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Integrated Photonic Quantum Chip Technology for Computing

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Outline

I. Introduction

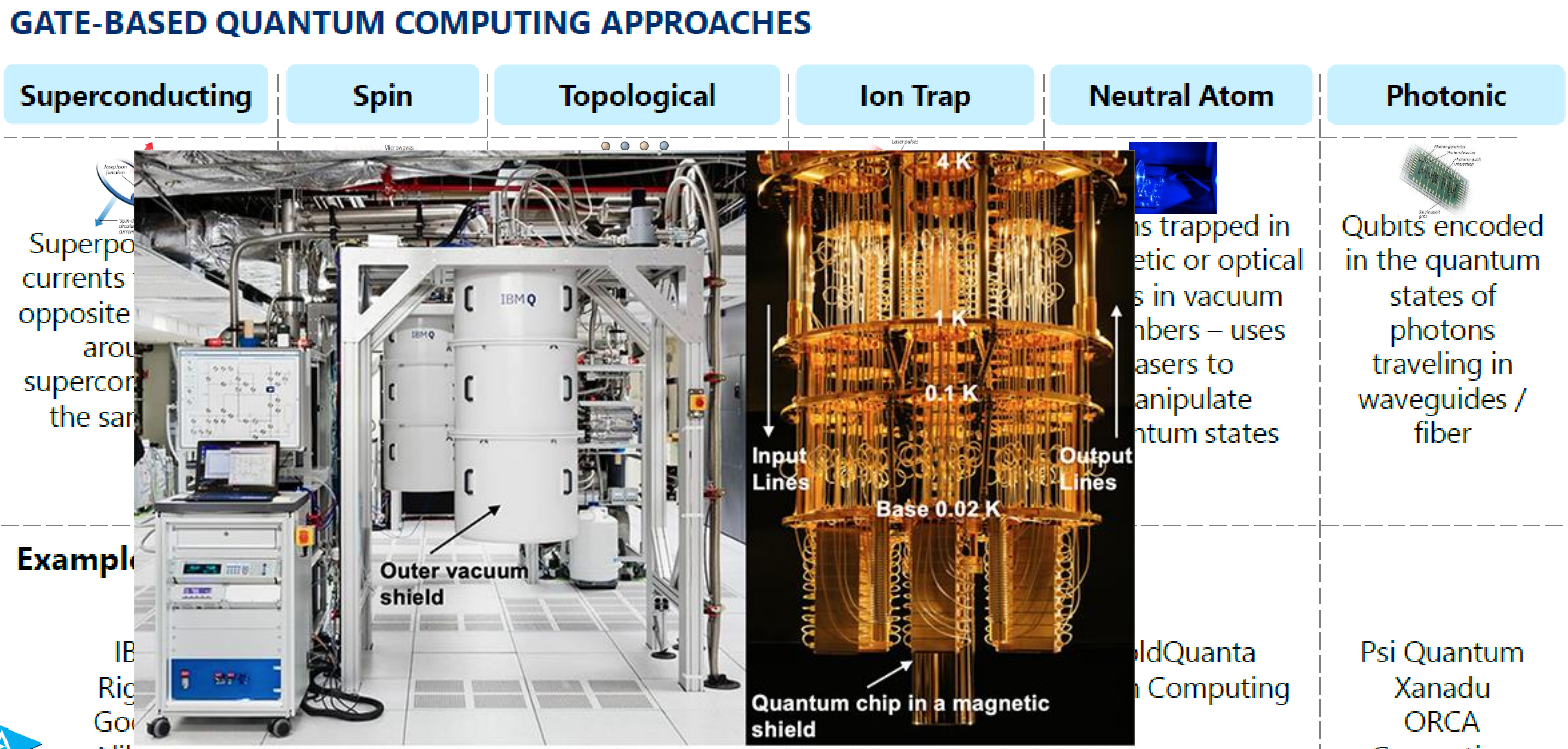
- Why and what are photonic qubits?
- Optical quantum computing

II. Toward on-chip photonic quantum computing

- Schemes: building blocks and material platforms
- Implementation methods

III. Outlook

Introduction



Dilution fridge setup: outside view

Dilution fridge setup: inside view

OSA Industry Development Associates

Introduction

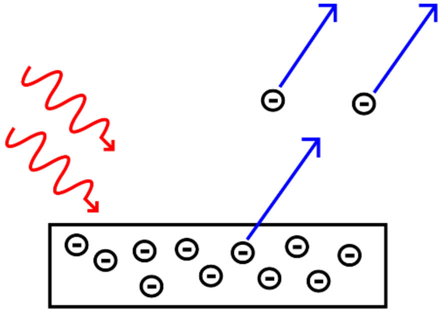
Quantum of Light

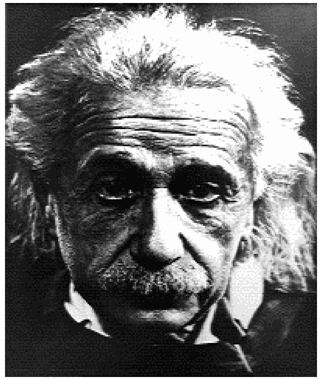
Planck (1858-1947)

Energy quanta of EM radiations:

$E = h\nu$

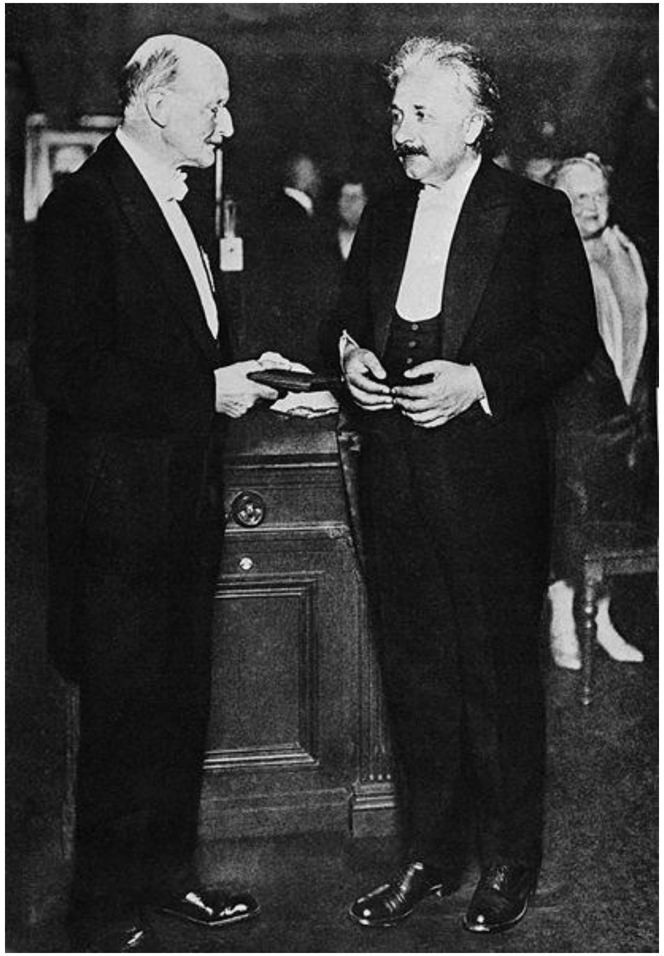
***h*: Planck's constant**





Einstein (1879-1955)

Photoelectric effect (light quanta – photons),
Stimulated emission (laser mechanism)



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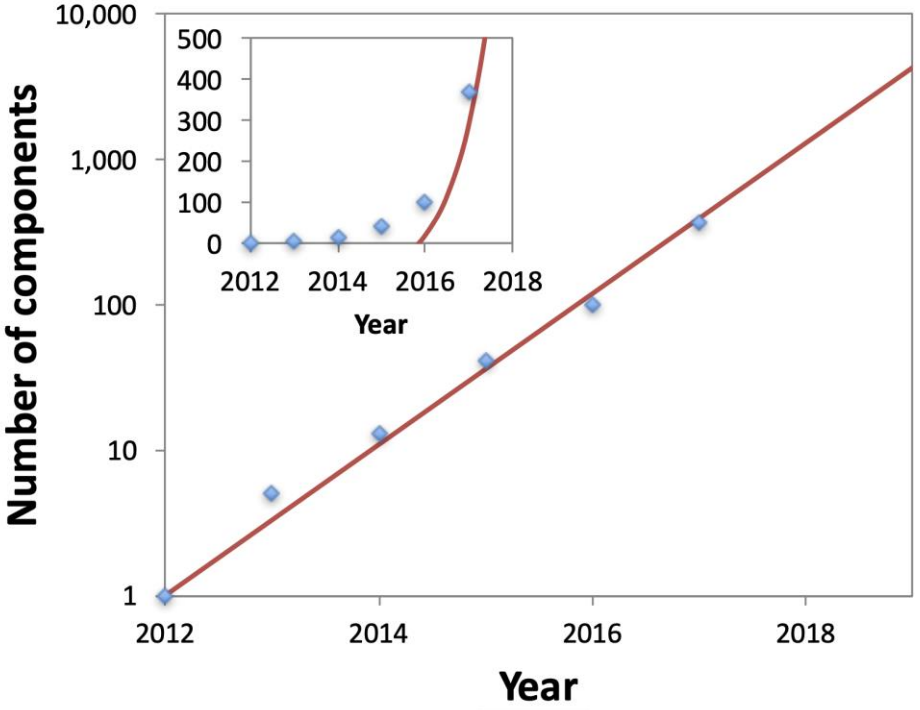
Introduction

Why Photonic Qubits?

- Single photon source, entangled photon pair, squeezed light
- Carrier frequencies: >100 THz; huge data bandwidths
- Room temperature
- On-chip, integrated photonic circuits
- Free from charge or magnetic shielding
- Free from vacuum systems
- Fiber-optic compatible
- CMOS-technology comparable
- Scalable: time-domain or frequency-domain multiplexing; various degrees of freedom including location (path), polarization, frequency, spatial and temporal modes.

Quantum Photonic Moore's Law



Challenges (though not yet addressed in this preliminary developing stage):

- Simultaneous detection of a large number of correlated photons in single photon level.
- Low-loss waveguide circuits and platforms.
- Fabrication error and variability when scaling to the wafer scale.
- Fully integrated quantum chips with sources, circuits and detectors.

Nature Photonics 14, 273–284 (2020)

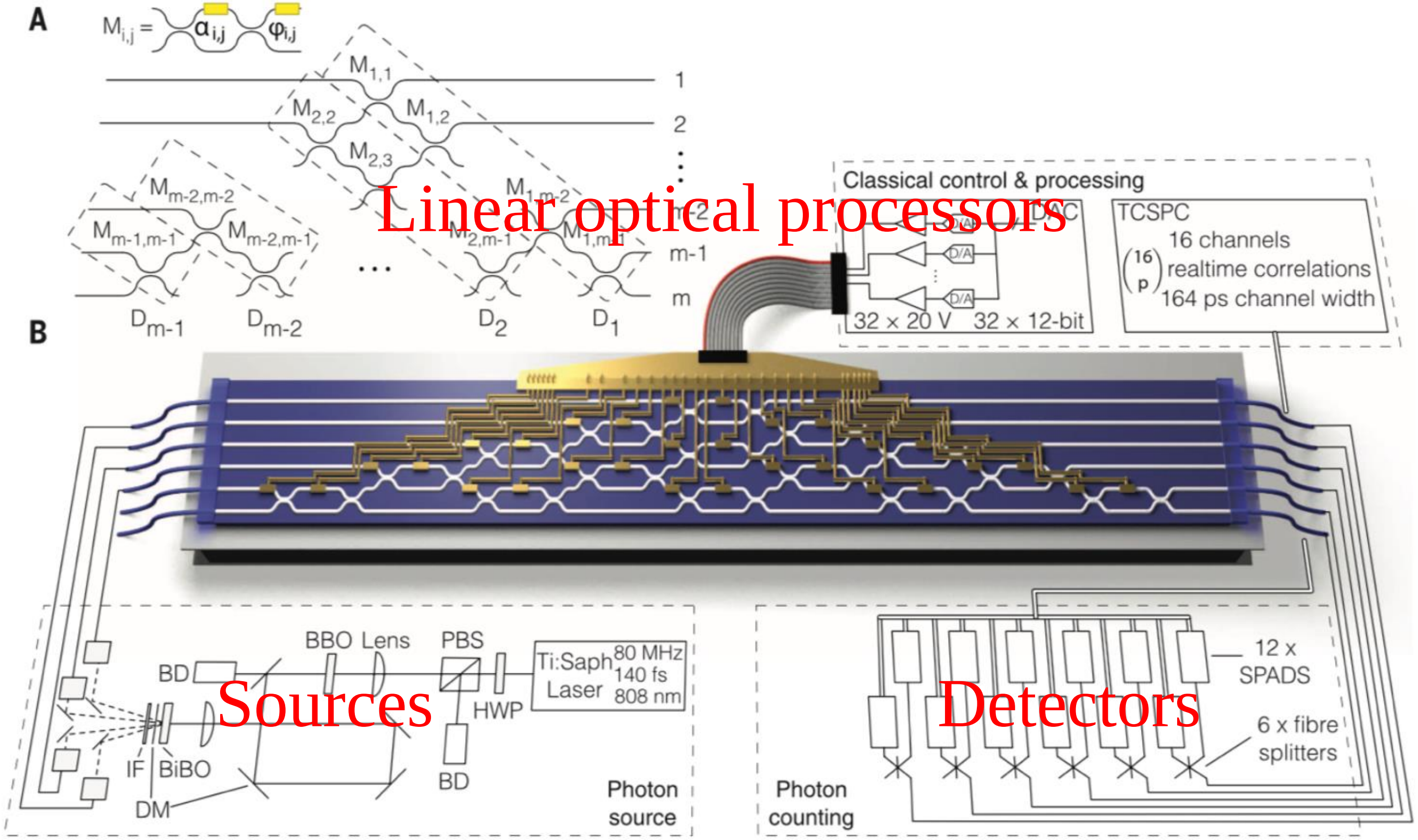
Introduction

Nature 409, 46-52.

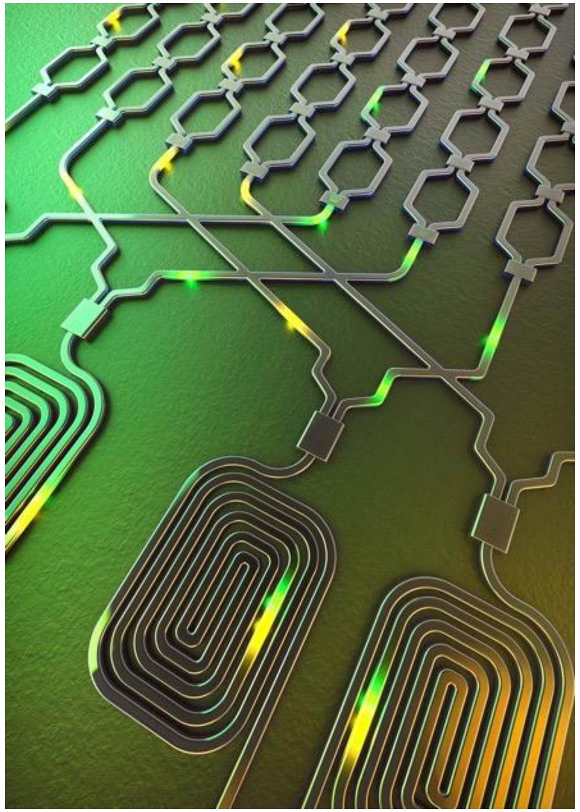
Linear Optical Quantum Computing—

"KLM scheme" : single photon sources, linear optical elements, and photon detectors

Relatively simple, efficient, integrable, scalable, room-temperature operational

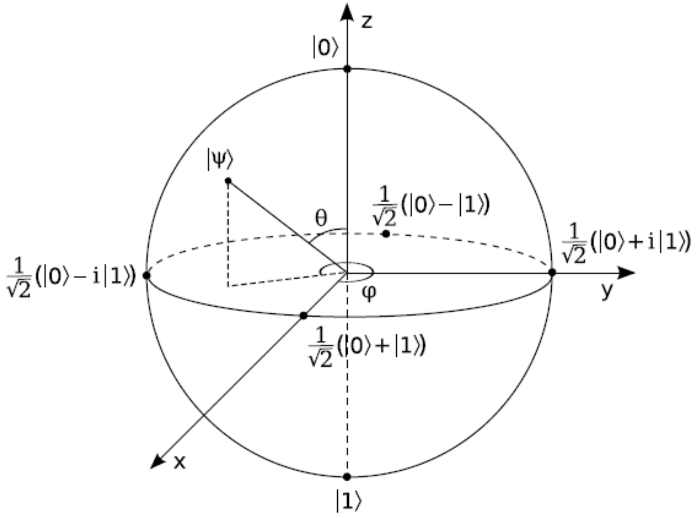


Science 349, 711 (2015)



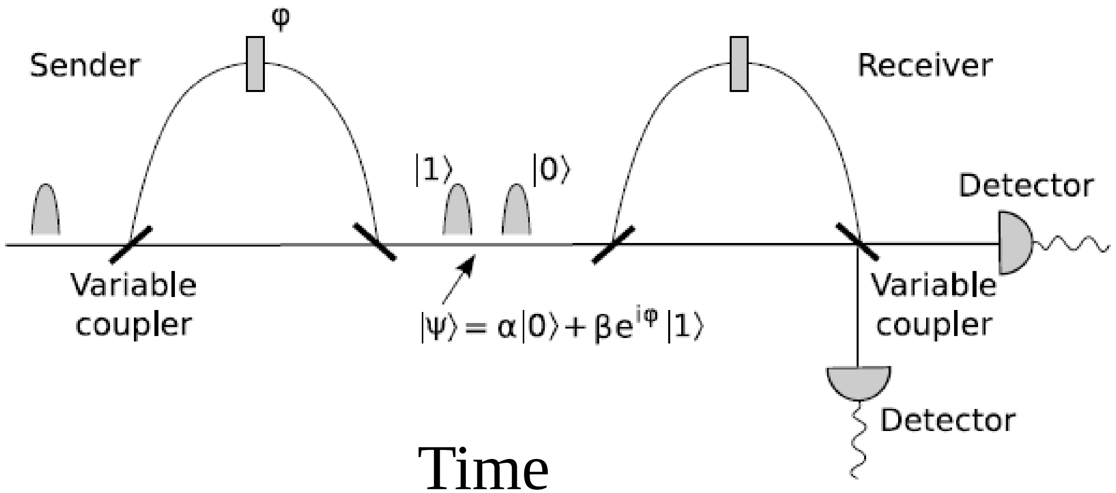
Nature Photonics 12, 534 (2018)

Single-photon Sources-- Qubits

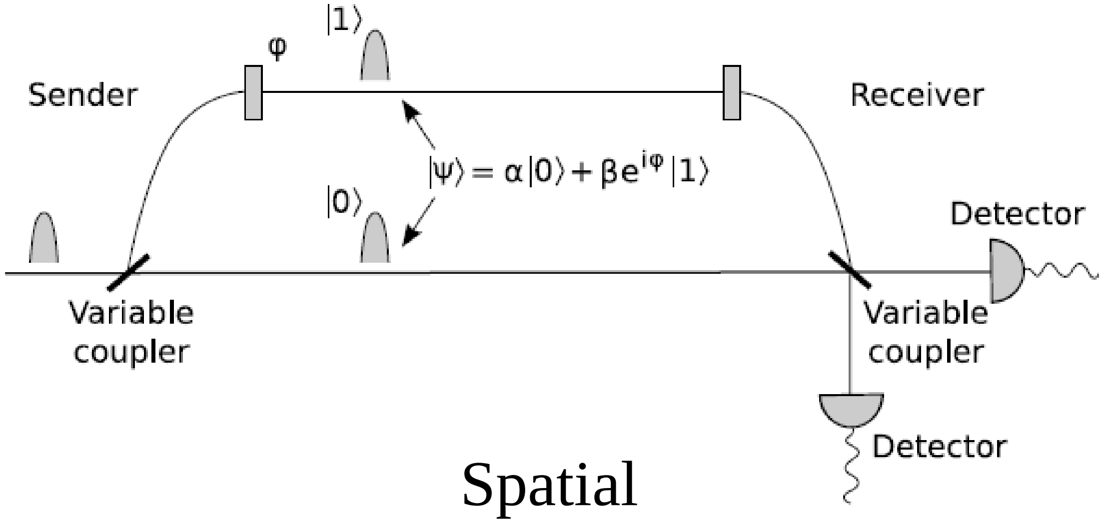


What is optical qubit?

(go another slide)

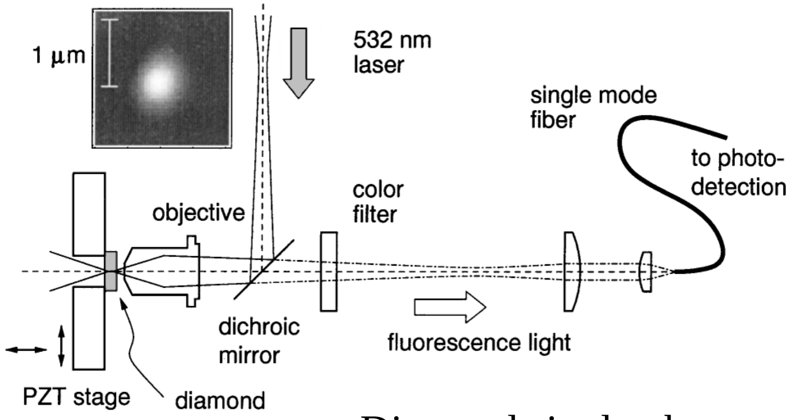


Time



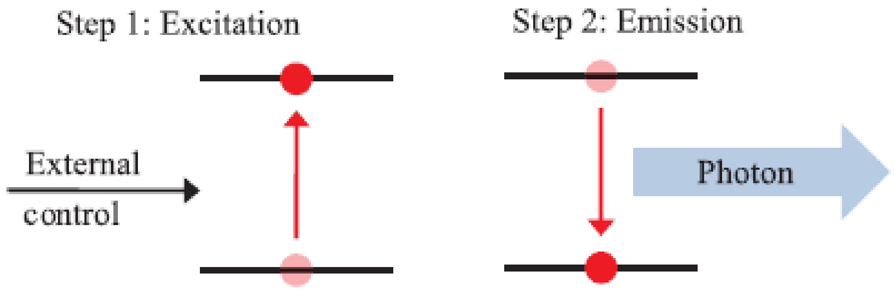
Spatial

Deterministic single photon sources

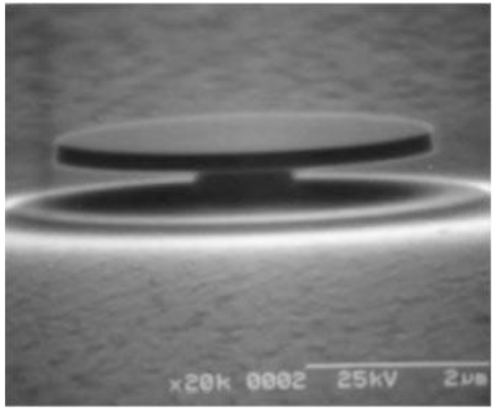


Color centers

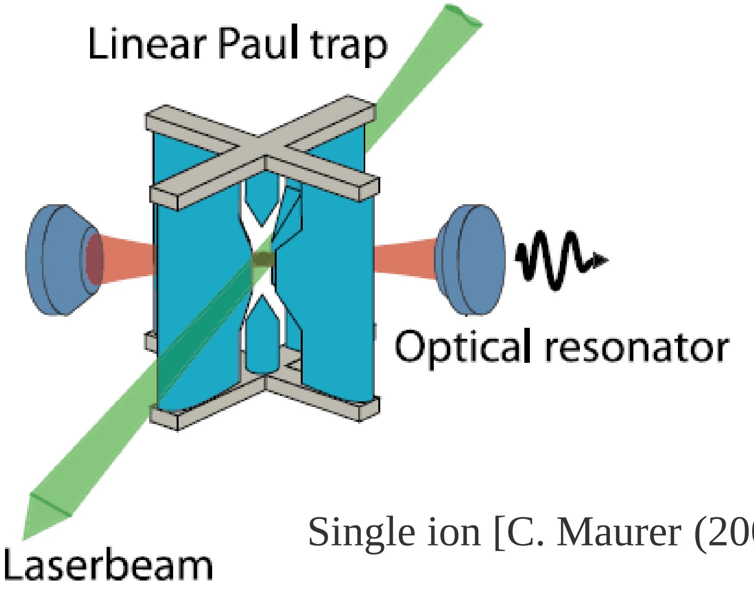
Diamond single photons
[Christian Kurtsiefer (2000), PRL]



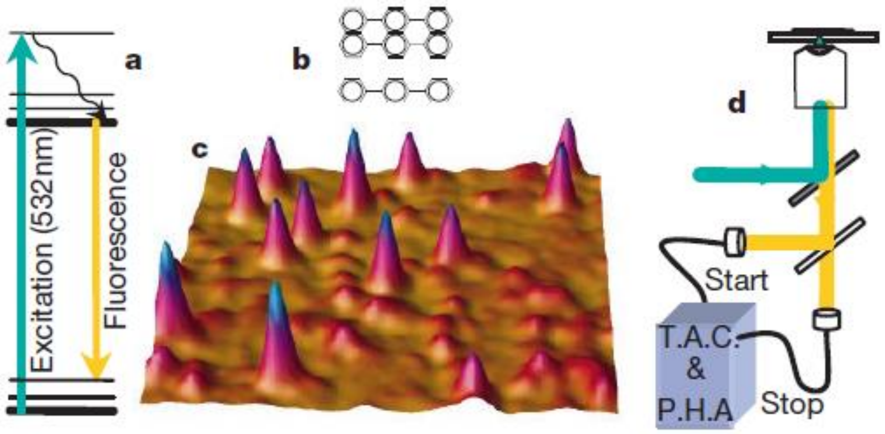
[M. D. Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011)]



Semiconductor quantum dot [P. Michler (2000), Science]

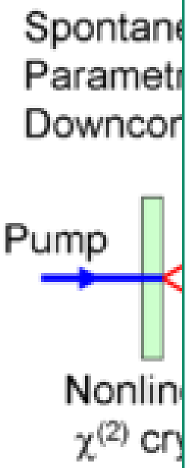


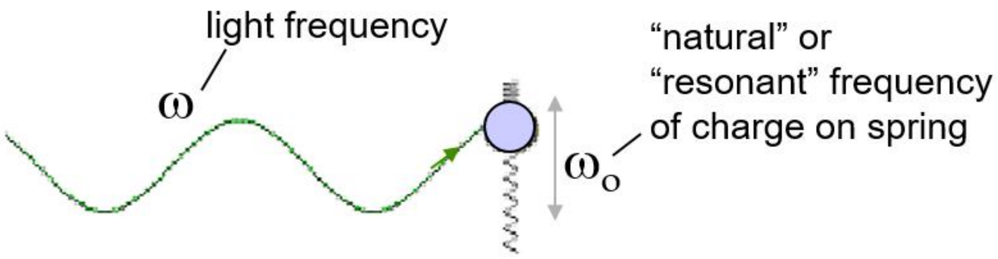
Single ion [C. Maurer (2004) New J. Phys.]

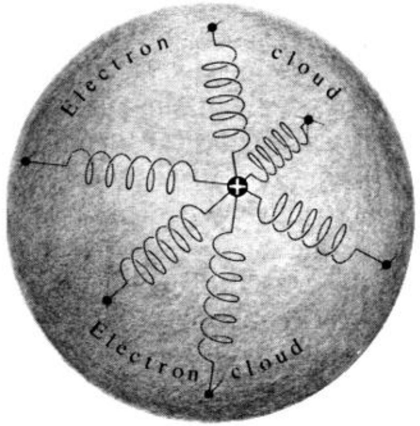


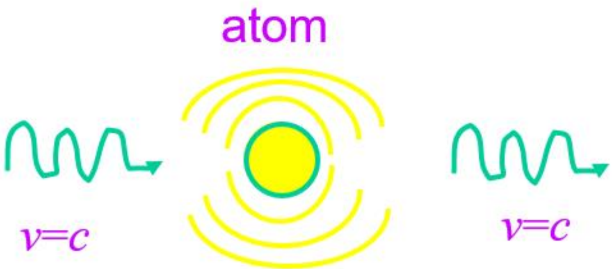
Single molecule [B. Lounis (2000), Nature]

nonlinear optics

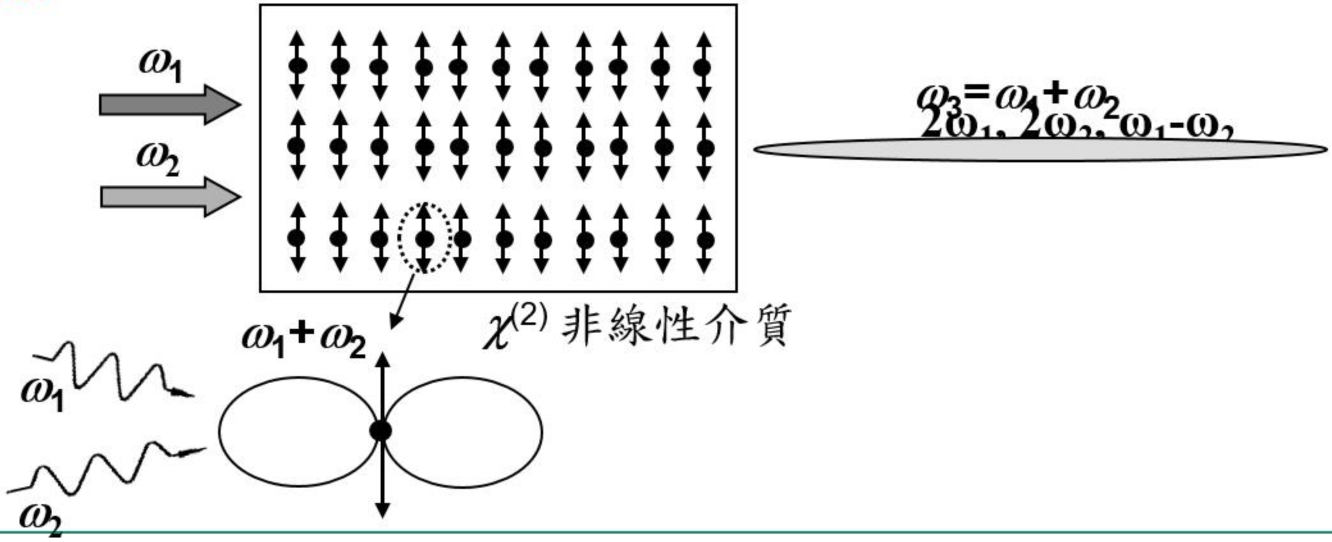








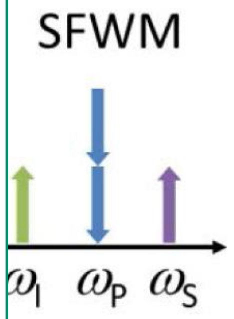
absorb & re-emit with
same phase delay



https://en.wiki

led photon pair

g/wiki/Spontane
-conversion

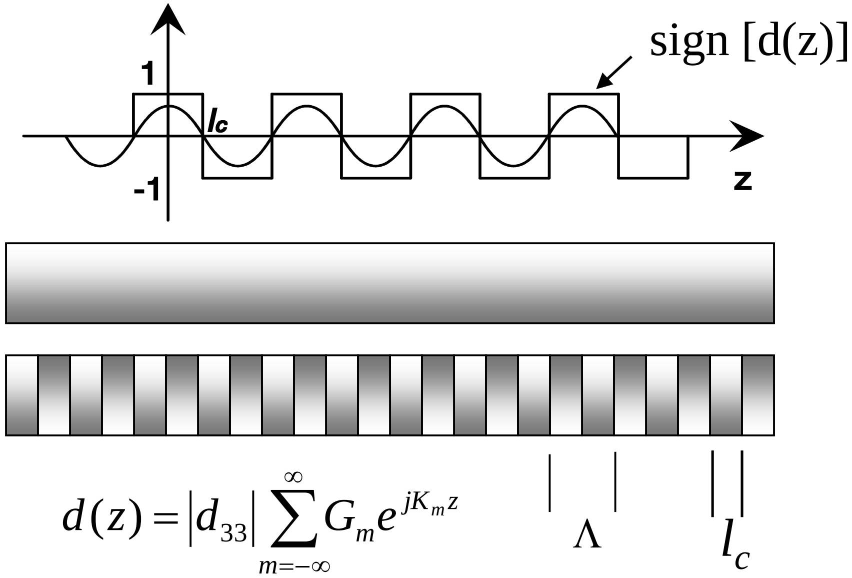


veguide

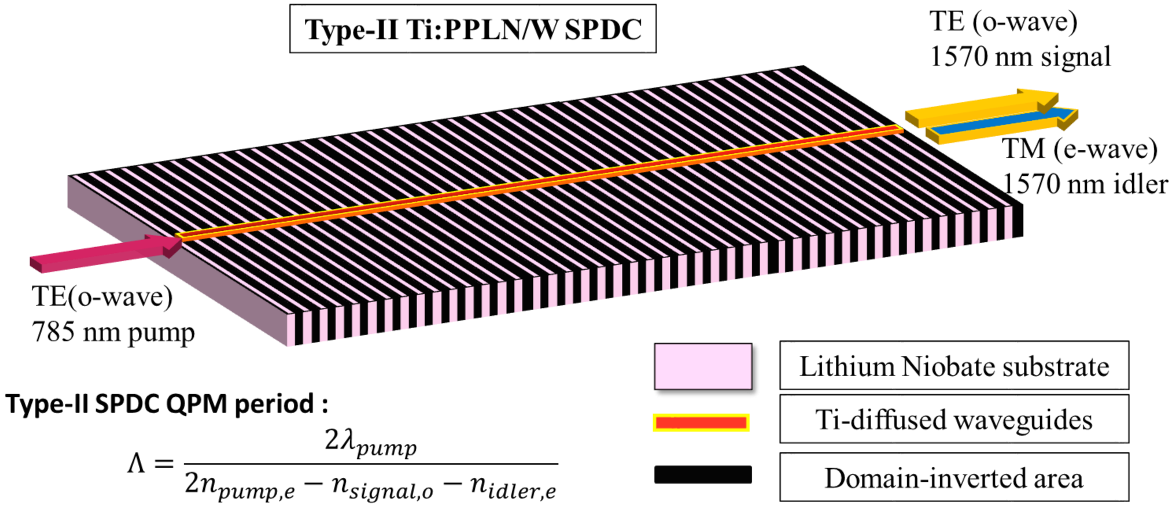
htt

Bulk SPDC

Quasi-phase-matching (QPM) SPDC in periodically poled (PP) crystals

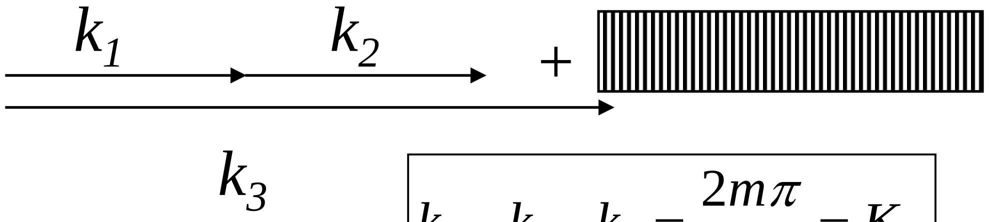


$$d(z) = |d_{33}| \sum_{m=-\infty}^{\infty} G_m e^{jK_m z}$$



Type-II SPDC QPM period :

$$\Lambda = \frac{2\lambda_{pump}}{2n_{pump,e} - n_{signal,o} - n_{idler,e}}$$



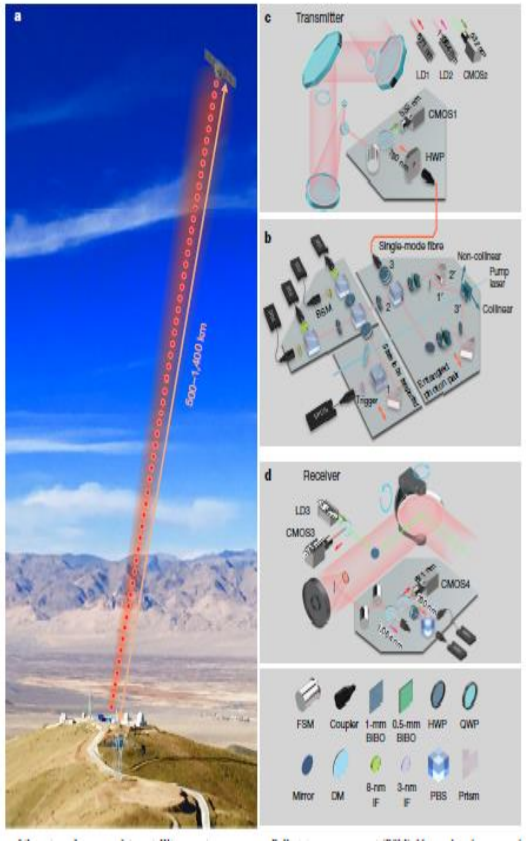
$$k_3 - k_1 - k_2 = \frac{2m\pi}{\Lambda} = K_\Lambda$$

- Noncritical phase-matching with engineerable QPM gratings
- No walk-off problem
- Access of the best nonlinear coefficient, d_{33}

High-efficient collinear photon pair generations

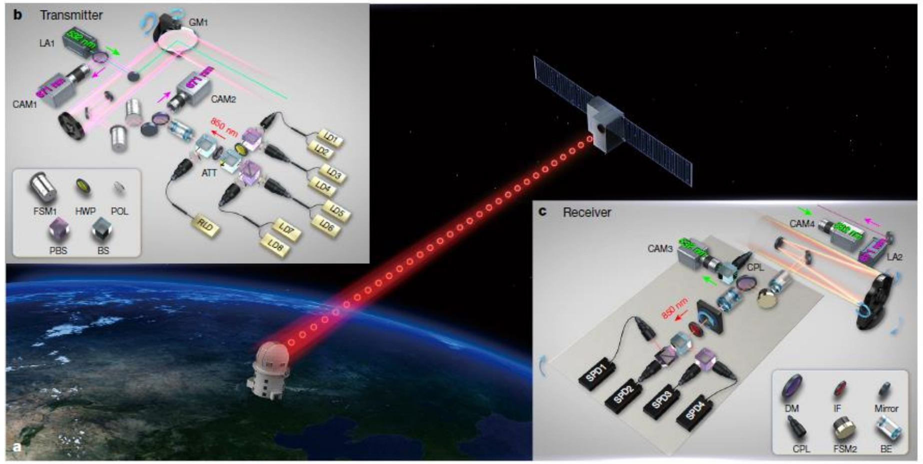
Bulk QPM SPDC

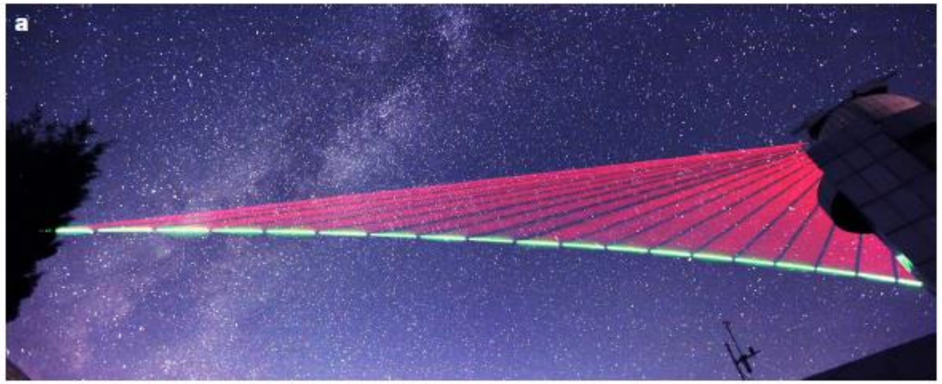
Ground-to-satellite quantum teleportation



Ren, Ji-Gang, et al., **Nature** 549, 70 (2017).

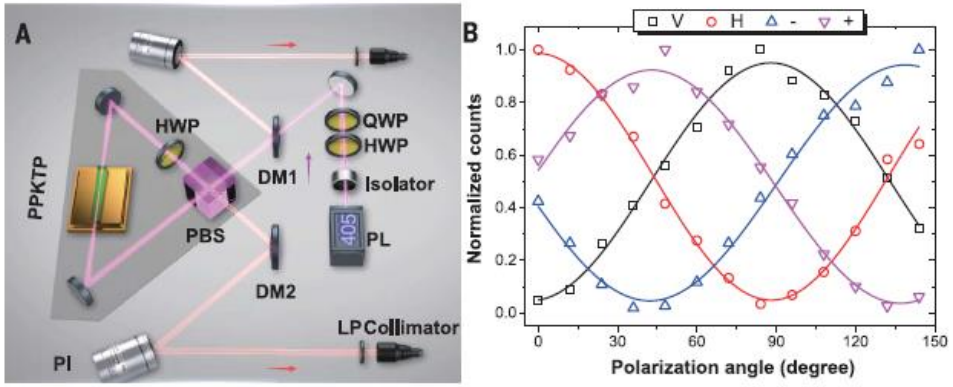
Satellite-to-ground QKD

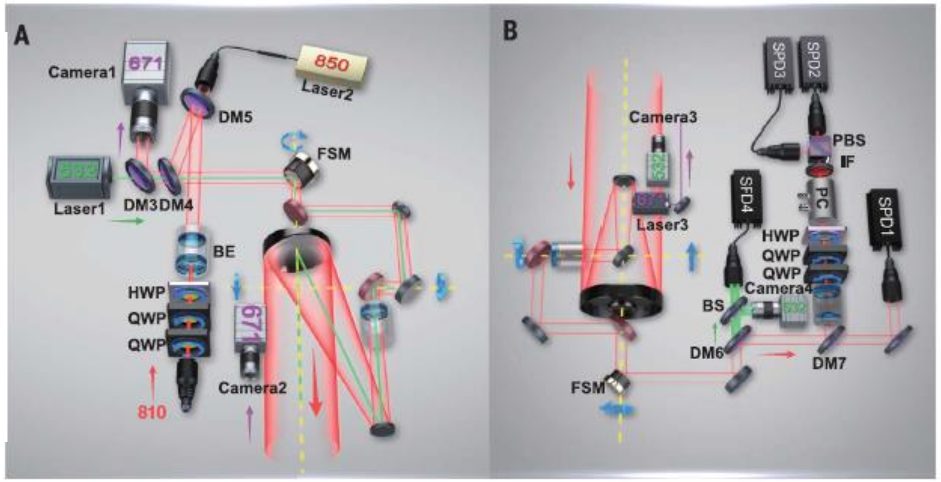




Liao, Sheng-Kai, et al., **Nature** 549, 43 (2017).

Satellite-based entanglement distribution





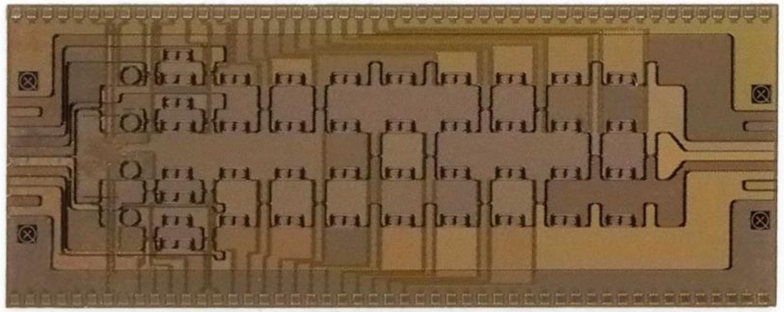
Yin, Juan, et al., **Science** 356, 1140-1144 (2017).

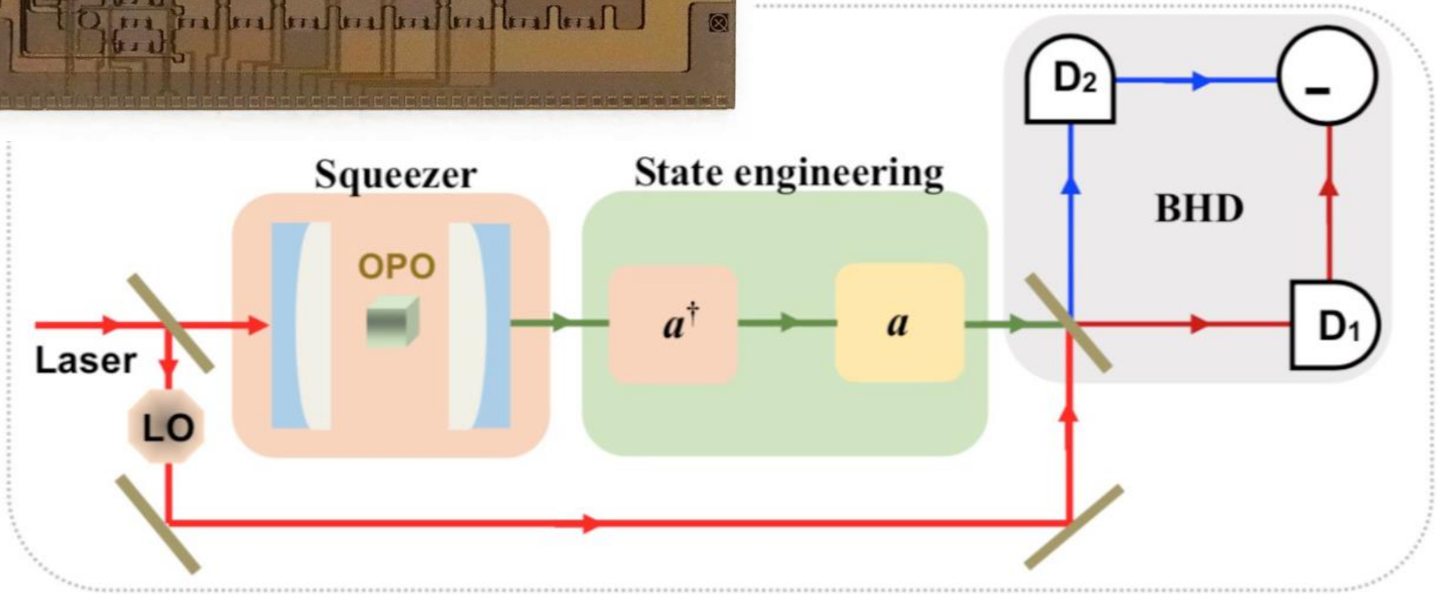
Comparison of single-photon sources

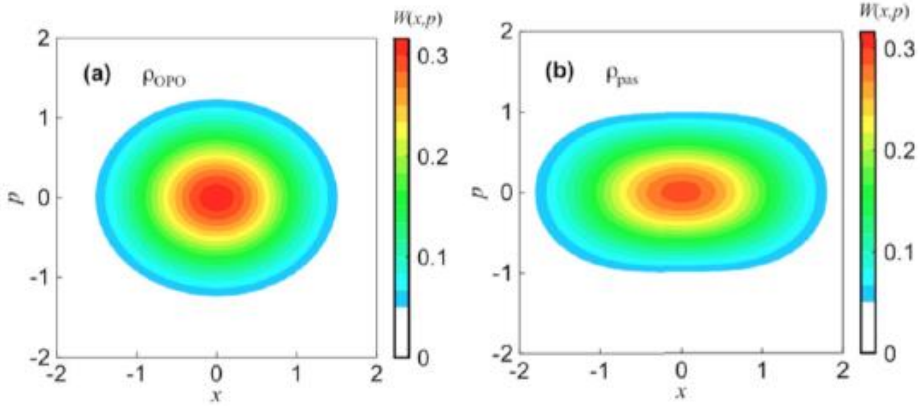
	Spontaneous Down Conversion	Four-Wave Mixing	Atoms and Ions	Quantum Dots	NV Centers	"Ideal" Single-Photon Source
Entanglement fidelity	0.9959	0.997	0.93	0.978	---	Approx. 1
Probabilistic / deterministic	Probabilistic	Probabilistic	Probabilistic, Deterministic	Deterministic	Deterministic	Deterministic
Emission range	600-1700 nm	600-1550 nm	Transition lines	IR, telecom	600-800 nm	Varies – many apps require telecom
Brightness	2.01 MHz	855 kHz	55 kHz	28.3 MHz	850 kHz	High
Best *g* (Purity)	0.004	0.007	0.0003	0.000075	0.07	Approx. 0
HOM visibility (Indistinguishability)	0.99	0.97	0.93	0.9956	0.66	Approx. 1
Operating temp.	273-473 K	Room temp.	Room temp., mK (in cavity)	Room temp., cryogenic	300-500 K	Room temp.
Efficiency max. (Deterministic)	0.84	0.26	0.88	0.97	0.35	Approx. 1
Likely quantum apps	Metrology, information, comms, foundations	Integrated photonics	Foundations	Comms, foundations	Comms, networks	--

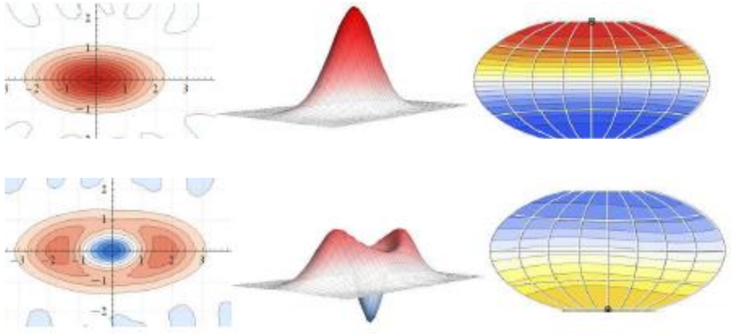
OPN September 2019 Issue: Single Photon Sources,

Quantum Squeezed States: Continuous Variable qubits









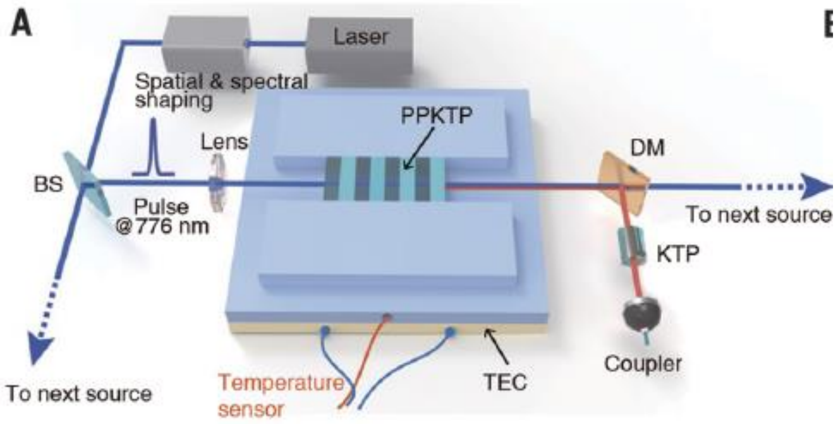
Photonic qubit with OPO as a squeezer, and state engineering through photon-addition/photon-subtraction

Wigner function

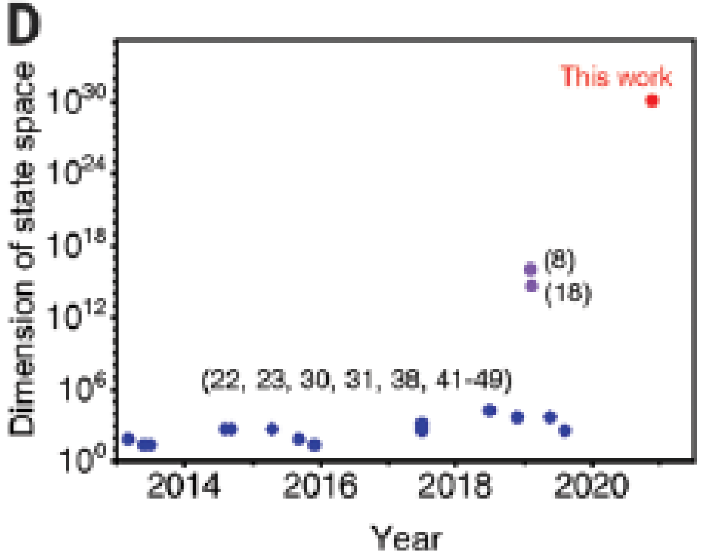
Quadrature: CV qubits

(Gaussian) boson sampling

Jiuzhang (九章) Science (2020)



25× PPKTP = 50 single-mode squeezed states

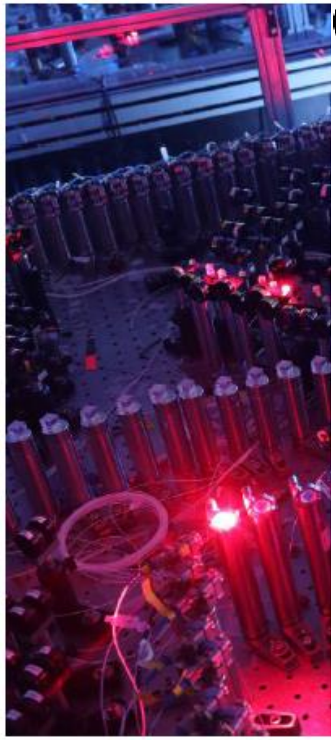


Quantum supremacy

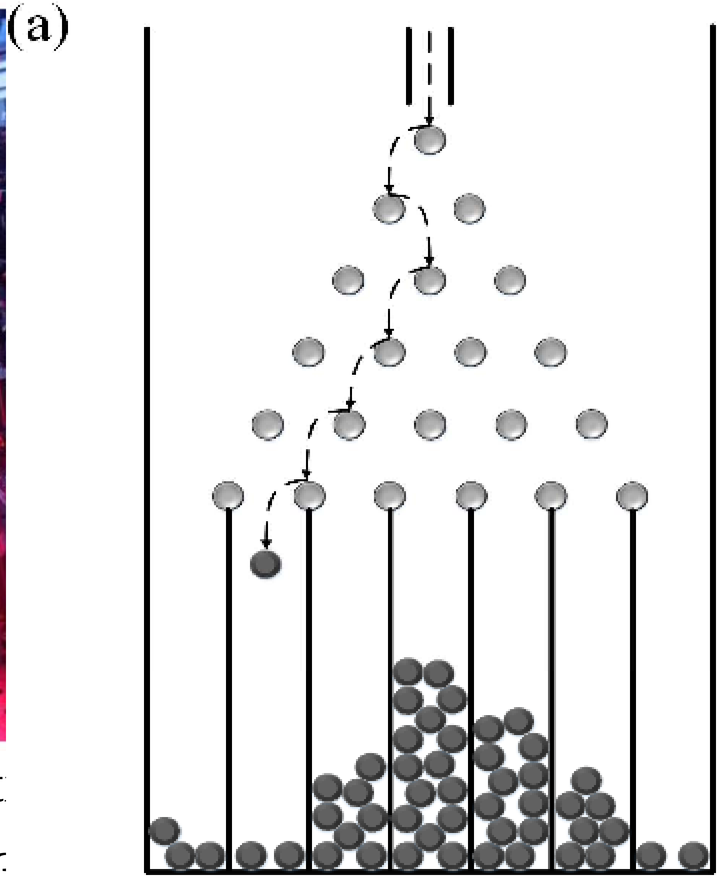
In this sampling task:

Jiuzhang: 200 s

Fugaku: 2×10^{16} s



Spatial-polarizat



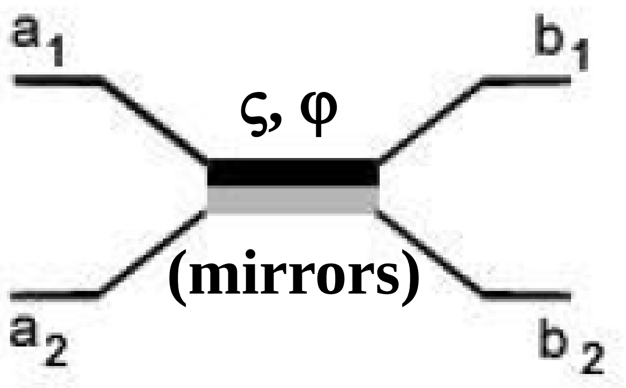
100 single-photon detectors

Linear optical elements

Essential linear optical elements

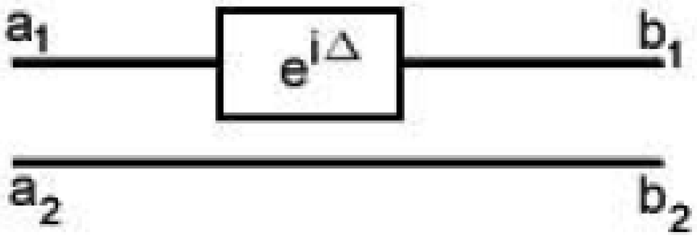
For every unitary operation there is a sequence of phase shifters and beam splitters that implements the corresponding operation up to a global phase

Beam splitter



$$\Lambda = \begin{pmatrix} \cos\zeta & -ie^{i\varphi}\sin\zeta \\ -ie^{-i\varphi}\sin\zeta & \cos\zeta \end{pmatrix}$$

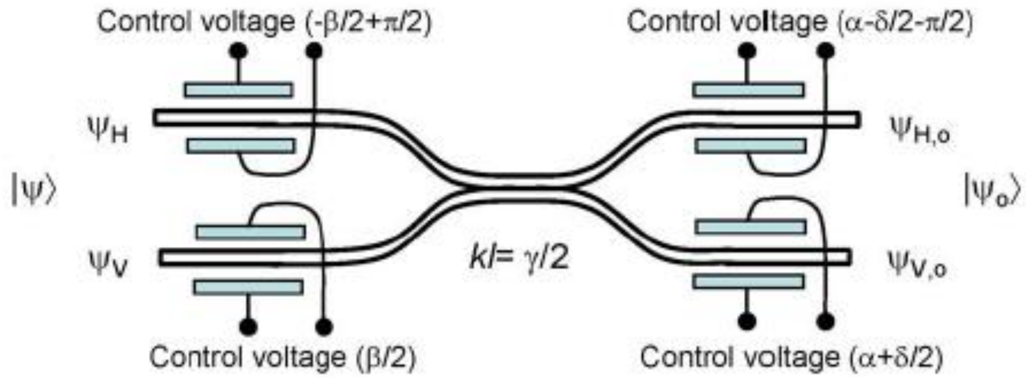
Phase shifter

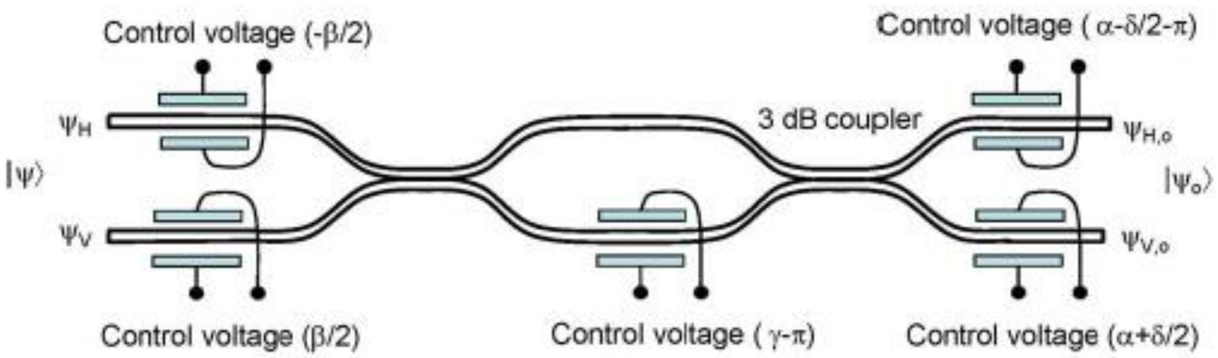


$$\Lambda = \begin{pmatrix} e^{i\Delta} & 0 \\ 0 & 1 \end{pmatrix}$$

Quantum gates: building blocks of quantum circuits

On the photonic implementation of quantum gates:
two elementary linear optical components:

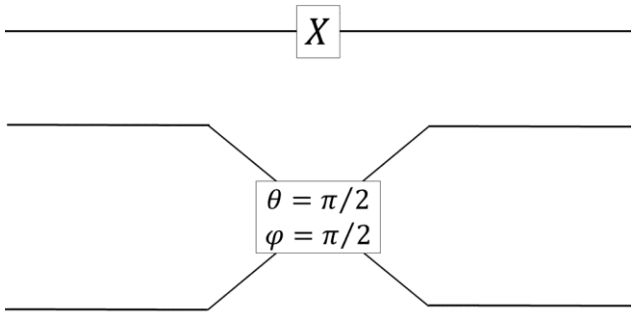


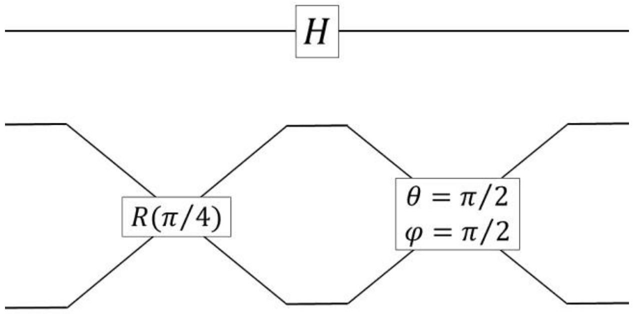


IEEE Photon. J. 2, 81 (2010)

Directional coupler (DC)

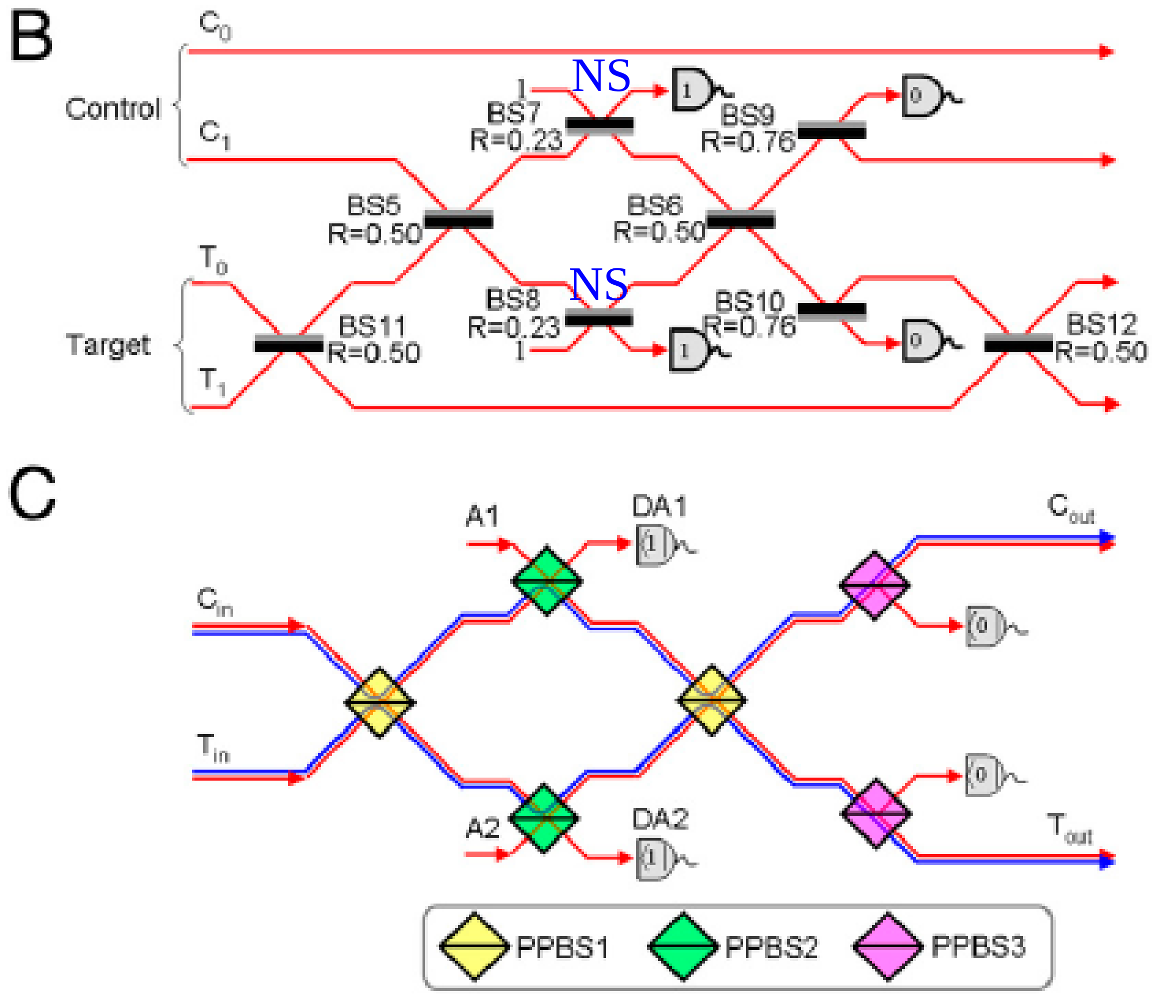
Mach—Zehnder interferometer (MZI)

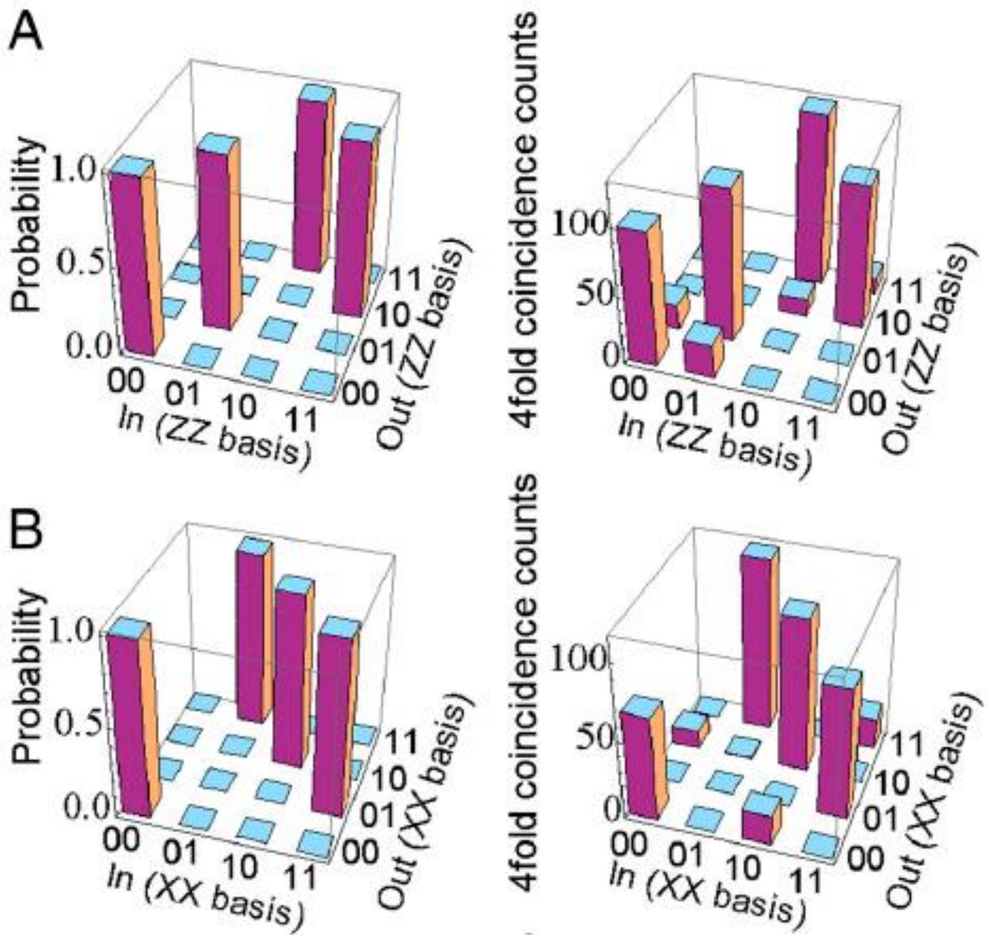




https://en.wikipedia.org/wiki/Linear_optical_quantum_computing

Realizing KLM CNOT circuit





Scheme I. Quantum Factoring

Initial state

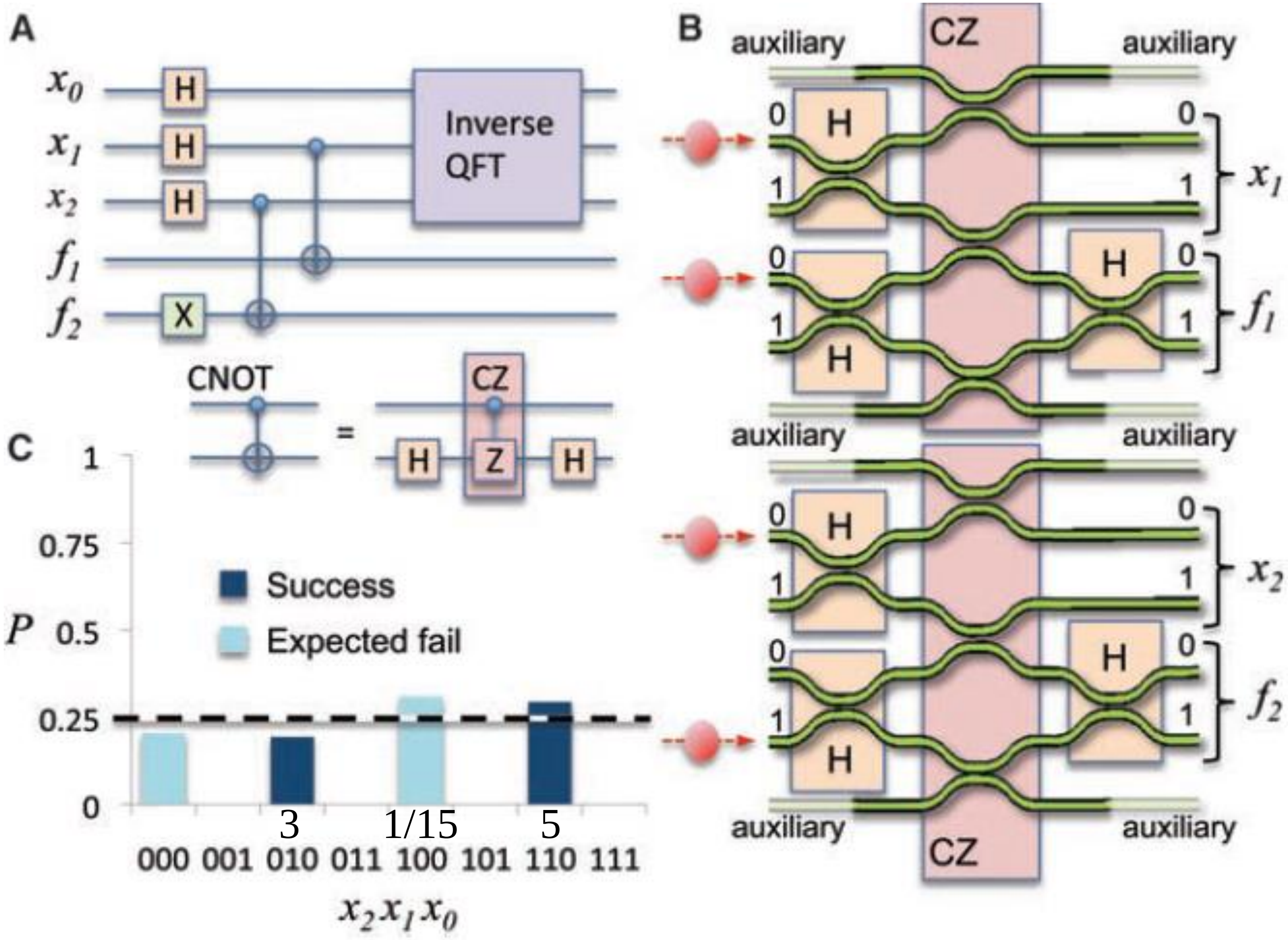
$$|\psi_{in}\rangle = |0\rangle_{x_1}|0\rangle_{x_2}|0\rangle_{f_1}|1\rangle_{f_2}$$

15= 3×5

Shor's algorithm

$$I_n = \sum_{k=1}^{n} P_1(k) = \frac{1}{2}\left[n + \sum_{k=1}^{n} \mathrm{Cos}\left(\frac{2\pi kN}{n}\right)\right]$$

$$\frac{N}{n} = \text{integer}, \longrightarrow I_n = n$$



Single-photon detectors

Single-photon detectors

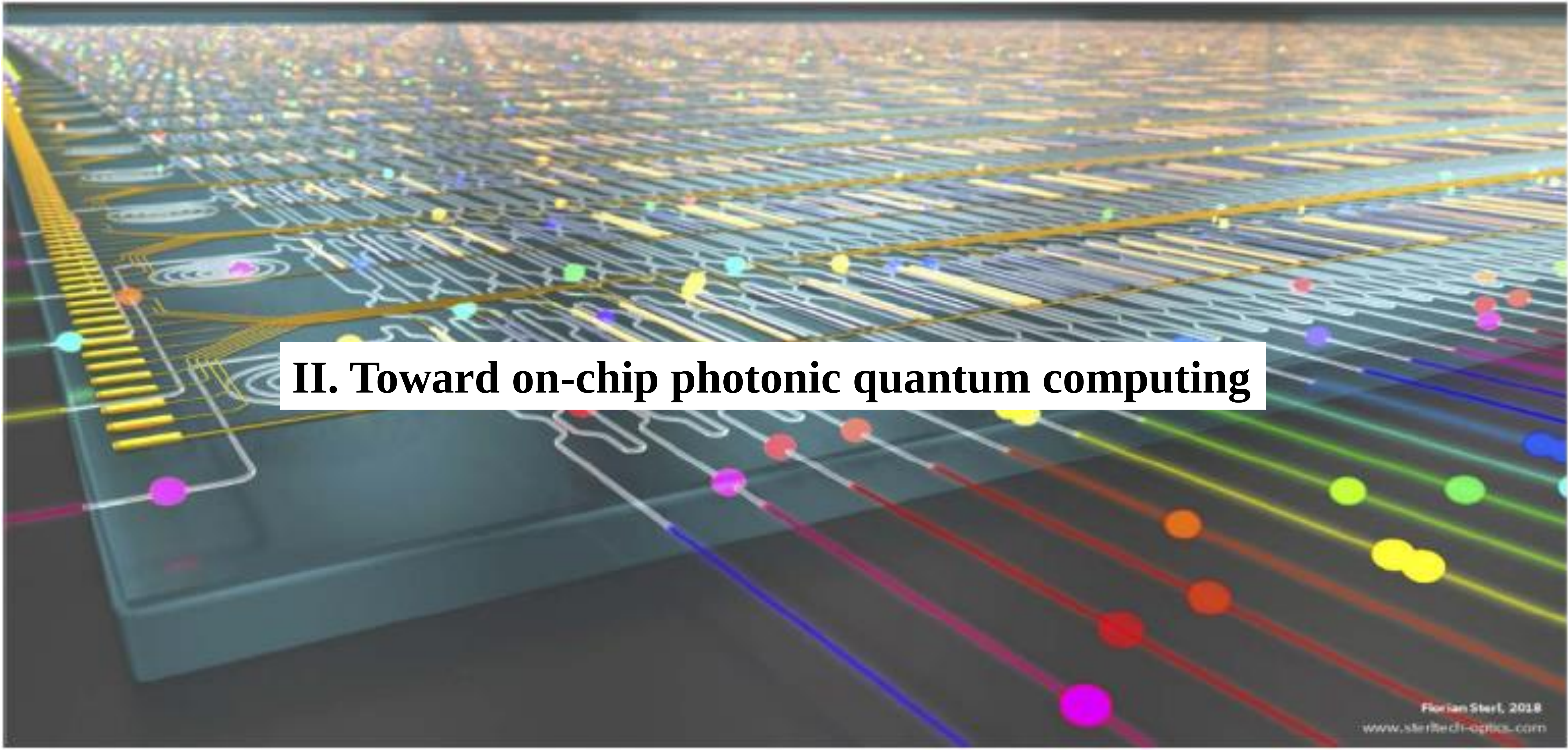
COMPARISON OF COMMON COMMERCIALLY AVAILABLE INFRARED SINGLE-PHOTON DETECTORS

	Avalanche Photodiode *InGaAs / InP, Geiger-Mode*	**Superconducting Nanowire SPD**	**"Ideal" SPD**
Example Product	ID Quantique ID230	Single Quantum Eos	--
Detector Efficiency at 1550 nm	10 - 25%	≥ 85%	100%
Reset Time	2 - 25 μs	≤ 30 ns	Approx. 0+
Jitter Time	150 ps	≤ 25 - 50 ps	0.0 ps
Dark Count Rate	<50 – 200 Hz	≤ 300 Hz	0.0 Hz
Operating Temperature	Non-Cryogenic (183 - 223K)	Cryogenic (~2.5K)	Room Temp. (~293K)
Relative Cost	Low	High	--
Intrinsically Photon Number Resolving	No	No	Yes

Sources: Data sheets from Single Quantum, IDQuantique

Quantum Computing with Light:
https://www.youtube.com/watch?v=nyK-vhoOBpE

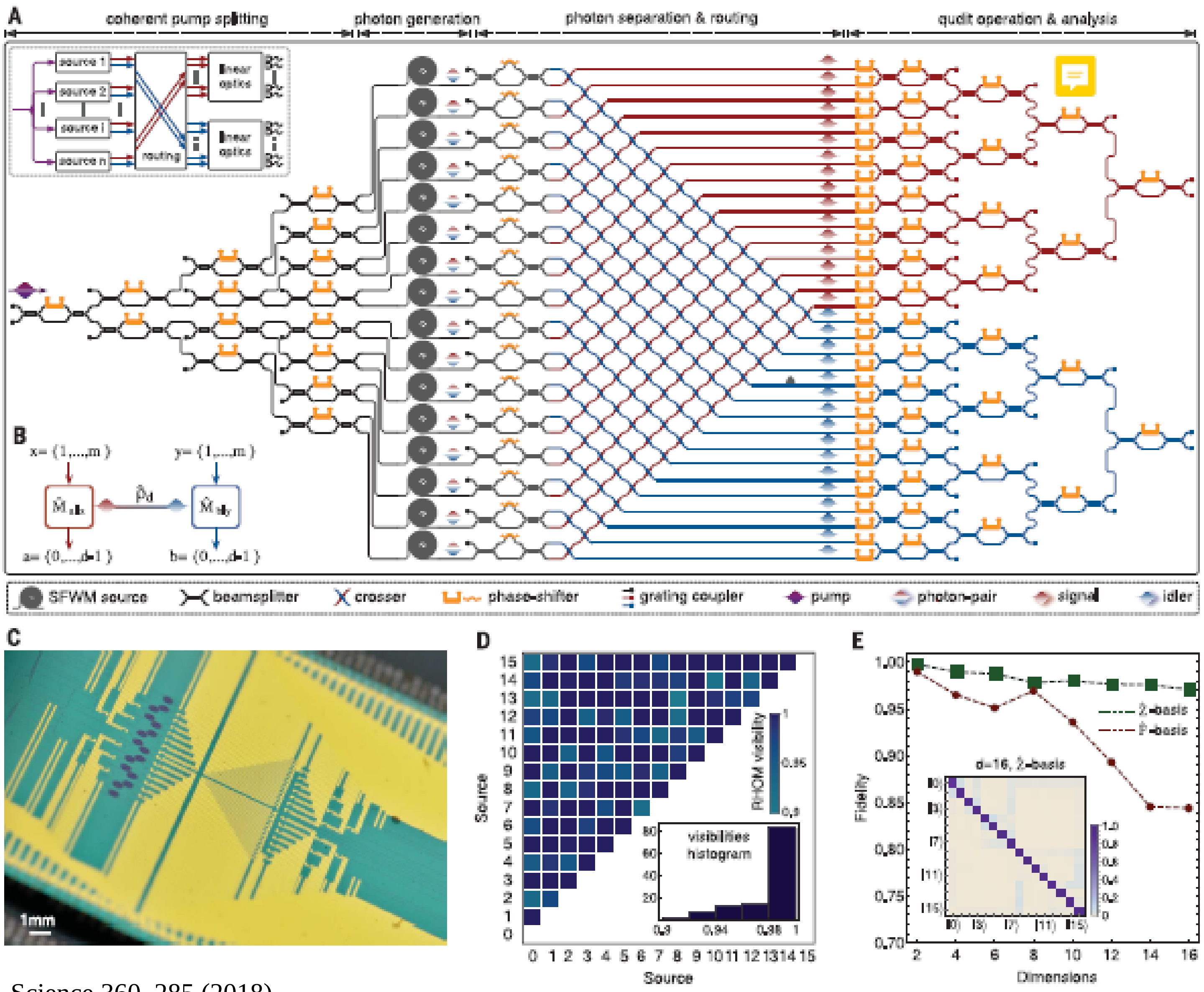
II. Toward on-chip photonic quantum computing



Optics Express 27, 26842 (2019)

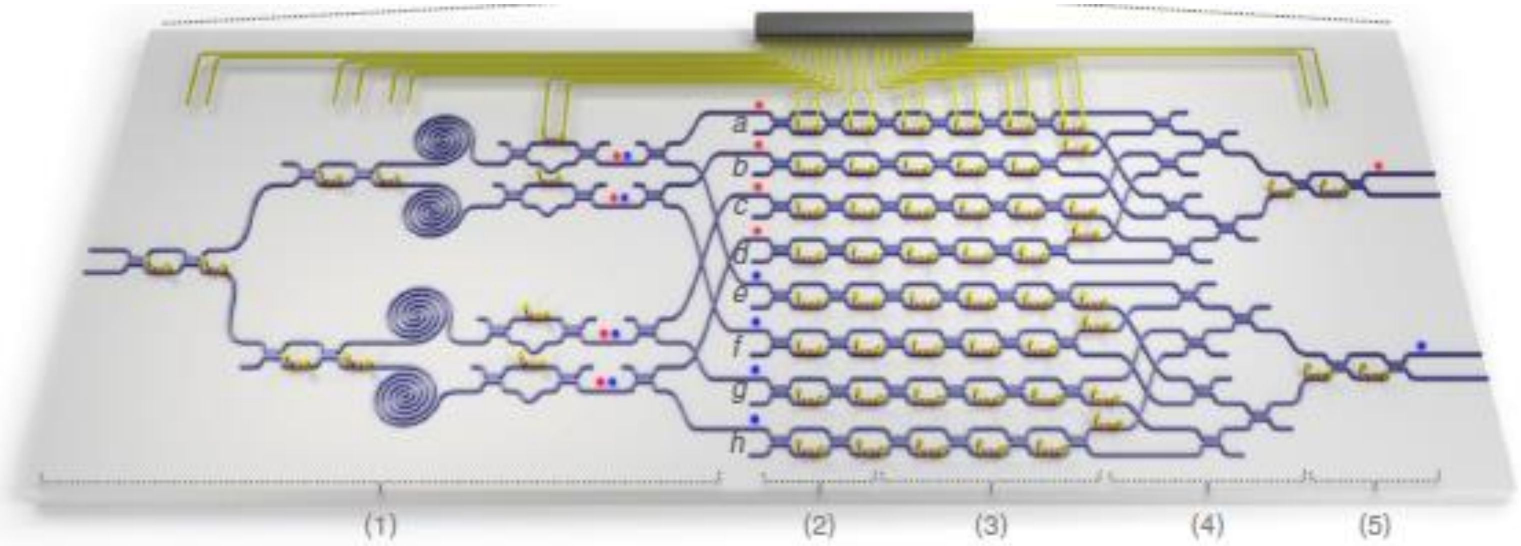
State-of-the art-- Large scale quantum circuits

16 SFWM photon-pair sources,
93 thermo-optical phase shifters,
122 multimode interferometer (MMI) beamsplitters,
256 waveguide crossers,
64 optical grating couplers.



Science 360, 285 (2018)

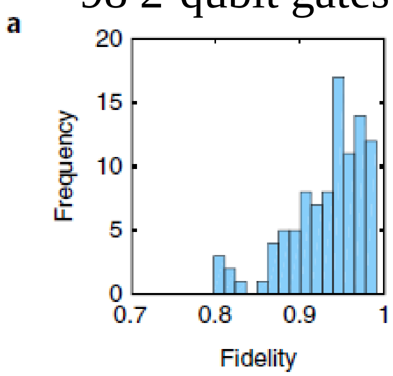
State-of-the art-- Large scale quantum circuits



(1) generating ququart entanglement; (2) preparing initial single-qubit states; (3) implementing single-qubit operations; (4) realizing linear combination; (5) changing the measurement basis.

4 SFWM photon-pair sources,
4 pump rejection filters,
58 thermo-optical phase shifters,
82 MMI beamsplitters,
18 waveguide-crossers, and
40 optical grating couplers.

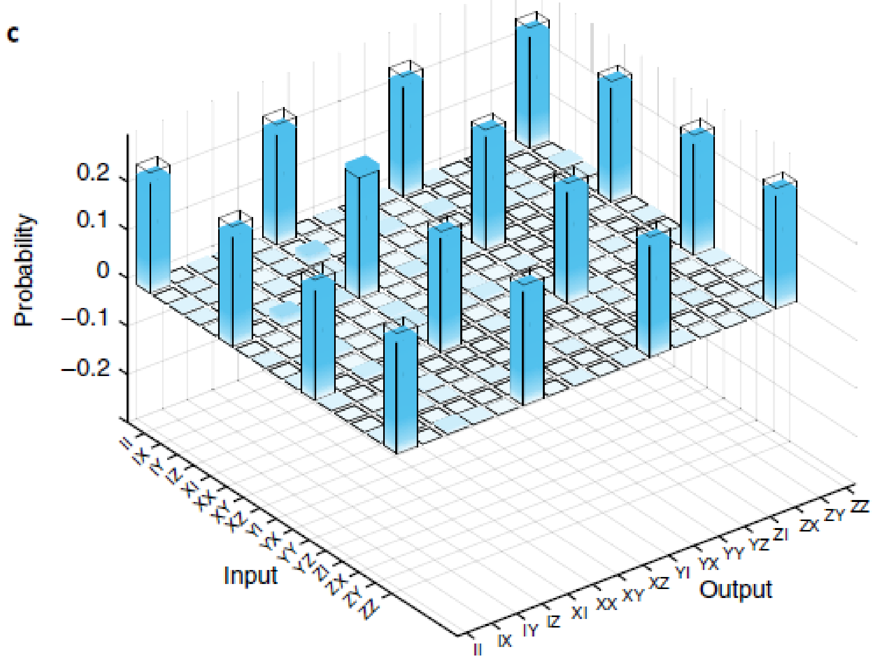
98 2-qubit gates



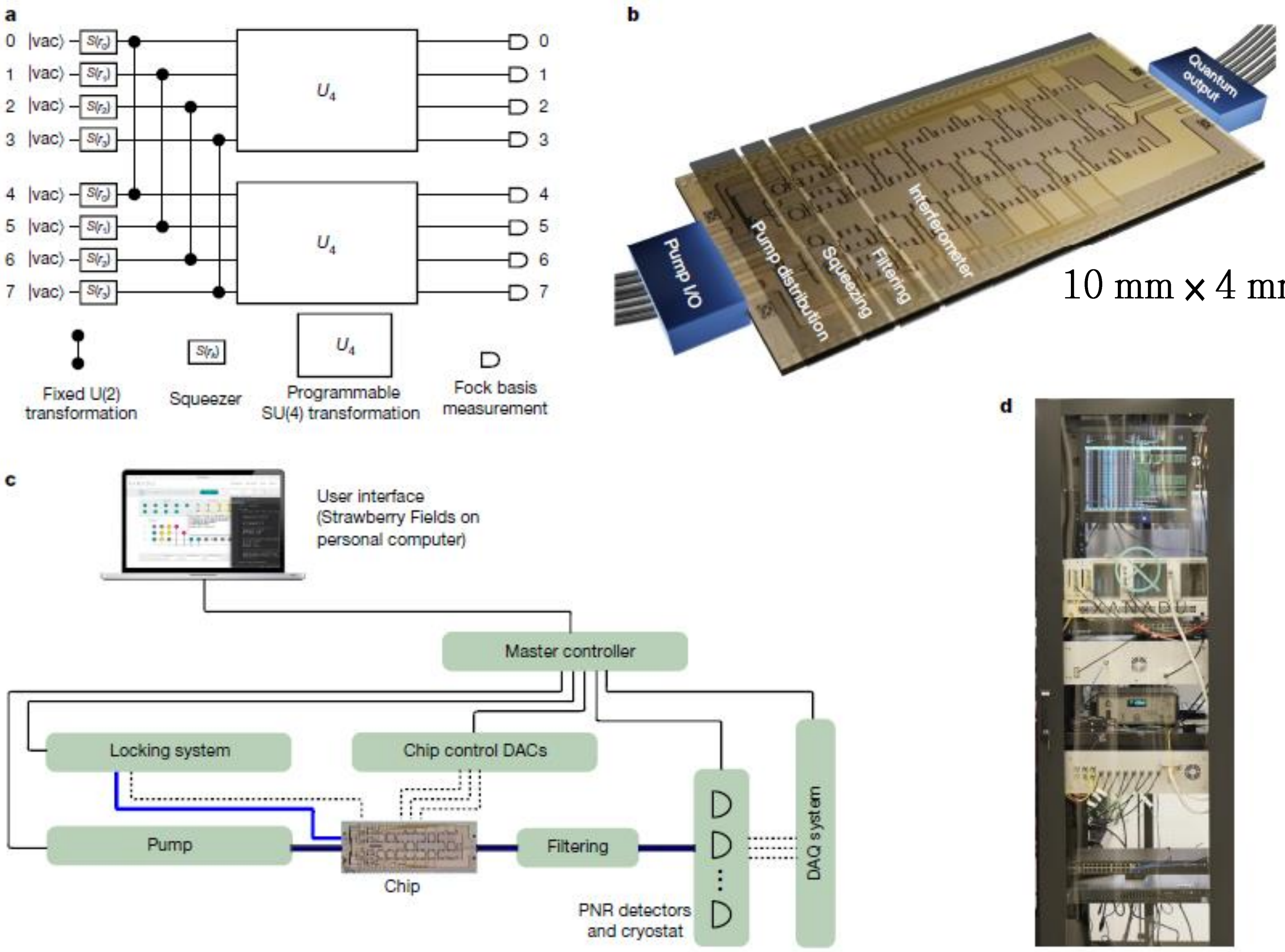
Reconfigurability

b

Gate	Fidelity (%)
CNOT	98.85 ± 0.06
CZ	96.90 ± 0.17
CH	97.57 ± 0.07
SWAP	95.33 ± 0.24
iSWAP	94.45 ± 0.27
$\sqrt{\text{SWAP}}$	92.41 ± 0.33



State-of-the art– CV programmable nanophotonic chip

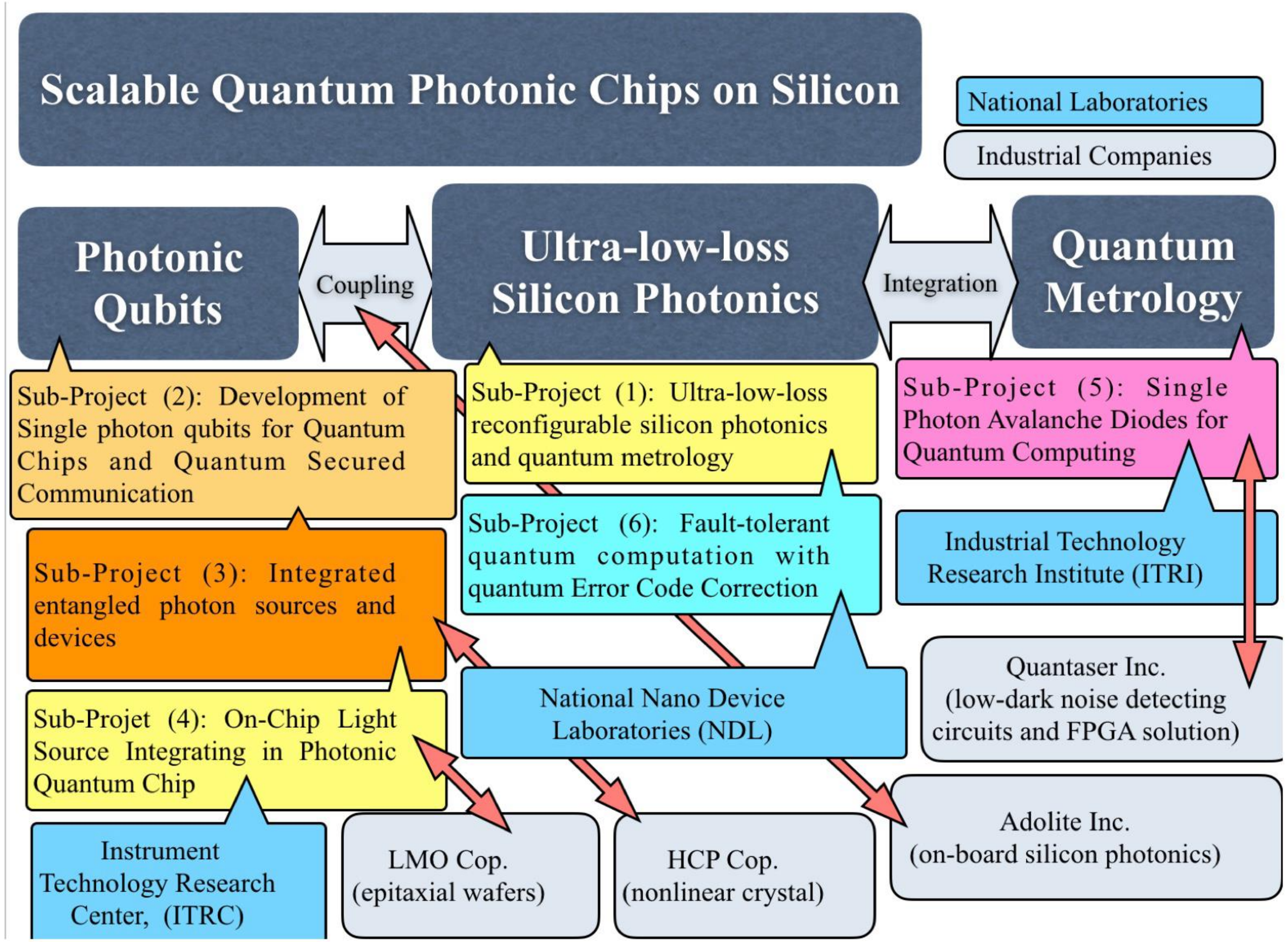


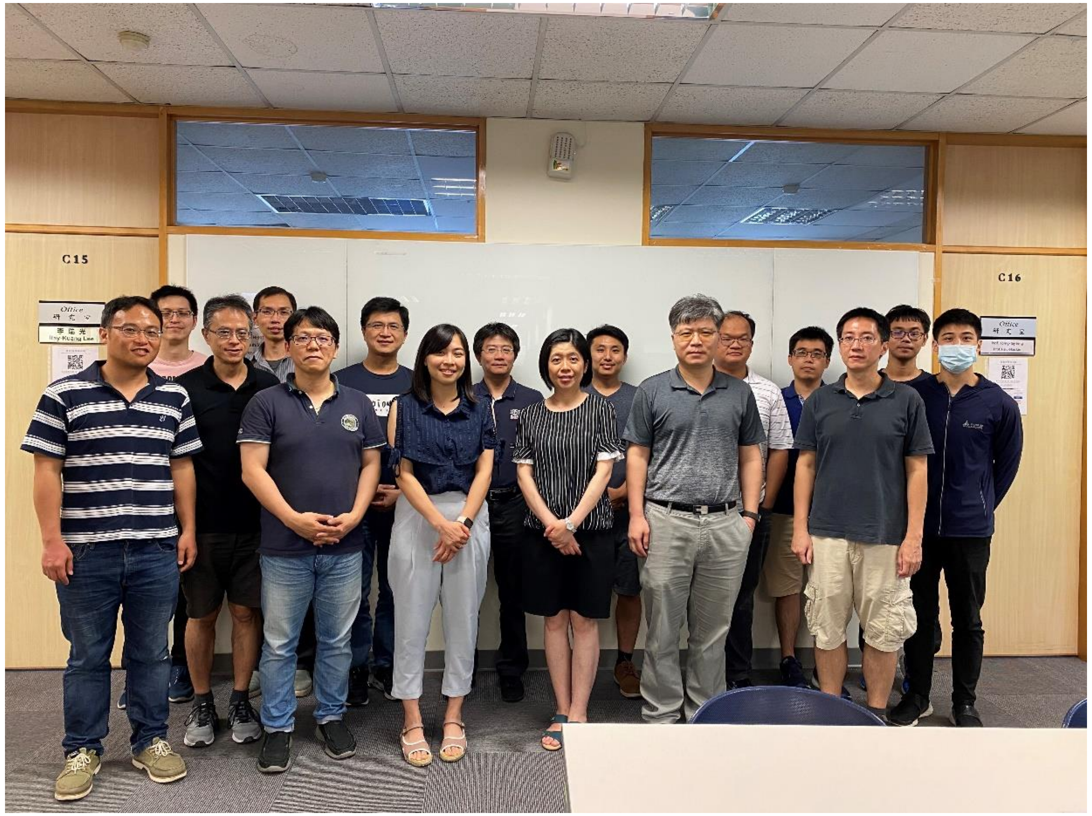
10 mm × 4 mm photonic chip

Nature 591, 54 (2021)

TAIWAN's Niche

The Team– “矽基量子光電晶片”





Project co-PIs:

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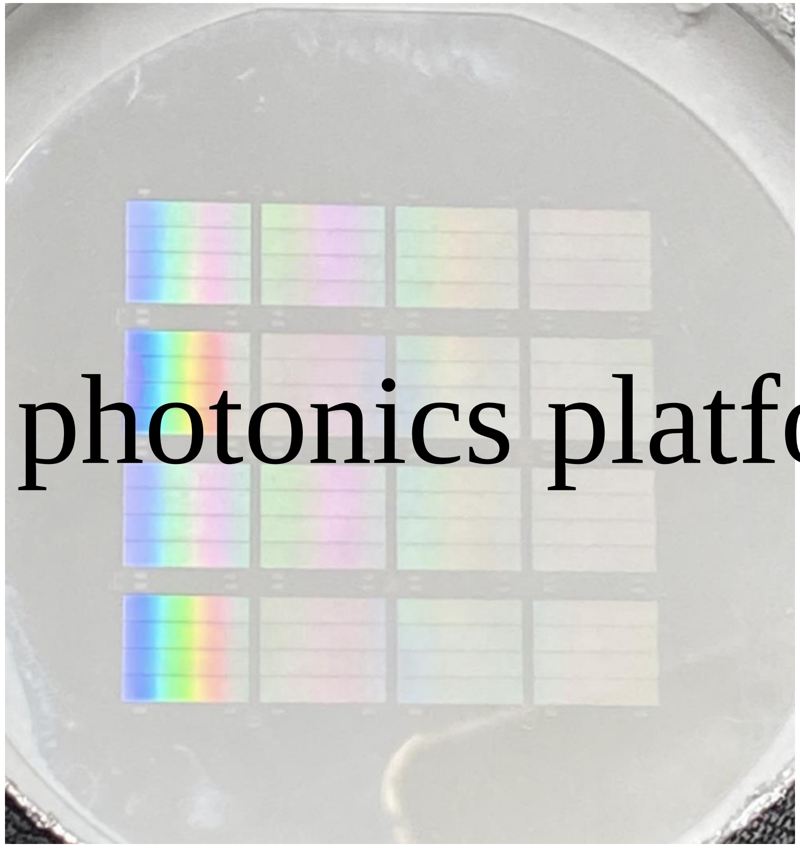
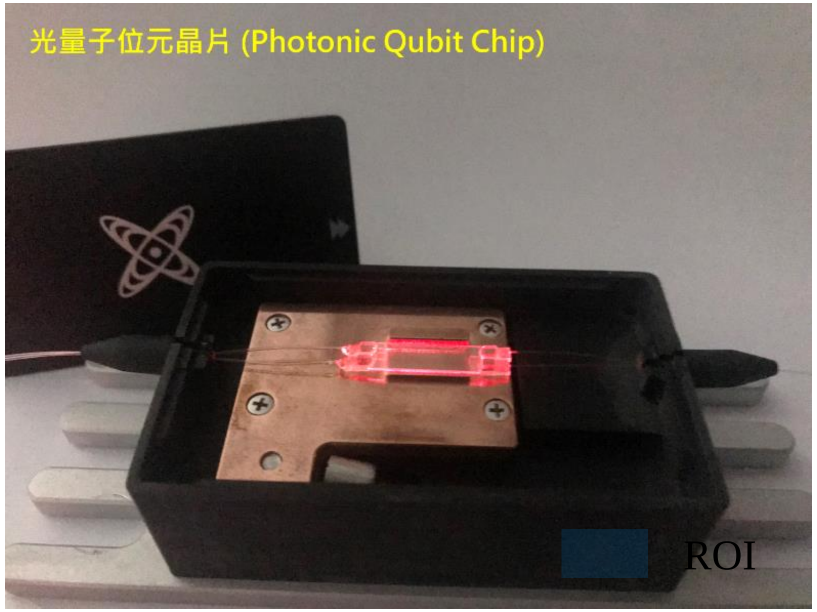
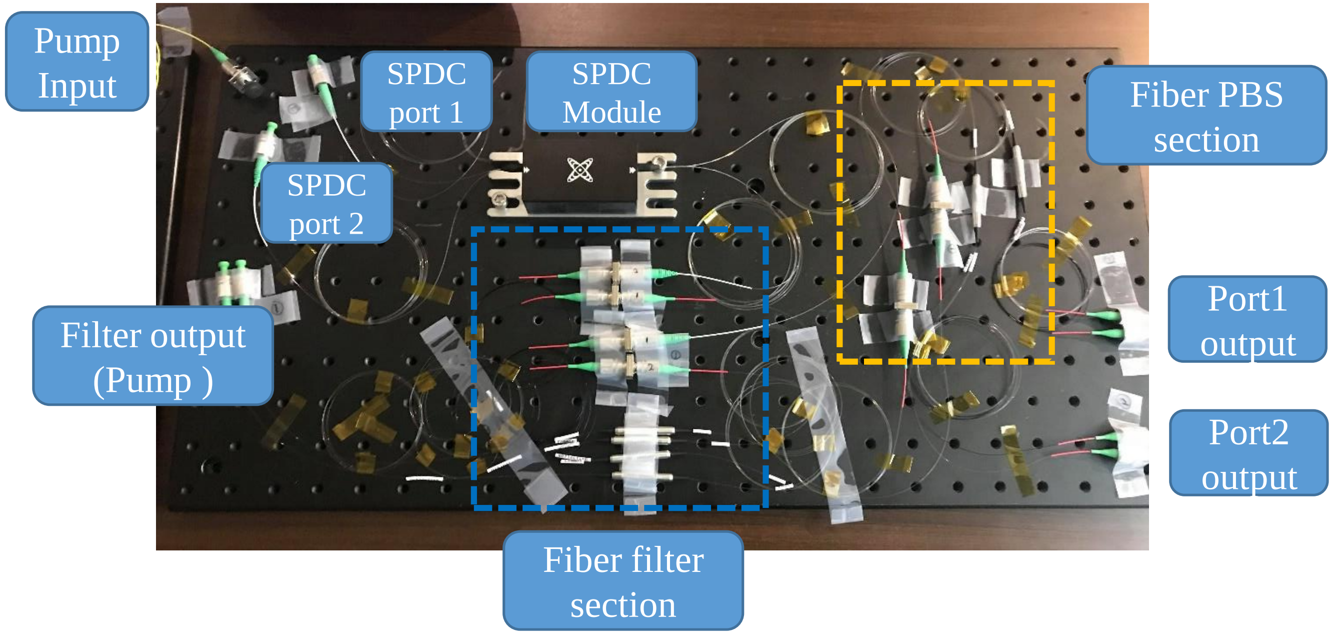
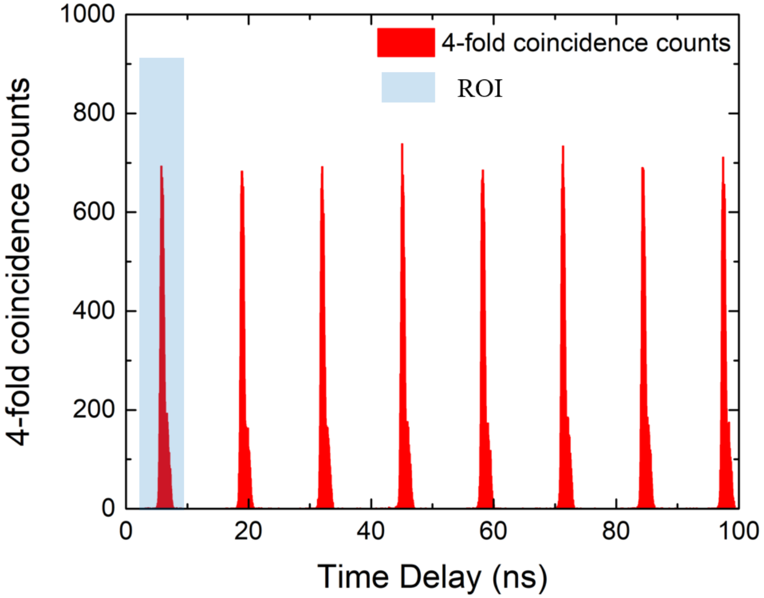
LN photonics platform

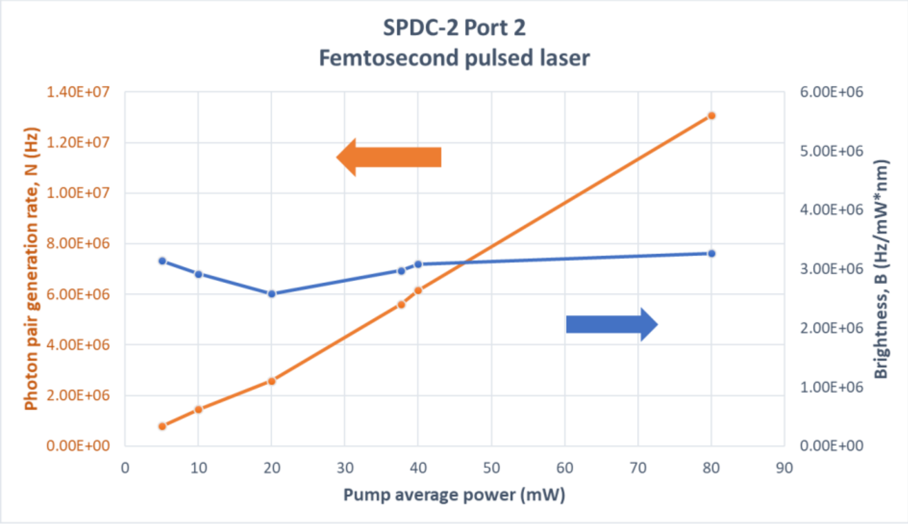


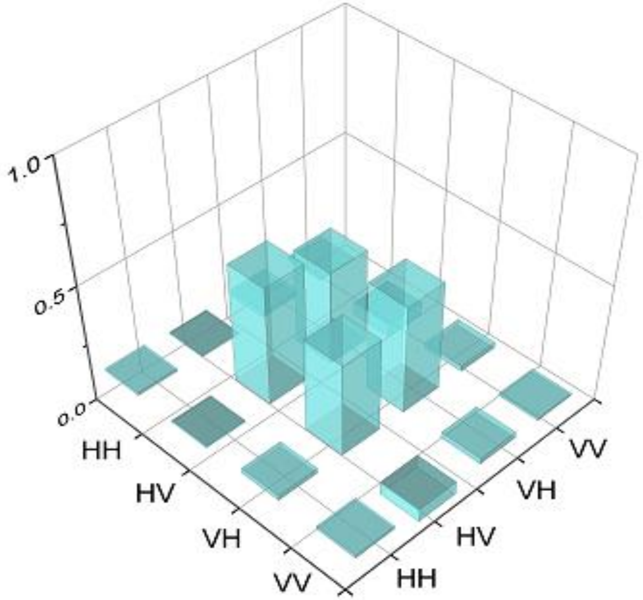
4-qubit PPLN SPDC source (四光量子位元晶片)



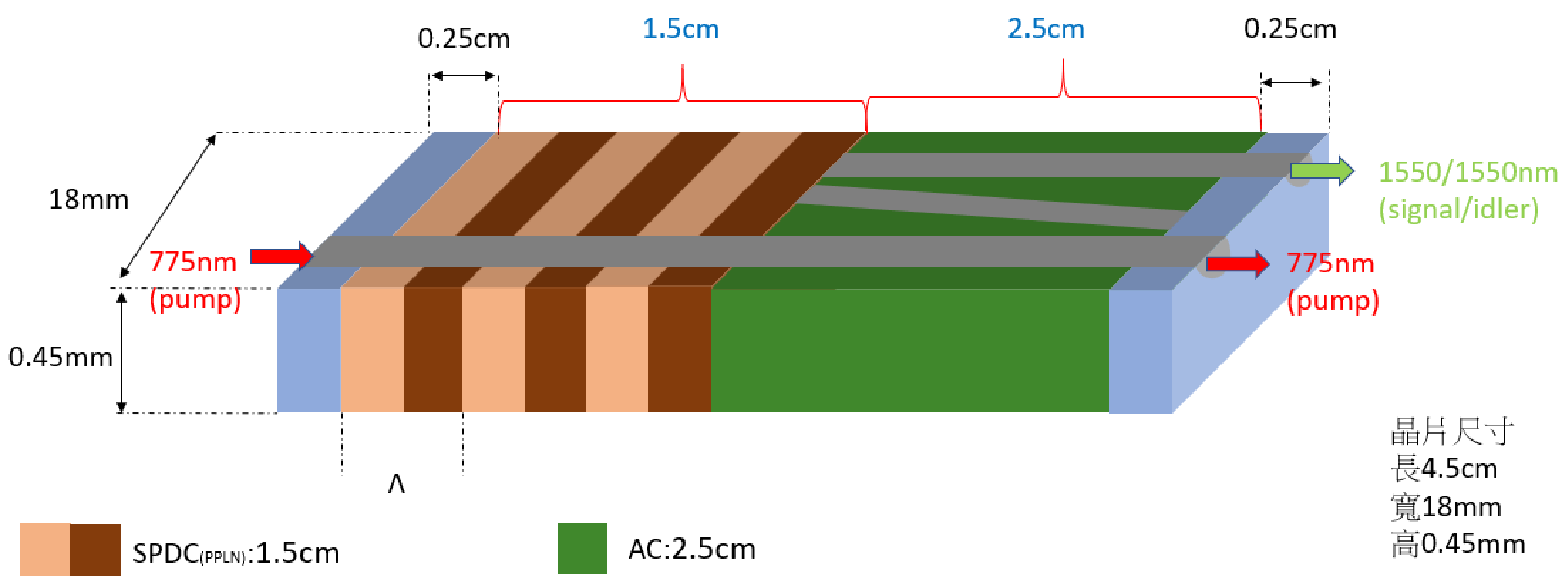




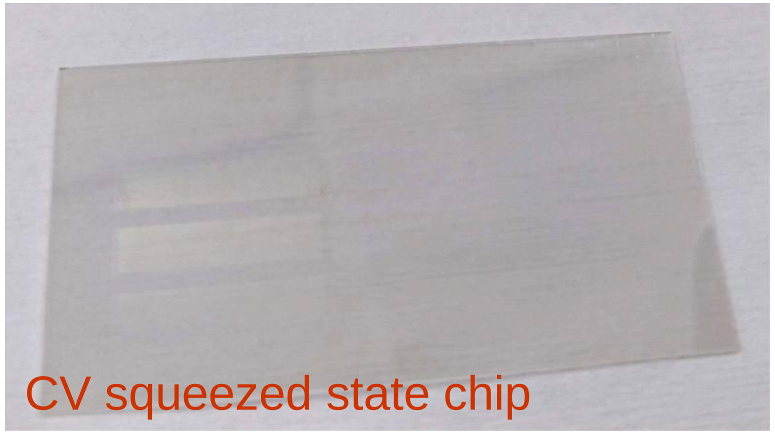




CV squeezed state source (壓縮態光量子位元積體晶片)



晶片尺寸
長4.5cm
寬18mm
高0.45mm



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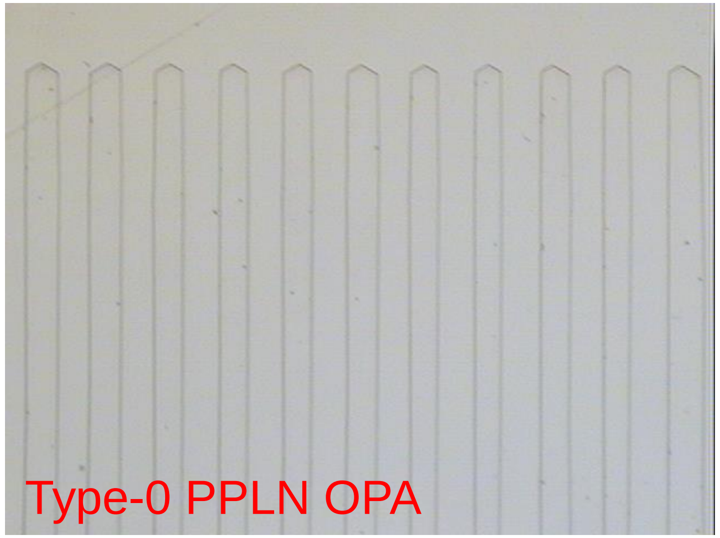

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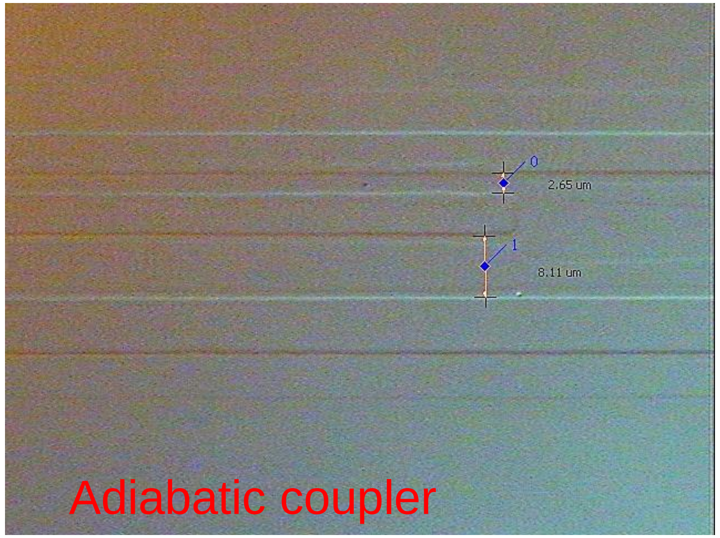
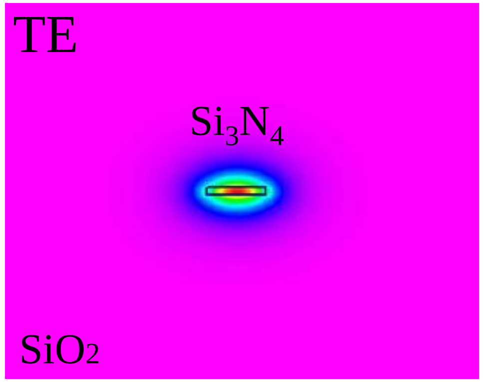


Si photonics platform

Configuration of Path-Encoded CNOT Quantum Gate

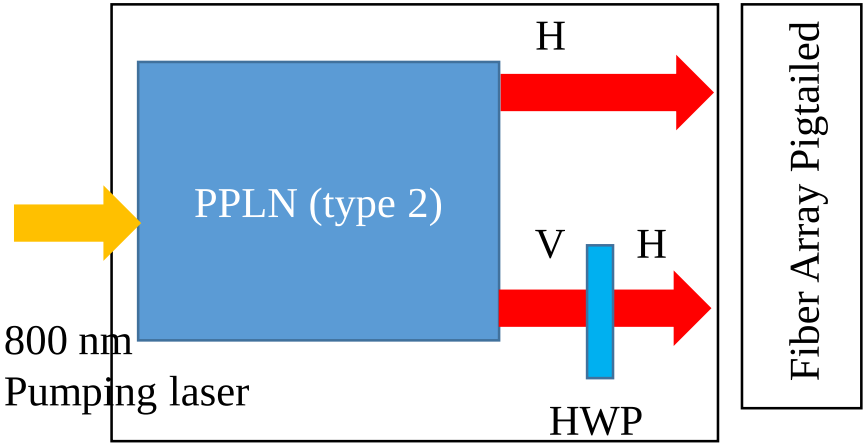
- Low-loss Si_3N_4 based integrated photonics
- Operating Wavelength: 1.6 μm
- Single polarization: TE (H)
- Multimode interferometer (MMI)
- Thermal phase tuning: Mach-Zehnder interferometer (MZI)

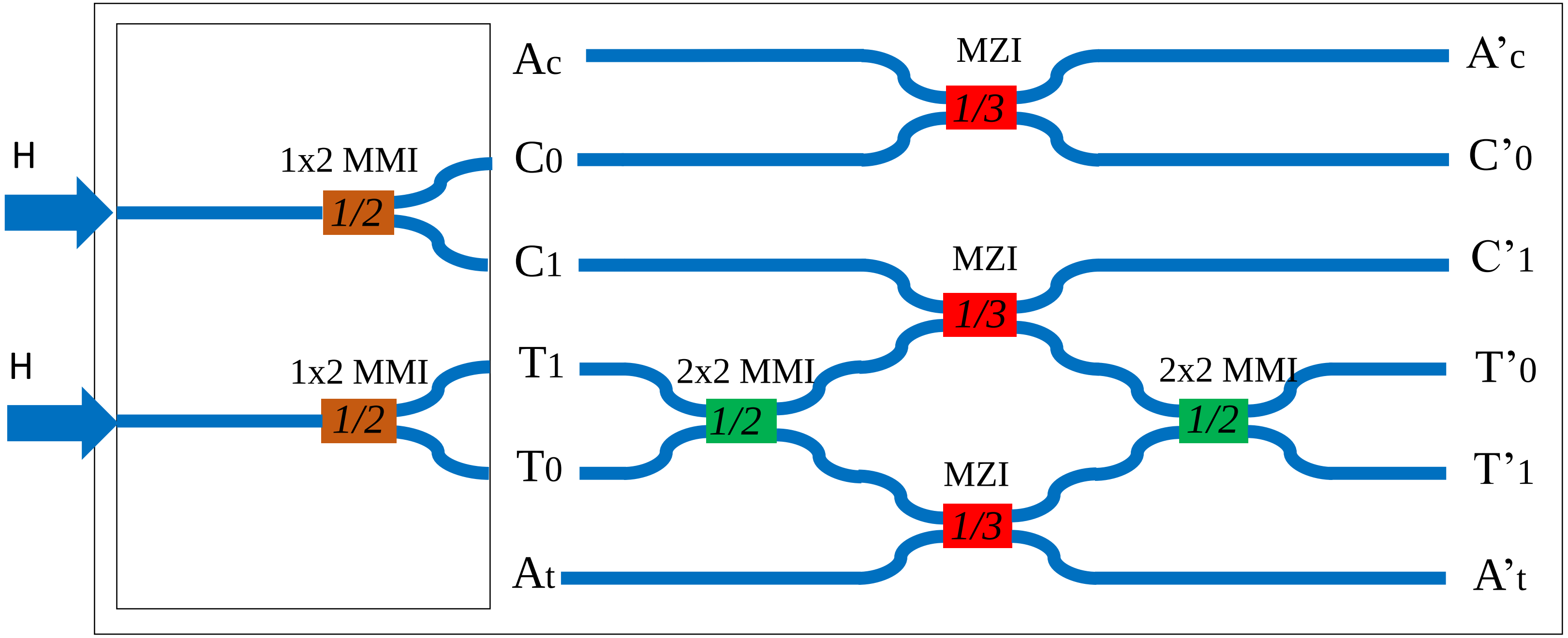
✓ *Si_3N_4 Waveguide mode profile*



Input wavelength: 1.6 μm
Width: 1.2 μm
Height: 0.22 μm
Neff: ~1.53138
Single mode

✓ *SPDC Chip @ 1.6 μm*

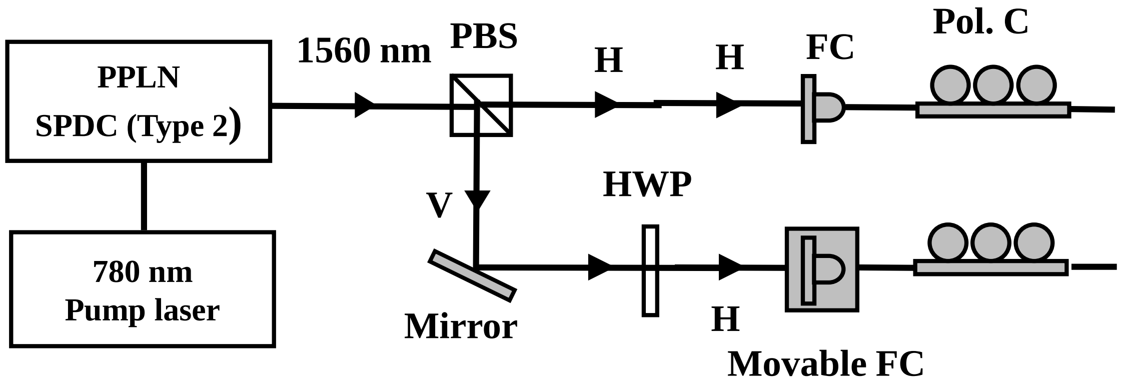


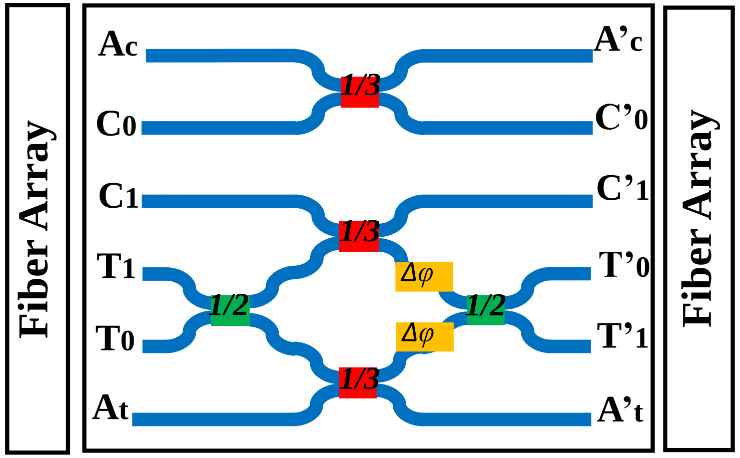


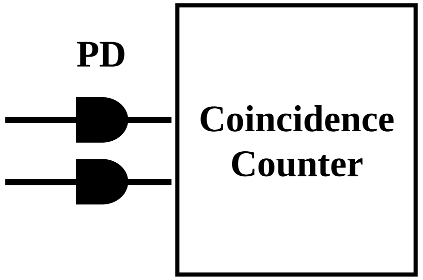
✓ *Initial state* ✓ *MMI-based-CNOT gate*

Measurement Setup & Result (Quantum)

Wavepacket width: ~ 1 mm
Coincident rate: ~ 400 c/s

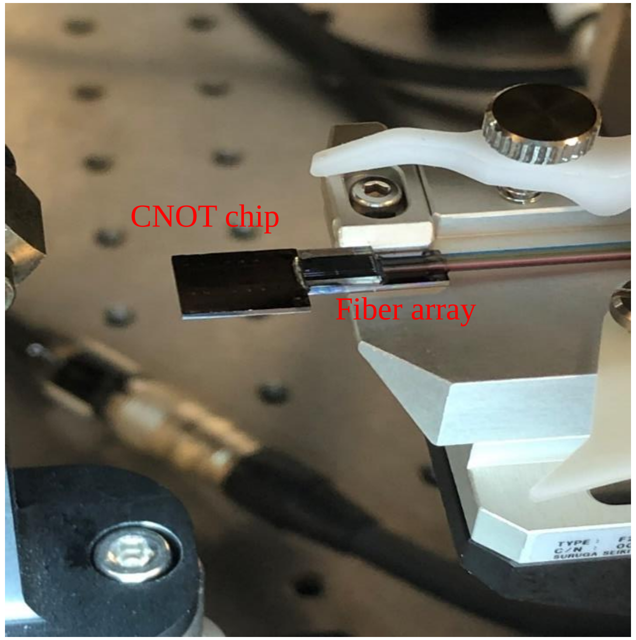


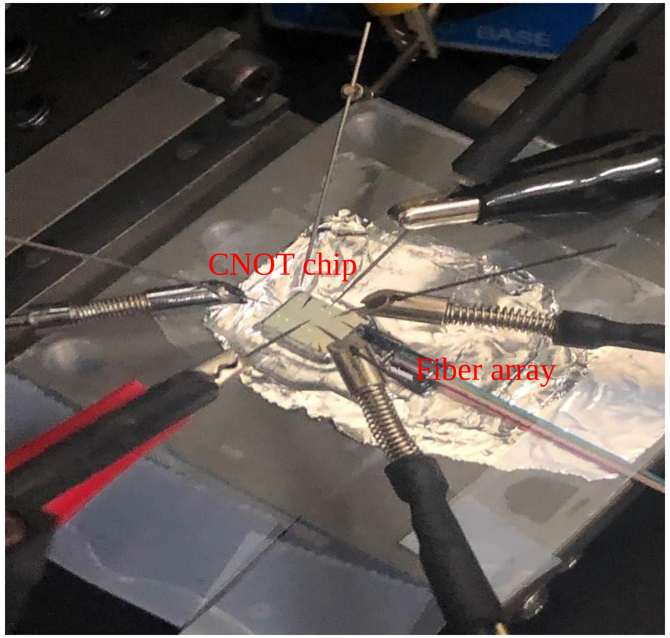


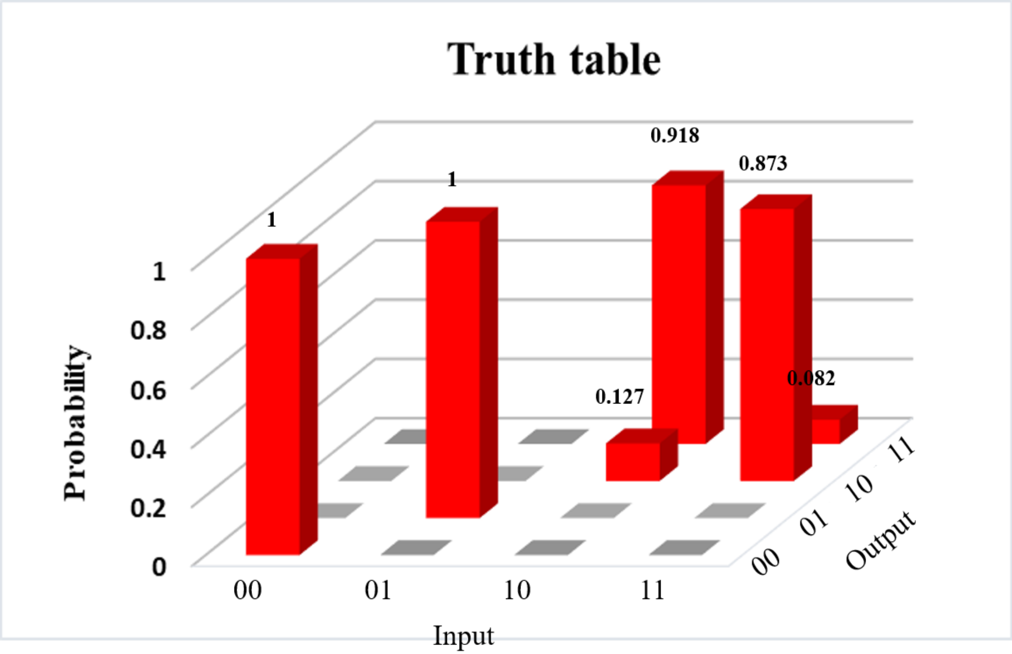


PD Model: ID230 from IDQ
Efficiency: ~ 20%
Dark count rate: ~ 50 Hz
Dead time: 10 μs

✓ ***Fiber-pigtailed CNOT chip***





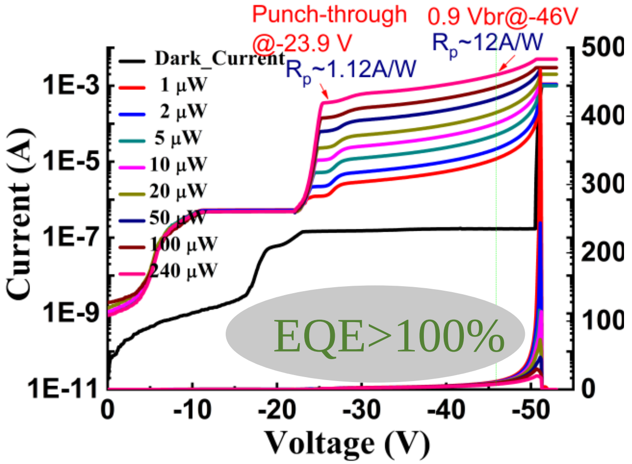


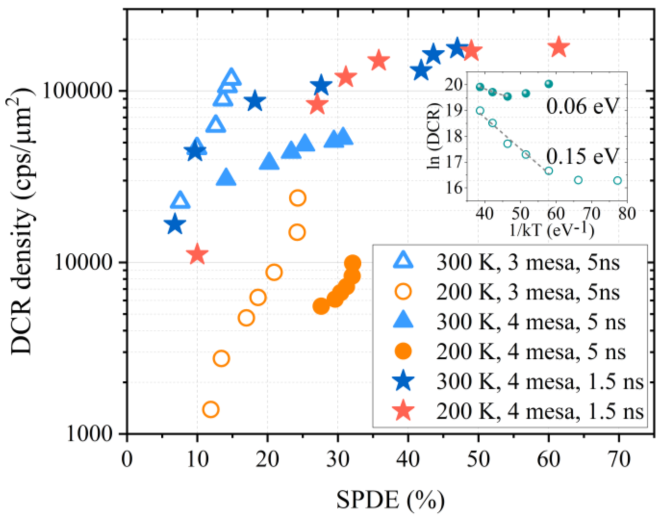
Diode photonics platform

Roon temperature SPAD

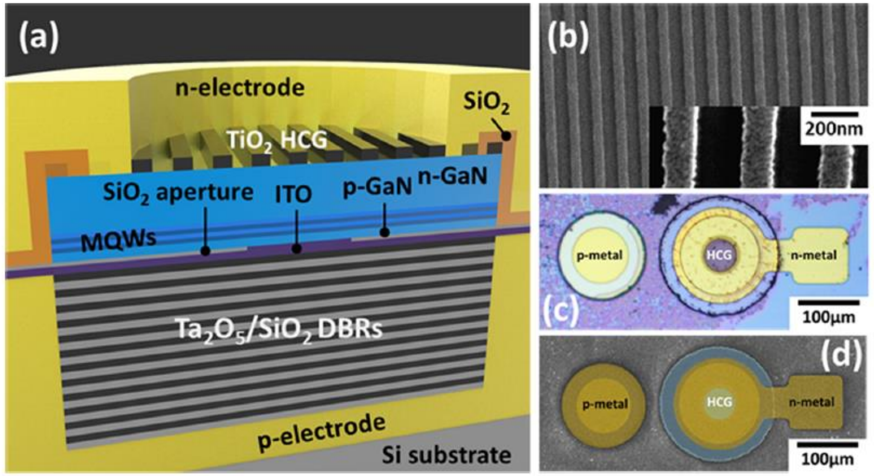
Neat Temporal Performance and High Efficiency InGaAs/InAlAs Single Photon Avalanche Diode

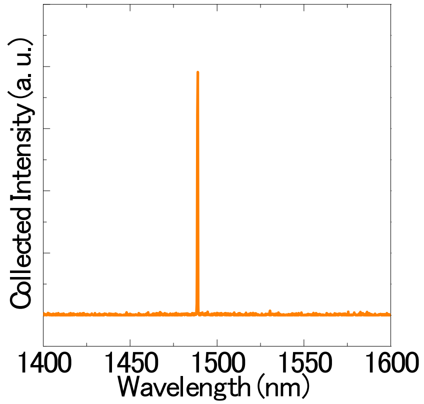
- High Responsivity: Exceeds 100 % external quantum efficiency at unity gain
- High single photon detection efficiency：61 % at 200 K, 47 % at room T
- Fast temporal performance ~ 60 ps
- Free from afterpulsing effect
- Ultra-high gain bandwidth product ~ 460 GHz

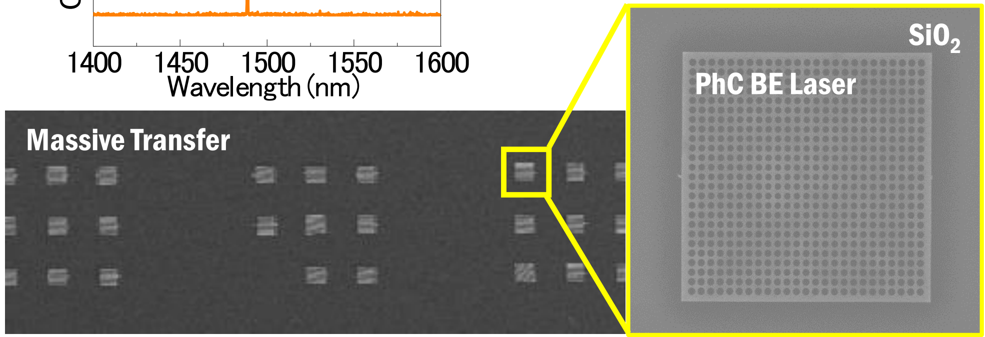




Compact coherent pumping sources

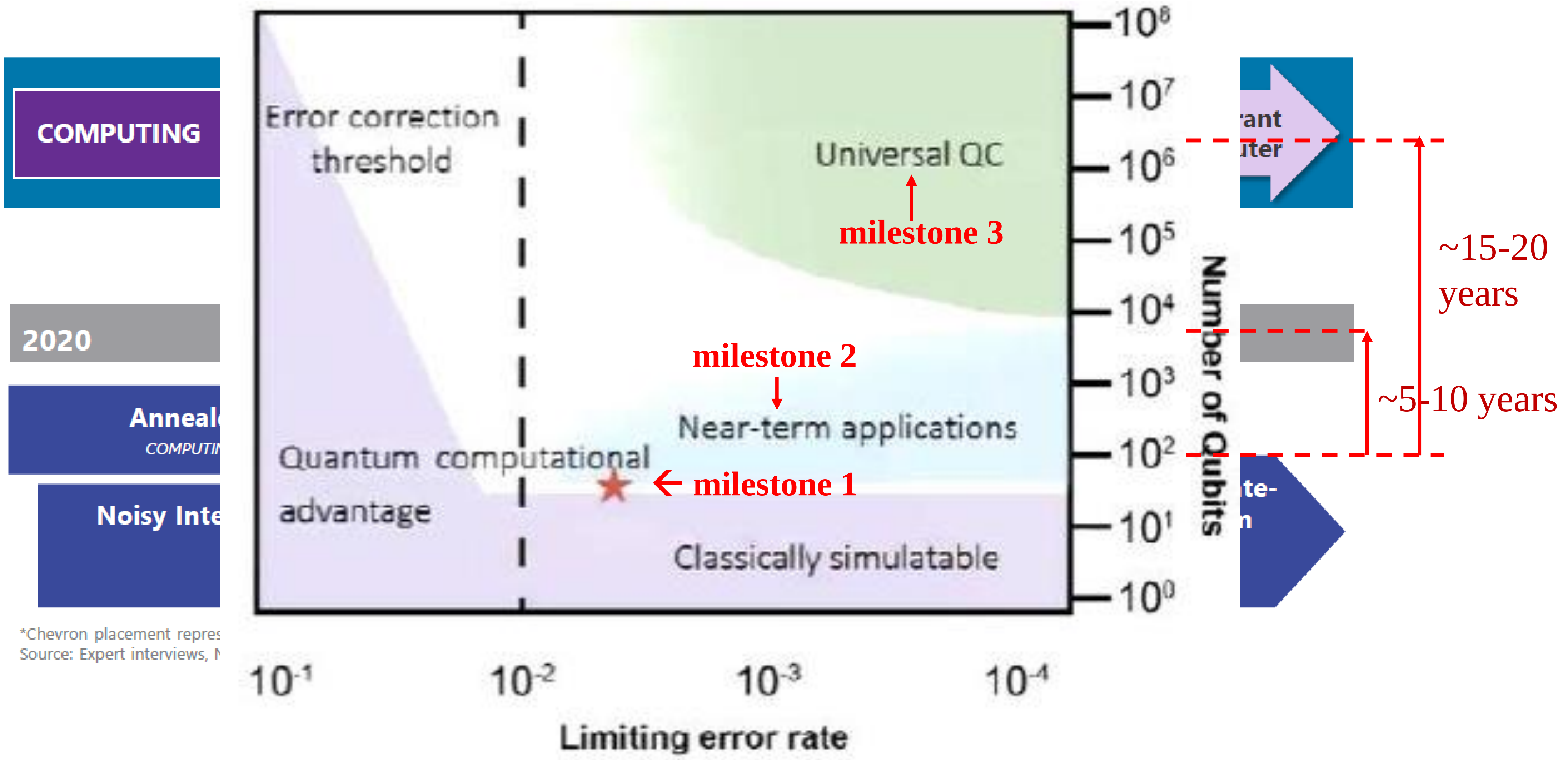






III. Outlook

Quantum Computing-- Milestones



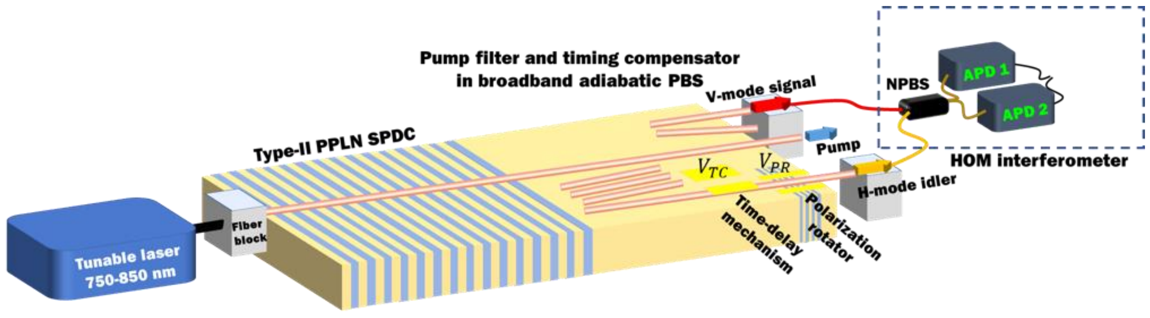
Jianwei Pan, OECC 2021

Challenges–Integrated Quantum Photonic Chips

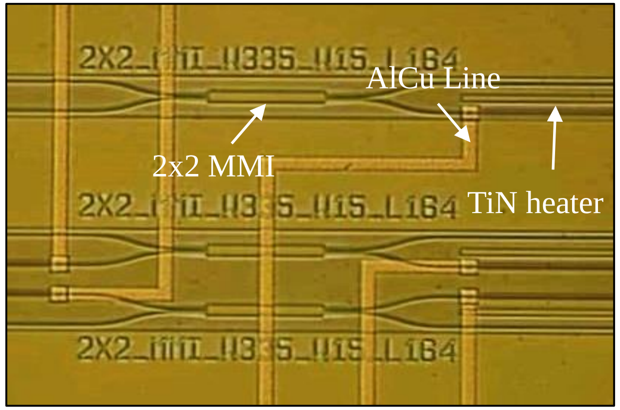
Chip-scale core components for linear optical quantum computing

Relatively simple, efficient, integrable, scalable, room-temperature operational

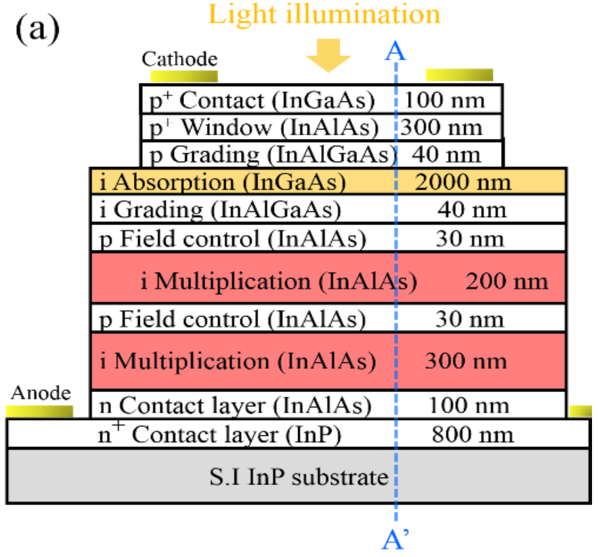
Photonic qubits source on a chip



Quantum logic gate chip



Room temperature SPAD chip



Challenges:

Photonic qubits source on a chip:

1. Low-loss robust solution for heterogeneous integration of the qubit source with the pump laser and Si-based quantum circuit chip.
2. Increase of the deterministic operation of the source.
3. Footprint miniaturization using thin-film LNOI.

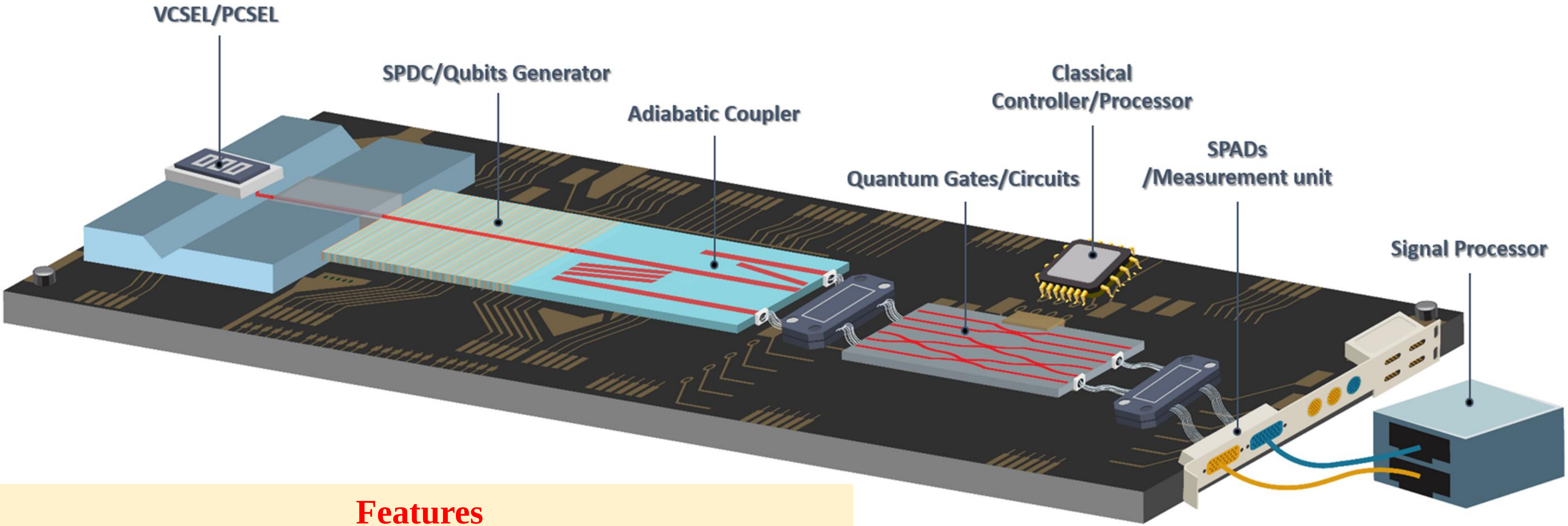
Quantum logic gate chip:

1. Low-loss waveguide circuits.
2. Maintaining high gate fidelity while scaling up.
3. Fast reconfiguration speed.
4. Reaching >99.9% fidelity or universal computing with the aid of error-correcting codes.

Room temperature SPAD chip:

1. Further increase of the quantum and detection efficiency.
2. Detection uniformity in SPAD arrays.
3. Photon number resolving.
4. Cost effective solutions.

Challenges– Hybrid Integrated Quantum Photonic Chips



Features

- **High Integrability: Pigtailing/on-chip coupling/Transfer Printing (Heterogeneous Integration)**
- **High Scalability: Multi-qubits on a monolithic Chip/Multiplexing**
- **High Fidelity: Error-Correction Code**
- **High Processing rate: Optical Control Switch**
- **CMOS and Fiber-optic compatibility: Si photonics**
- **Room temperature operability**

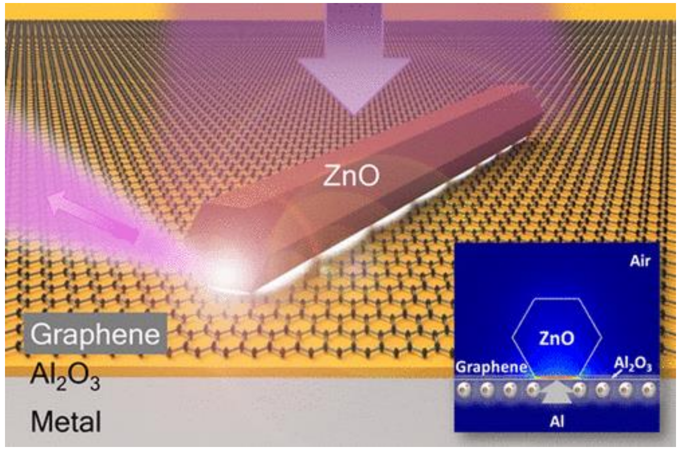
Si Photonics × LN Photonics

Integrated Photonics-- material platforms

	● Si Photonics	● LN Photonics	● LNOI
Fabrication technologies	☑ Mature, semiconductor industry	☐ Ion indiffusion, lower fidelity	☐ Etching, relatively complex
Scalability/versatility	☑ The state-of-the-art large-scale IPC	☐ Highly challenging	☐ Potentially yes
Footprint	☑ Nanometric circuits	☐ >> mm^2	☑ Nanometric circuits
Wavelength range	☐ NIR	☑ Visible-Mid-IR	☑ Visible-Mid-IR
Active modulation	☐ Thermal-optical	☑ Electro-optical	☑ Electro-optical
Nonlinearity	☐ Poor	☑ Excellent	☑ Excellent
Cost	☑ Relatively low	☐ Moderate	☐ High

New material platform!

Towards on-chip integration of **nanometric** devices



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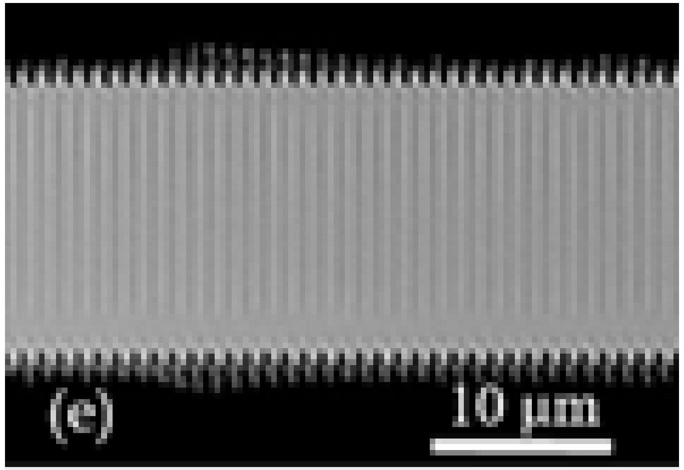
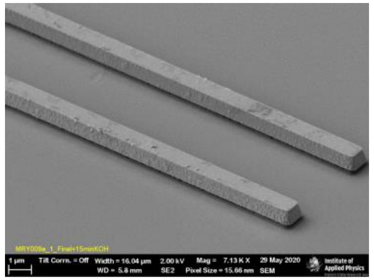
Nano lasers

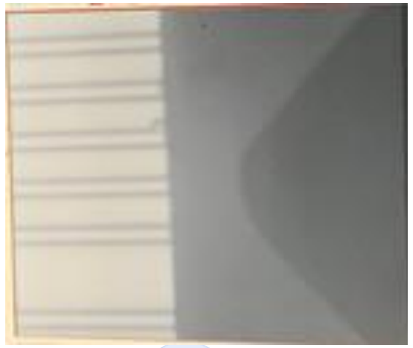


LNOI SPDC

+

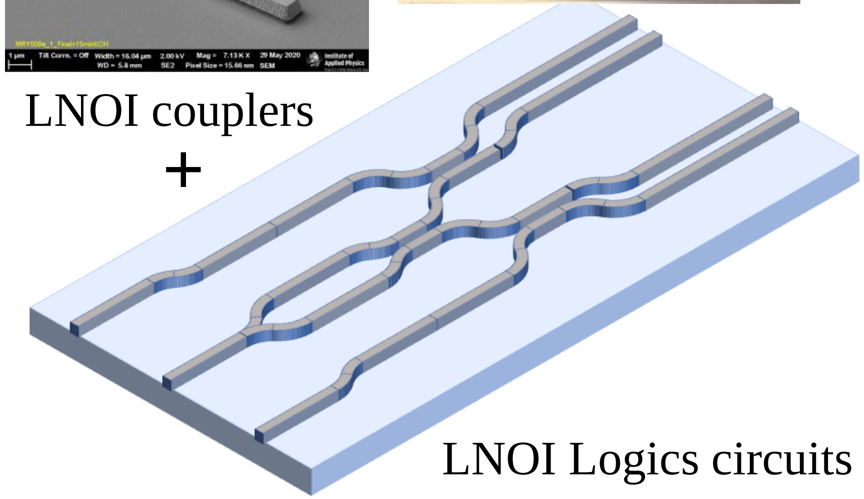
99% footprint reduction:
Opt. Express 29, 27362 (2021)





LNOI couplers

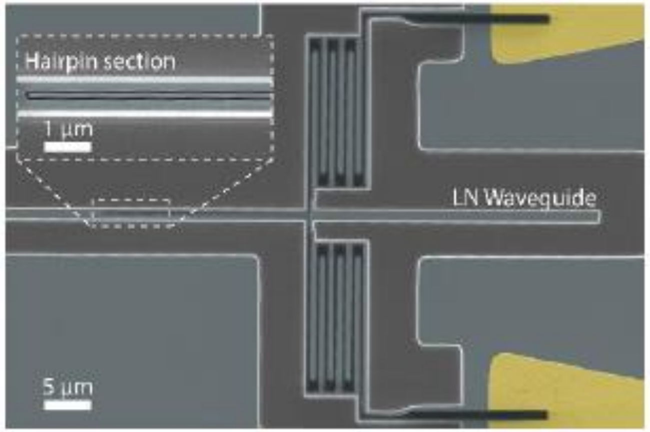
+



LNOI Logics circuits

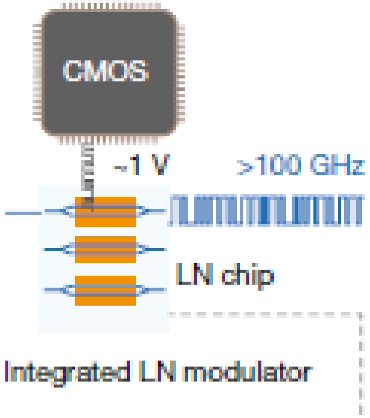
Nanometric scale LN circuits

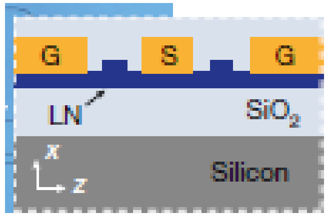
+



SM4O.4, CLEO 2020

LNOI superconducting nanowire single-photon detector





LNOI EO modulator

Nature **562**, 101–104 (2018)

Thank You for Your Attention

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