12/10/2023 Munich

NEXT GENERATION LIGHT SWITCHES FOR OPTICAL QUANTUM TECHNOLOGIES

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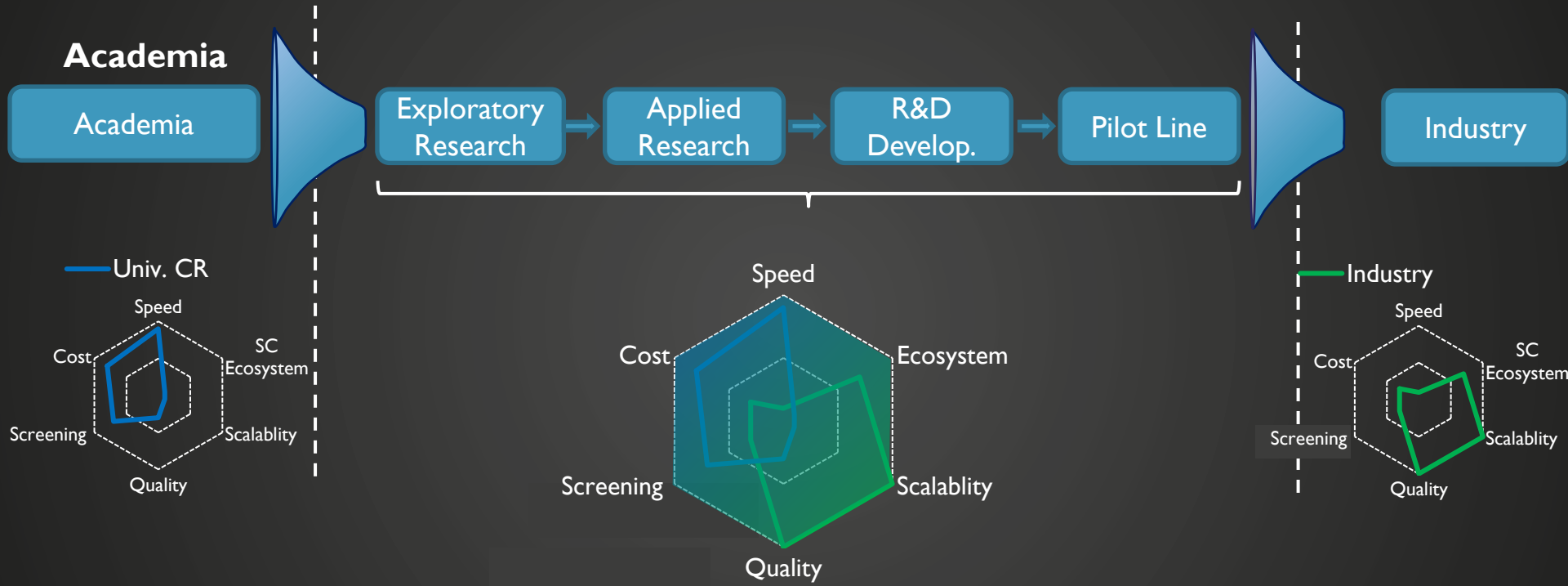
Principal Member of Technical Staff

IMEC's vertical value chain – a unique cross-road



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Public: Presenter Christian Haffner – Christian.Haffner@imec.be

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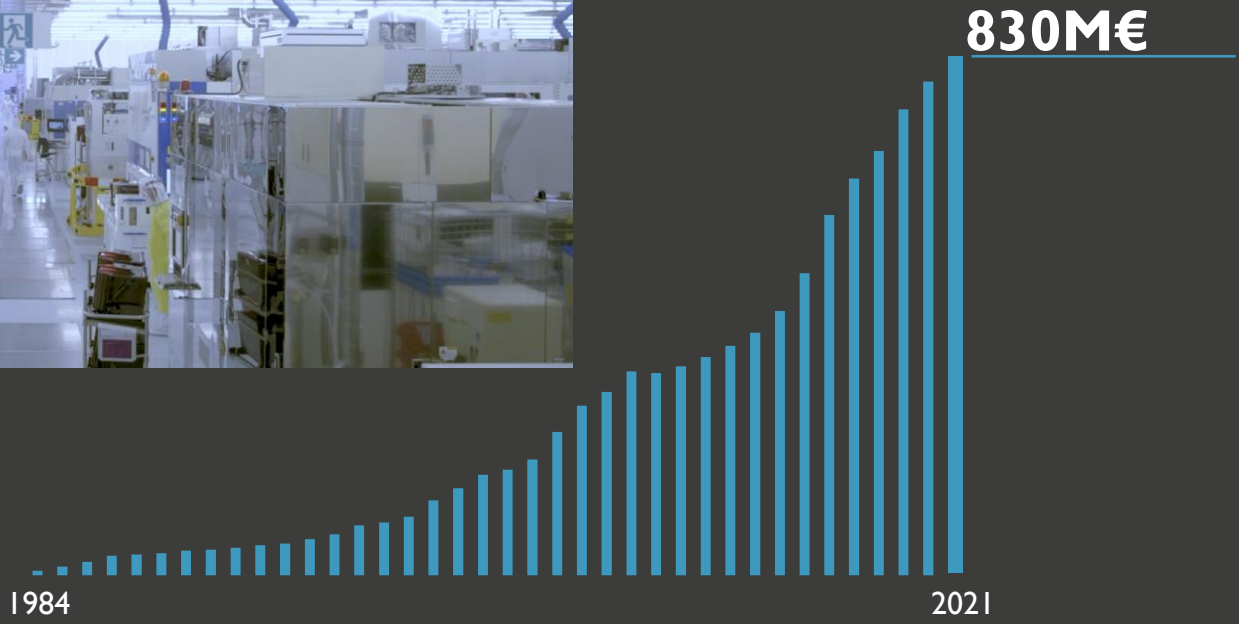
IMEC: INVESTMENT ~3 B€



From Free space optics to integrated photonics

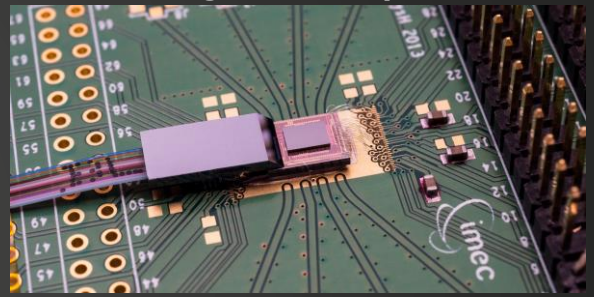
10s Qubits → Scaling Photonics: one effort among the 24B$ → **1k, 10K, …**

Gaussian boson sampling

100 single-photon detectors

H. Zhong, et al, "Quantum computational advantage using photons", Science, 2020.

Integration is key, but…



…losses need to be mastered
… coherence maintained

	Fiber/FS	PIC
Loss	$\leq dB/km$	$\leq dB/m$

… Photon control

100 mode Interferometer
($\delta L_{paths} \leq few\ \mu m$)

100 phase lockers

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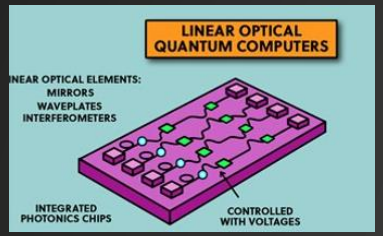
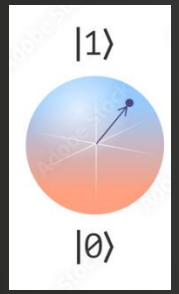
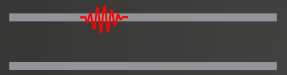
Excursion: Photonic Qubit Encoding

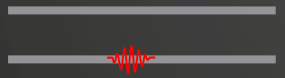




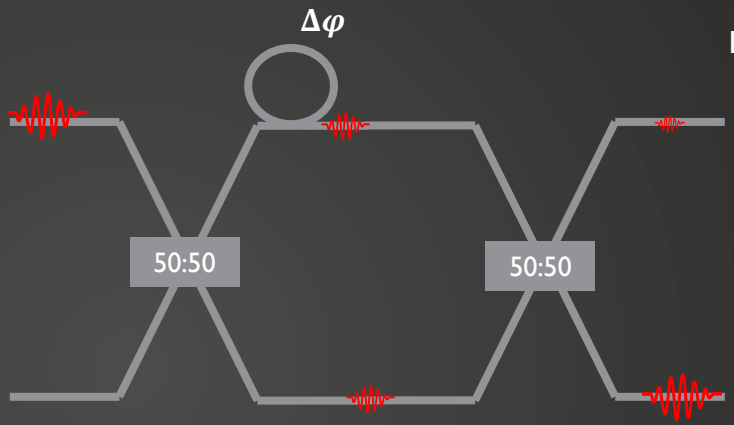
Upper Waveguide → $|1\rangle$



Lower Waveguide → $|0\rangle$



$$|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle$$



$$|\varphi\rangle = |1\rangle \qquad |\varphi\rangle = \frac{1}{\sqrt{2}}(i|0\rangle + e^{i\Delta\varphi}|1\rangle)$$

$$|\varphi\rangle \propto \cos(\Delta\varphi/2)\,|0\rangle + \sin(\Delta\varphi/2)\,|1\rangle$$

Error in state preparation

Imbalance: ER↓
~20dB ER ~ % Error

Scattering/Absorption
IL: ~0.1dB ~ % Error

MZI building block for quantum information processing

- Chip-based quantum communications [1]
- Gate-based quantum information processing [2]
- Simulation of molecular dynamics[3]

[1] P. Sibson et al. Integrated silicon photonics for high-speed quantum key distribution. Optica (2017).
[2] J. Carolan et al. Universal linear optics Science (2015).
[3]E. Sparrow Simulating the vibrational quantum dynamics of molecules using photonics. Nature, (2018)

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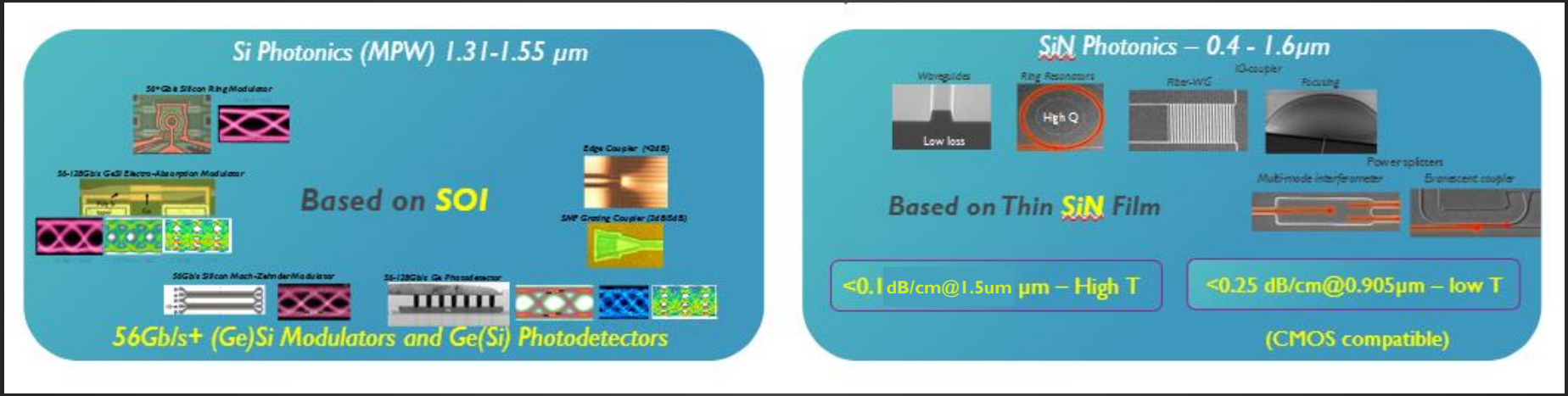
Imec photonics platforms



Telecom/data focused
Industry-standard

Visible application
Biophotonics, sensing, metrology, ...

Status-quo is not enough

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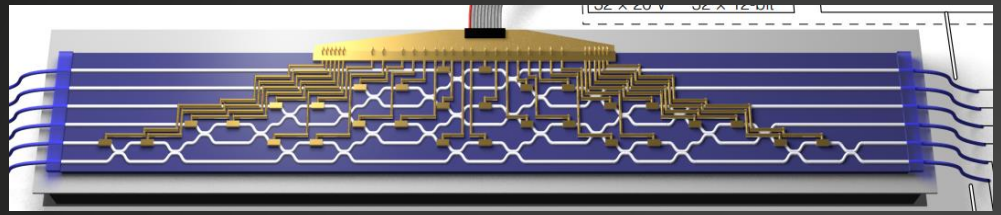
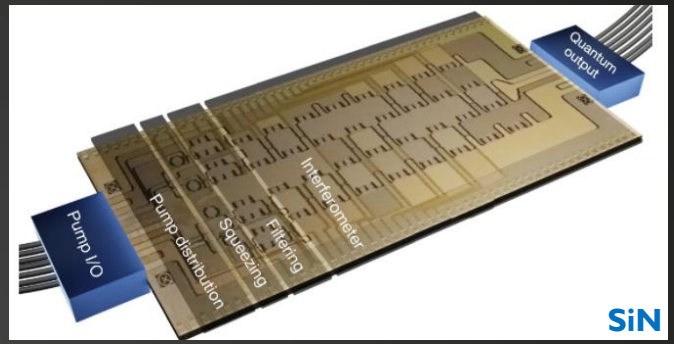
Integrated photonic quantum technologies

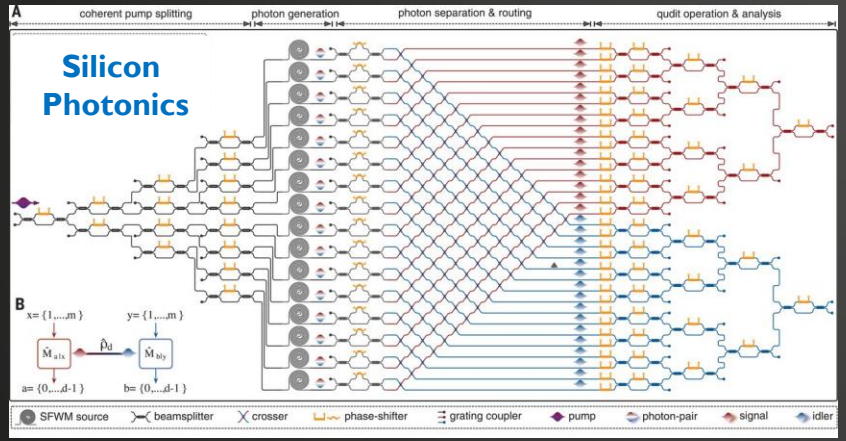


Carolan J. et al., *Universal Linear Optics,* Science (2015)

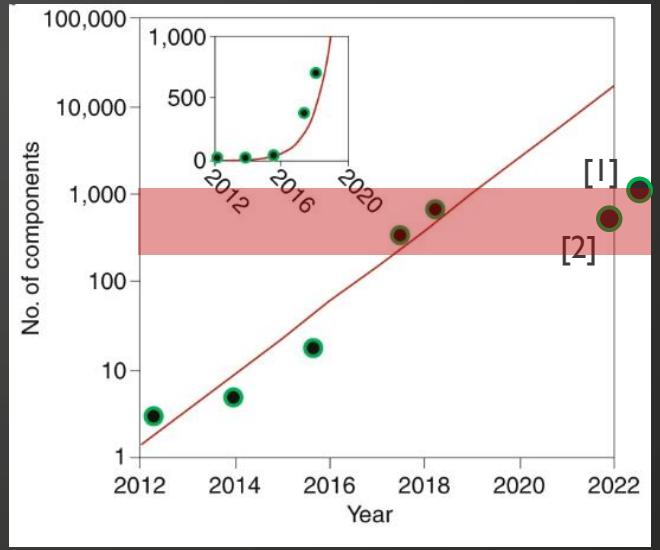
Silica on Silicon WG



Arrazola, Quantum circuits with many photons on a programmable nanophotonic chip Nature (2021)



J. Wang et al. *Multidimensional quantum entanglement with large-scale integrated optics*. Science (2018)



10s of W
~50mW/PS
→Classical Elements are the roadblock

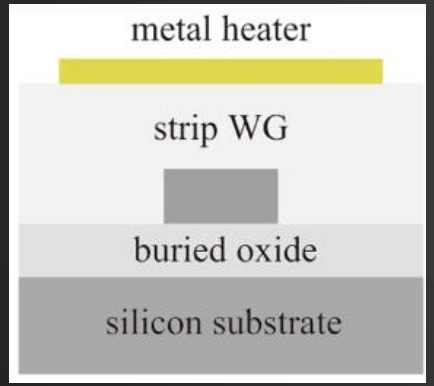
Wang, J. Integrated photonic quantum technologies Nature Photonics (2019)

[1] Quix - 20-Mode Universal Quantum Photonic Processor arXiv:2203.01801v4 (2023)
[2]Chi. Y et al. A programmable qudit-based quantum processor – Nature (2022)

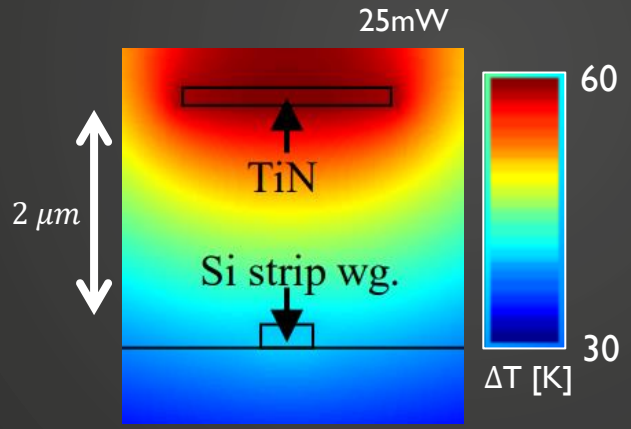
* Propagation limited (Si →2dB/cm)

Electro-optical engines for quantum

Effect	Δn_{eff}	Loss	Speed	Dissipation [W]
Thermo-optic (Si)	$\frac{dn_{Si}}{dT} \propto 10^{-4}\ K^{-1} \rightarrow L_{\pi} \approx 250\mu m$	$\leq 0.05dB$	$\gg 1\mu s$	10s of mW



[1]



[2]

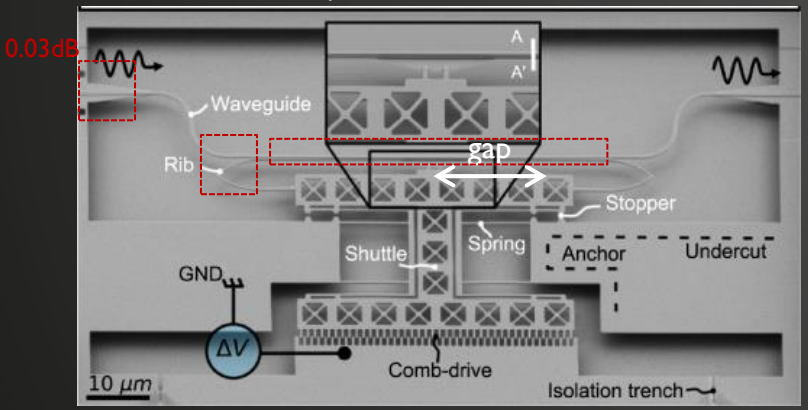
[1] Thermo-optic phase shifters based on silicon-on-insulator platform: state-of-the-art and a review (2022)
[2] Optimization of thermo-optic phase-shifter design and mitigation of thermal crosstalk on the SOI platform, Optics Express (2019)

Electro-optical engines for quantum

[2] Johnson et al., Perturbation theory for Maxwell's equations with shifting material boundaries. Phys. Rev. E Stat. Nonlin. Soft Matter Phys. (2002).

Effect	Δn_{eff}	Loss	Speed	Dissipation [W]
Thermo-optic (Si)	$10^{-4}K^{-1} \xrightarrow{30K} L_\pi \approx 250\mu\mathrm{m}$	$\leq 0.05\mathrm{dB}^*$	$\gg 1\mu\mathrm{s}$	10s of mW
Opto-electro-mechanics	$2.5 \cdot \Delta\Gamma^{-1} \xrightarrow{1\%} L_\pi \approx 30\mu\mathrm{m}$	$\boxed{\sim 0.33\mathrm{dB}}$	$\sim 1\mu\mathrm{s}$	$\geq 100s$ of nW

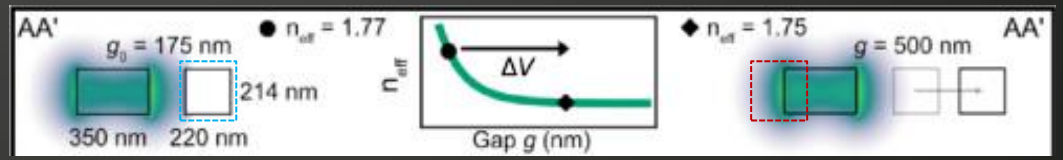
$IL = 0.33 \pm 0.15/0.1$



[1] Edinger et al., Silicon photonic microelectromechanical phase shifters for scalable programmable photonics, Optics Express 2021
- based on IMEC's iSiPP50G

$$\Delta n_{\mathrm{eff}}^{[2]} \propto \frac{\int \left((\varepsilon_{\mathrm{r,air}} - \varepsilon_{\mathrm{r,Si}}) |E|^2 \right) dV_{actutation}}{\int \varepsilon_{\mathrm{r}} \, |E|^2 dV_{total}} \approx \Delta\Gamma_{\mathrm{Air/Si}}$$

$\Delta n_{\mathrm{eff}} \approx 0.02$



$\Delta\Gamma_{\mathrm{Air/Si}} \approx 1\%$

$\Delta n_{\mathrm{air,Si}} \approx 2.5$

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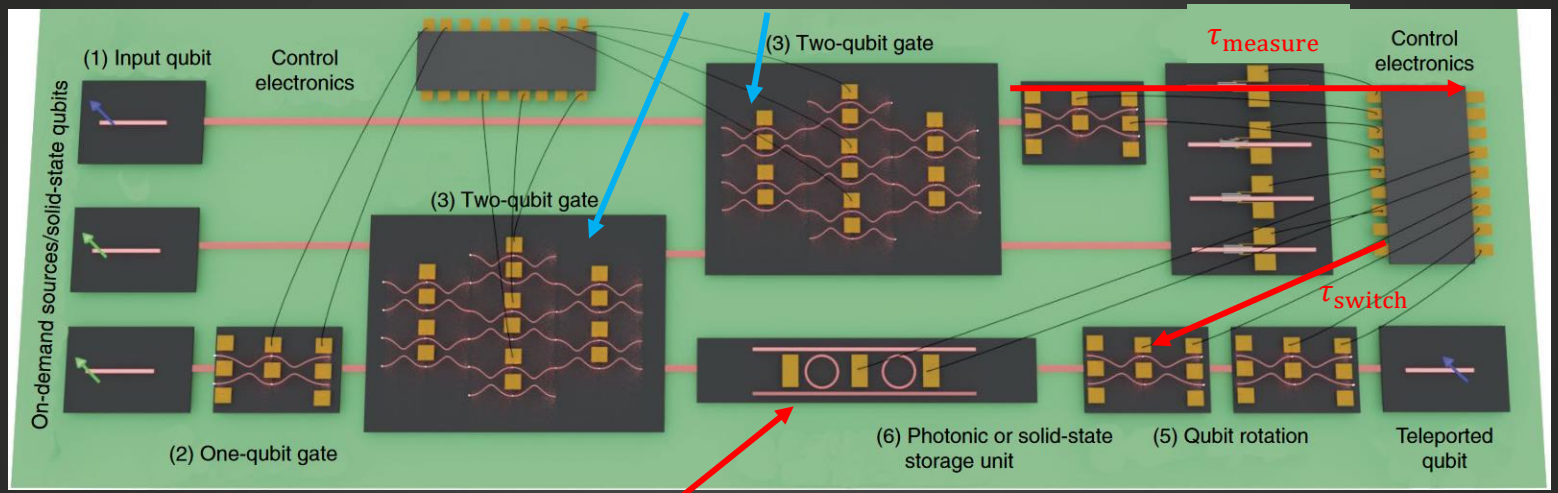
On-chip teleportation with active feed-forward

Entanglement
(ancillary/target qubits)

Ancillary Qubit

Target Qubit



τ_{delay}:

Solid-state Memory

Resonator
$Q_{delay} \ll Q_{Source}$

Delay
$\ll \frac{L_{prop}}{c}$

$\tau_{switch} \leq \tau_{delay} \approx$ ns… sub-ns

$L_{\pi} \ll L_{prop}$

[1] Elsharri et al., Hybrid integrated quantum photonic circuits, Nature Photonics, 2020

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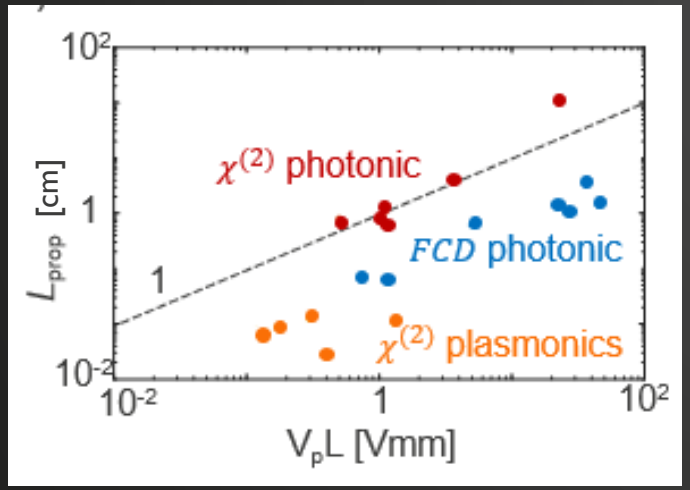
Electro-optical engines for quantum

Effect	Δn_{eff}	Loss	Speed	Dissipation [W]
Thermo-optic (Si)	$10^{-4}K^{-1} \xrightarrow{30K} L_\pi \approx 250\mu m$	$\leq 0.05dB^*$	$\gg 1\mu s$	10s of mW
Opto-electro-mechanics	$2.5 \cdot \Delta\Gamma^{-1} \xrightarrow{1\%} L_\pi \approx 30\mu m$	$< 0.1dB^*$	10s of ns*	N. A.
Electro-optics	$n^3 r \cdot E_{RF} \rightarrow L_\pi > 100\mu m^*$	$< 1dB^*$	Sub-ns	N. A.

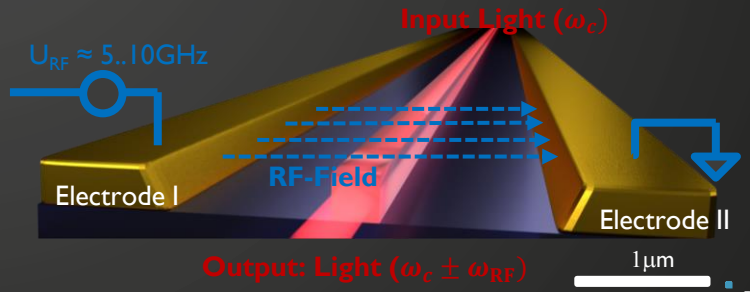


Key messages ($L_{prop} \gg V_\pi L$):

I) Plasmonics & Quantum = dead end

II) Silicon FCD to lossy

III) Photonic-$\chi^{(2)}$ might do it



Haffner et al. Nano–opto-electro-mechanical switches operated at CMOS-level voltage, Science 2019