Mode Division Multiplexing in Silicon Photonics for High-Speed Communication, Computation, and Quantum Information

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the Photonic DataCom team

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Our Research Team and Presentation Outline

McGill University, Montréal, Québec, Canada

Our research in Photonic DataCom lab:

- ❖ Photonic integration for data communications
- ❖ Emerging photonic applications such as computing for Machine Learning, AI, and quantum photonics

Presentation Outline

- ❖ Mode-Division-Multiplexing Motivation and PDK
- ❖ Application in Switching
- ❖ Application in Quantum Computing
- ❖ Application in Classical Computing
- ❖ Summary and Future Works

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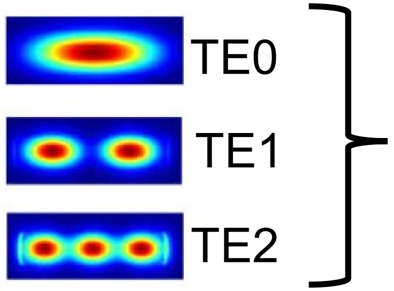
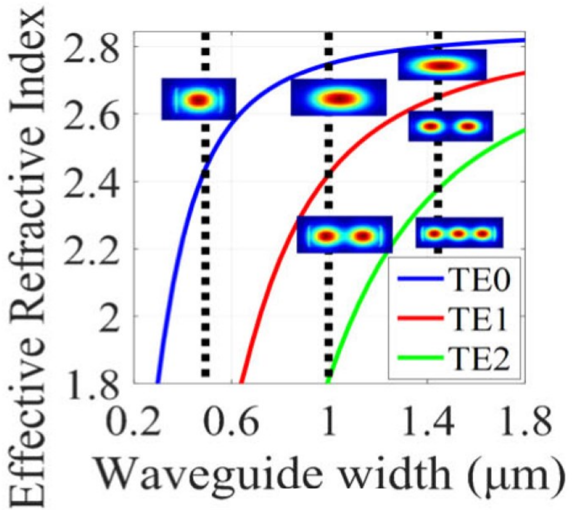
Why Multi-Transverse-Mode Photonics?

Waveguide cross section



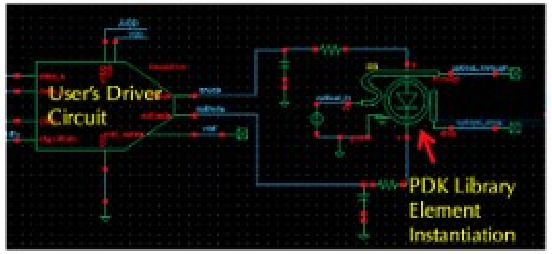
Solutions of Maxwell equation
They are **orthogonal**

Transverse electric (TE) modes

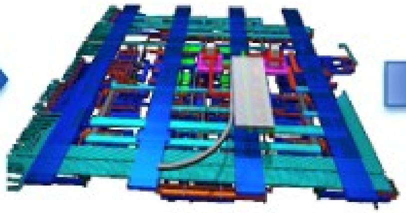


We can use different transverse modes as orthogonal channels - Similar to different wavelength channels in wavelength division multiplexing (WDM)

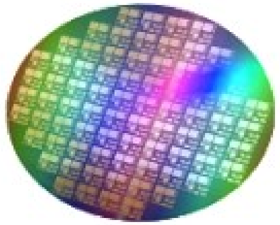
Multi-Transverse-Mode PDK for 220 nm SiPh



PDK
(Process Design Kit)



State of the Art
300mm Fab



MPW
(Multi Project Wafer)

Standard foundries PDKs are single mode only.

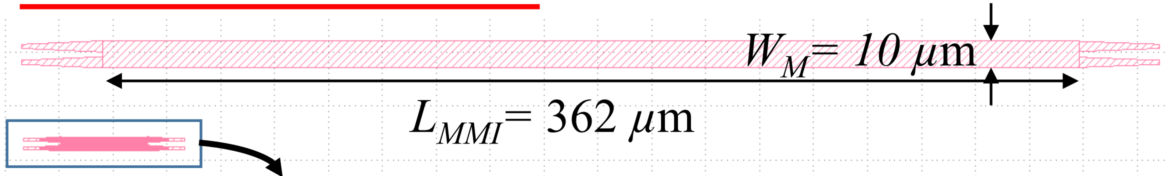
Open access PDK with validated Multi-transverse-mode components:

github.com/KavehMojaver/SiPh_MDM_PDK

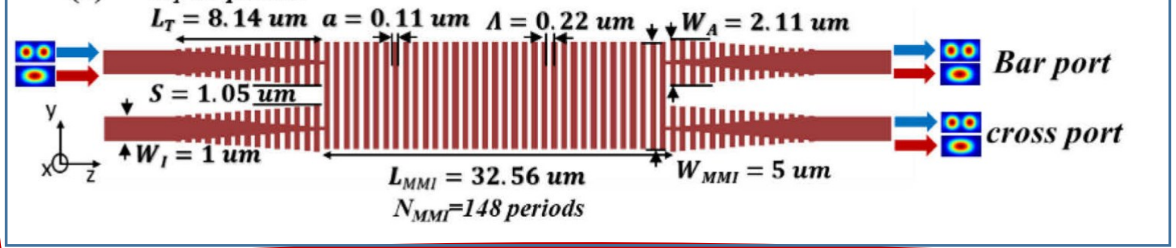
Multi-Transverse-Mode PDK for 220 nm SiPh (cont.)

Mode insensitive MMIs

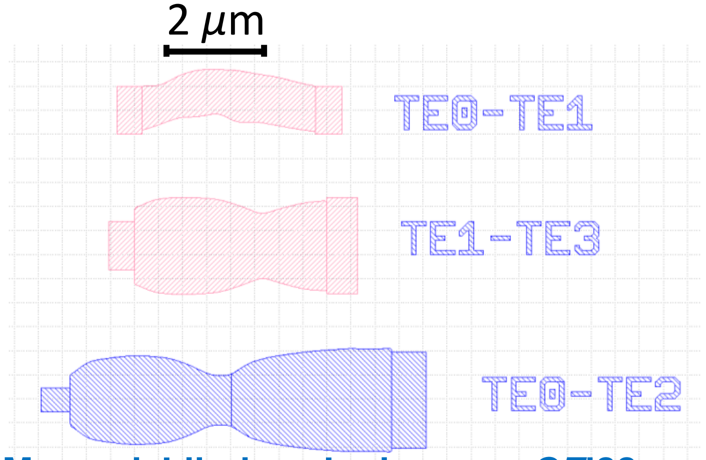
Das, Liboiron-Ladouceur, *PTL*'22.



Shiran, Liboiron-Ladouceur, *OE* '21.



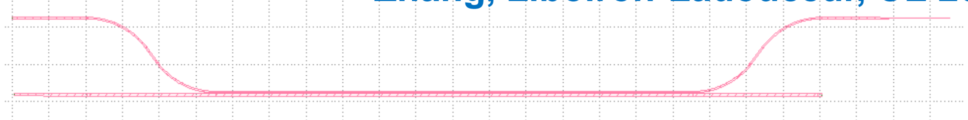
Mode converters



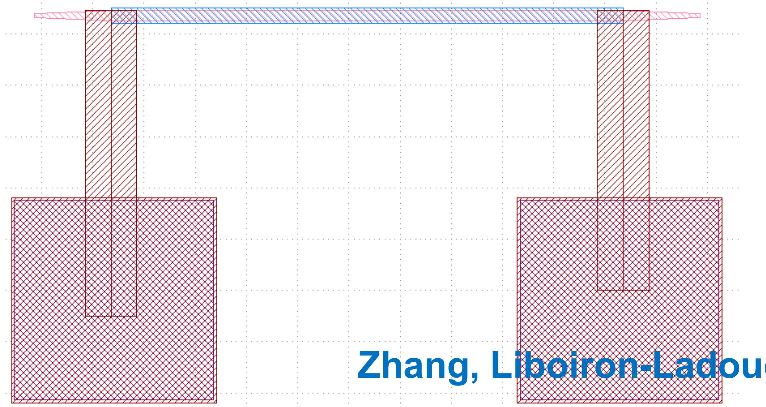
Masnad, Liboiron-Ladouceur, *OE*'22.

(de)Multiplexer

Zhang, Liboiron-Ladouceur, *OL*'20.



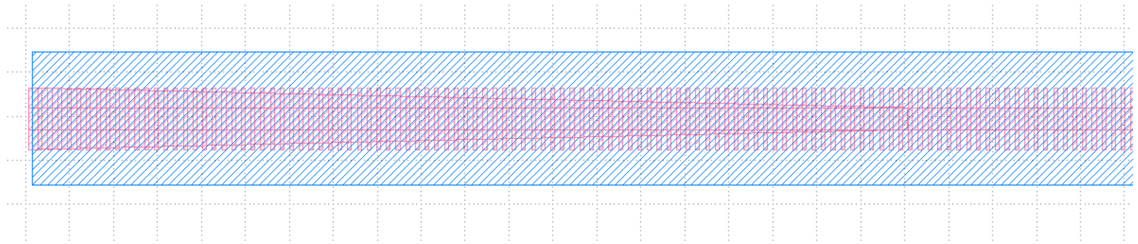
Mode-insensitive thermo-optic phase shifter (TOPS)



Zhang, Liboiron-Ladouceur, *OL*'20.

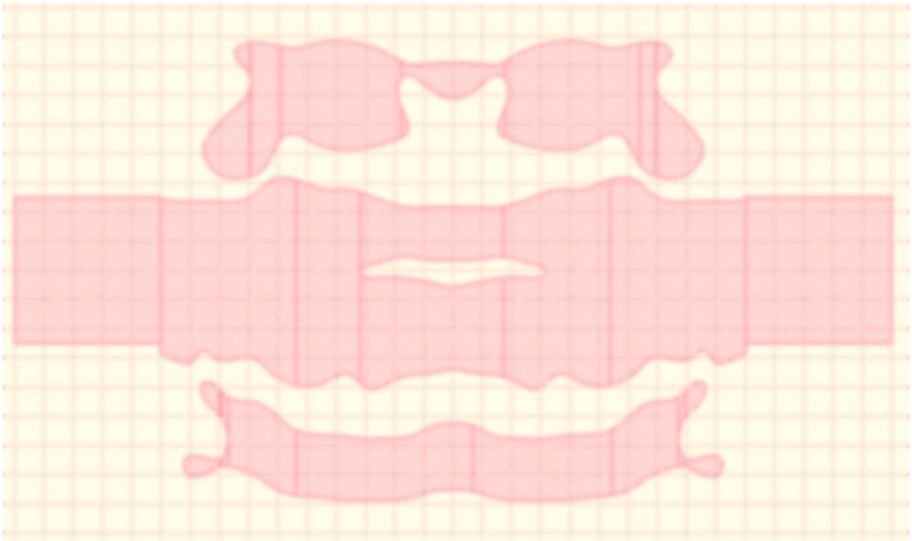
Multi-Transverse-Mode PDK for 220 nm SiPh (cont.)

Mode Sensitive TOPS



Mojaver, Liboiron-Ladouceur, *IPC*'22.

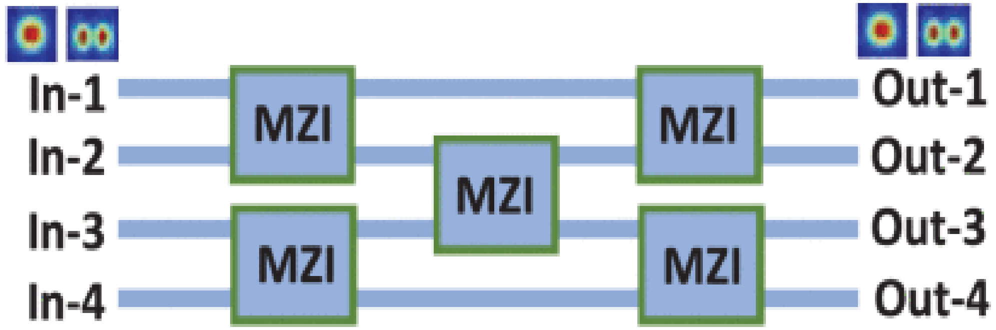
Mode Exchanger

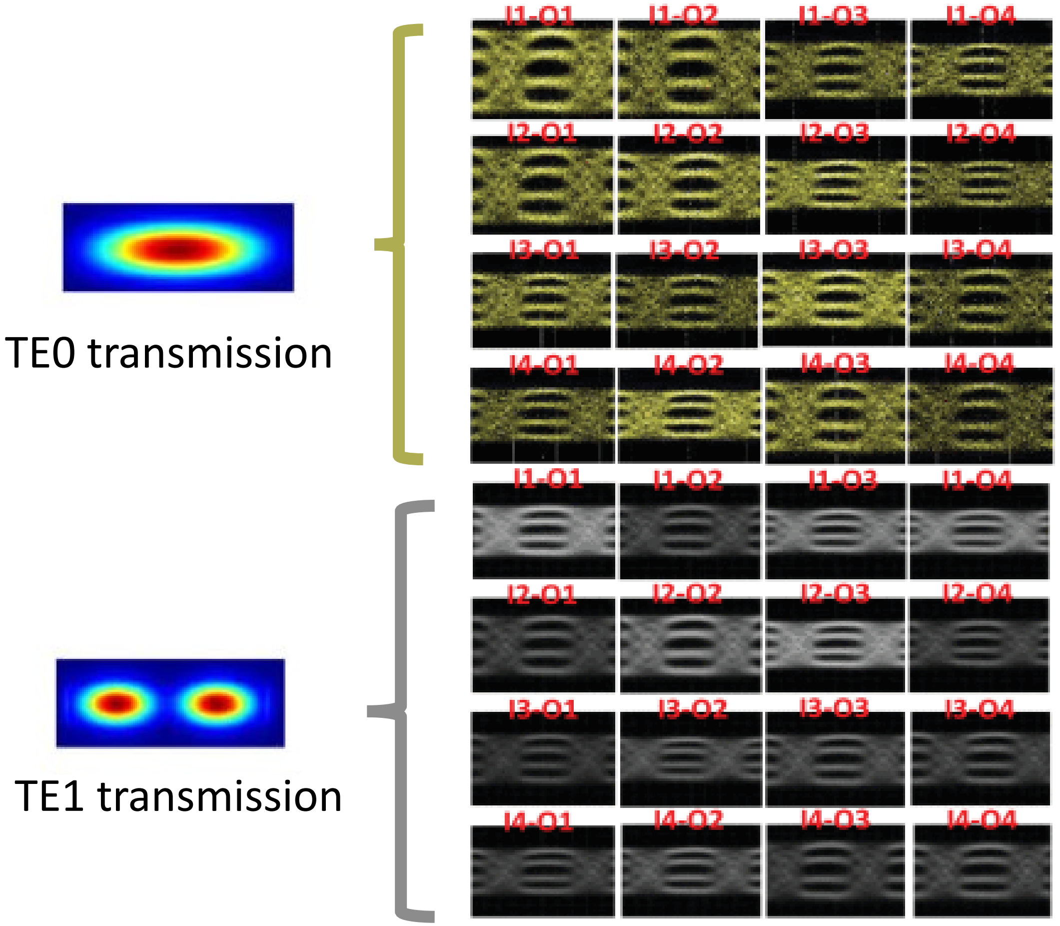


Zhang, Liboiron-Ladouceur, *OE*'22.

Applications in Switching

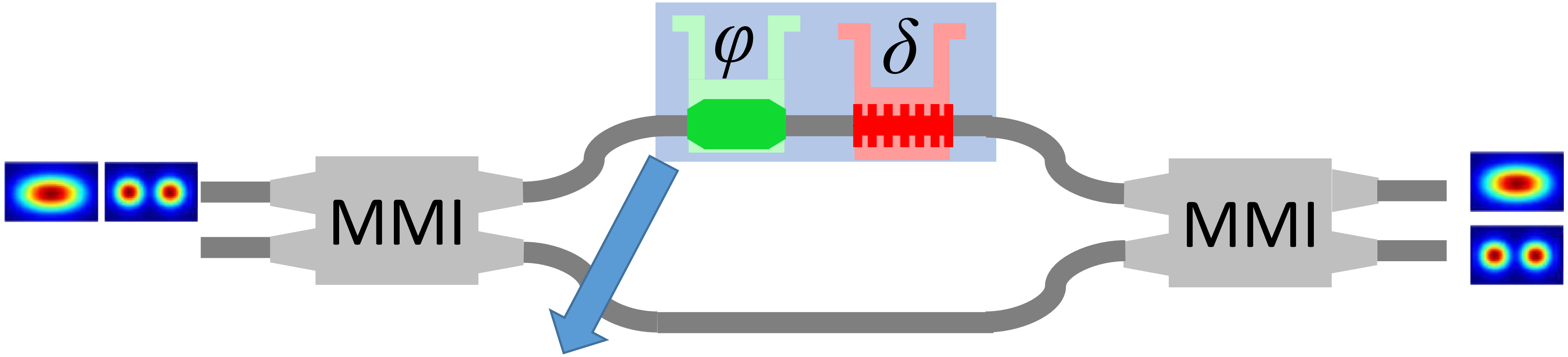
Applications in Switching



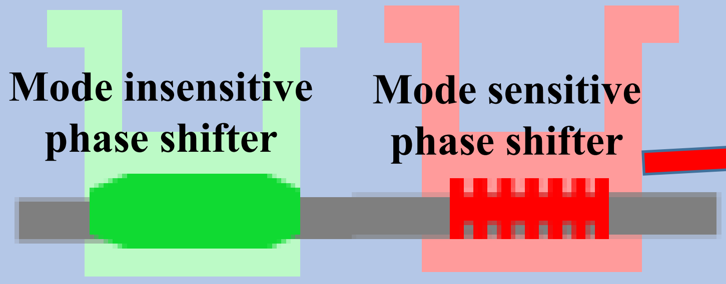


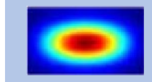
A. Das, G. Zhang, K. R. Mojaver and O. Liboiron-Ladouceur, *IEEE PTL* 33 (11), 2021.

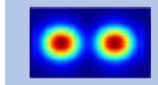
Applications in Switching (cont.)

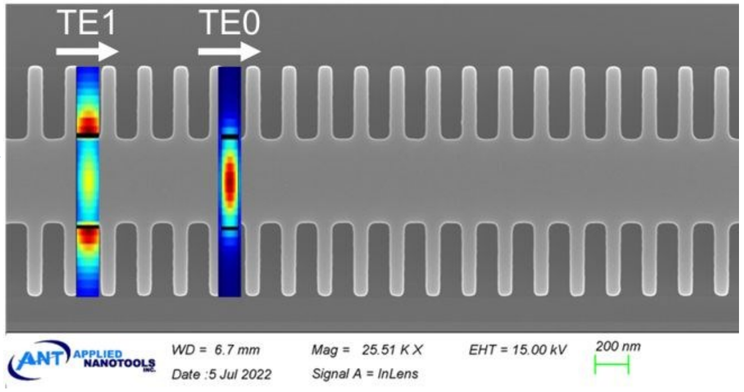


Multimode phase shifter



 $\alpha + \gamma \times \beta = \theta_0$

 $\alpha + \beta = \theta_1$

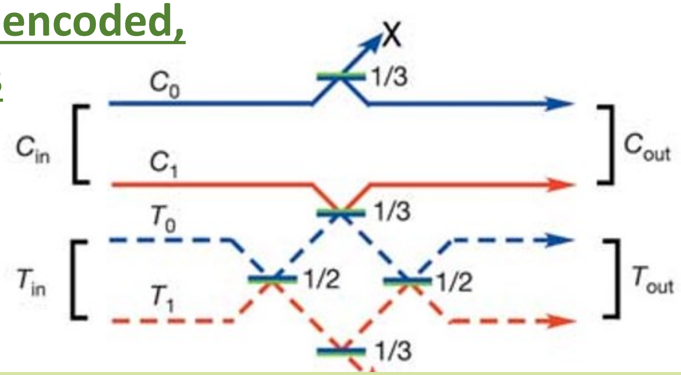


Mode sensitive TOPS on 220 nm SiPh
Fabricated at Applied Nano Tools (ANT)

Applications in Quantum Computing

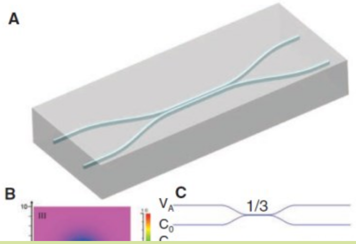
Evolution of Optical Quantum Gates/Processors

2003: Path encoded, Bulk Optics

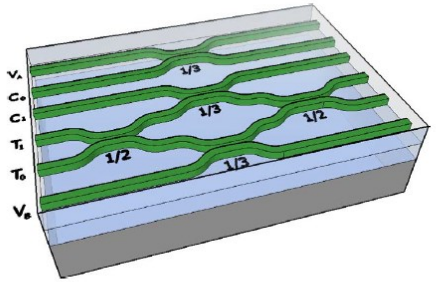


Jeremy ... quantum ...

2008-2009: Path encoded, Integrated Silica on Silicon



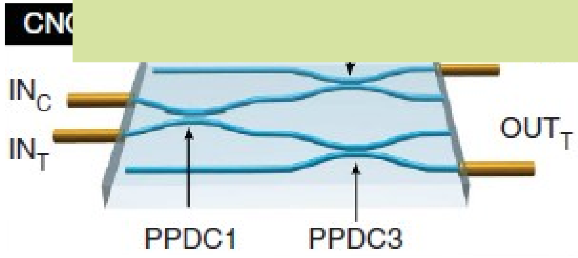
A. Politi, M. Cryan, J. Rarity, S. Yu, and J. O'Brien, "Silica-on-silicon waveguide quantum circuits," *Science* 320.5876, 2008.



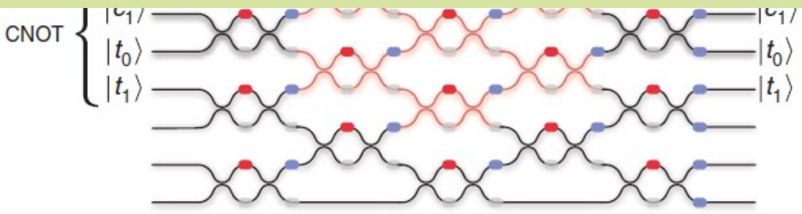
A. Politi, J. C. F. Matthews, M. G. Thompson and J. L. O'Brien, ... *of Selected Topics* ... 684, Nov. 2009.

Next Step:
Programmable **AND** Transverse-mode-encoded Optical Processor

2011: P... borosil...

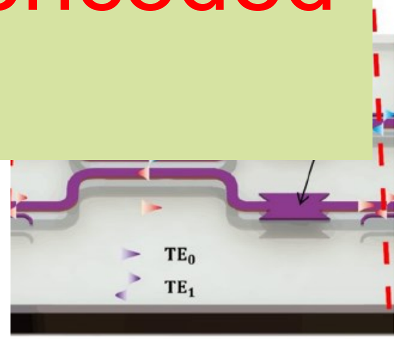


Crespi, A., Ramponi, R., Osellame, R. et al., "Integrated photonic quantum gates for polarization qubits," Nat Commun 2, 566, 2011.



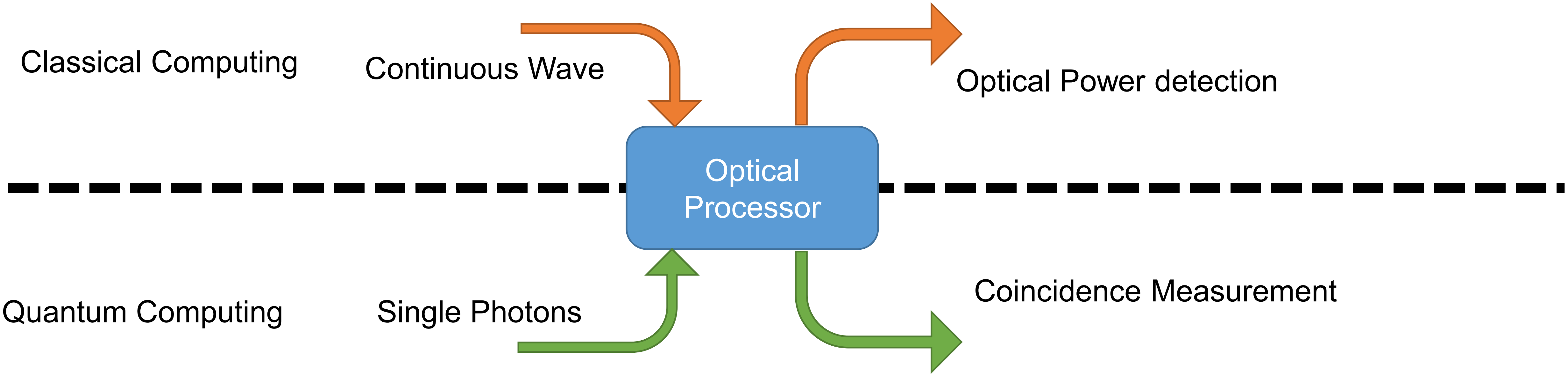
N. Harris, D. Bunandar, M. Pant, G.Steinbrecher, J. Mower, M. Prabhu, M. Hochberg, and D. Englund, "Large-scale quantum photonic circuits in silicon," *Nanophotonics*, vol. 5, no. 3, 2016.

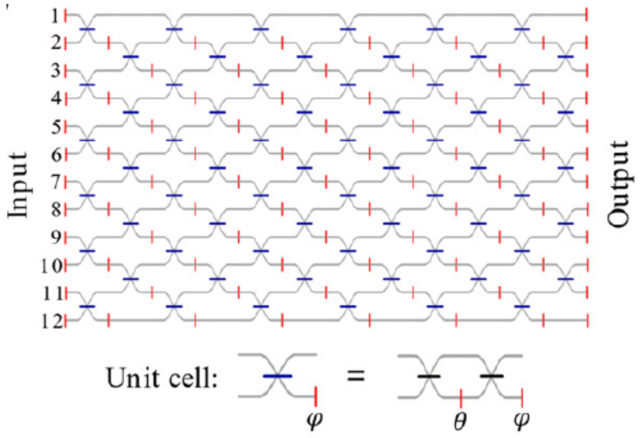
...coded, SOI

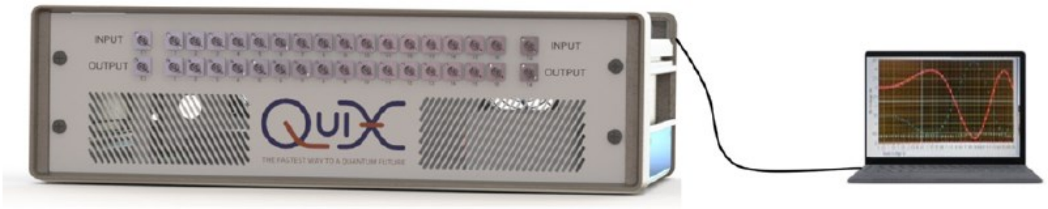


L.Feng, M. Zhang, X. Xiong, D. Liu, Y. Cheng, F. Jing, X. Qi, Y. Chen, D. He, G. Guo, G. Guo, D. Dai, and X. Ren, "Transverse Mode-Encoded Quantum Gate on a Silicon Photonic Chip," Phys. Rev. Lett. 128, 2022.

Optical Linear Transformation for Classical and Quantum Computing

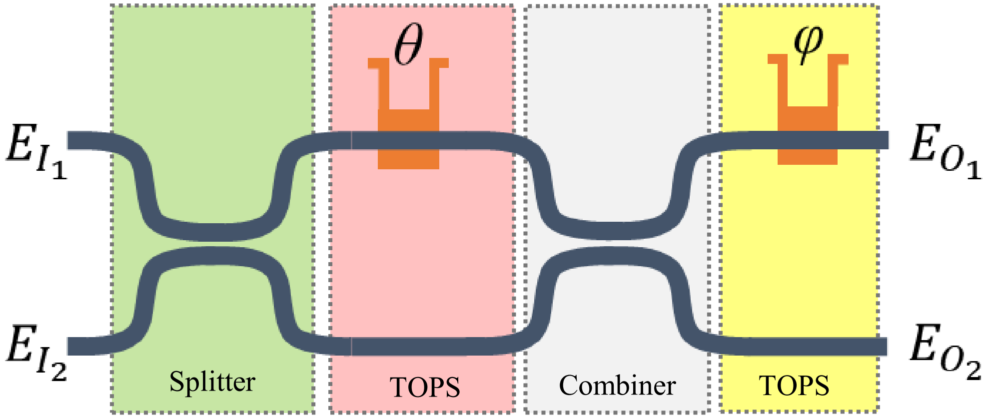






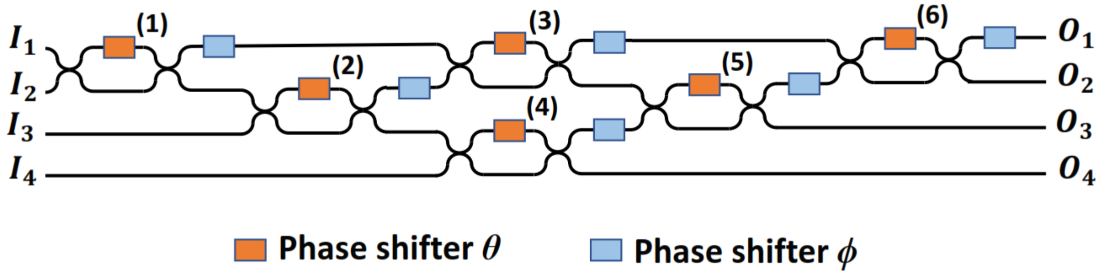
Caterina Taballione et al 2021 Mater. Quantum. Technol. 1 035002.

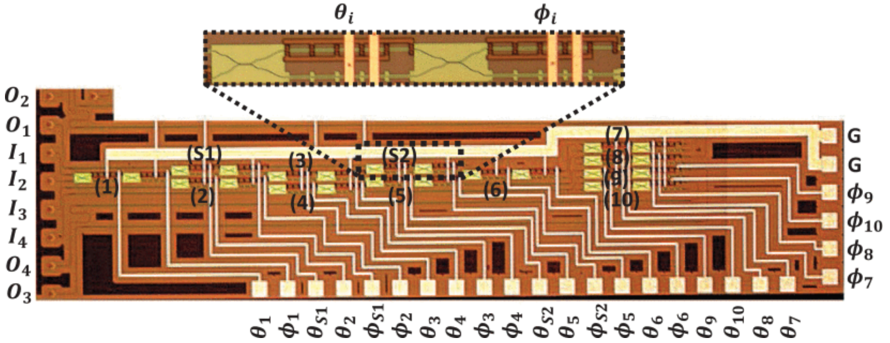
Conventional MZI-based Programmable Optical Processors



$$\begin{bmatrix} E_{O_1} \\ E_{O_2} \end{bmatrix} = \begin{bmatrix} e^{j\phi} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \sqrt{\rho} & j\sqrt{1-\rho} \\ j\sqrt{1-\rho} & \sqrt{\rho} \end{bmatrix} \begin{bmatrix} e^{j\theta} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \sqrt{\rho} & j\sqrt{1-\rho} \\ j\sqrt{1-\rho} & \sqrt{\rho} \end{bmatrix} \begin{bmatrix} E_{I_1} \\ E_{I_2} \end{bmatrix}$$

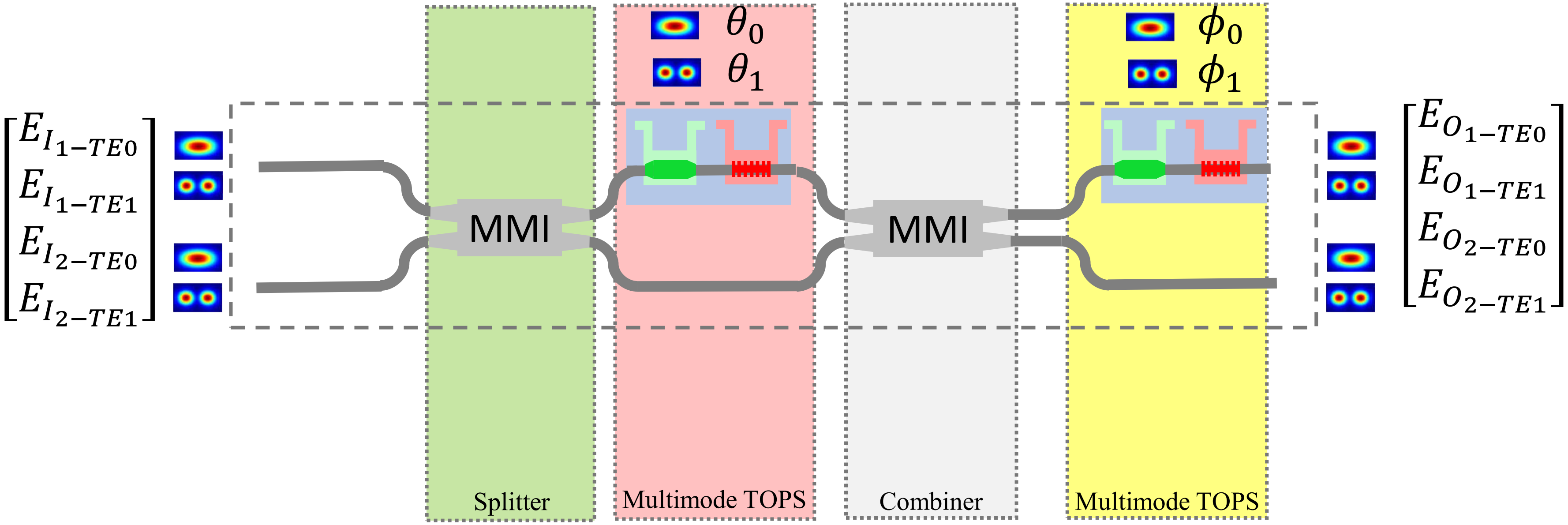
For $\rho = 0.5$ →
$$\begin{bmatrix} E_{O_1} \\ E_{O_2} \end{bmatrix} = j e^{j(\theta/2)} \begin{bmatrix} e^{j\phi}\sin(\theta/2) & e^{j\phi}\cos(\theta/2) \\ \cos(\theta/2) & -\sin(\theta/2) \end{bmatrix} \begin{bmatrix} E_{I_1} \\ E_{I_2} \end{bmatrix}$$





F. Shokraneh, M. S. Nezami and O. Liboiron-Ladouceur, *IEEE JLT*, 38 (6), 2020.

Finding Transfer Matrix

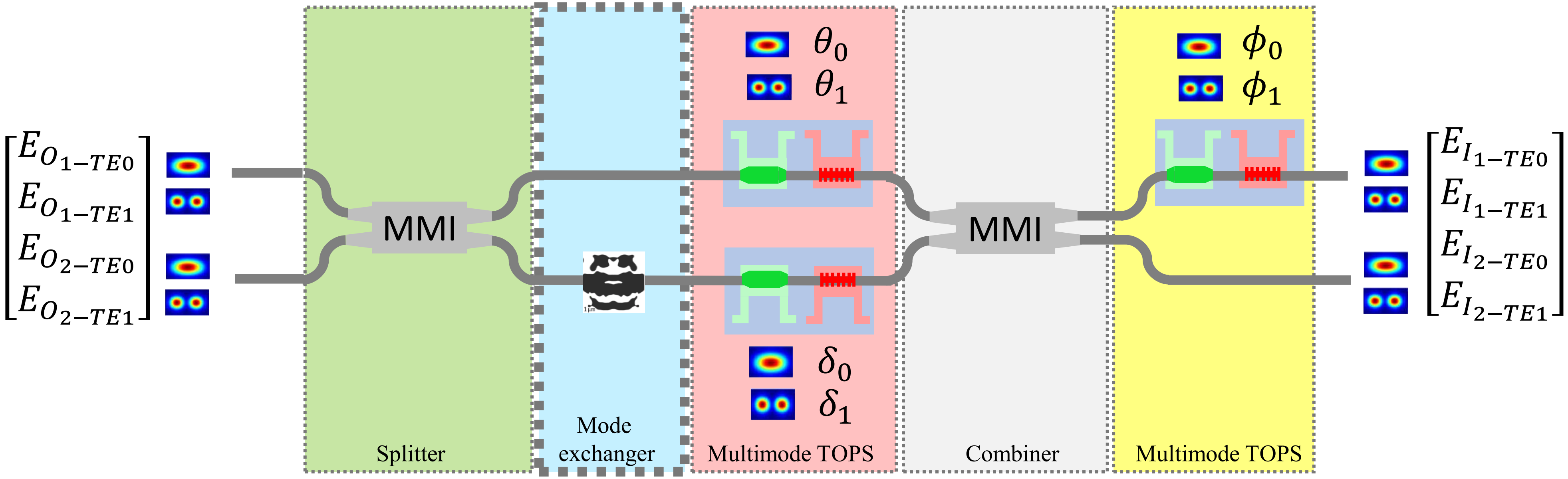


$$\begin{bmatrix} E_{O_1-TE0} \\ E_{O_1-TE1} \\ E_{O_2-TE0} \\ E_{O_2-TE1} \end{bmatrix} = \begin{bmatrix} e^{j\phi_0} & 0 & 0 & 0 \\ 0 & e^{j\phi_1} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sqrt{\rho} & 0 & j\sqrt{1-\rho} & 0 \\ 0 & \sqrt{\rho} & 0 & j\sqrt{1-\rho} \\ j\sqrt{1-\rho} & 0 & \sqrt{\rho} & 0 \\ 0 & j\sqrt{1-\rho} & 0 & \sqrt{\rho} \end{bmatrix} \begin{bmatrix} e^{j\theta_0} & 0 & 0 & 0 \\ 0 & e^{j\theta_1} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sqrt{\rho} & 0 & j\sqrt{1-\rho} & 0 \\ 0 & \sqrt{\rho} & 0 & j\sqrt{1-\rho} \\ j\sqrt{1-\rho} & 0 & \sqrt{\rho} & 0 \\ 0 & j\sqrt{1-\rho} & 0 & \sqrt{\rho} \end{bmatrix} \begin{bmatrix} E_{I_1-TE0} \\ E_{I_1-TE1} \\ E_{I_2-TE0} \\ E_{I_2-TE1} \end{bmatrix}$$

For $\rho = 0.5 \rightarrow$

$$\begin{bmatrix} E_{O_1-TE0} \\ E_{O_1-TE1} \\ E_{O_2-TE0} \\ E_{O_2-TE1} \end{bmatrix} = j \begin{bmatrix} e^{j(\theta_0/2)} e^{j\phi_0} \sin(\theta_0/2) & 0 & e^{j(\theta_0/2)} e^{j\phi_0} \cos(\theta_0/2) & 0 \\ 0 & e^{j(\theta_1/2)} e^{j\phi_1} \sin(\theta_1/2) & 0 & e^{j(\theta_1/2)} e^{j\phi_1} \cos(\theta_1/2) \\ e^{j(\theta_0/2)} \cos(\theta_0/2) & 0 & -e^{j(\theta_0/2)} \sin(\theta_0/2) & 0 \\ 0 & e^{j(\theta_1/2)} \cos(\theta_1/2) & 0 & -e^{j(\theta_1/2)} \sin(\theta_1/2) \end{bmatrix} \begin{bmatrix} E_{I_1-TE0} \\ E_{I_1-TE1} \\ E_{I_2-TE0} \\ E_{I_2-TE1} \end{bmatrix}$$

Adding Mode Exchanger



$$\begin{bmatrix}E_{O_1-TE0}\\E_{O_1-TE1}\\E_{O_2-TE0}\\E_{O_2-TE1}\end{bmatrix} = \begin{bmatrix} e^{j\phi_0}&0&0&0\\0&e^{j\phi_1}&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}\sqrt{\rho}&0&j\sqrt{1-\rho}&0\\0&\sqrt{\rho}&0&j\sqrt{1-\rho}\\j\sqrt{1-\rho}&0&\sqrt{\rho}&0\\0&j\sqrt{1-\rho}&0&\sqrt{\rho}\end{bmatrix}\begin{bmatrix}e^{j\theta_0}&0&0&0\\0&e^{j\theta_1}&0&0\\0&0&e^{j\delta_0}&0\\0&0&0&e^{j\delta_1}\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}\begin{bmatrix}\sqrt{\rho}&0&j\sqrt{1-\rho}&0\\0&\sqrt{\rho}&0&j\sqrt{1-\rho}\\j\sqrt{1-\rho}&0&\sqrt{\rho}&0\\0&j\sqrt{1-\rho}&0&\sqrt{\rho}\end{bmatrix}\begin{bmatrix}E_{I_1-TE0}\\E_{I_1-TE1}\\E_{I_2-TE0}\\E_{I_2-TE1}\end{bmatrix}$$

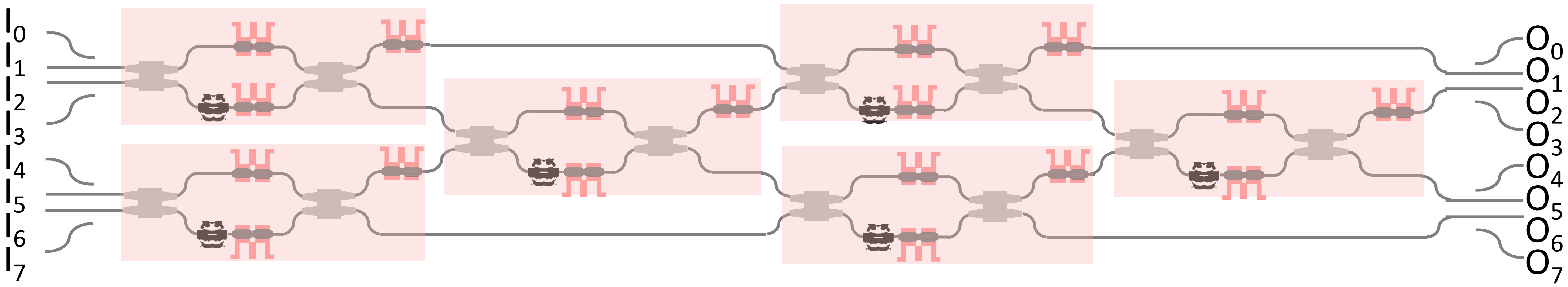
For $\rho = 0.5$ →

$$\begin{bmatrix}E_{O_1-TE0}\\E_{O_1-TE1}\\E_{O_2-TE0}\\E_{O_2-TE1}\end{bmatrix} = \frac{1}{2}\times\begin{bmatrix} e^{j\phi_0+j\theta_0} & -e^{j\phi_0+j\delta_0} & je^{j\phi_0+j\theta_0} & je^{j\phi_0+j\delta_0}\\ -e^{j\phi_1+\delta_1} & e^{j\phi_1+\theta_1} & je^{j\phi_1+\delta_1} & je^{j\phi_1+\theta_1}\\ je^{j\theta_0} & je^{j\delta_0} & -e^{j\theta_0} & e^{j\delta_0}\\ je^{j\delta_1} & je^{j\theta_1} & e^{j\delta_1} & e^{j\theta_1}\end{bmatrix}\begin{bmatrix}E_{I_1-TE0}\\E_{I_1-TE1}\\E_{I_2-TE0}\\E_{I_2-TE1}\end{bmatrix}$$

→ 4 × 4 Unitary Transformation with one MZI

McGill

Scaling to Higher Dimensions



	Path encoded	**Transverse mode encoded**
Number of MZIs required for $N \times \mathrm{N}$ linear transformation	$\frac{N(N-2)}{2}$	$\mathbf{\frac{N(N-2)}{8}}$
Number of MZIs required for 8×8 linear transformation	24	**6**

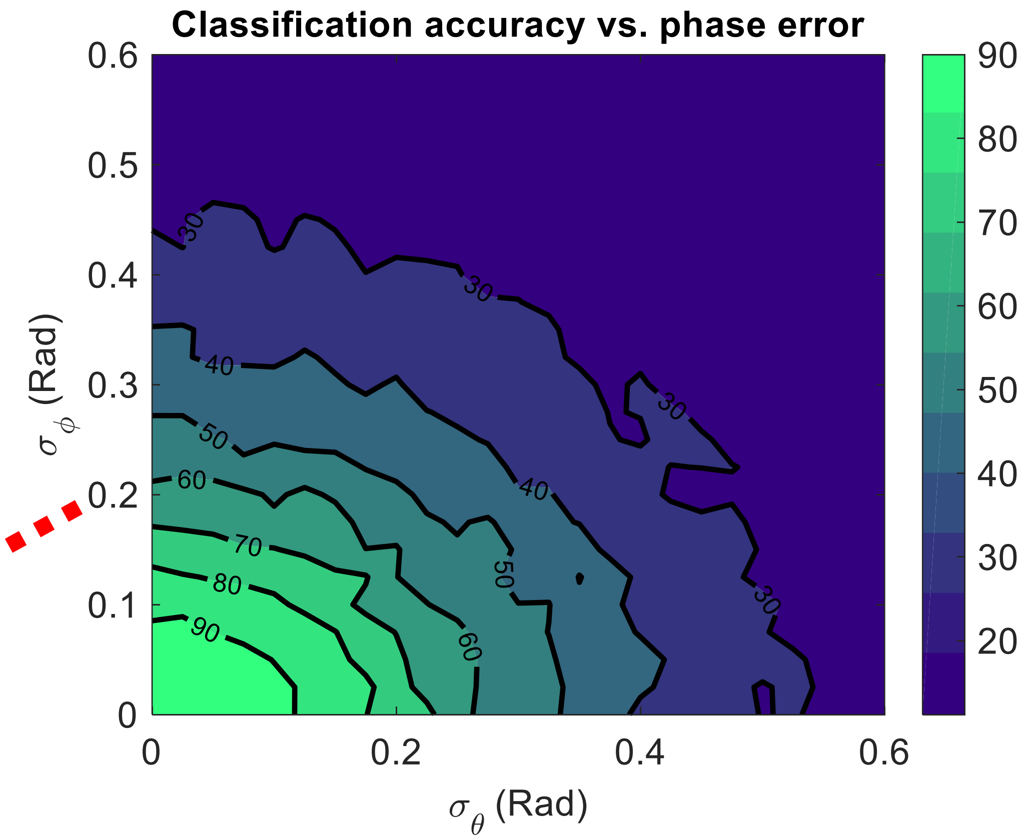
Applications in Classical Computing

Phase error, calibration, and programming

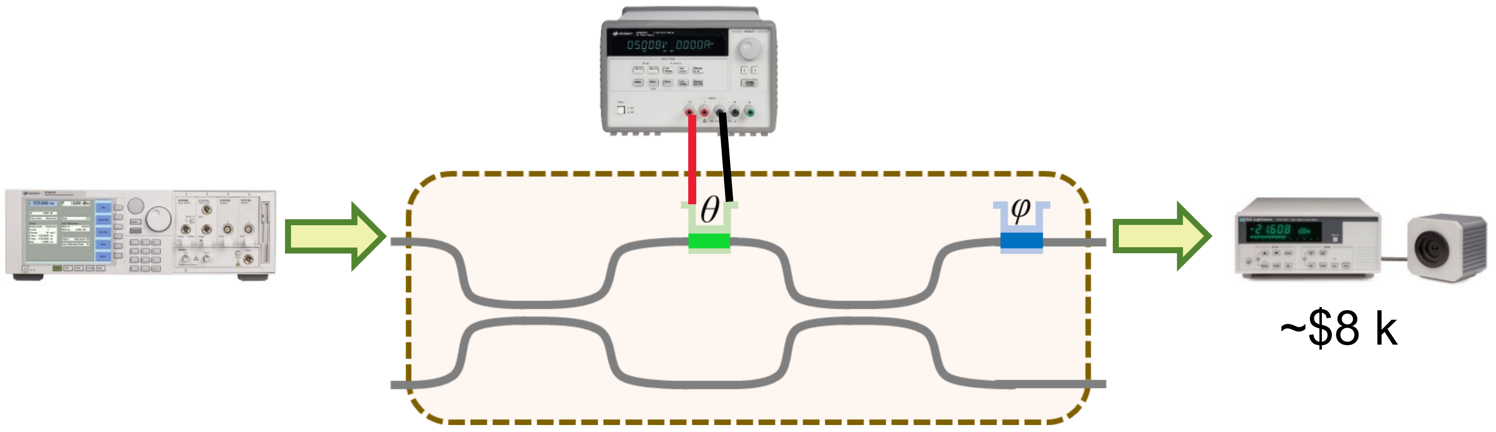
How precise should the phase setting be?

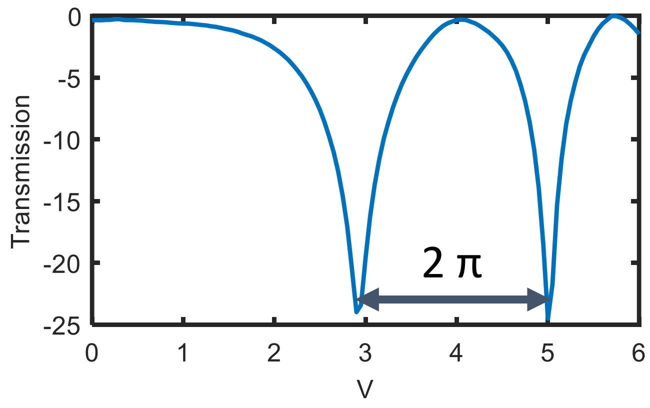
- Phase shifter inaccuracy caused by various effects, mainly thermal crosstalk and electro-optic precision (bias voltage accuracy and stability)
- Accuracy drops from 90% down to 60 for phase variance of less than 0.1 rad to approximately 0.2 rad.
- A 100 um TiN-based TOPS with a 2.7K temperature fluctuation lead to an accuracy drop to 60%
- This is equivalent to approximately 30 mV of voltage deviation

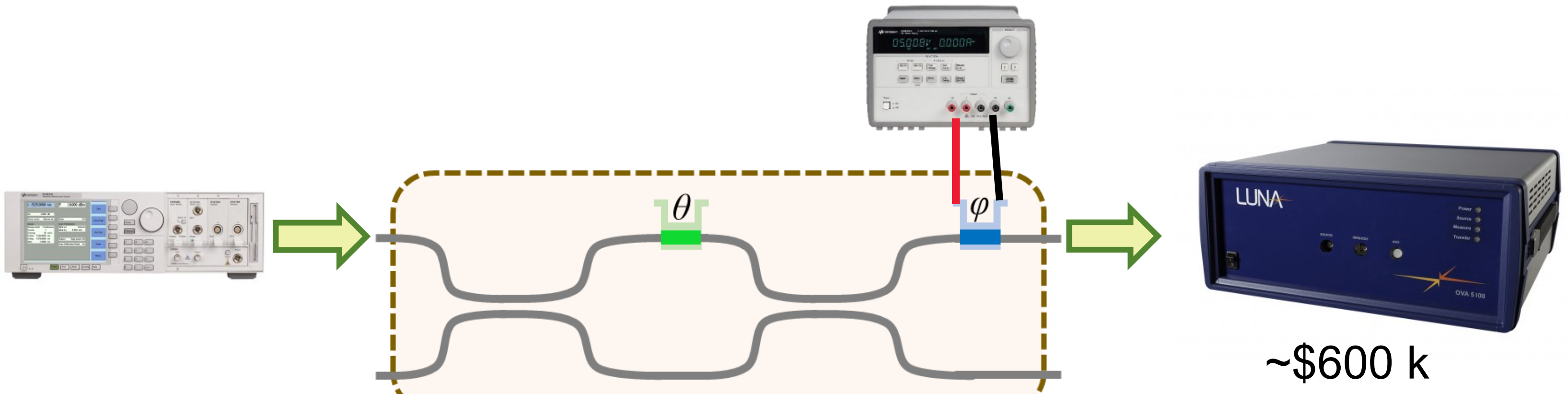
2.7 K of temperature error
or 30 mV voltage deviation



Calibration and Programming the Optical Processors

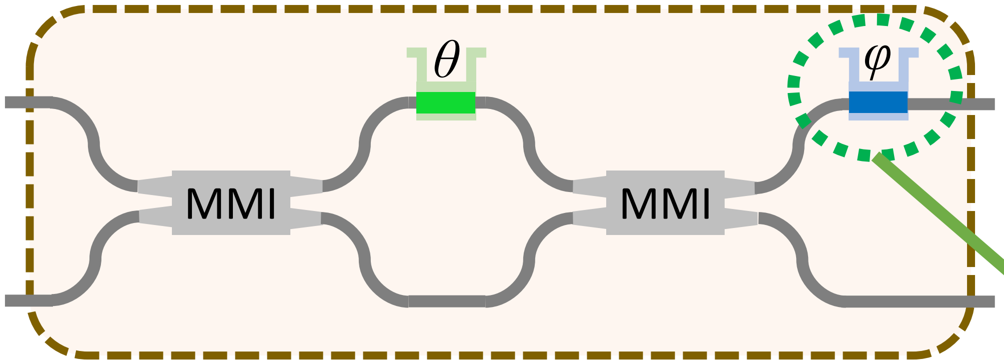






Measure the optical phase

Application in Optical Computing



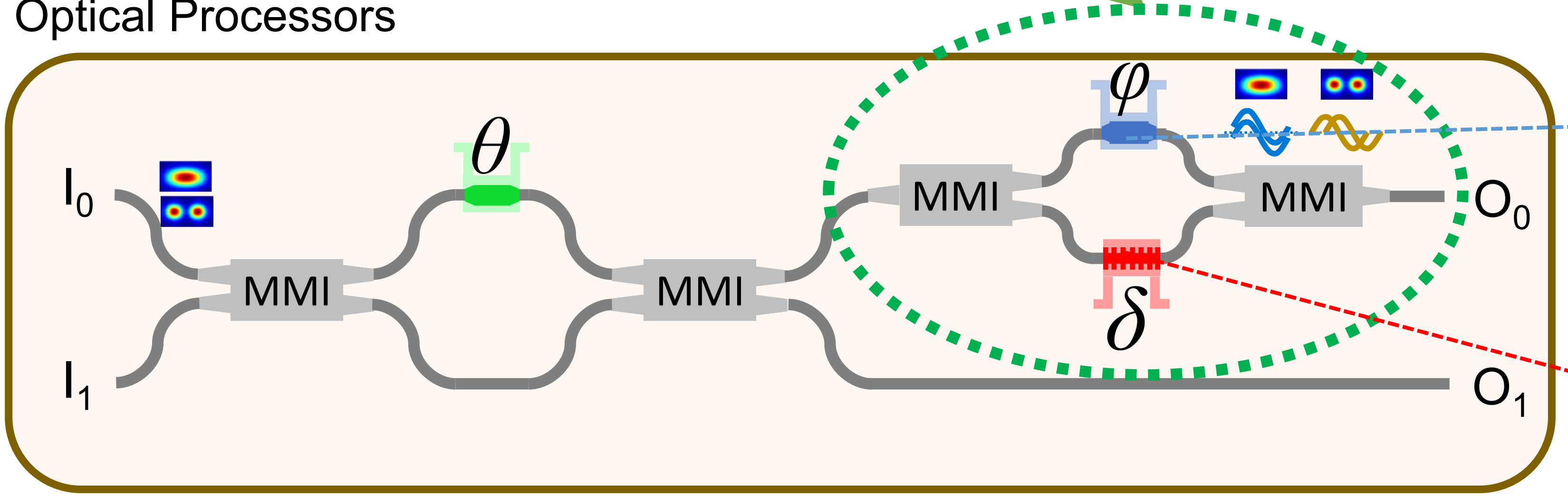
Conventional 2×2 Building Block of MZI-based Optical Processors

Conventional MZI-based optical processors:

- Optical phase measurement is needed

MTMOP:

- TE0 for computation and TE1 for monitoring
- We translate TE0 phase to TE1 power
- No need to measure the phase



Multi-Transverse-Mode Optical Processor (MTMOP) 2×2 Building Block

Mode insensitive phase shifter

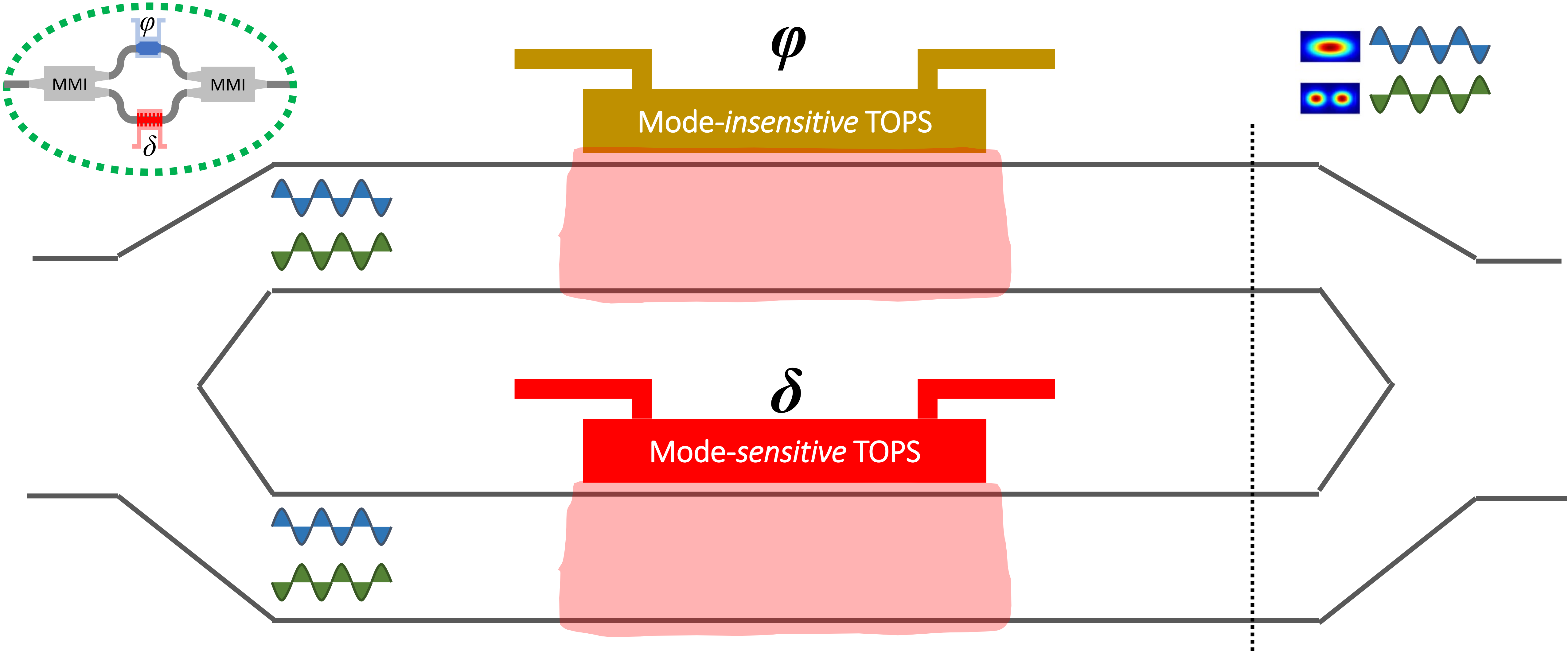
$$\frac{dn_{eff}(TE0)}{dT} = \frac{dn_{eff}(TE1)}{dT}$$

Mode sensitive phase shifter

$$\frac{dn_{eff}(TE0)}{dT} \neq \frac{dn_{eff}(TE1)}{dT}$$

- K. R. Mojaver and O. Liboiron-Ladouceur, "On-chip Optical Phase Monitoring in Multi-Transverse-Mode Integrated Silicon-based Optical Processors," IEEE JSTQE, 28 (6), 2022.
- US Provisional 63/344,174

Phase Monitoring in MTMOP



Conclusion

Conclusion

- Provided an open access PDK for multi-transverse-mode SiPh
- Demonstrated the application of multi-transverse-mode SiPh in optical switching and computing
- Demonstrated the design of the first programmable transverse-mode-encoded quantum processors
- With Transverse-mode-encoded quantum processors we can process 4 qubits with 6 MZI (8 qubits with only 24 MZI).

Future work

- Experimental validation of the transverse-mode-encoded quantum processors
- Performing the quantum measurements in collaboration with the University of Twente
- Use Prefab to correct the SWG/inverse design structures

github.com/PreFab-Photonics/

PreFab
AI Photonics

Open Positions: MSc and PhD for Winter 2024

COLORADO STATE UNIVERSITY

If you are interested in Optical Computing, please send your CV to:

hassan.rahbardarmojaver@mcgill.ca
mojaver@ieee.org

Thank you!

the Photonic DataCom team

McGill

Fonds de recherche Nature et technologies Québec

CMC MICROSYSTEMS

NSERC CRSNG

UNIVERSITY OF TWENTE.

Slides are available at:
http://rahbardar.research.mcgill.ca/