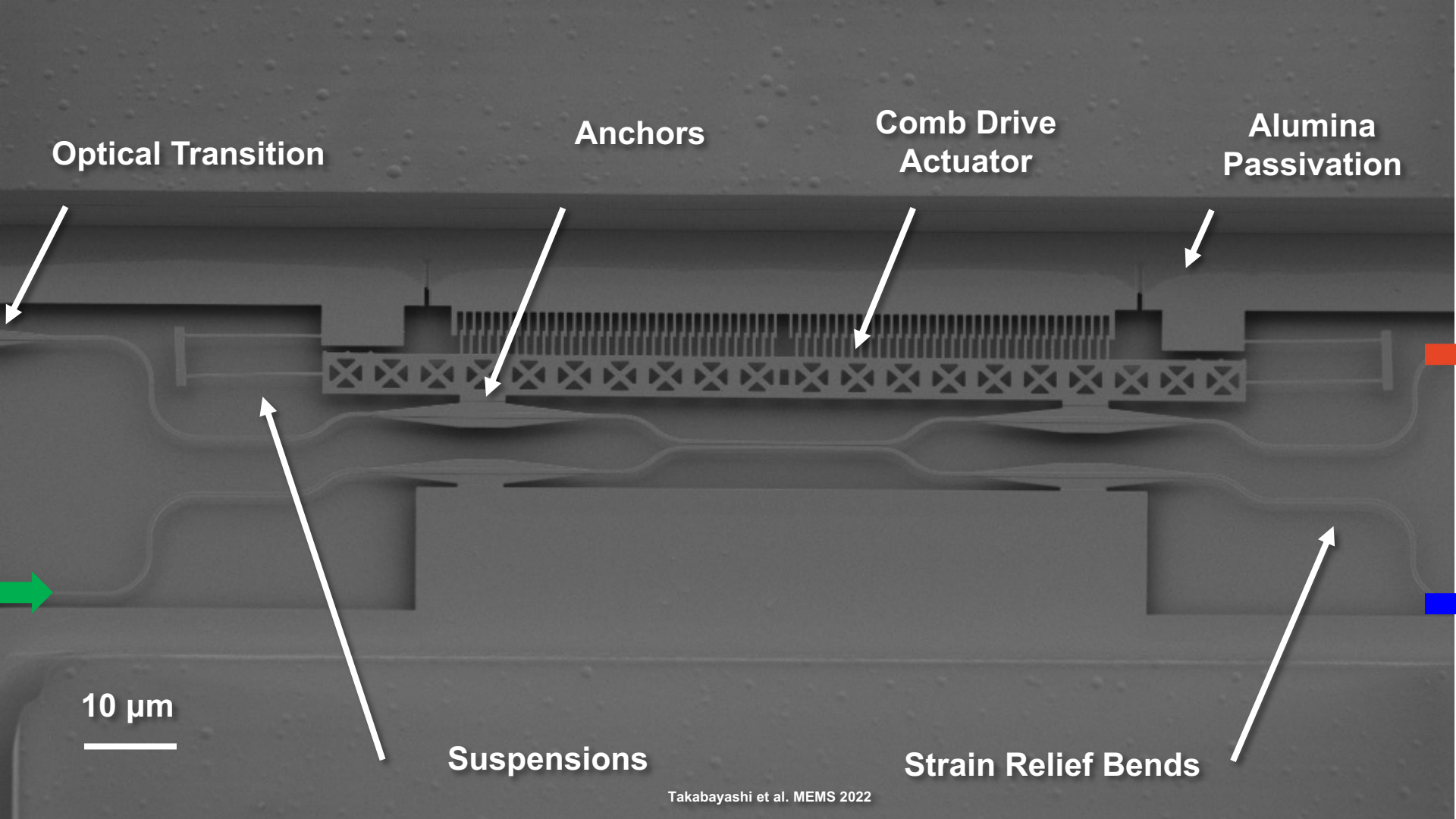


- FDTD Simulation [1]
- Initial Gap 200 nm
- 150 nm Displacement
- Full Dynamic Range
- Tolerant to Fab Variations



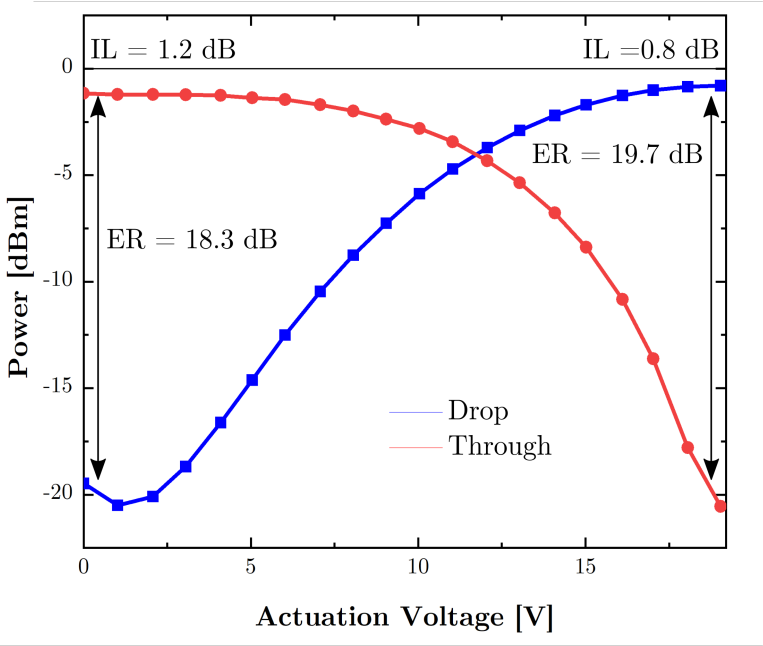
[1] Coupler: H. Sattari et al.,Opt. Lett. 45, 2997-3000, 2020.


Grating
Couplers
Waveguides
IN
THROUGH
DROP
Waveguides
MEMS
MEMS
Cavity
Electrical
Routing
(2 Levels)
Electrical
Contact
Pad
50 µm
Takabayashi et al. MEMS 2022

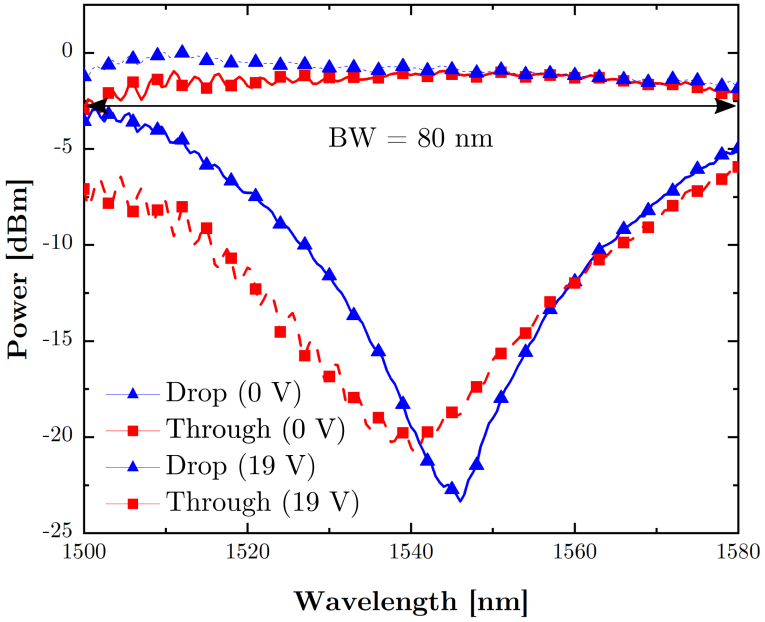


Takabayashi et al. MEMS 2022

Silicon Photonic MEMS Tunable Coupler Performance

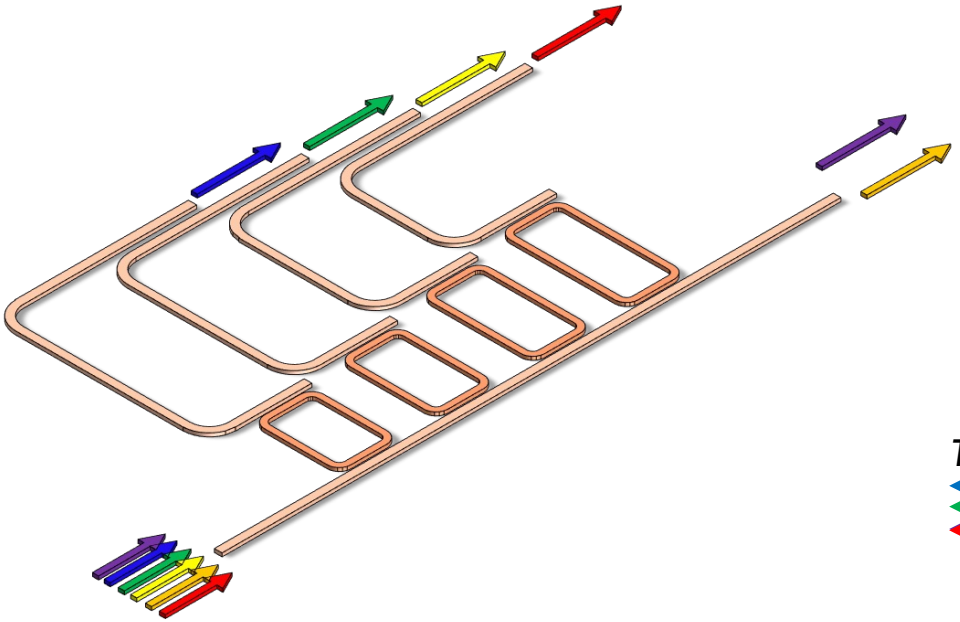


- **MEMS Actuated Power Coupling**
- **High Extinction Ratio (>18.3dB)**
- **Low Insertion Loss (>1.2dB)**



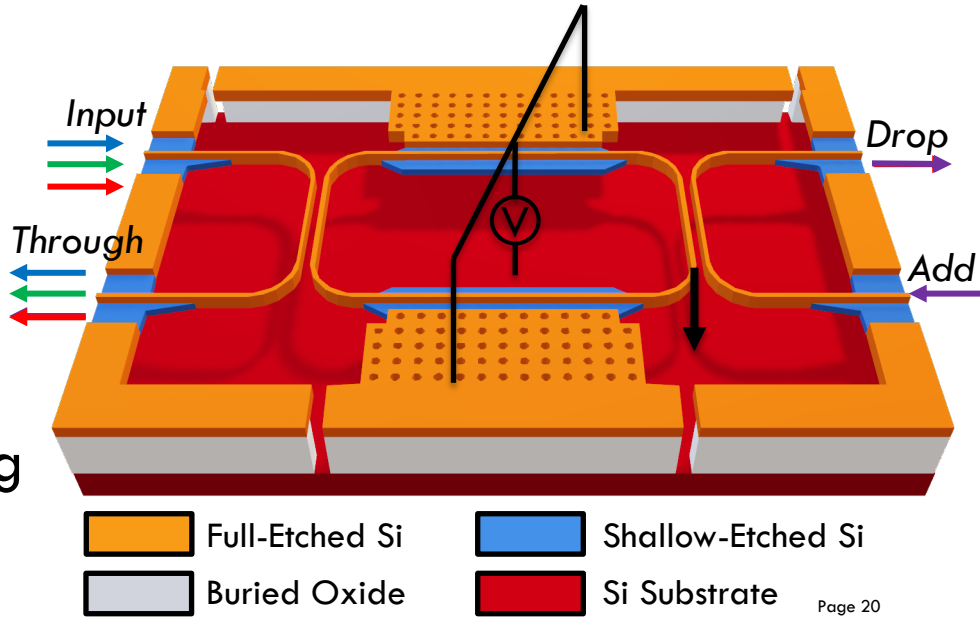
- **Spectral Response**
- **Broadband Coupling (C-Band)**
- **3dB Bandwidth >80nm**

Silicon Photonic MEMS Tunable Add/Drop Filter



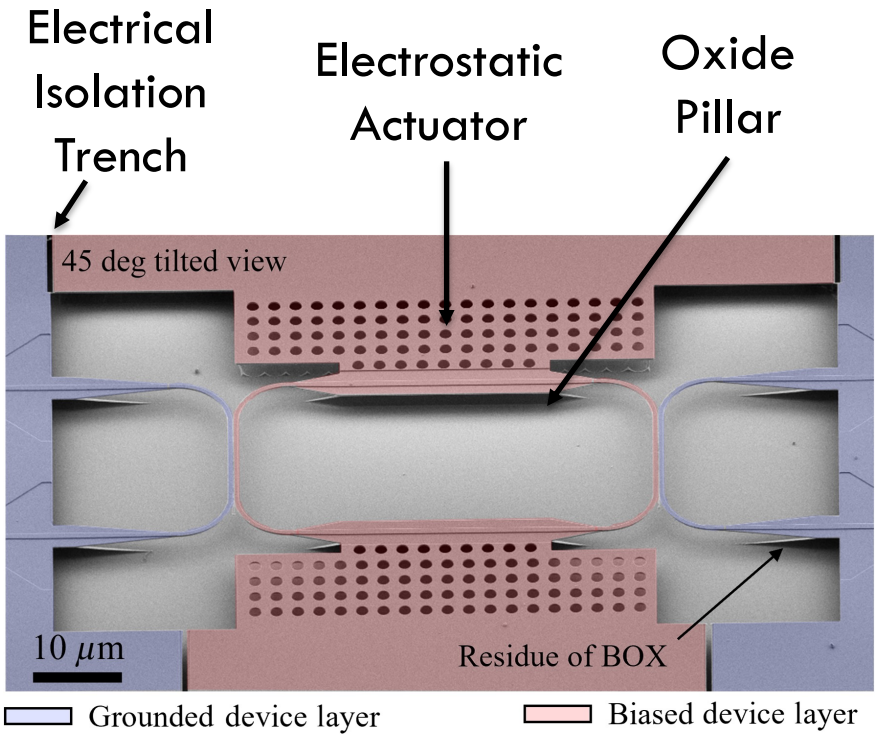
Optical Carrier Multiplexing with Ring Resonators

Vertically Moving Silicon Photonic MEMS Ring Resonator

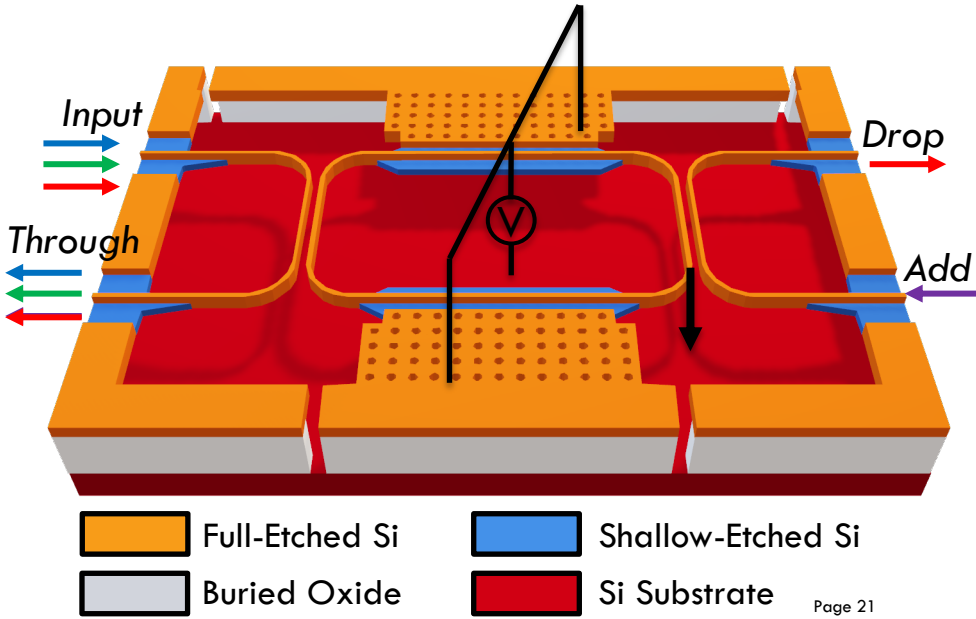


Sattari et al. JOM, 2, 4, 044001, 2022

Silicon Photonic MEMS Tunable Add/Drop Filter



Vertically Moving Silicon Photonic MEMS Ring Resonator



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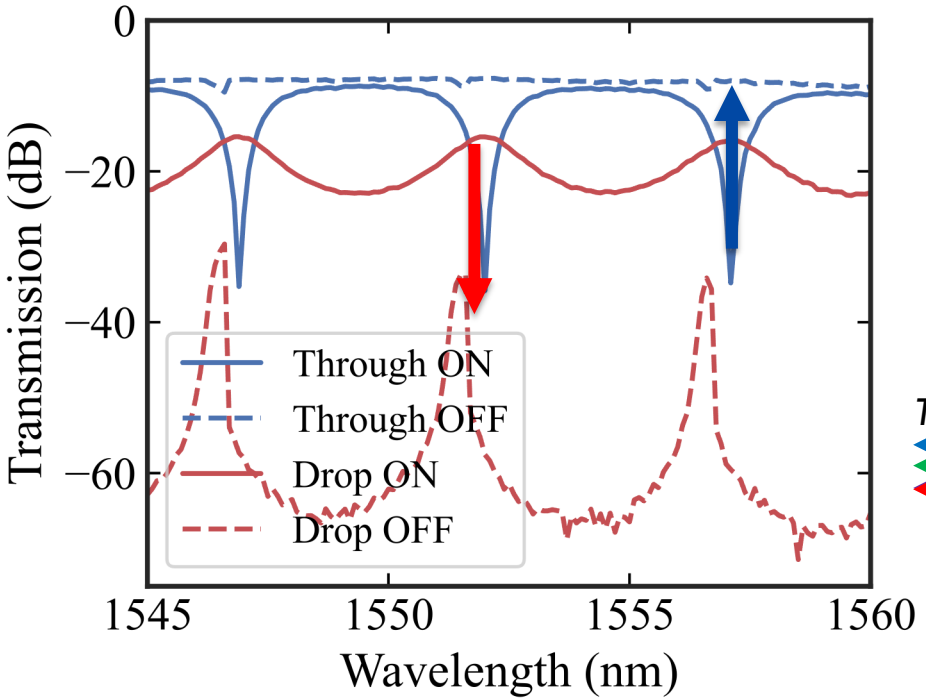
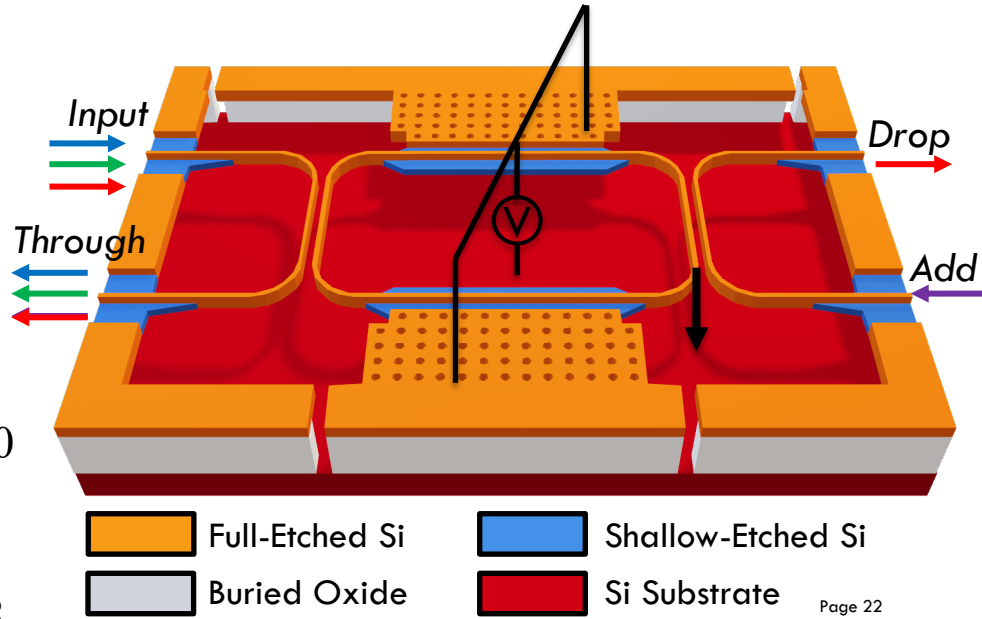
Silicon Photonic MEMS Tunable Add/Drop Filter

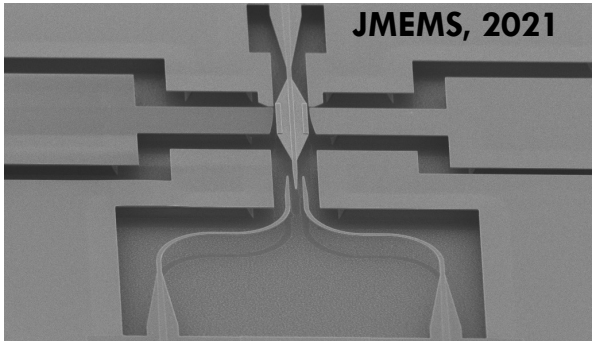


Vertically Moving Silicon Photonic MEMS Ring Resonator

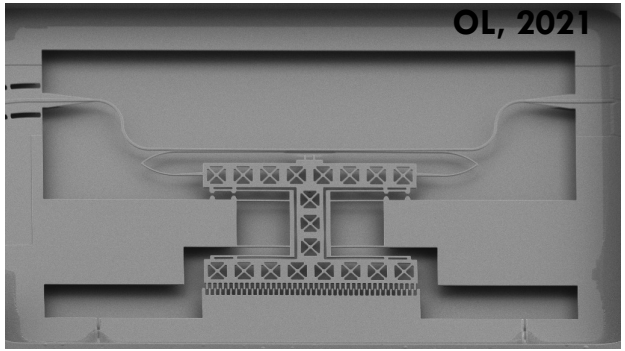


Sattari et al. JOM, 2, 4, 044001, 2022

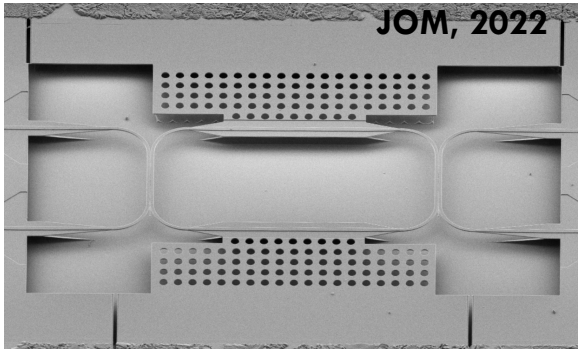
Silicon Photonic MEMS - Versatile Components



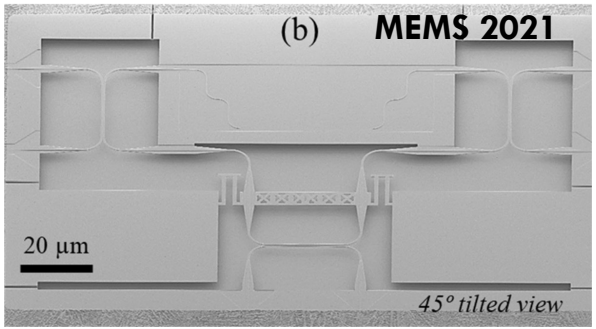
1 x 2 Switch



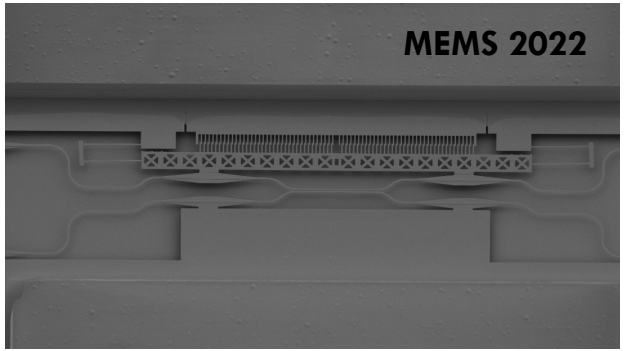
Phase Shifter



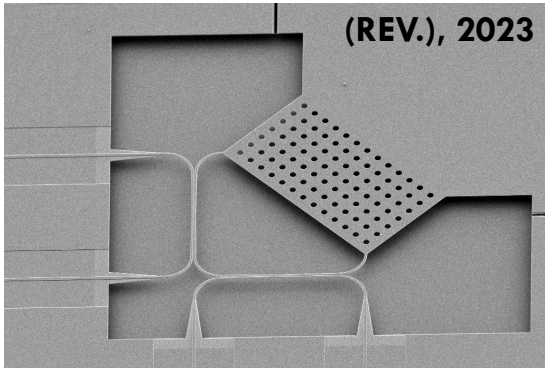
Tunable Filter



Low Voltage Coupler

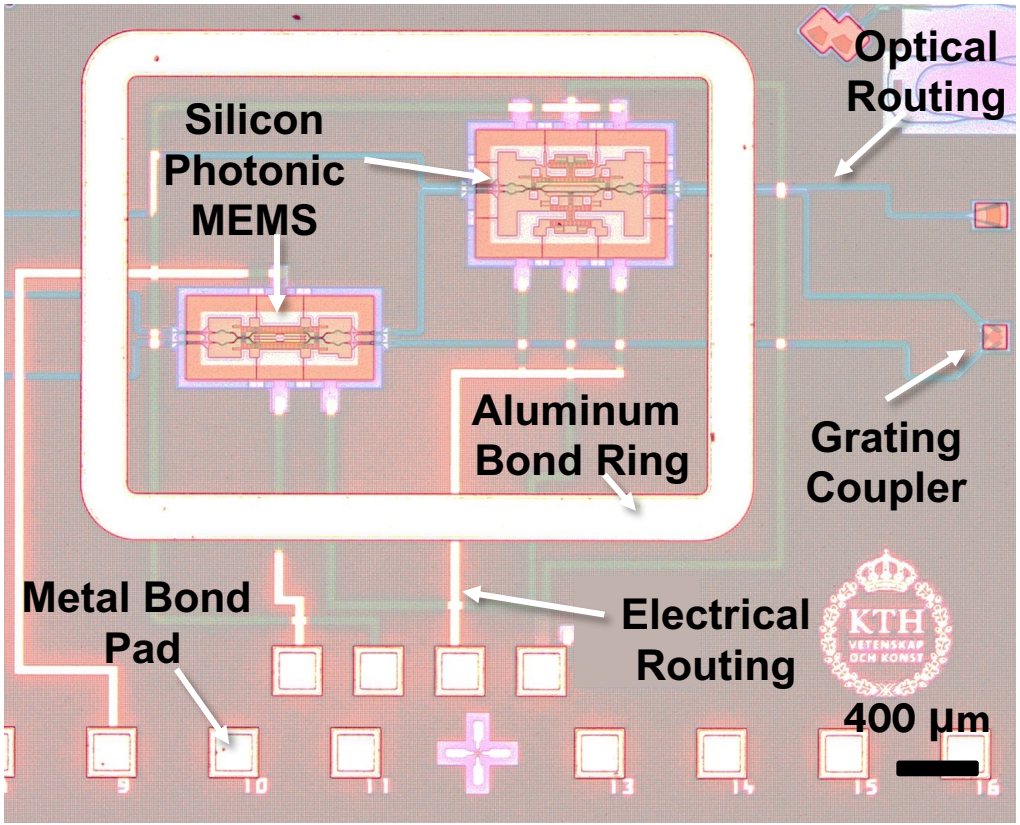


In-Plane Coupler



Vertical Coupler

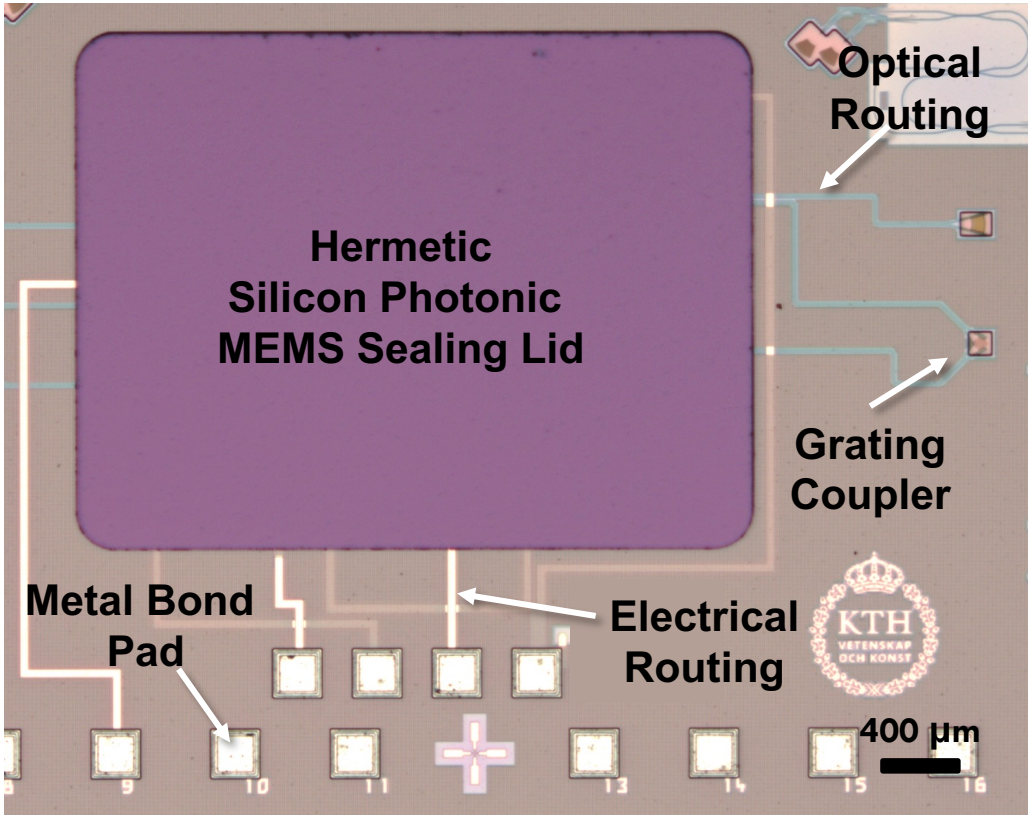
Wafer Level Photonic MEMS Sealing



- Aluminum Bond Ring
- Wafer Level Sealing
- Au-Al Thermocompression Bonding

Gaehun Jo et al. Photonics Research, 2022

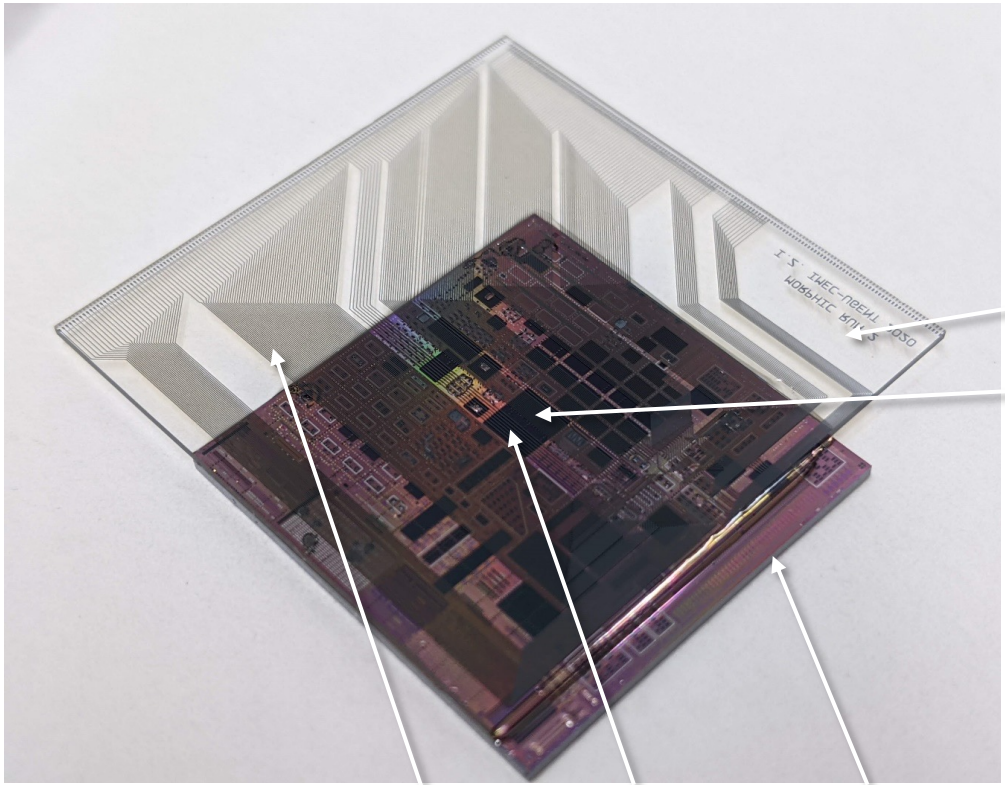
Wafer Level Photonic MEMS Sealing



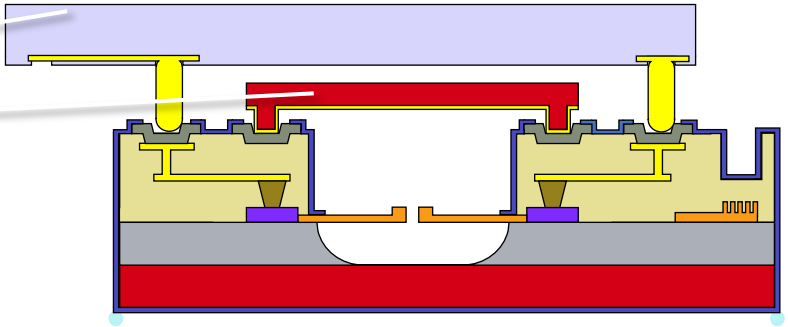
- Aluminum Bond Ring
- Wafer Level Sealing
- Au-Al Thermocompression Bonding
- Silicon (SOI) Lid
- ~20 µm high
- Hermetic
- Long Term Reliabilty for MEMS Devices

Gaehun Jo et al. Photonics Research, 2022

Electrical and Optical Interfaces



- Solder Jetting
- Flip-Chip Bonding
- Glass Interposer



- ~20 µm high
- Hermetic

The University of Sydney

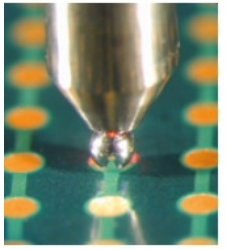
Interposer

Sealing Lids (various shapes)

Recess for Fiber Array

Quack et al. 2022, in Revision

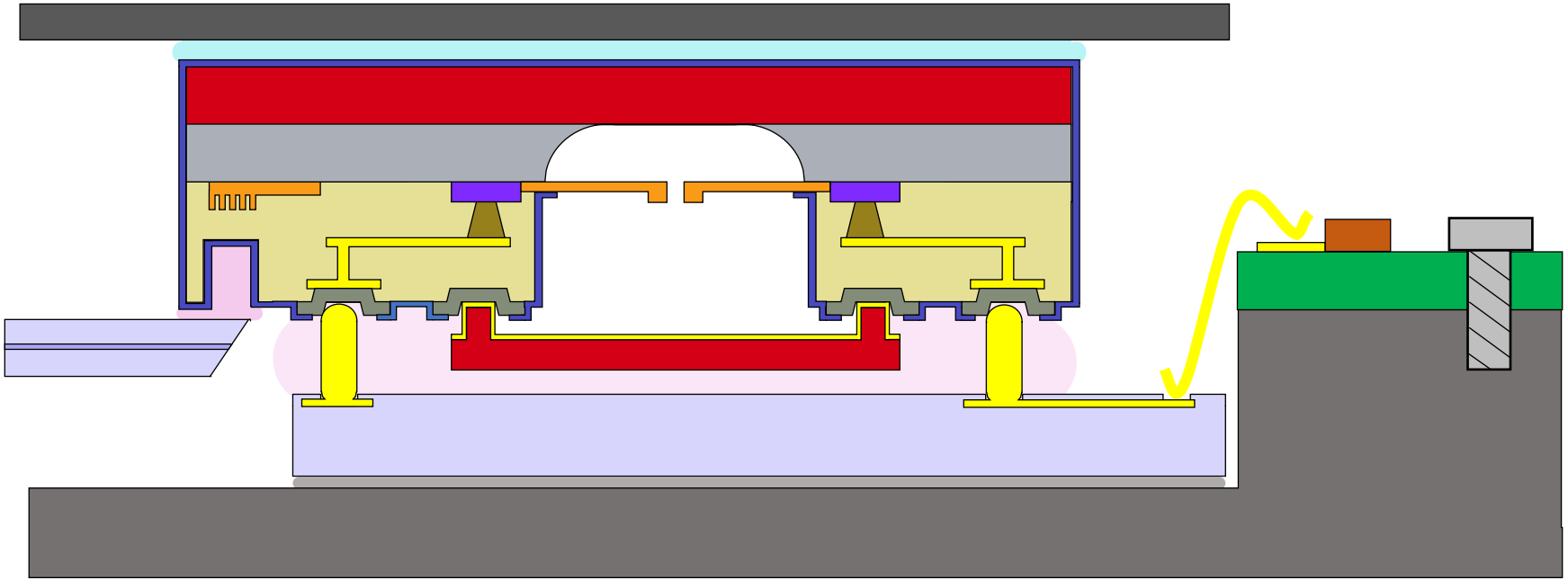
Solder Jetting – Sovereign Capability for Australia?



- Solder Jetting
- 40um – 200um solder balls
- Photonic/Electronic Assembly
- Dry Process (! MEMS), Chips, Wafers…

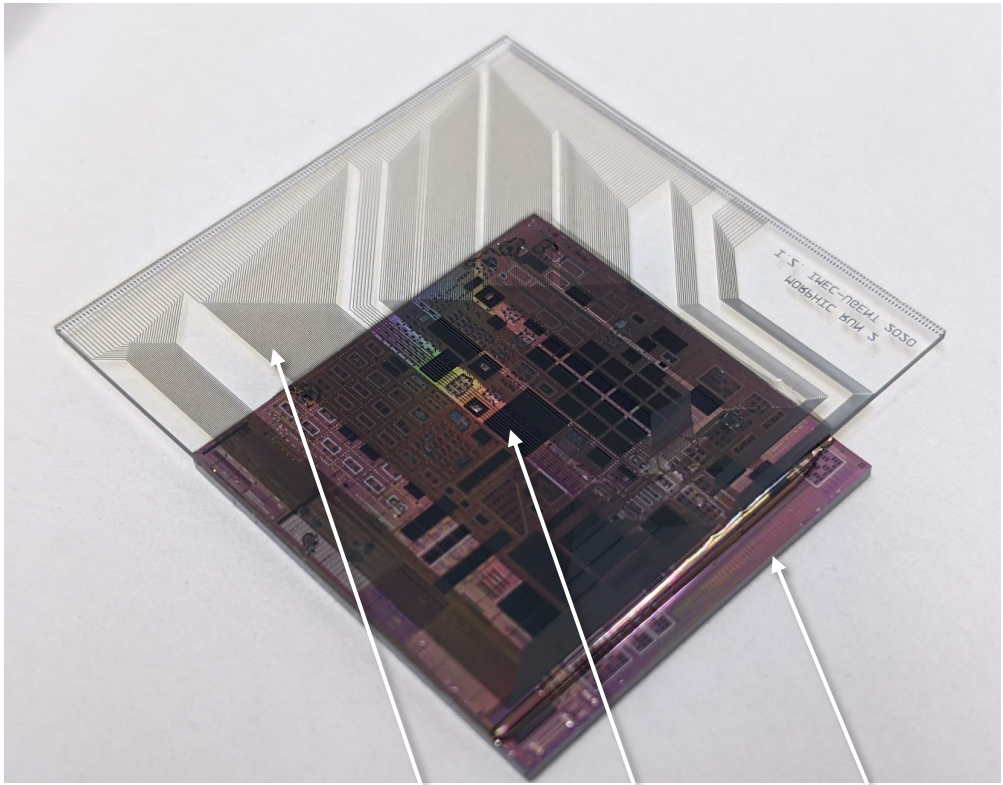
- Heterogenous Integration
- Research Prototypes
- Materials Research
- Packaging, Reworking …

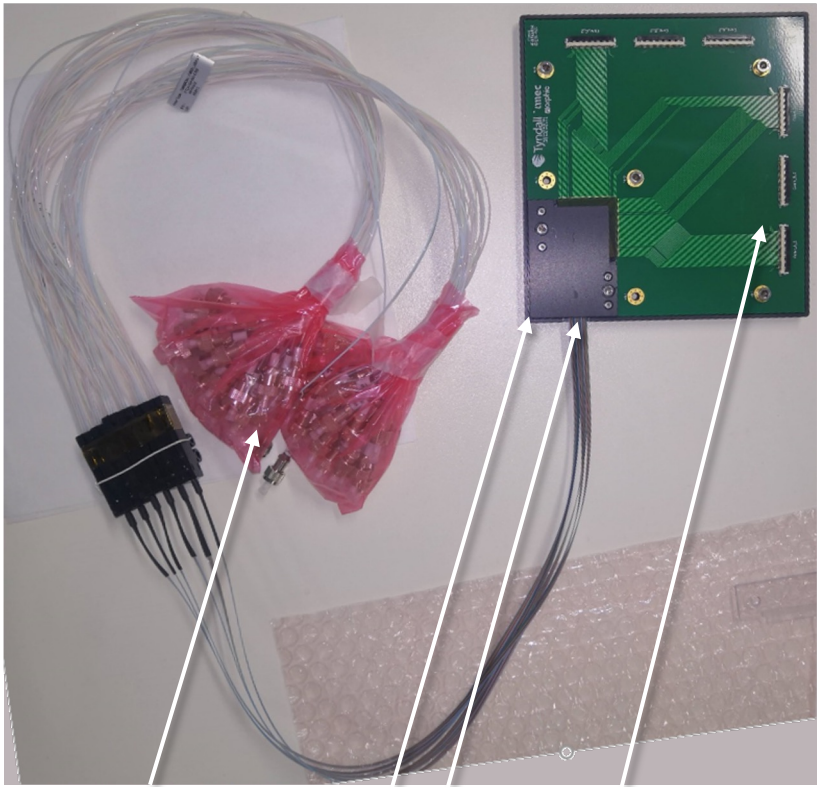
Electronic-Photonic Assembly



Quack et al. 2022, in Revision

Electrical and Optical Interfaces





The University of Sydney

Interposer

Sealing Lids (various shapes)

Recess for Fiber Array

Fiber Connectors

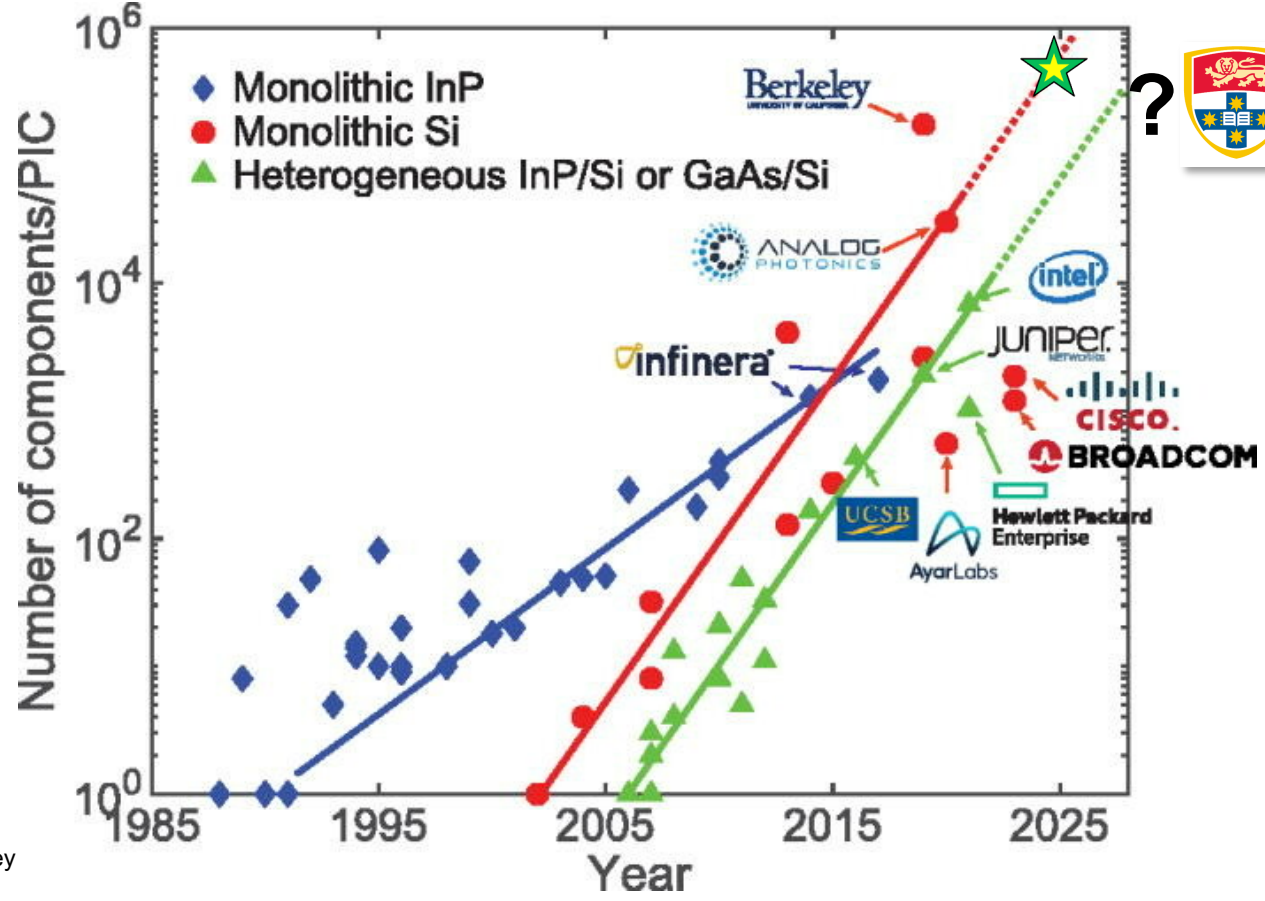
Mechanical Support

Fiber Array

PCB

Quack et al. 2022, in Revision

Photonic Integration and Scaling – MEMS Opportunity?

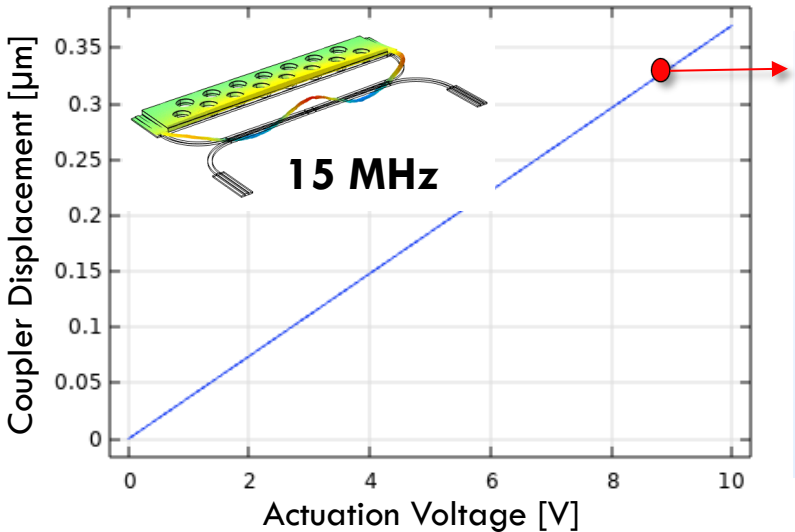


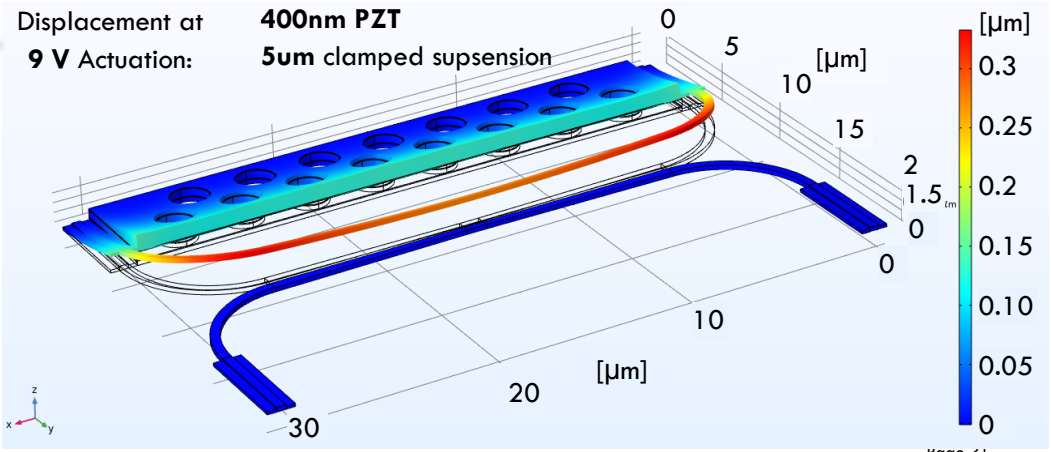
Margalit et al. 2021

Outlook: Programmable Piezo Photonics (P^3)

THE UNIVERSITY OF SYDNEY

MEMS Actuator \ Performance	Photonics Compatibility	Power Consumption	Footprint	Response Time	Movement	Electrostatic Discharge
Electrostatic	High	Low	Medium	Medium	Unilateral	Failure
Piezoelectric	Medium	Low	Small	Fast	Bidirectional	Recovery





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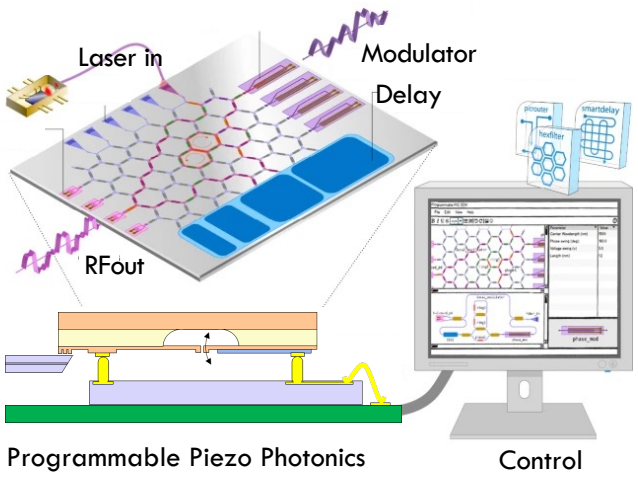
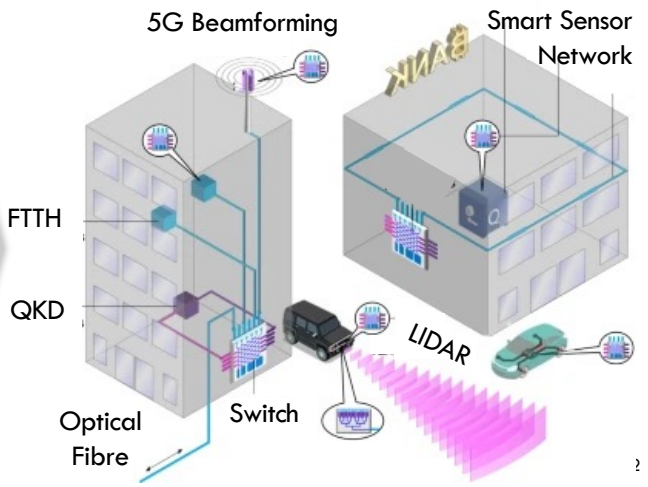


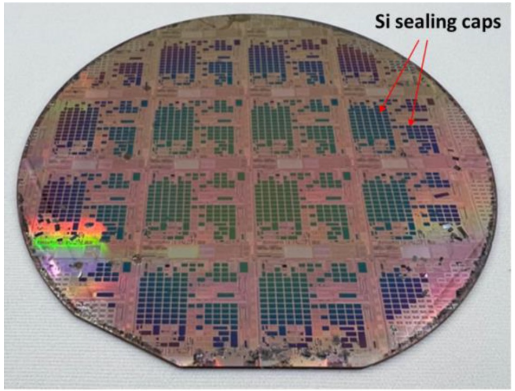
Low Power
Compact
Low Loss
Broadband
Fast
=
Scalable
Programmable
Piezo Photonics

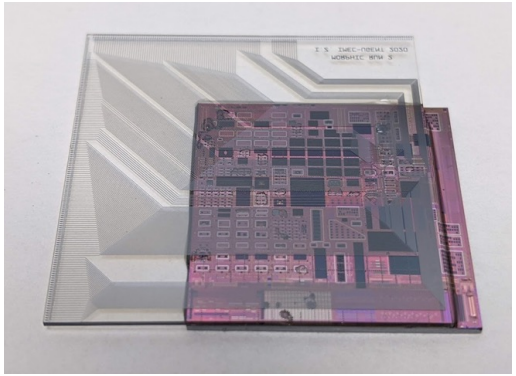


Graphics adapted from Bogaerts et al. Nature 586, 207–216 (2020).

Silicon Photonic MEMS – A Scalable Technology

- **Silicon Photonic MEMS Technology**
- **Scalable Technology**
  - Compact, Low Loss, Broadband, Low-Power, Fast
- **Devices, Circuits, Sealing, Interfacing**
- **Decisive Technology Step for Programmable Photonics**
- **Next: Scaling with Piezo-Actuators**
- **Technology for Sensing, Quantum, AI**





Thank you for your Attention.

Questions?

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THE UNIVERSITY OF SYDNEY

References & Selected Publications

Photonic MEMS:

- Carlos Errando-Herranz, Alain Yuji Takabayashi, Pierre Edinger, Hamed Sattari, Kristinn B. Gylfason, Niels Quack, "MEMS for Photonic Integrated Circuits", IEEE JSTQE, 2019.
- Niels Quack, Hamed Sattari, Alain Yuji Takabayashi, Yu Zhang, Peter Verheyen, Wim Bogaerts, Pierre Edinger, Carlos Errando-Herranz, and Kristinn B. Gylfason, "MEMS-enabled Silicon Photonic Integrated Devices and Circuits", IEEE JQE, 2019.

Silicon Photonic MEMS Switch Matrices:

- Tae Joon Seok, Niels Quack, Sangyoon Han, Richard S. Muller and Ming C. Wu, Highly scalable digital silicon photonic MEMS switches, Journal of Lightwave Technology, Vol. 34, Issue 2, p. 365-371, 2016
- Tae Joon Seok, Niels Quack, Sangyoon Han, Richard S. Muller and Ming C. Wu, "Large-scale broadband digital silicon photonic switches with vertical adiabatic couplers", Optica, vol 3, num. 1, p. 64-70, 2016.

Packaging of Photonic MEMS:

- Gaehun Jo, Pierre Edinger, Simon J Bleiker, Xiaojing Wang, Alain Yuji Takabayashi, Hamed Sattari, Niels Quack, Moises Jezzini, Jun Su Lee, Peter Verheyen, Iman Zand, Umar Khan, Wim Bogaerts, Göran Stemme, Kristinn B Gylfason, Frank Niklaus, "Wafer-level hermetically sealed silicon photonic MEMS", Photonics Research, 10, 2, A14-A21.
- Hwang, H.Y., Lee, J.S., Seok, T.J., Forencich, A., Grant, H.R., Knutson, D., Quack, N., Han, S., Muller, R.S., Papen, G.C., Wu, M.C., O'Brien, P., "Flip Chip Packaging of Digital Silicon Photonics MEMS Switch for Cloud Computing and Data Centre," IEEE Photonics Journal, 2017.

MORPHIC Technology:

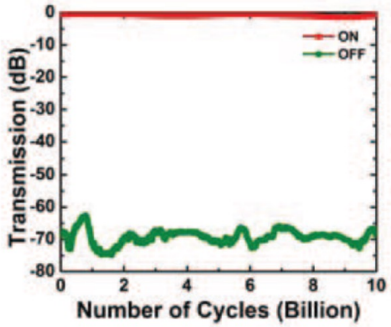
- Alain Yuji Takabayashi, Hamed Sattari, Pierre Edinger, Peter Verheyen, Kristinn B Gylfason, Wim Bogaerts, Niels Quack, "Broadband Compact Single-Pole Double-Throw Silicon Photonic MEMS Switch", JMEMS, 2021.
- Wim Bogaerts, Hamed Sattari, Pierre Edinger, Alain Yuji Takabayashi, Iman Zand, Xiojing Wang, Antonio Ribeiro, Moises Jezzini, Carlos Errando-Herranz, Giuseppe Talli, Kumar Saurav, Marco Garcia Porcel, Peter Verheyen, Banafsheh Abasahl, Frank Niklaus, Niels Quack, Kristinn B. Gylfason, Peter O'Brien, and Umar Khan: "MORPHIC: Programmable photonic circuits enabled by silicon photonic MEMS", Proceedings of SPIE OPTO, January 2020.

Nonvolatile Photonic MEMS Switch Concept

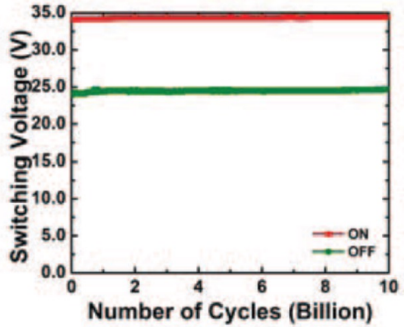
- Hamed Sattari, Adrien Toros, Teodoro Graziosi, Niels Quack, "Bistable Silicon Photonic MEMS Switches", SPIE OPTO, MOEMS and Miniaturized Systems XVIII, 10931-13, 2019.

Reliability of MEMS

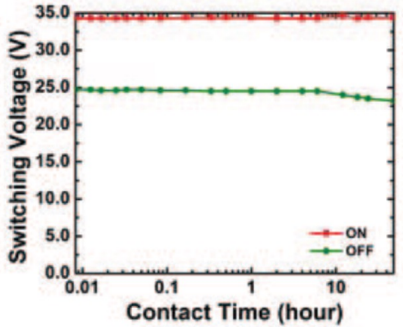
Optical transmissions / # operating cycles



Switching Voltage / # operating cycles



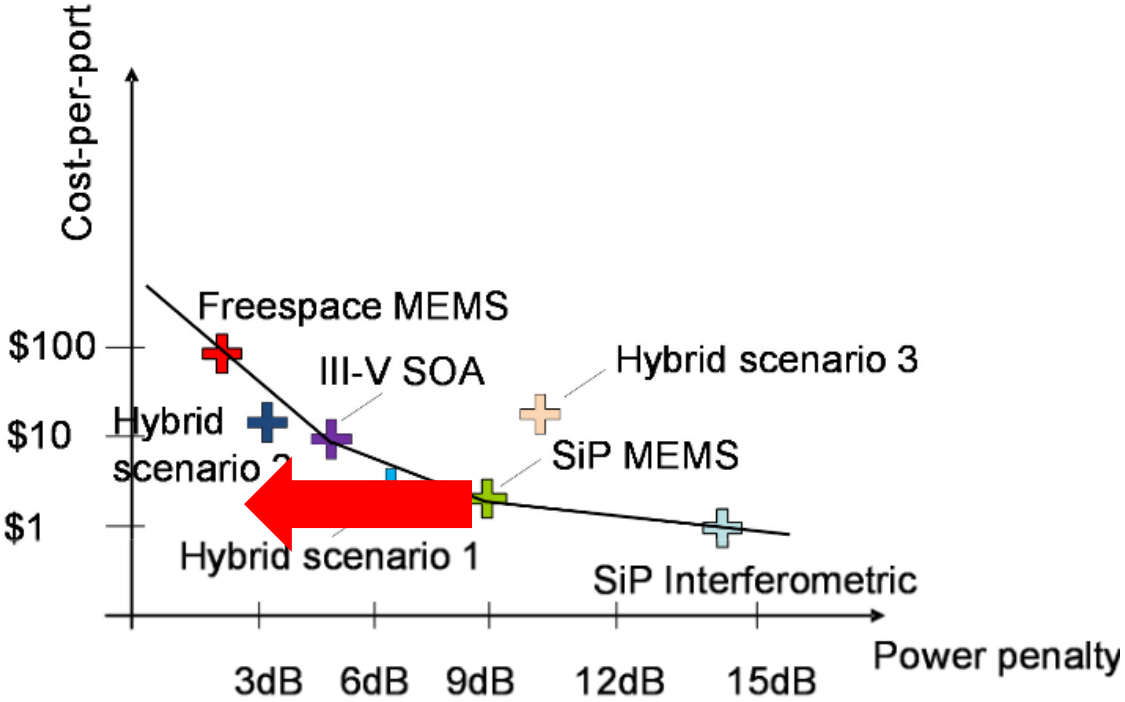
Switching voltages / contact time



- **Reliability has been proven for MEMS**
- **Solved Problem, e.g. DLP by TI:**
  - ~ 1000 x 1000 pixels
  - ~ @ 1 MHz
  - ~ 2778 h = 10 Ms
- **-> 10^{19} switching cycles**
- **-> and then fails: the lamp!**

also: MEMS accelerometers, gyroscopes, resonators, etc.

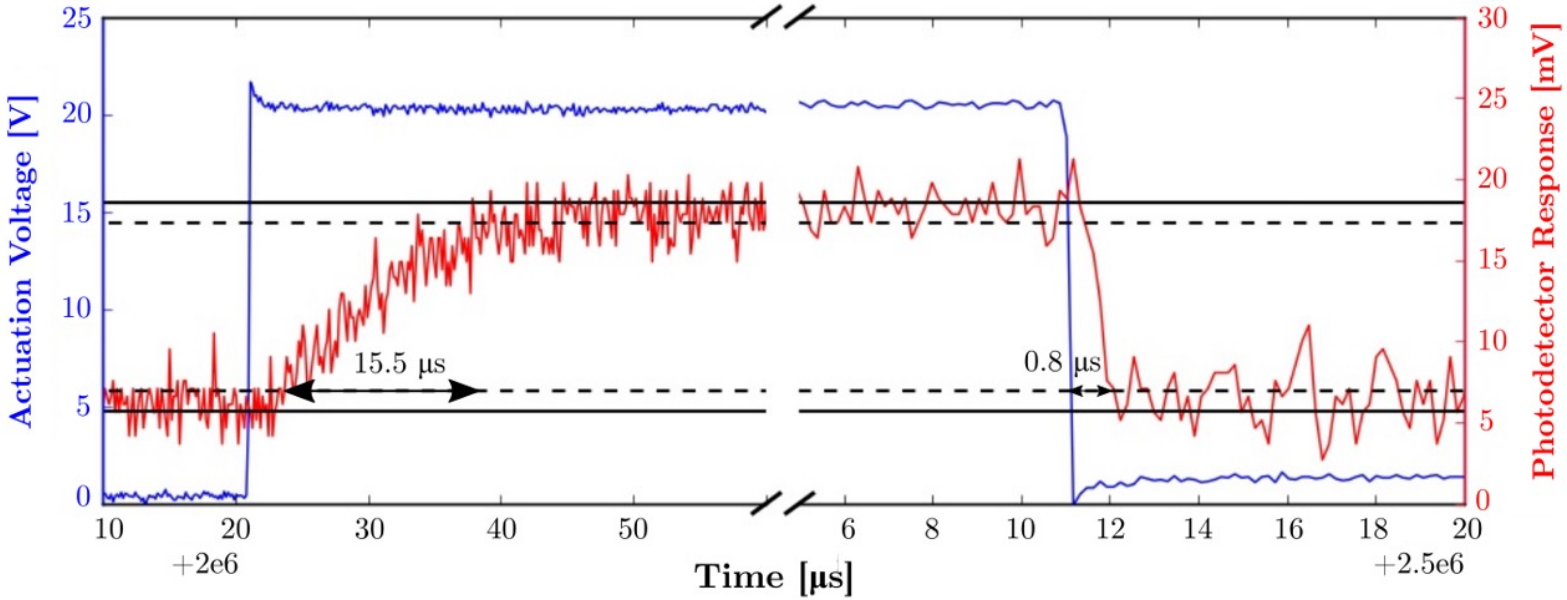
Power Penalty vs. Cost/Port for Photonic Switches



Cheng et al.
/Bergman group
/Columbia

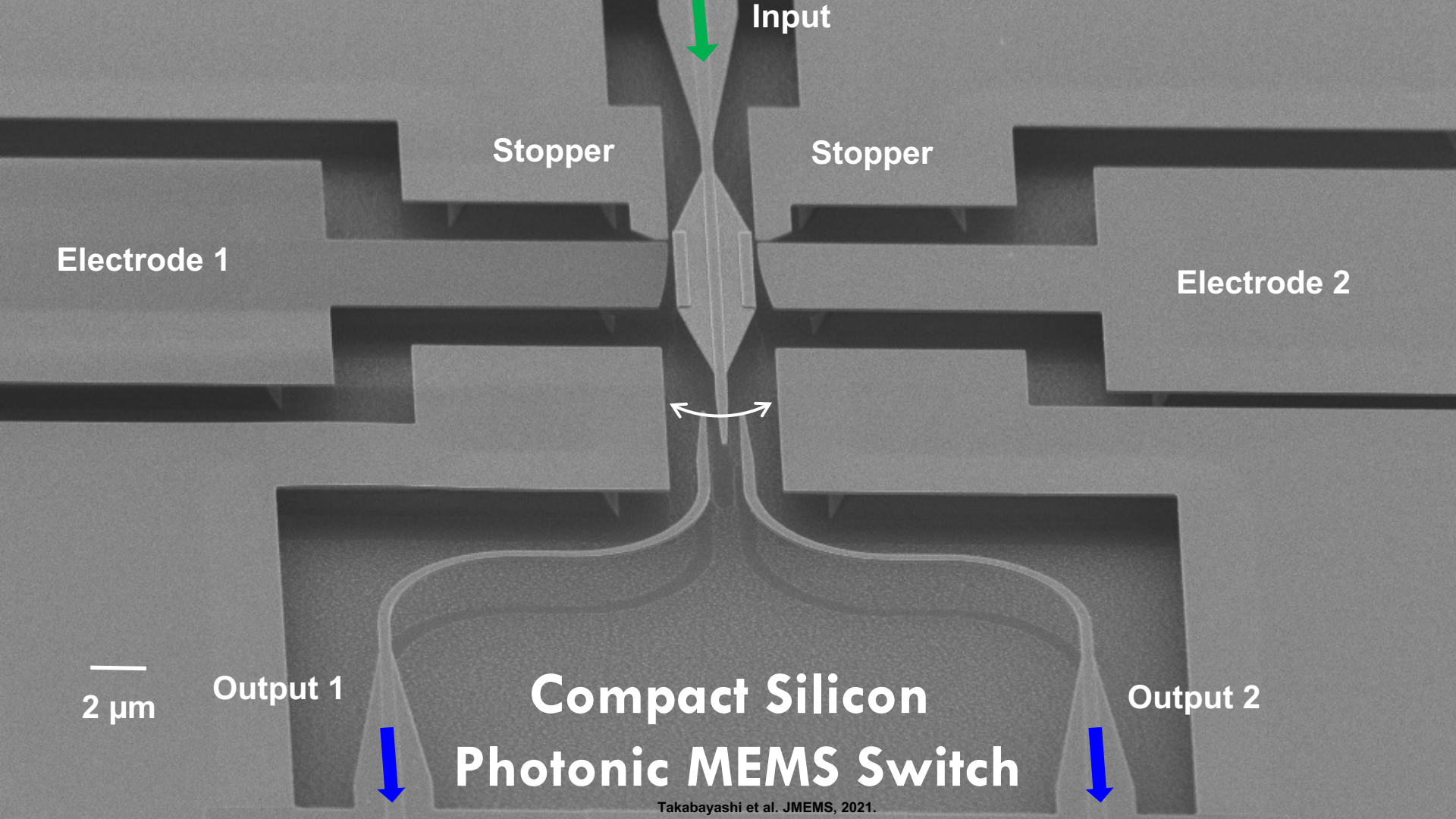
Review
Vol. 26, No. 12 | 11 Jun 2018 | OPTICS EXPRESS 16043
Optics EXPRESS

Response Time Comb-Drive Actuated Coupler



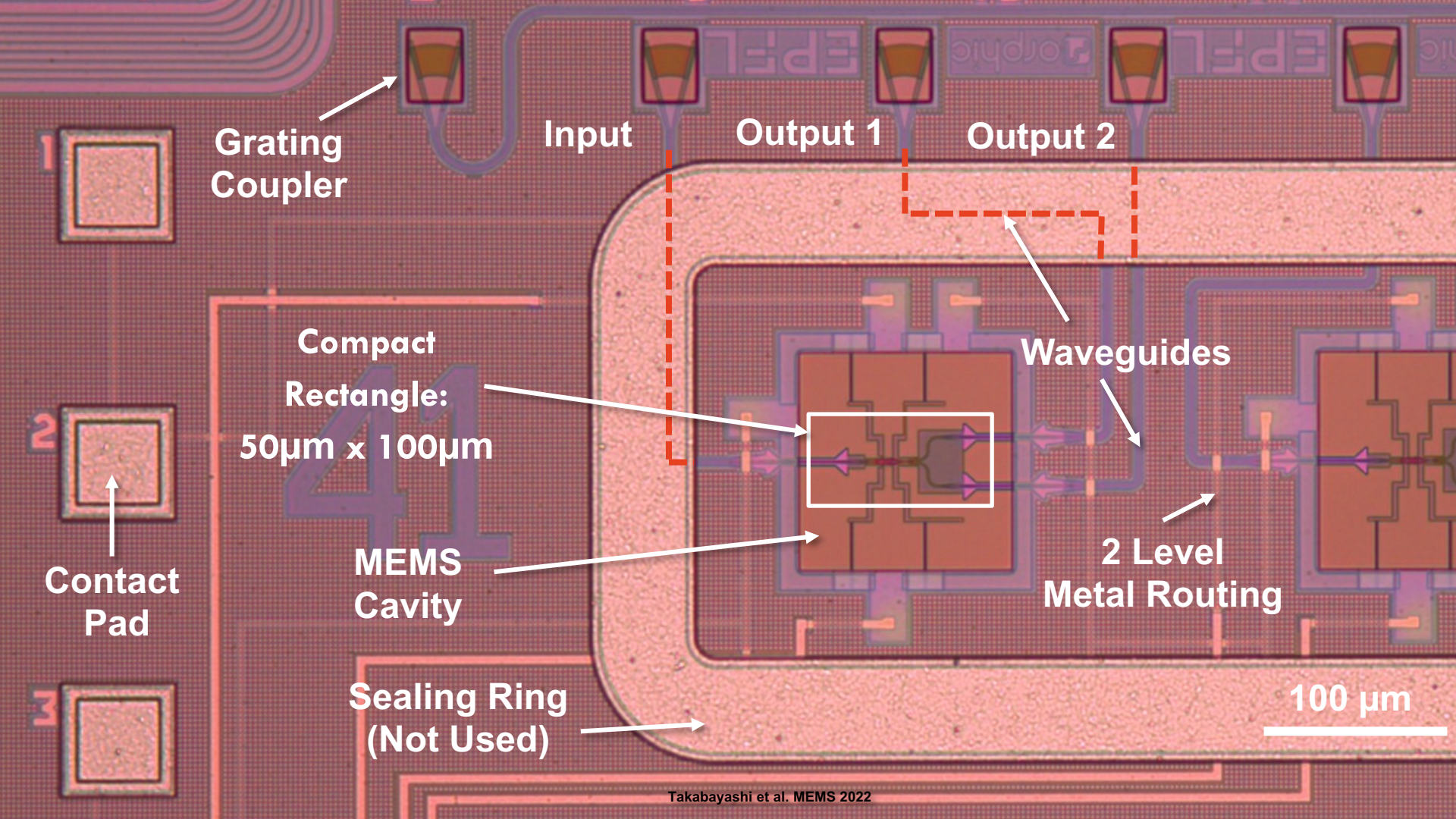
- Fast Electro-Opto-Mechanical Response Time
- Step Response (Voltage Step Input, Optical Signal at Fast Detector)
- Rise Time 15.5 µs, Fall Time 0.8 µs, dominated by Mechanical Response

Takabayashi et al. MEMS 2022



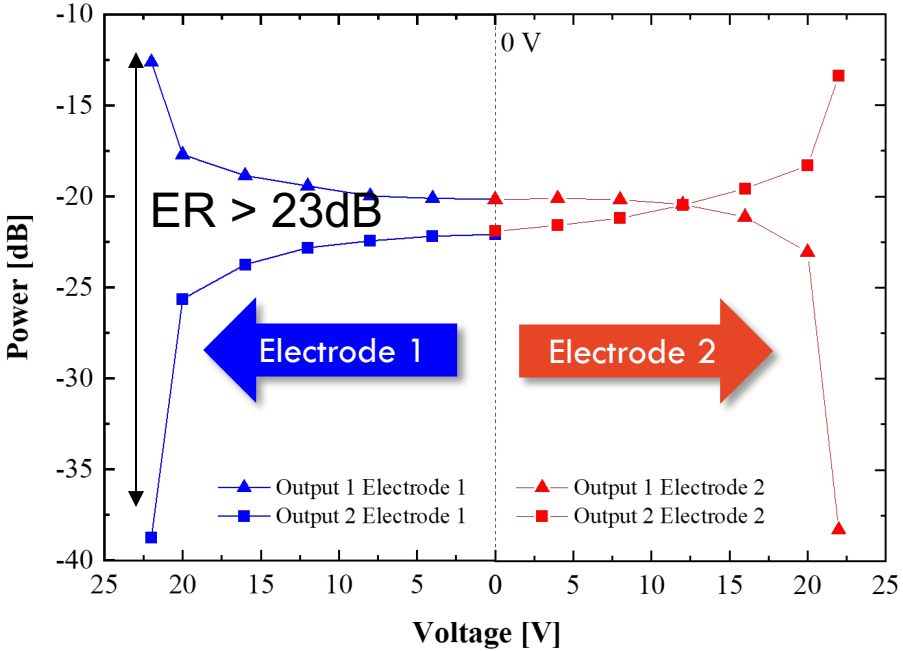
Compact Silicon Photonic MEMS Switch

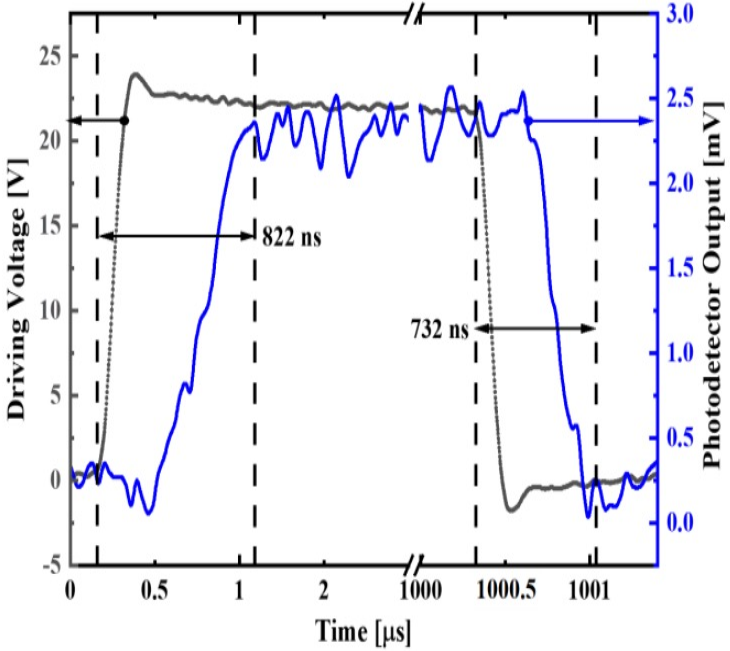
Takabayashi et al. JMEMS, 2021.



Takabayashi et al. MEMS 2022

Compact Silicon Photonic MEMS Switch





- **Compact (65 x 62 µm2), Low Loss**
- **High Extinction Ratio > 23 dB**
- **Broadband > 70nm**

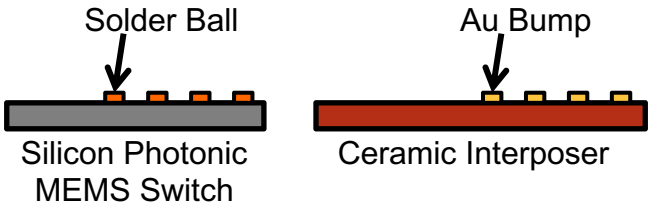
- **Fast**
- **822 ns rise time**
- **732 ns fall time**

Takabayashi et al. JMEMS, 2021.

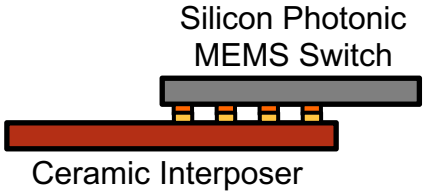
Electrical Interface Scaling
3D Integration

Packaging Process Flow

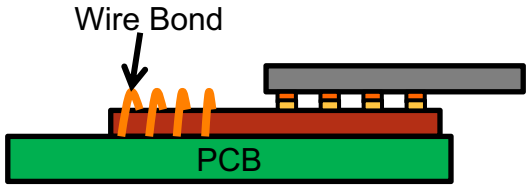
1. Bonding Pad Preparation



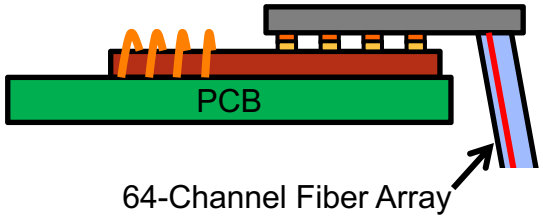
2. Flip Chip Bonding



3. PCB and Wire-Bonding

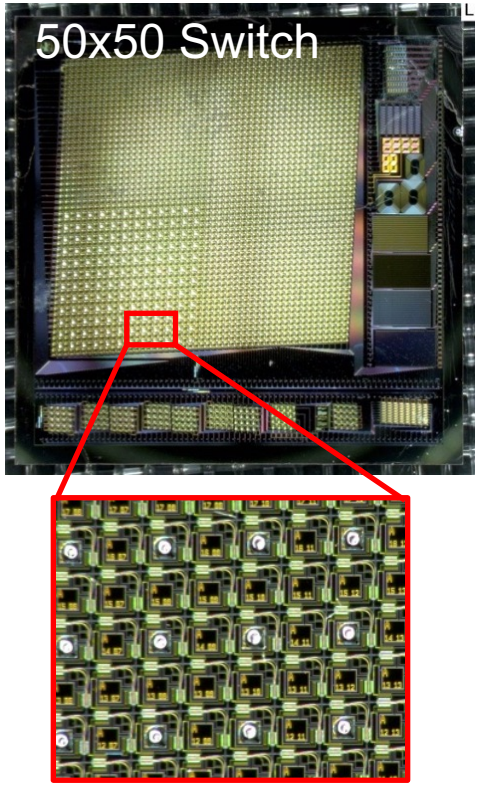


4. Attaching Fiber Array

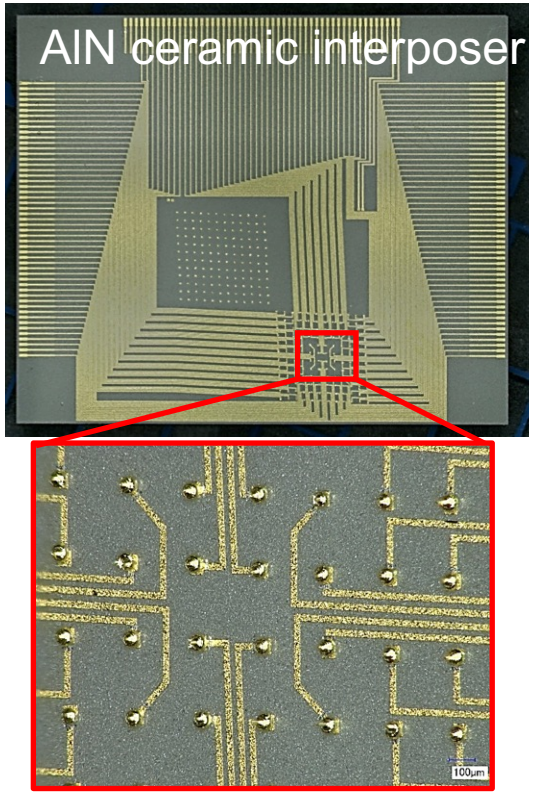


Seok et al., IEEE IPC, Sept. 2016.

Switch and Interposer Chips



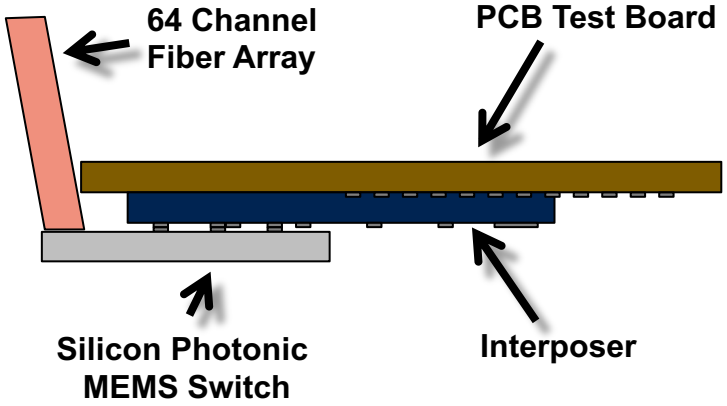
- Silicon Photonic Switch with Jetted Solder Balls

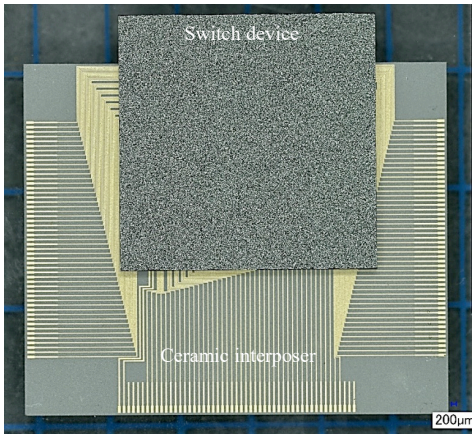


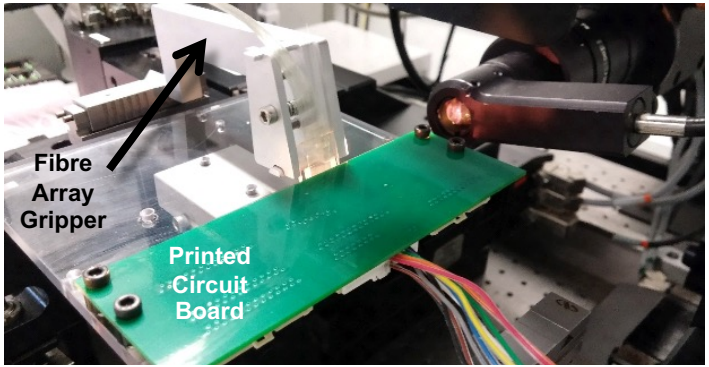
- Ceramic (AlN) Interposer with Gold Stud Bumps

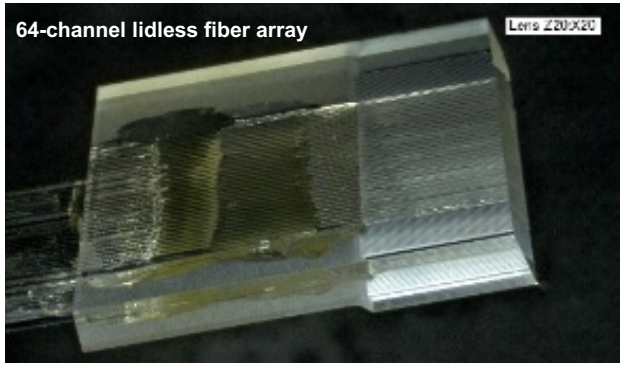
Seok et al., IEEE IPC, Sept. 2016.

3D Integration



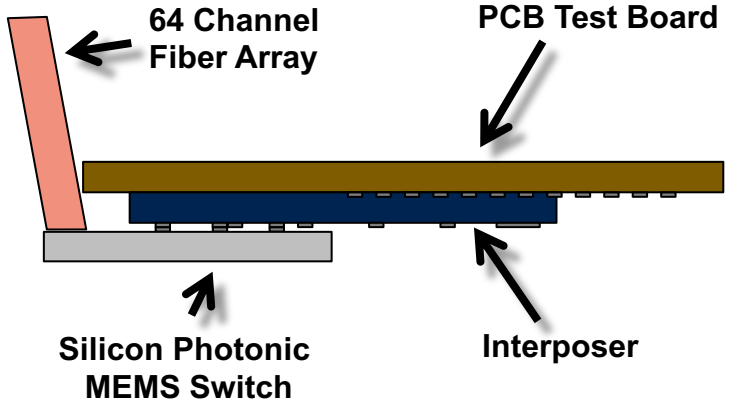


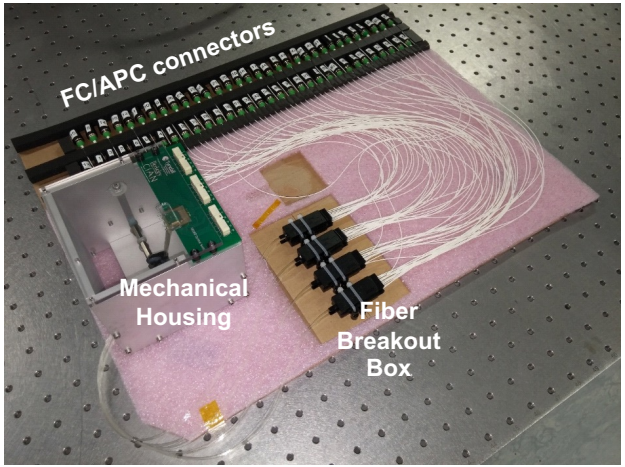


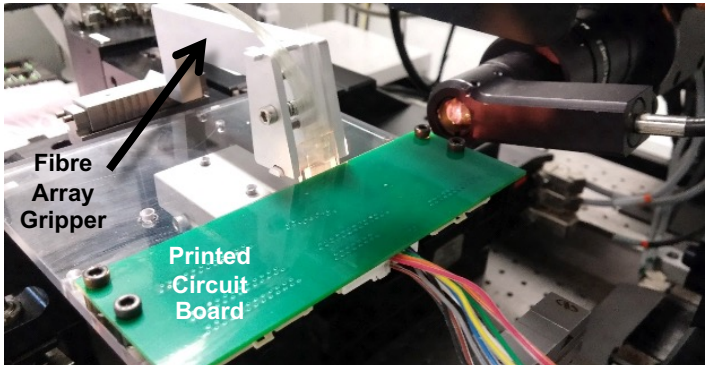


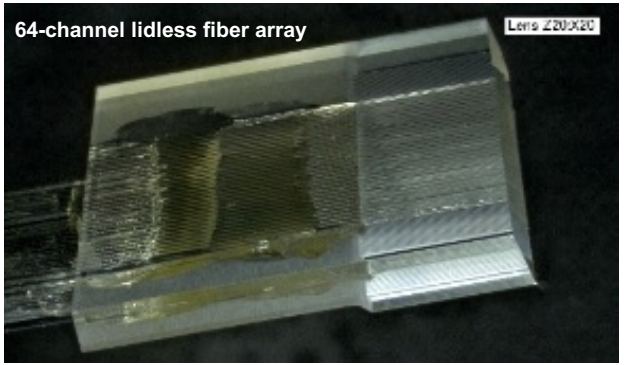
H. S. Hwang *et al.*, "Flip Chip Packaging of Digital Silicon Photonics MEMS Switch for Cloud Computing and Data Centre," in *IEEE Photonics Journal*, vol. 9, no. 3, pp. 1-10, June 2017.

3D Integration









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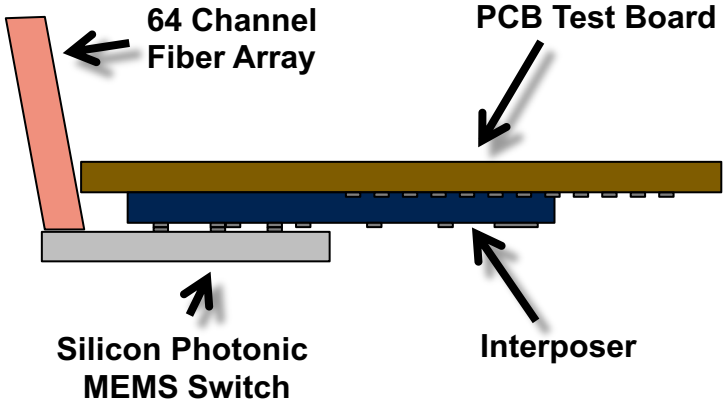
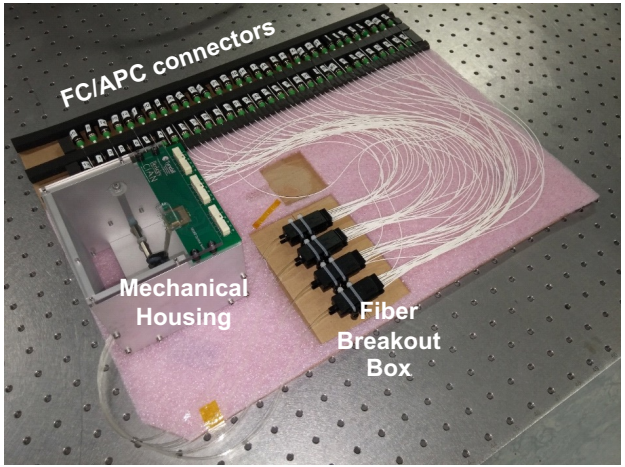
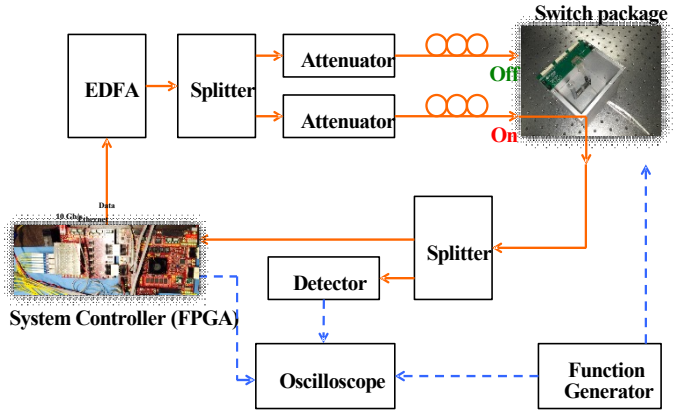
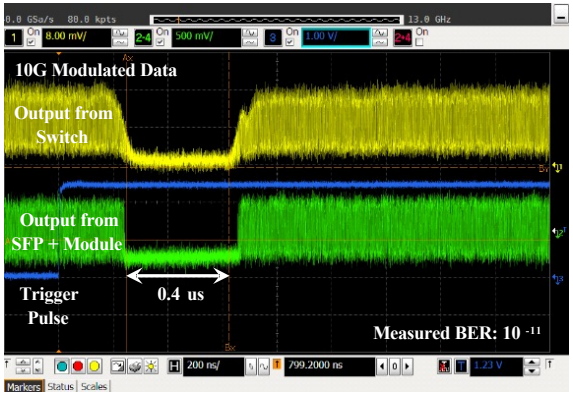
3D Integration









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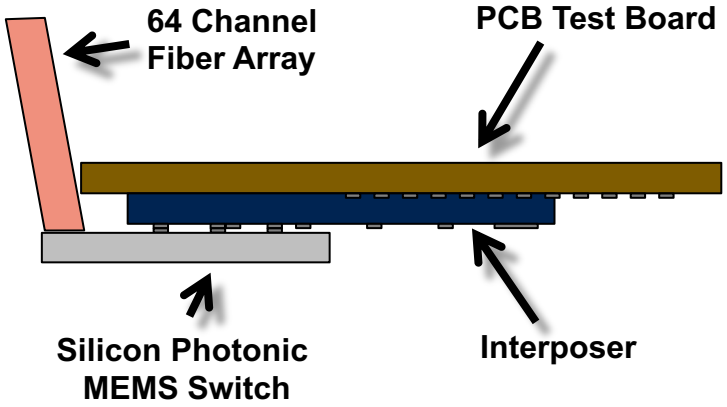
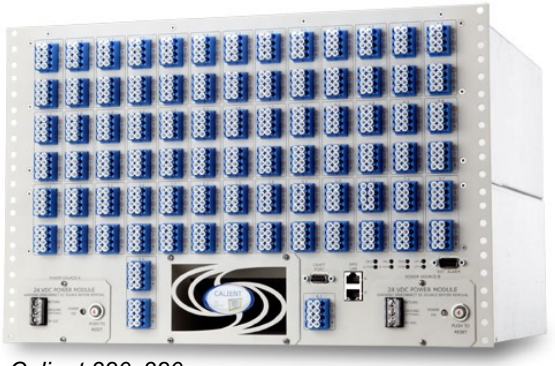
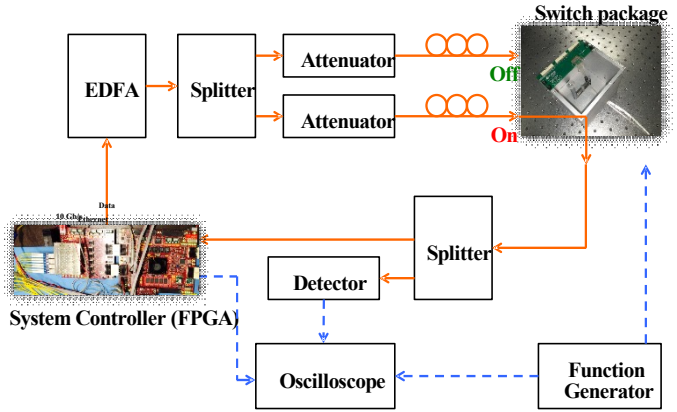
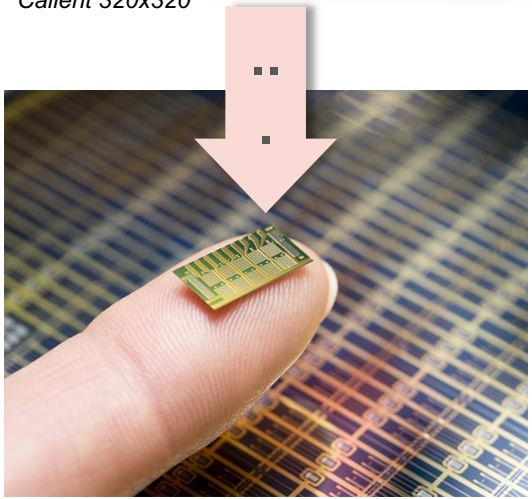
Scalable On-Chip Optical Switches





Calient 320x320





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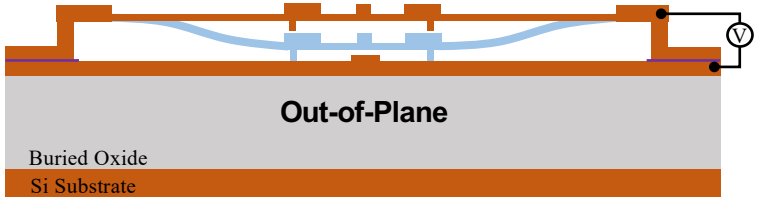
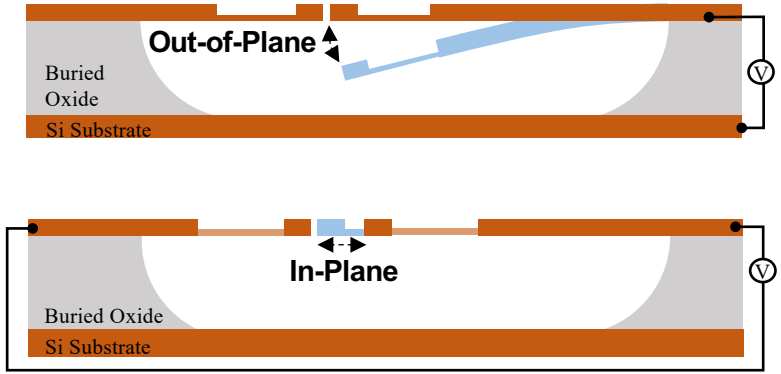
In- and Out-Of-Plane Acutators

Silicon Photonic MEMS

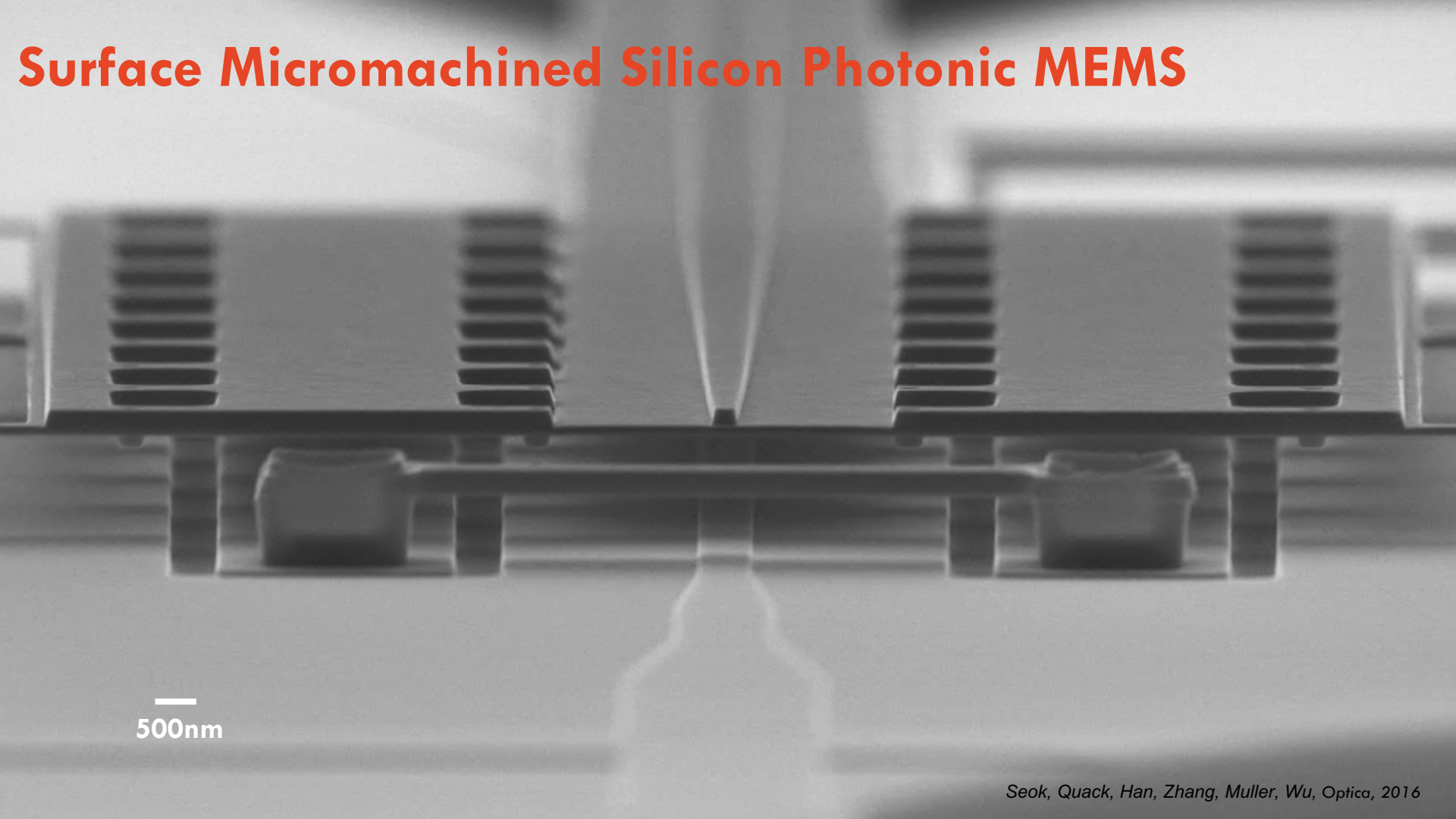


Multi-Layer
(Surface Micromachined)



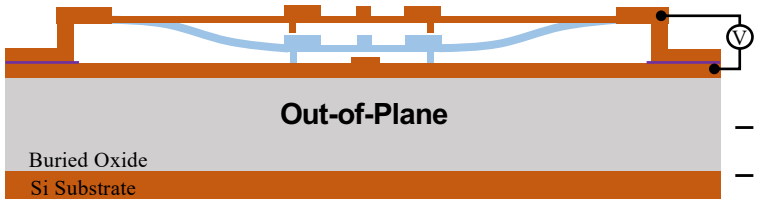
Single-Layer
(SOI Device Layer)

Surface Micromachined Silicon Photonic MEMS



Seok, Quack, Han, Zhang, Muller, Wu, Optica, 2016

Silicon Photonic MEMS

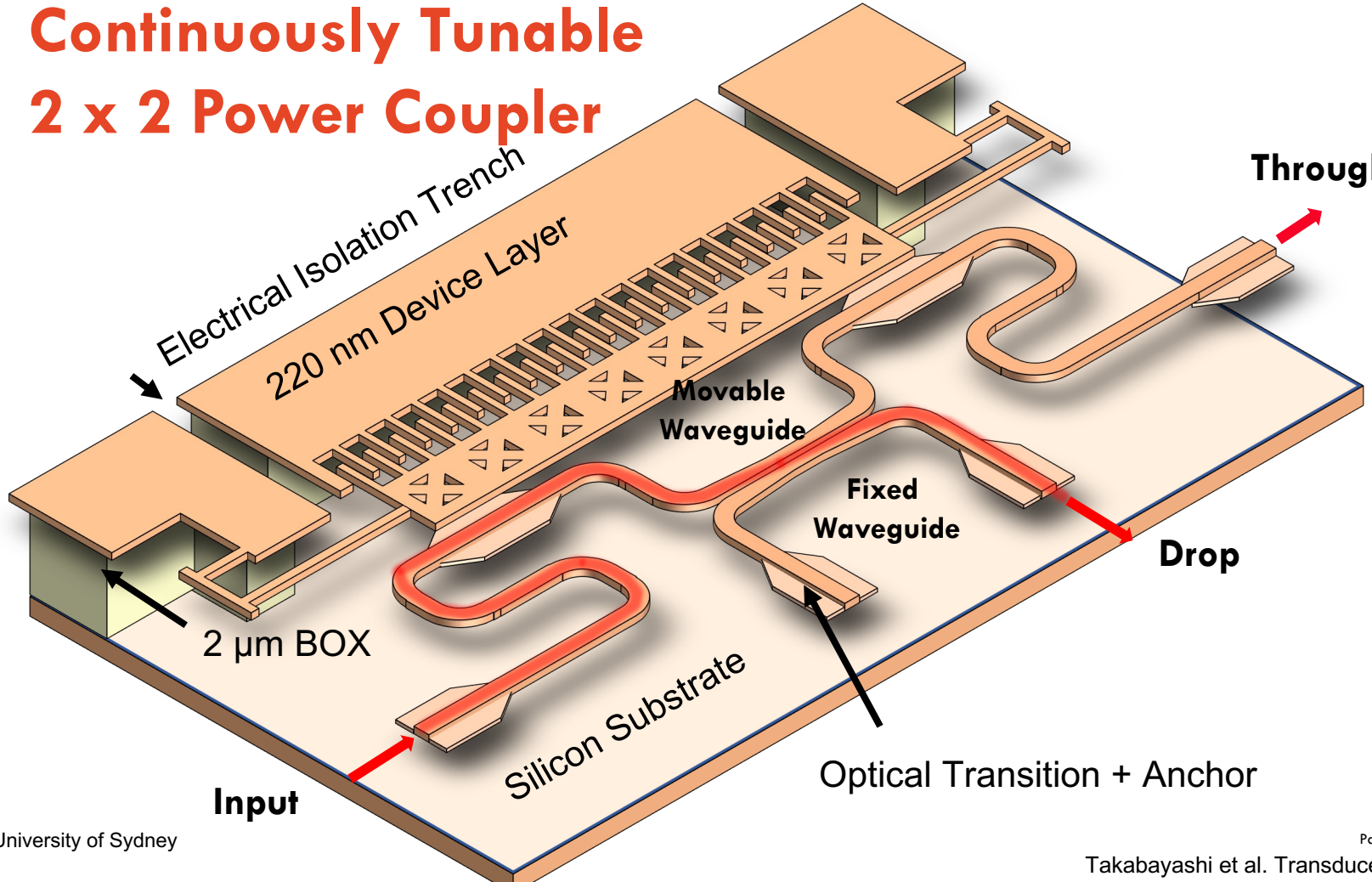


Multi-Layer
(Surface Micromachined)

- Photonic MEMS Switches *Optica, 2016*
- Digital Phase Shifters *OMN 2018*
- Variable Optical Attenuators *SPIE 2018*
- Analog Phase Shifters *OE 2019*
- Wavelength Sel. Switches *APL Ph. 2019*
- Multi-Cast Switching *OE 2019*
- Non-Volatile Photonics *SPIE 2019*
- Optical Beam Steering *CLEO 2020*
- … stay tuned for more… …

Continuously Tunable Power Coupler

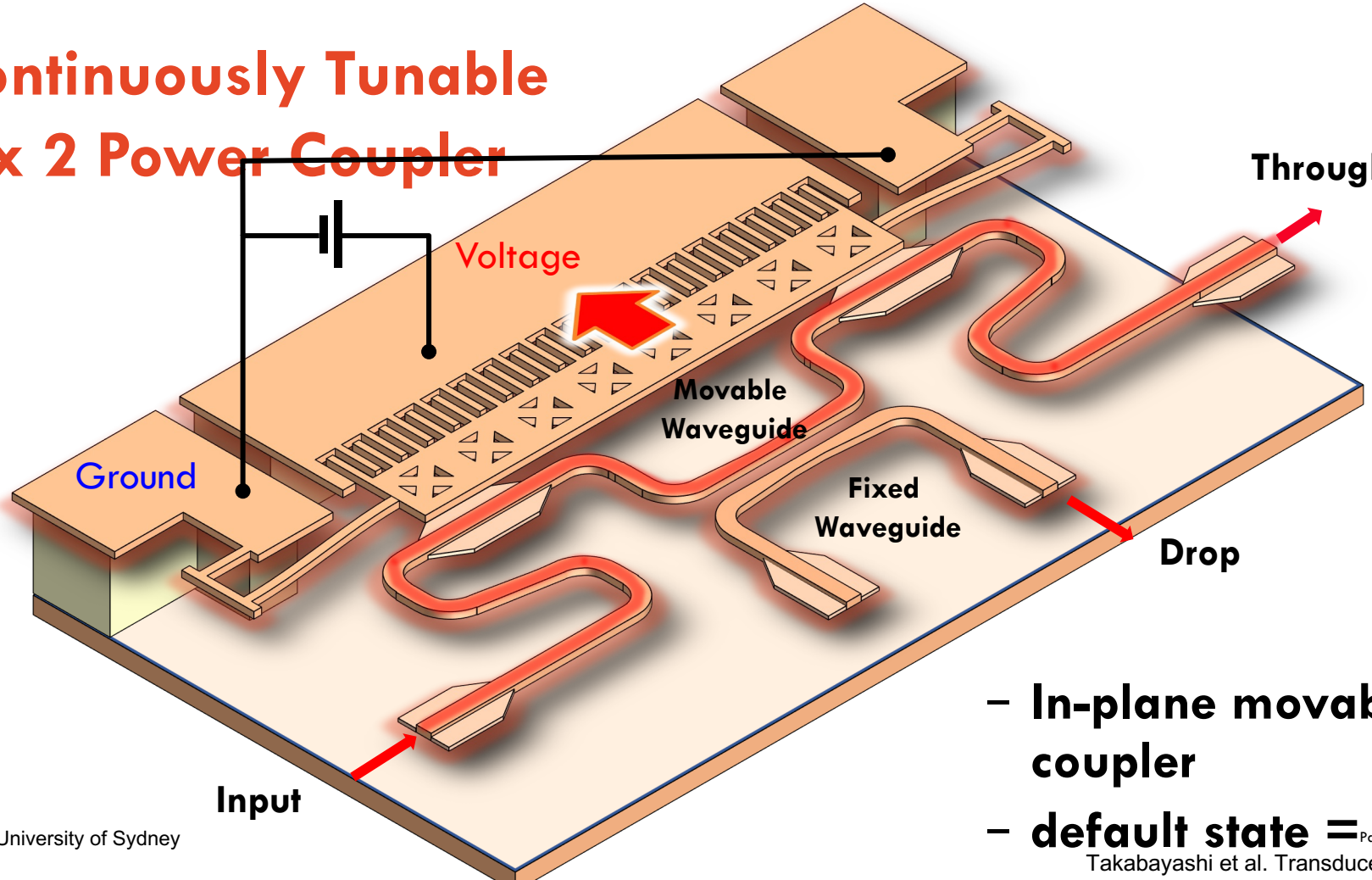
Continuously Tunable 2 x 2 Power Coupler



Silicon Photonic MEMS © niels.quack@sydney.edu.au

Takabayashi et al. Transducers, 2021.

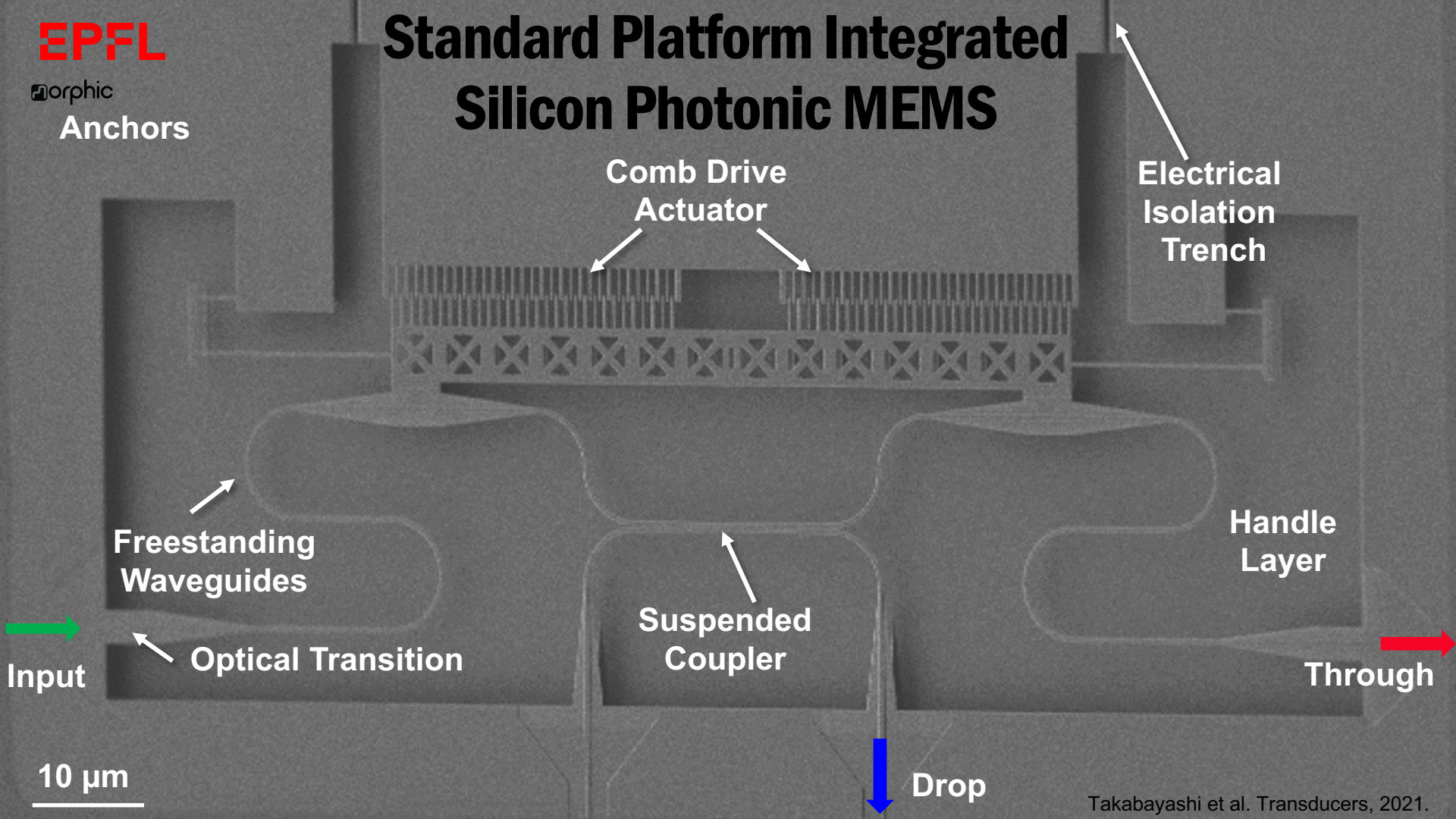
Continuously Tunable 2 x 2 Power Coupler



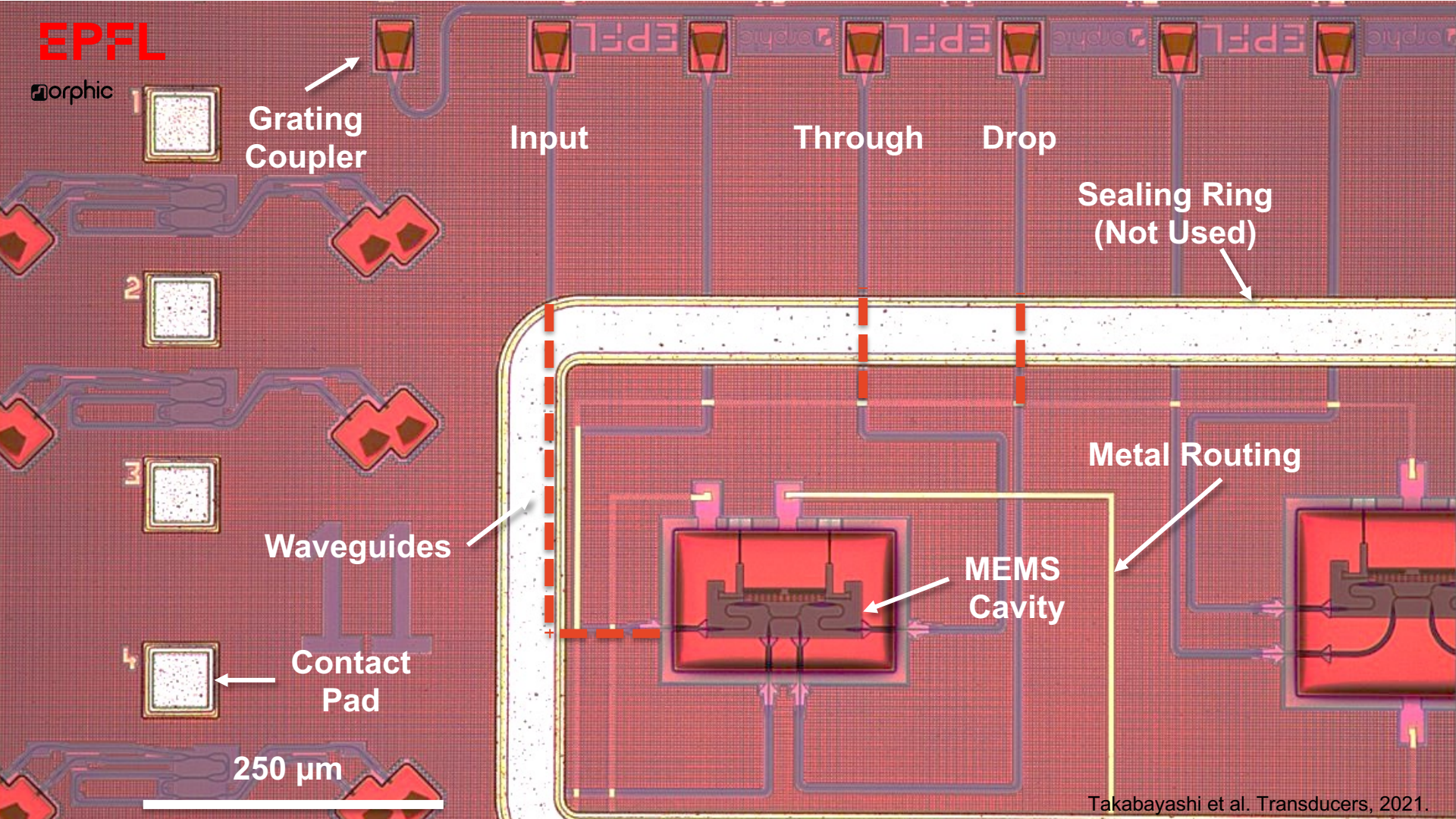
- In-plane movable coupler
- default state = cross

Takabayashi et al. Transducers, 2021.

Silicon Photonic MEMS © niels.quack@sydney.edu.au



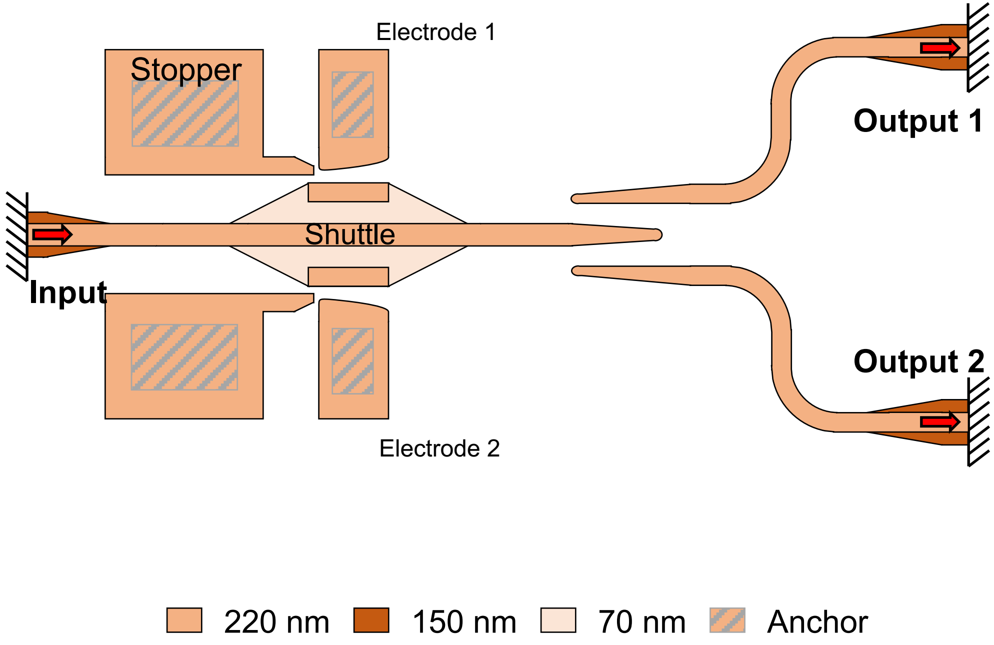
Takabayashi et al. Transducers, 2021.

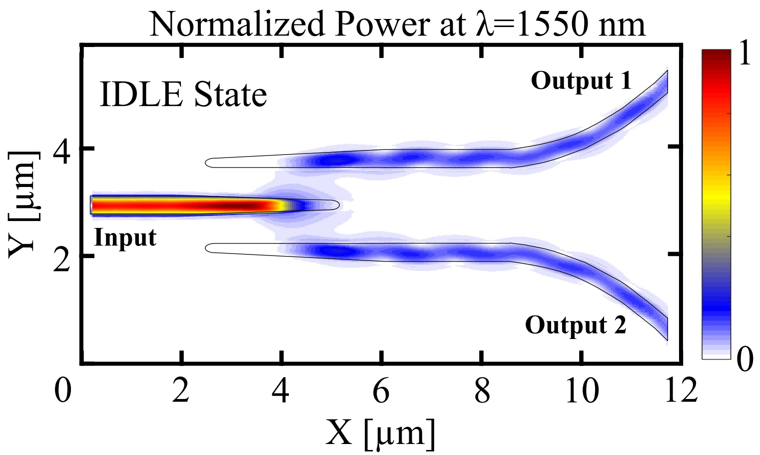


Takabayashi et al. Transducers, 2021.

Compact Silicon Photonic MEMS Switch

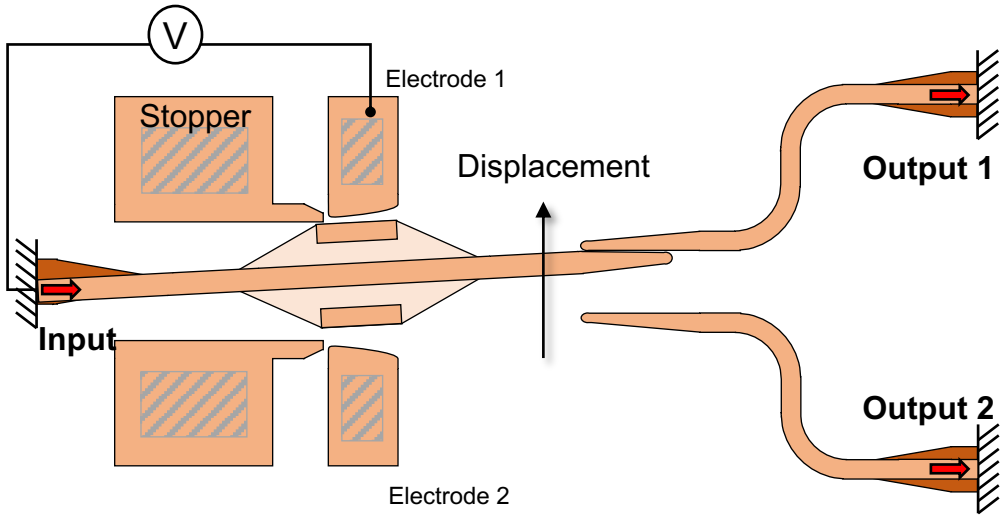
1 x 2 Silicon Photonic MEMS Switch

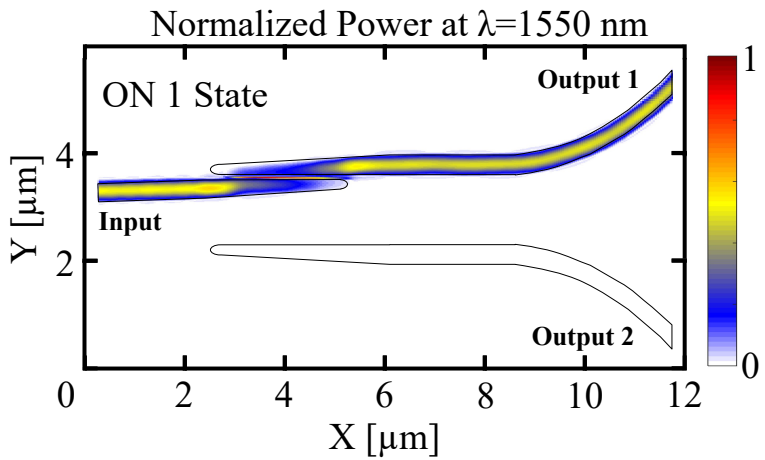




Takabayashi et al. JMEMS, 2021.

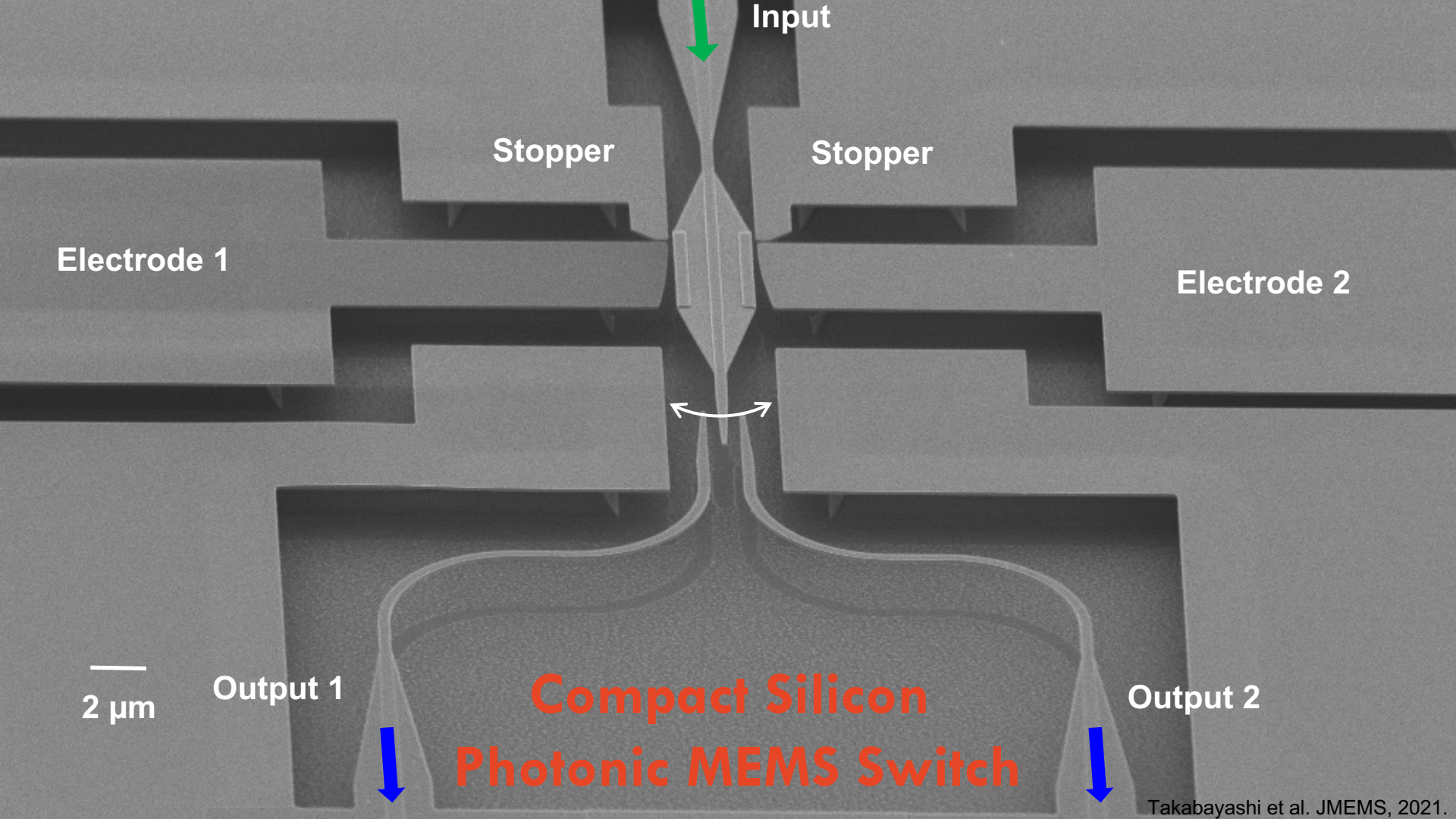
1 x 2 Silicon Photonic MEMS Switch



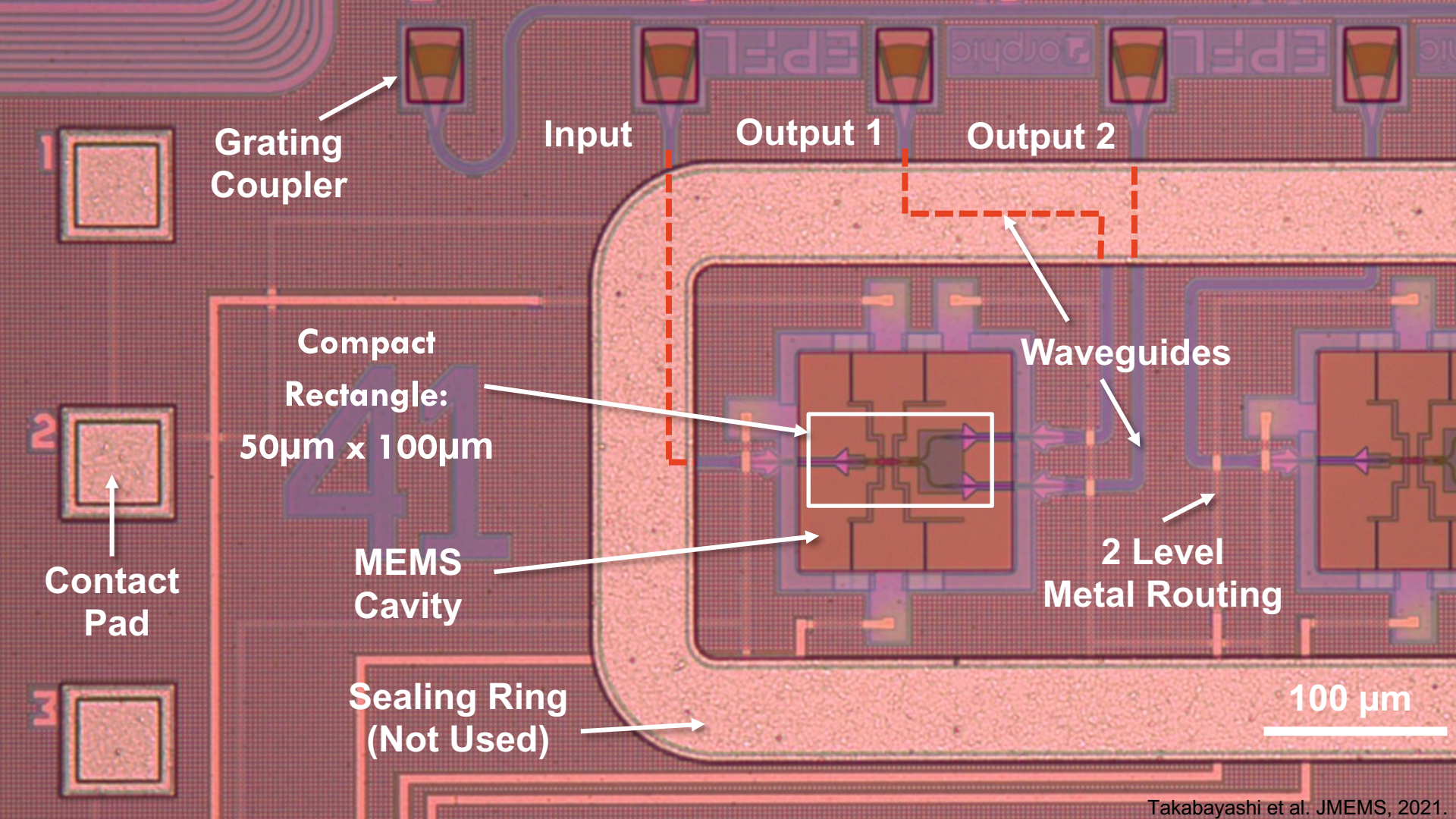


220 nm 150 nm 70 nm Anchor

Takabayashi et al. JMEMS, 2021.

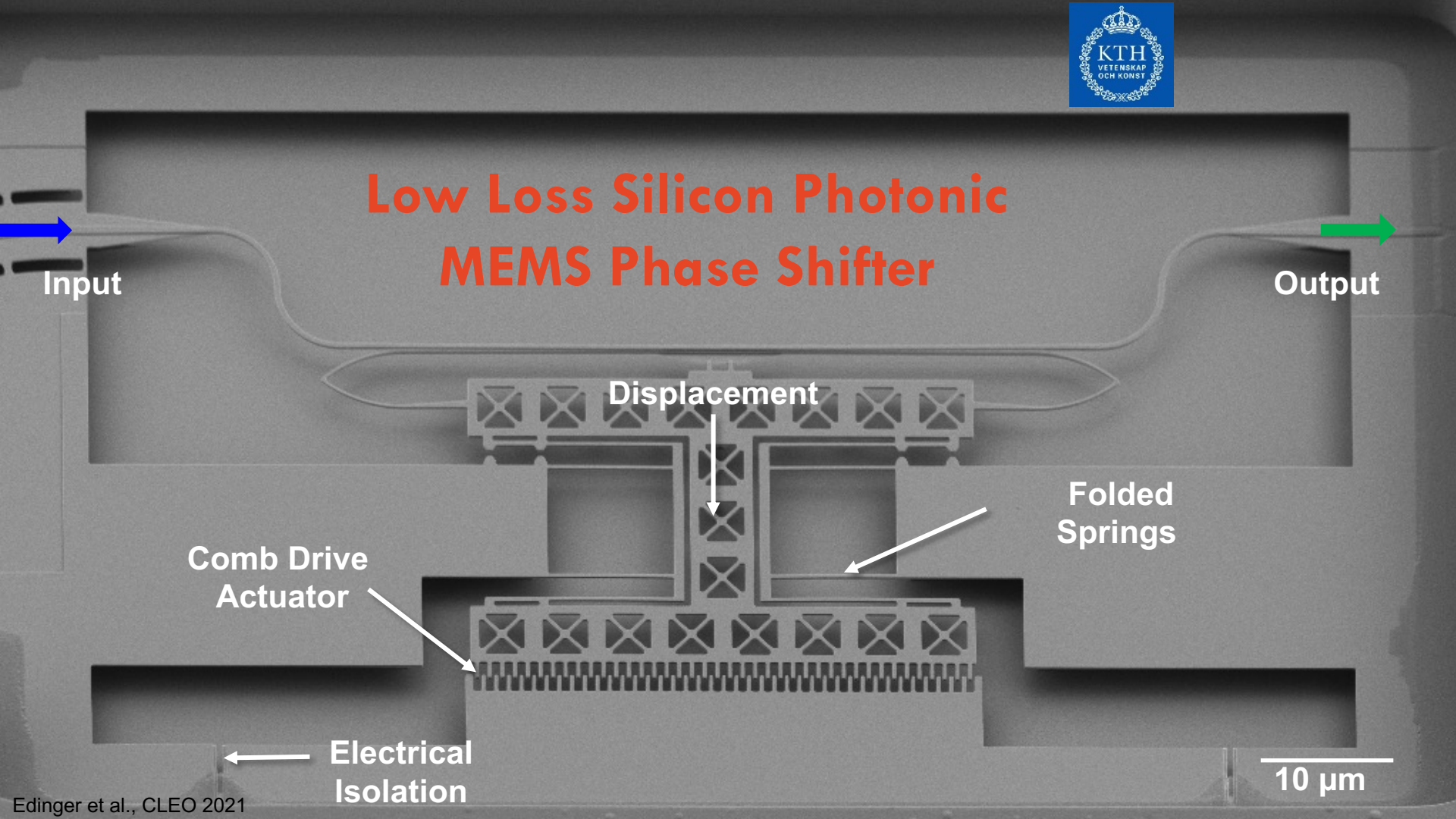


Takabayashi et al. JMEMS, 2021.



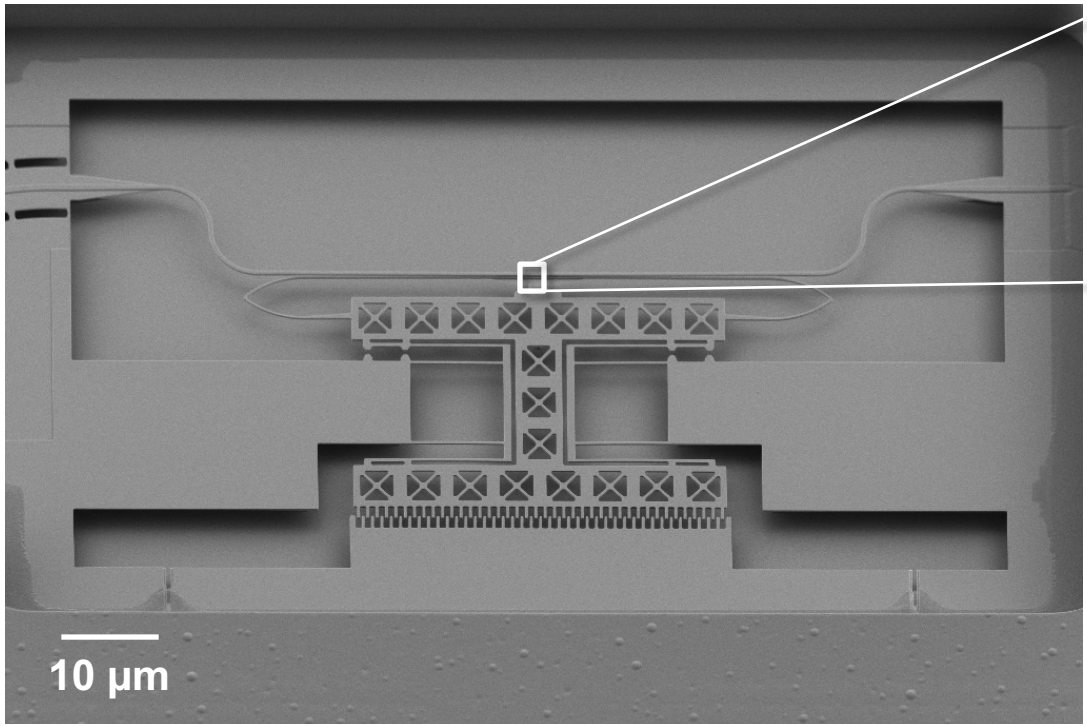
Takabayashi et al. JMEMS, 2021.

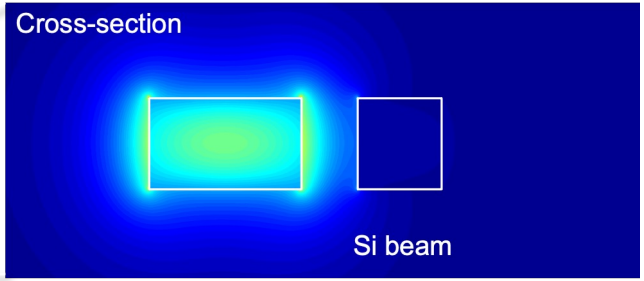
Silicon Photonic MEMS Phase Shifter



Edinger et al., CLEO 2021

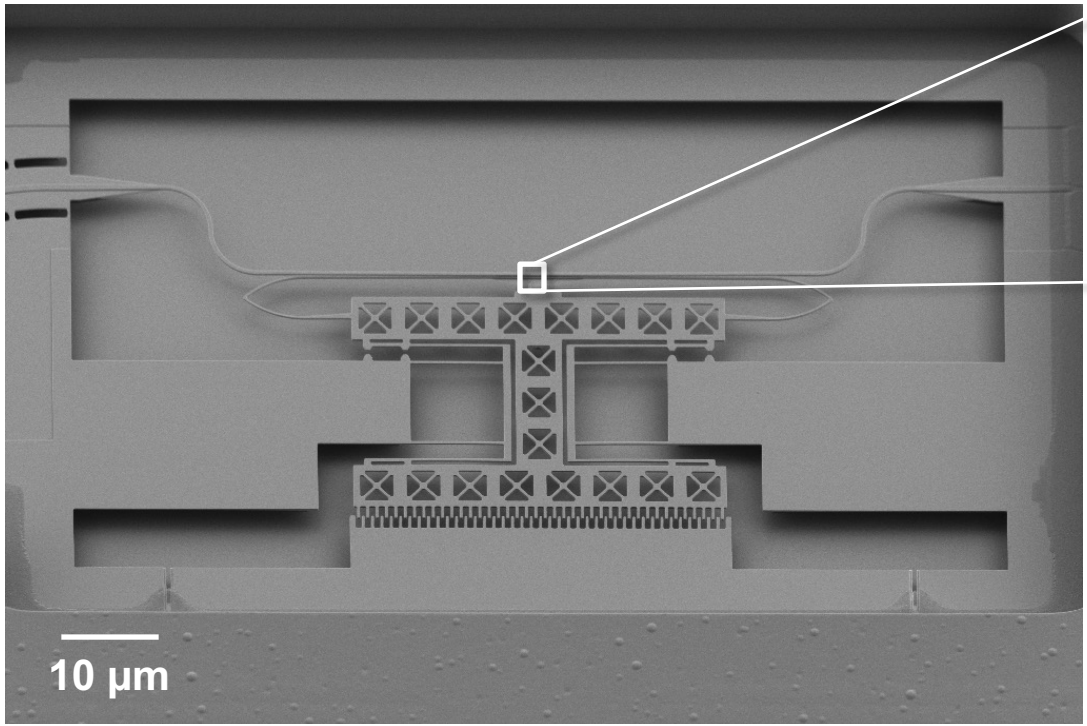
Silicon Photonic MEMS Phase Shifter

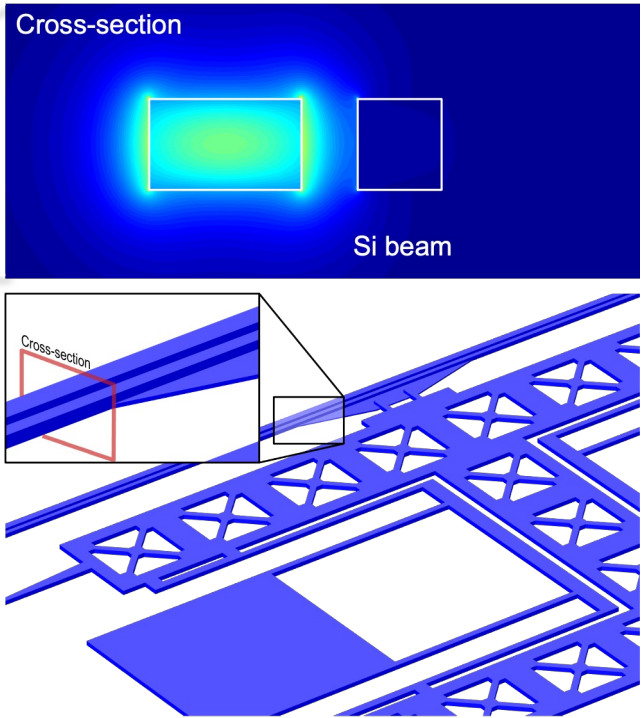




Edinger et al., CLEO 2021

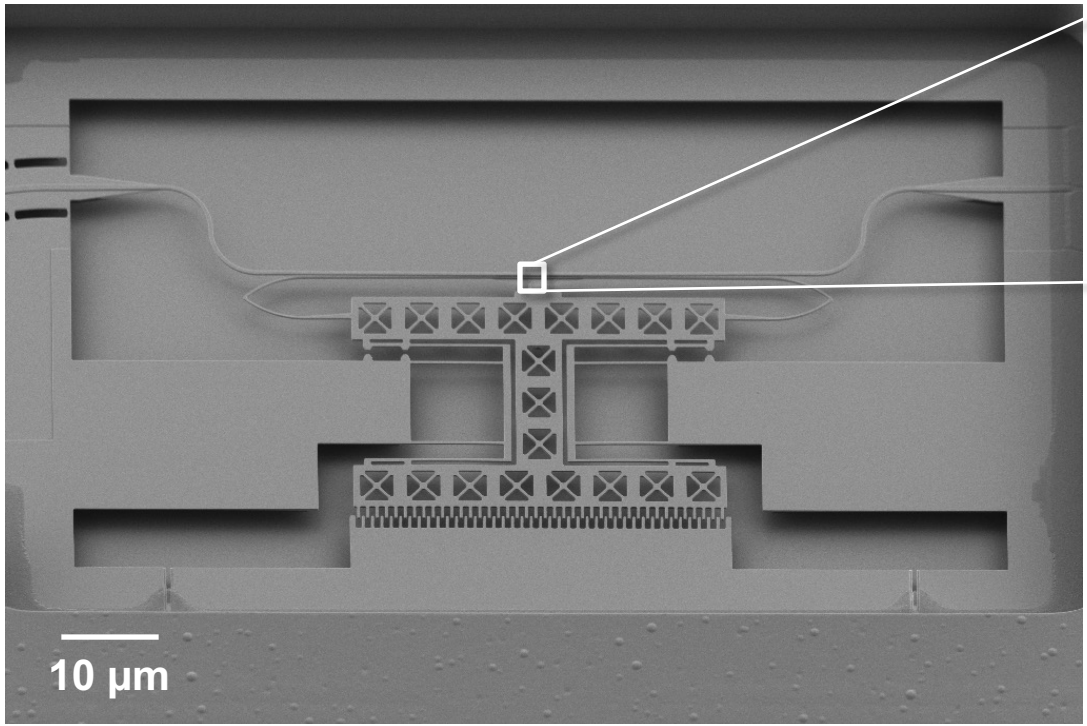
Silicon Photonic MEMS Phase Shifter

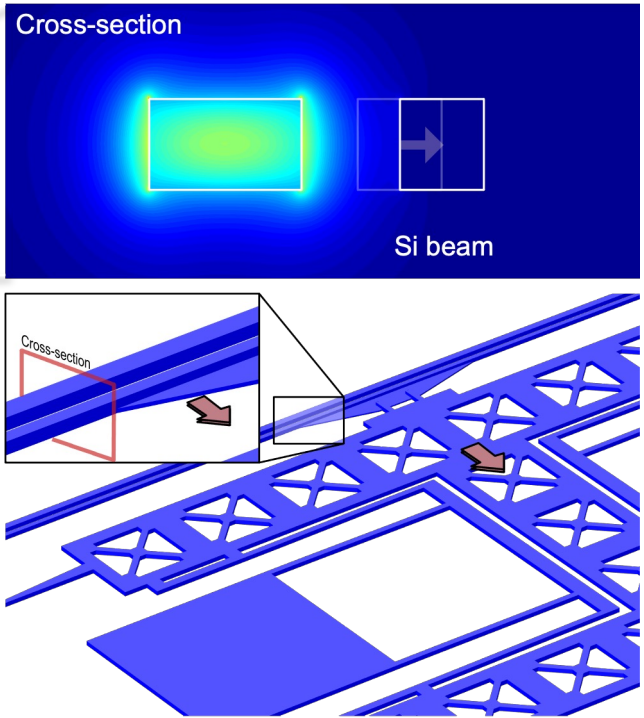




Edinger et al., CLEO 2021

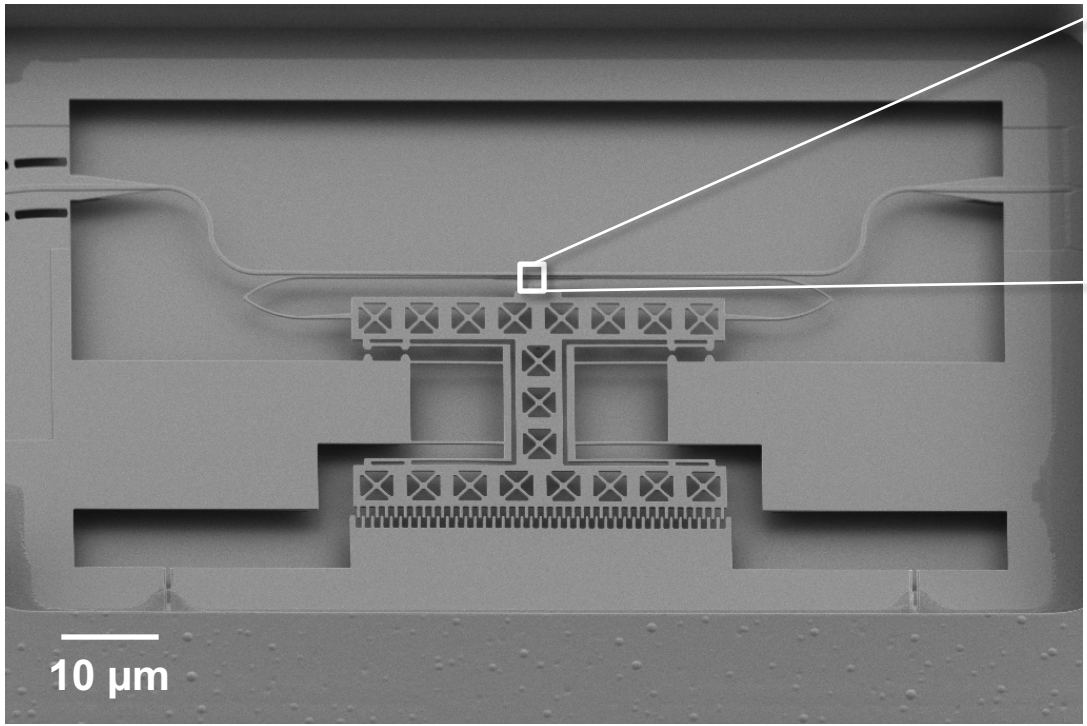
Silicon Photonic MEMS Phase Shifter

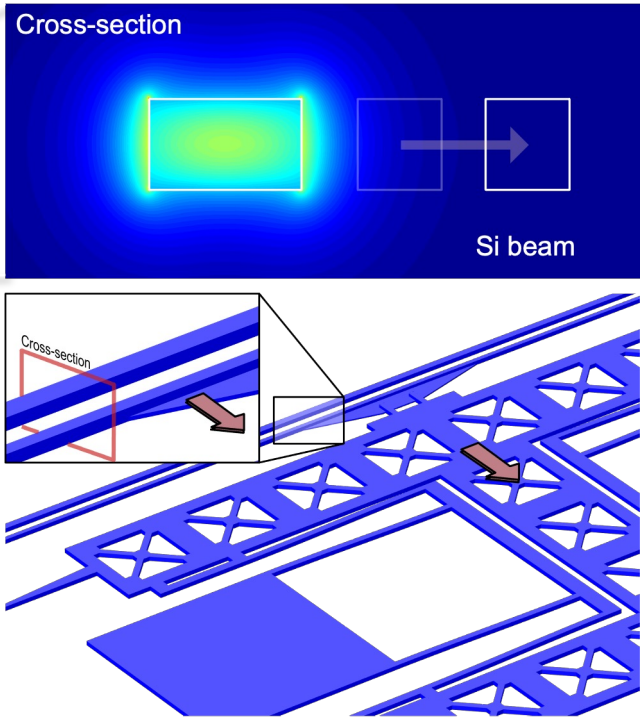




Edinger et al., CLEO 2021

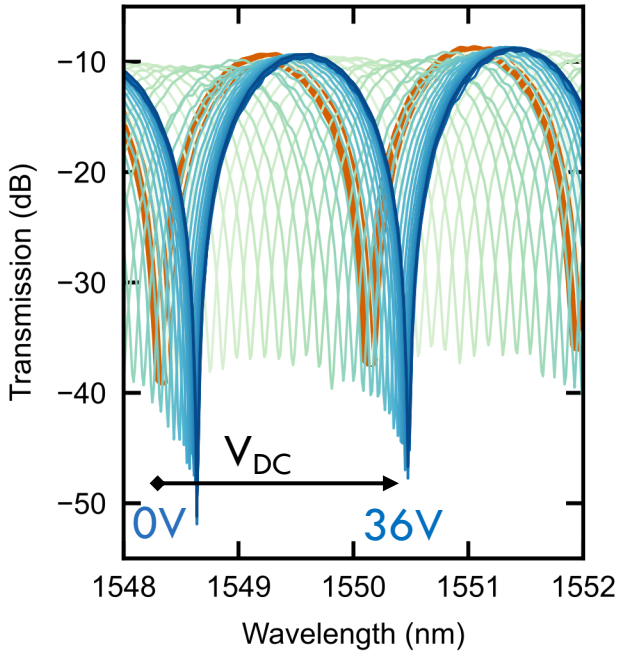
Silicon Photonic MEMS Phase Shifter

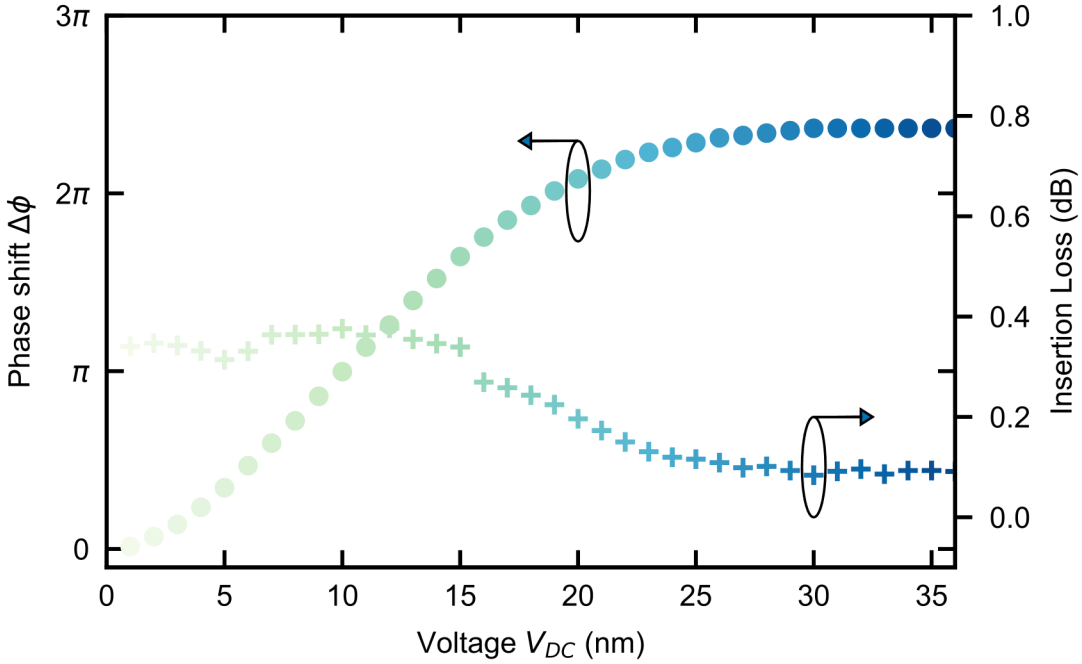




Edinger et al., CLEO 2021

Silicon Photonic MEMS Phase Shifter





- **Compact**
- **2 π Phase Shift @ 36V**
- **Low Insertion Loss < 0.5dB**

- Fast
- Resonance Frequency 461 kHz

Edinger et al., CLEO 2021