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# Integrated Photonic Chips And Its Applications

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**Center for Quantum Technologies, NUS**
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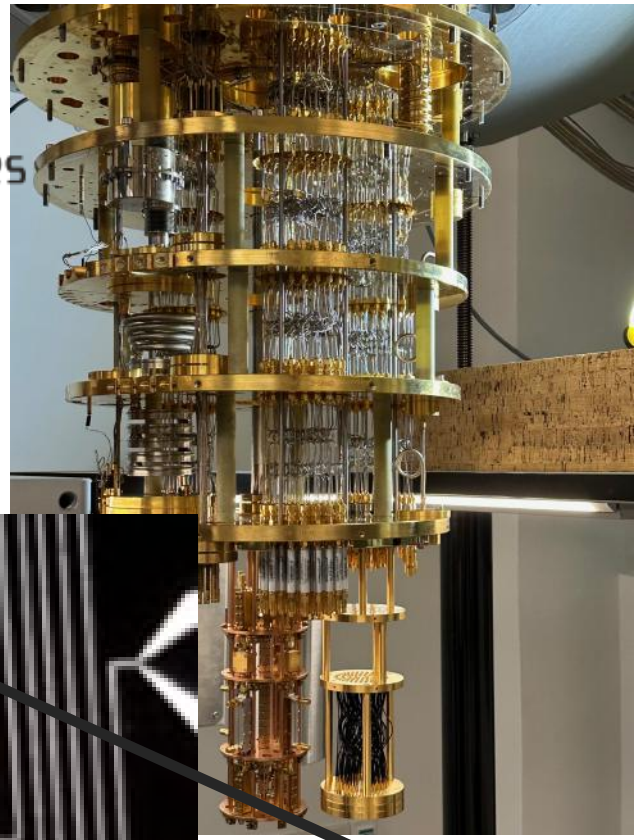
**CNRS-UNS-NUS-NTU International Joint Research Unit, UMI 3654**
**Quantum Science and Engineering Center, NTU**

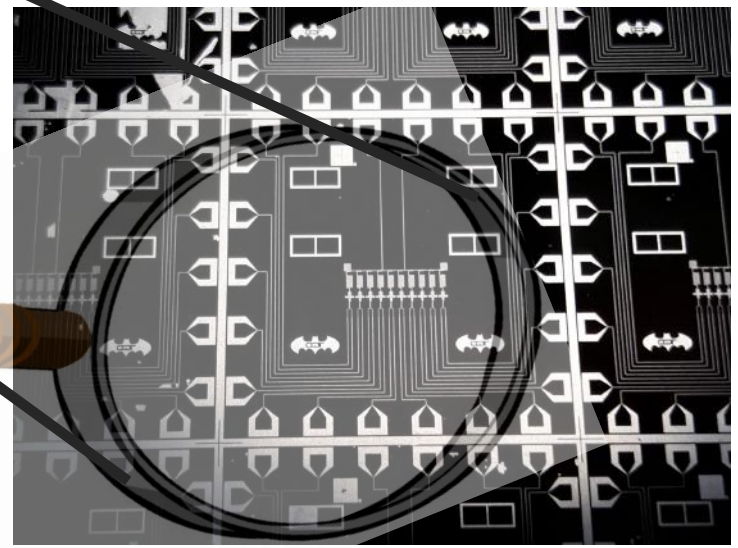
**QISKIT Fall Fest, Malaysia**
**Nov 7, 2025**

Centre for Quantum Technologies

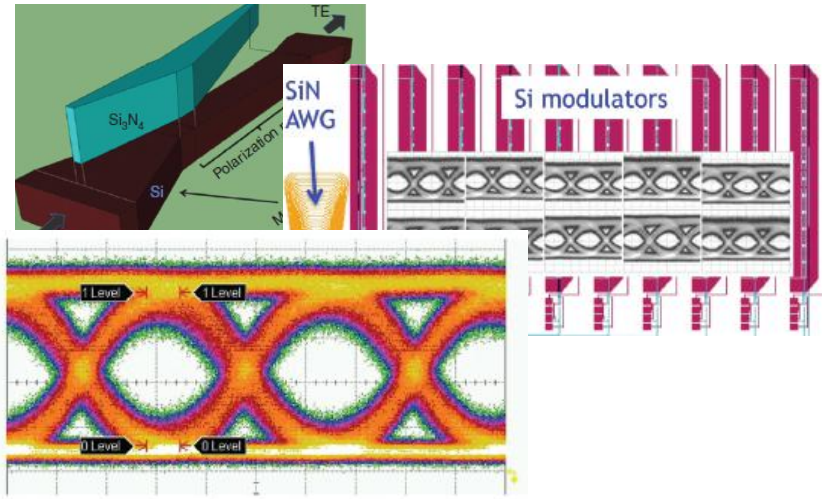


INTERNATIONAL YEAR

# Quantum Science and Technology



# Brief History




High-bandwidth silicon modulators, hybrid lasers, polarization rotators/combiners/splitters, wavelength division multiplexing (WDM) transmitters, WDM receivers, dual-polarization coherent transmitters and receivers; Interconnects

nature photonics

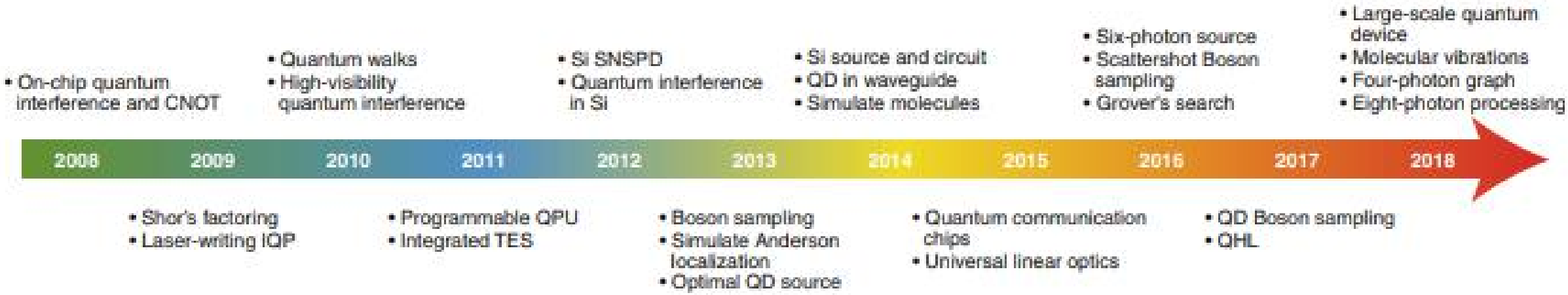
FOCUS | REVIEW ARTICLE

https://doi.org/10.1038/s41566-019-0532-1

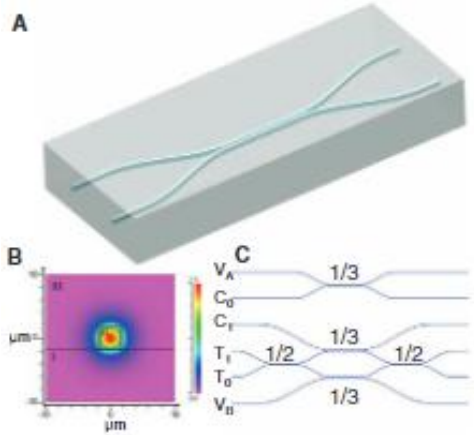
# Integrated photonic quantum technologies

Jianwei Wang[1], Fabio Sciarrino[2], Anthony Laing[3] and Mark G. Thompson[3*]

**Quantum technologies comprise an emerging class of devices capable of controlling superposition and entanglement of quantum states of light or matter, to realize fundamental performance advantages over ordinary classical machines. The technology of integrated quantum photonics has enabled the generation, processing and detection of quantum states of light at a steadily increasing scale and level of complexity, progressing from few-component circuitry occupying centimetre-scale footprints and operating on two photons, to programmable devices approaching 1,000 components occupying millimetre-scale footprints with integrated generation of multiphoton states. This Review summarizes the advances in integrated photonic quantum technologies and its demonstrated applications, including quantum communications, simulations of quantum chemical and physical systems, sampling algorithms, and linear-optic quantum information processing.**




*Source: Nature Photonics*, *14*(5), 273-284 (2020).




## Silica-on-Silicon Waveguide Quantum Circuits

Alberto Politi, Martin J. Cryan, John G. Rarity, Siyuan Yu, Jeremy L. O'Brien*

Quantum technologies based on photons will likely require an integrated optics architecture for improved performance, miniaturization, and scalability. We demonstrate high-fidelity silica-on-silicon integrated optical realizations of key quantum photonic circuits, including two-photon quantum interference with a visibility of 94.8 ± 0.5%; a controlled-NOT gate with an average logical basis fidelity of 94.3 ± 0.2%; and a path-entangled state of two photons with fidelity of >92%. These results show that it is possible to directly "write" sophisticated

sists of nested classical and quantum interferometers (e.g., Fig. 1C). In a standard optical implementation, the photons propagate in air, and the circuit is constructed from mirrors and beam splitters (BSs), or half-reflective mirrors, which split and recombine optical modes, giving rise to both classical and quantum interference. High-visibility quantum interference (*24*) demands excellent optical mode overlap at a BS, which requires exact alignment of the modes, whereas high visibility classical interference also requires subwavelength stability of optical path lengths, which often necessitates the design and imple-

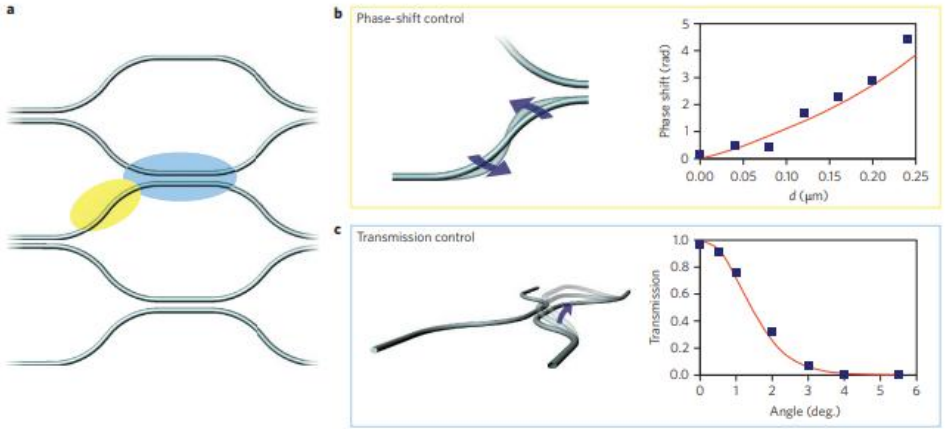
Politi, A., Cryan, M. J., Rarity, J. G., Yu, S., & O'brien, J. L. (2008). Silica-on-silicon waveguide quantum circuits. *Science*, *320*(5876), 646-649

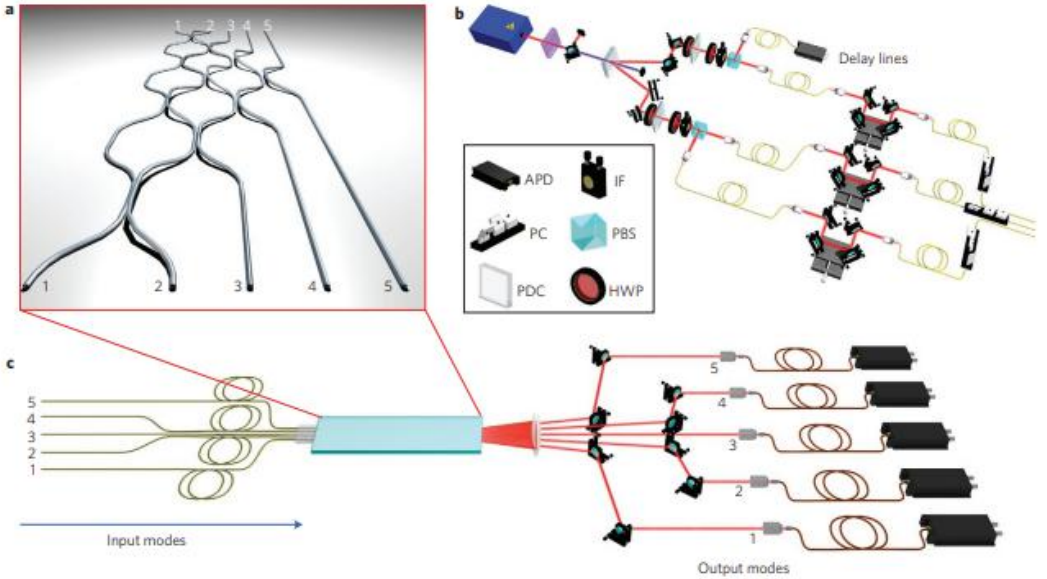
- On-chip quantum interference and CNOT
- Quantum walks
- High-visibility quantum interference
- Si SNSPD
- Quantum interference in Si
- Si source and circuit
- QD in waveguide
- Simulate molecules
- Six-photon source
- Scattershot Boson sampling
- Grover's search
- Large-scale quantum device
- Molecular vibrations
- Four-photon graph
- Eight-photon processing

2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

- Shor's factoring
- Laser-writing IQP
- Programmable QPU
- Integrated TES
- Boson sampling
- Simulate Anderson localization
- Optimal QD source
- Quantum communication chips
- Universal linear optics
- QD Boson sampling
- QHL

*Nature Photonics*, *14*(5), 273-284 (2020).




• On-chip quantum interference and CNOT

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• High-visibility quantum interference

• Si SNSPD
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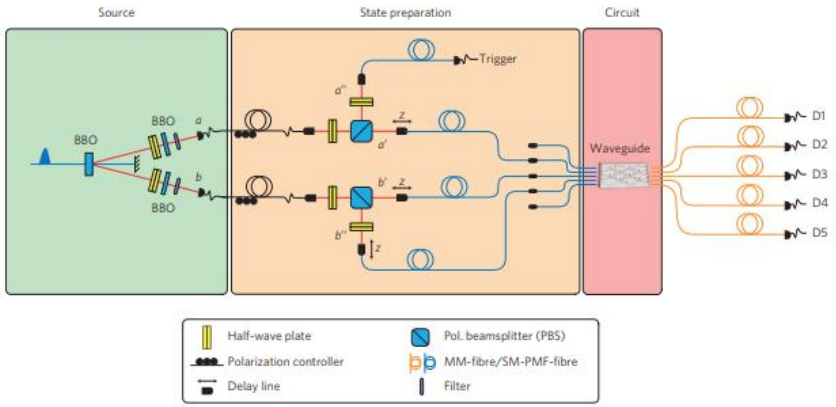
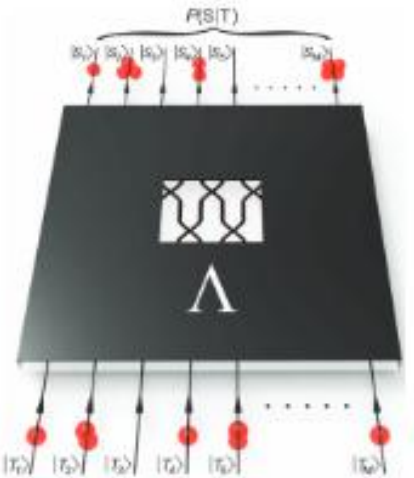
• QD Boson sampling
• QHL




Crespi, A., Osellame, R., Ramponi, R., Brod, D. J., Galvao, E. F., Spagnolo, N., ... & Sciarrino, F. (2013). Integrated multimode interferometers with arbitrary designs for photonic boson sampling. *Nature photonics*, *7*(7), 545-549.

Tillmann, M., Dakić, B., Heilmann, R., Nolte, S., Szameit, A., & Walther, P. (2013). Experimental boson sampling. *Nature photonics*, *7*(7), 540-544.

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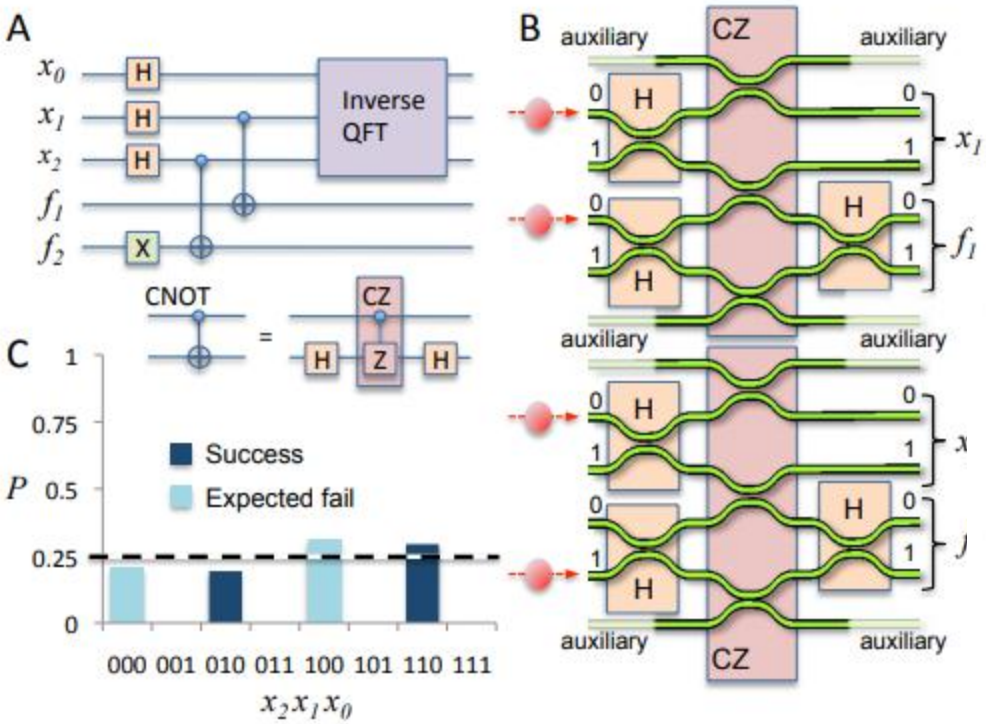
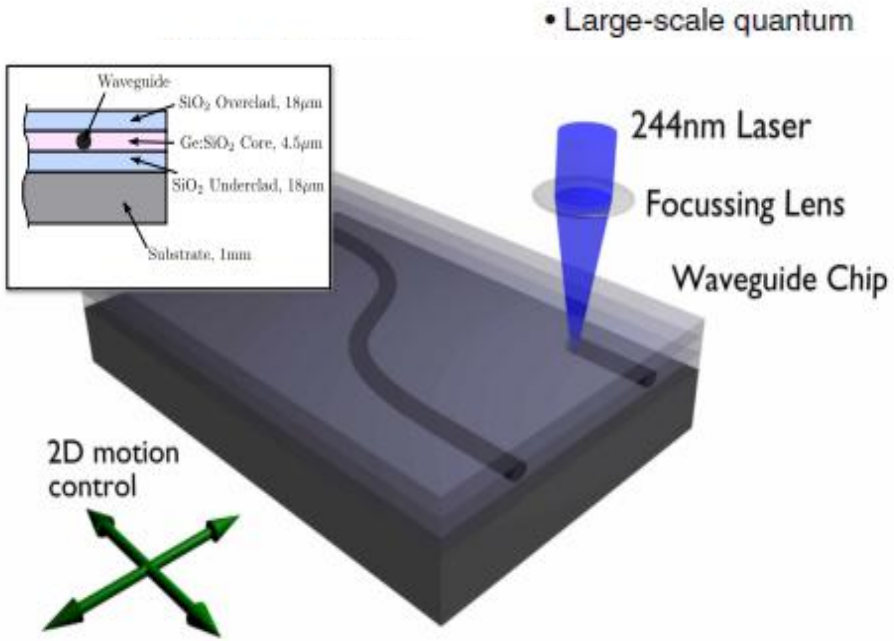



Politi, A., Matthews, J. C., & O'brien, J. L. (2009). Shor's quantum factoring algorithm on a photonic chip. *Science*, *325*(5945), 1221-1221.

• Large-scale quantum

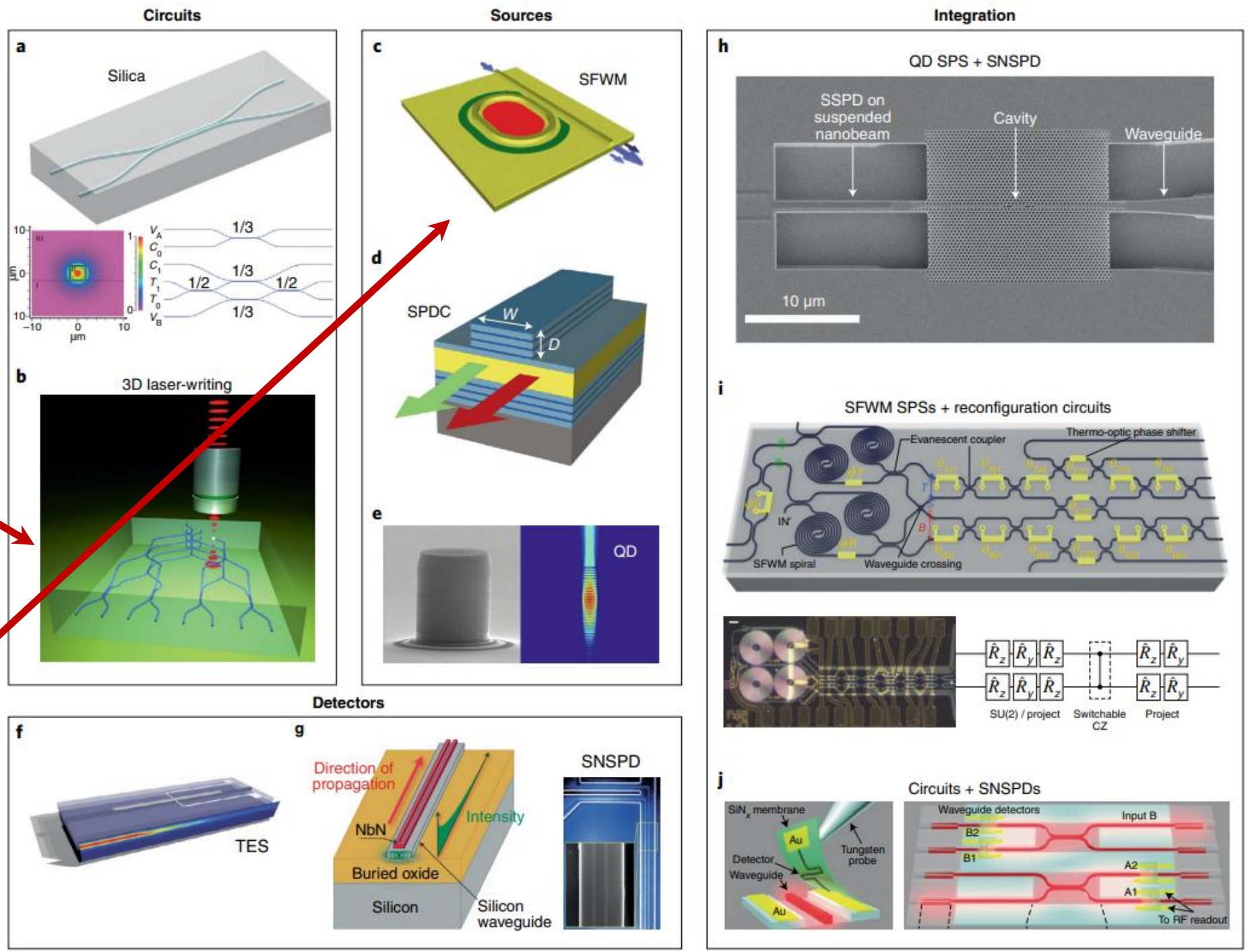



Smith, B. J., Kundys, D., Thomas-Peter, N., Smith, P. G. R., & Walmsley, I. A. (2009). Phase-controlled integrated photonic quantum circuits. *Optics Express*, *17*(16), 13516-13525.

# Integrated Photonic Chips

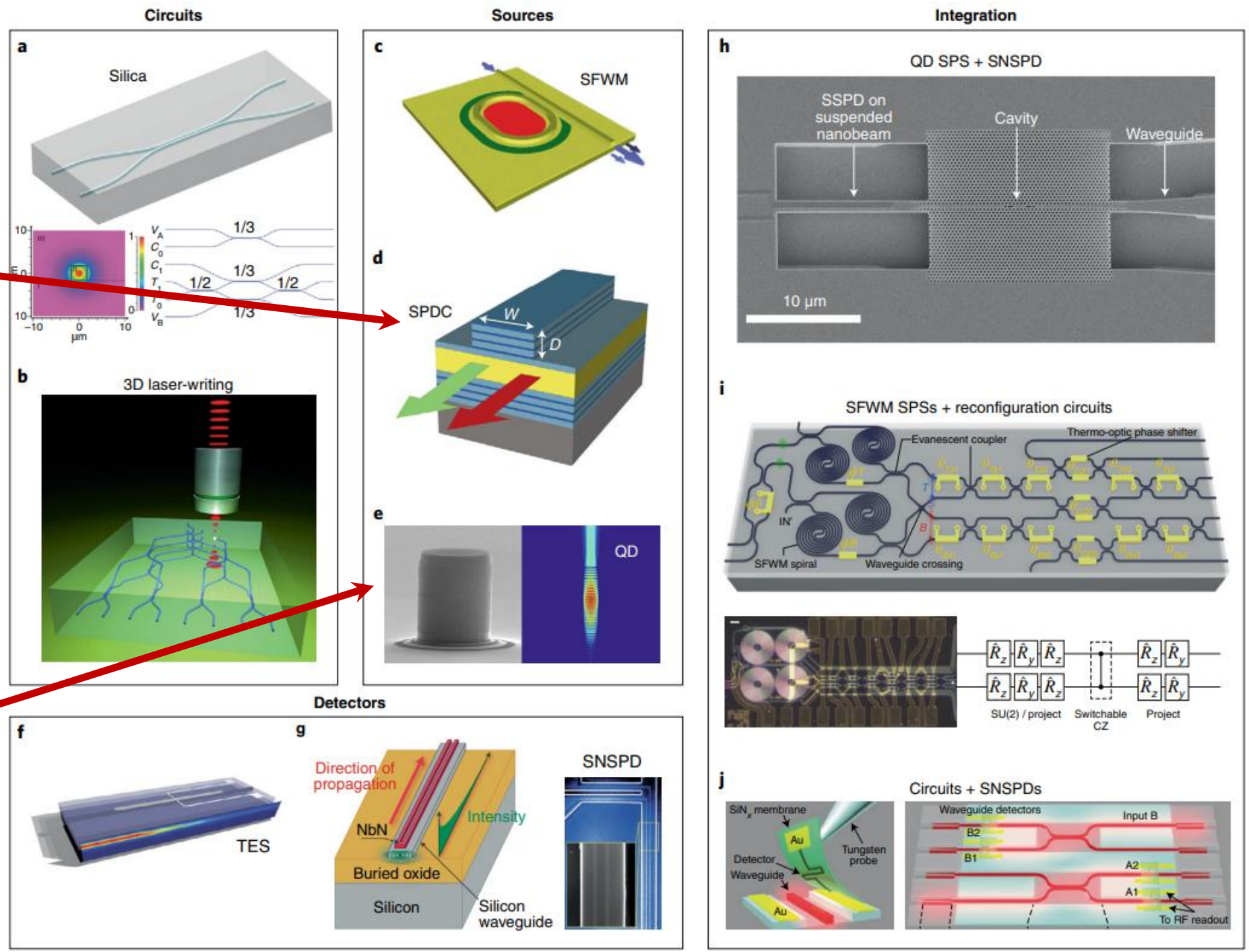
Laser-writing quantum circuit in silica that allows complex three-dimensional integration

An integrated SFWM SPS in Si photonic waveguides or microresonators that allows the generation of pure and identical photons.

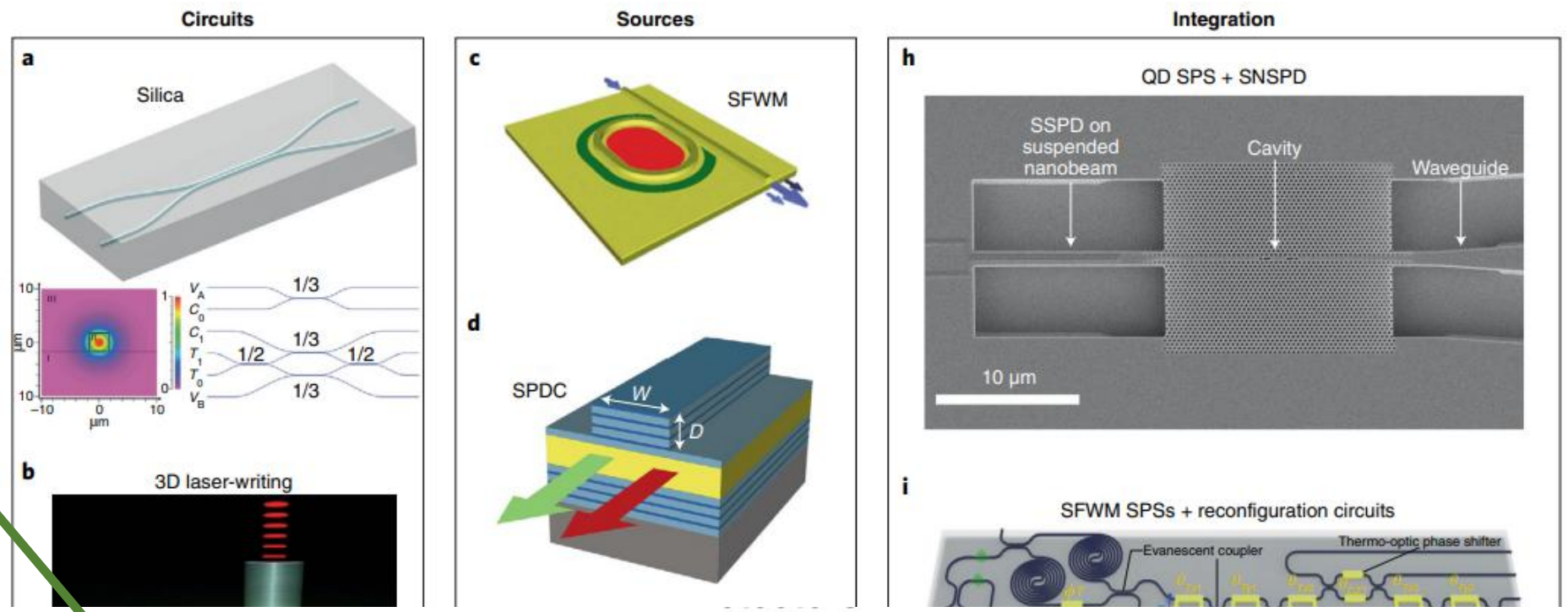


An integrated SPDC SPS in GaAs waveguides that sustains two different types of eigenmodes meeting the phase matching condition. W and D are the width and height of the waveguide, respectively

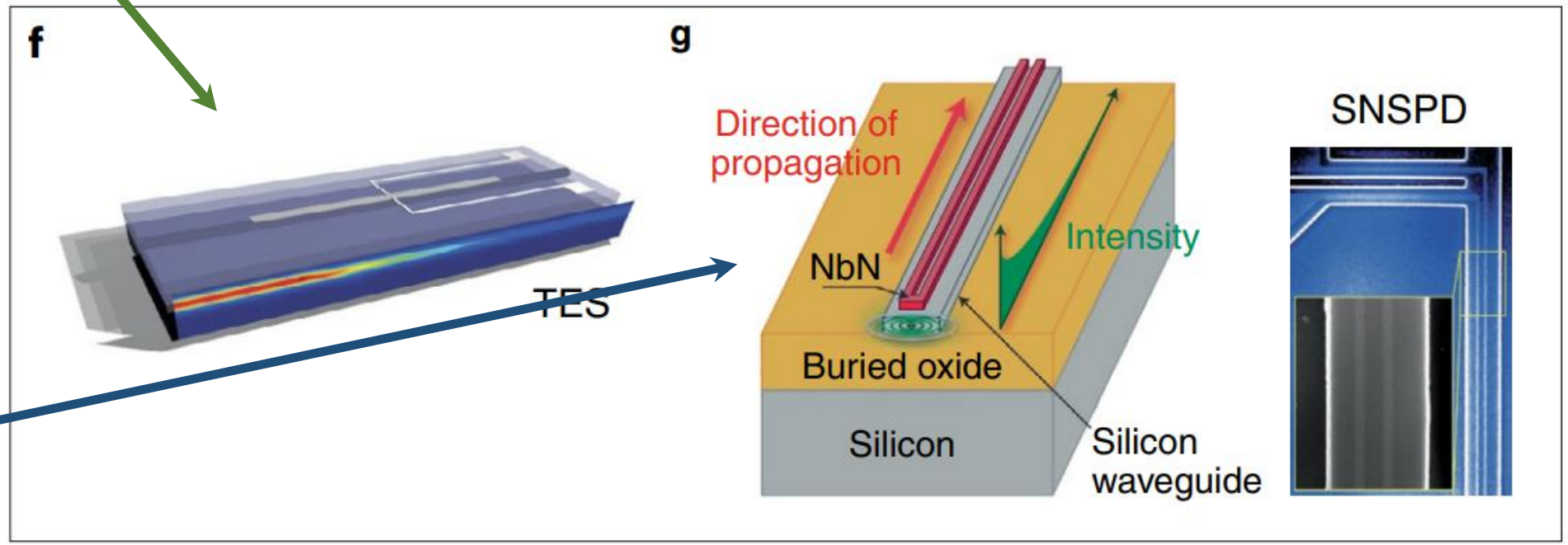
A semiconductor InGaAs/GaAs QD SPS that can efficiently emit pure single photons from a single dot embedded in a micropillar.

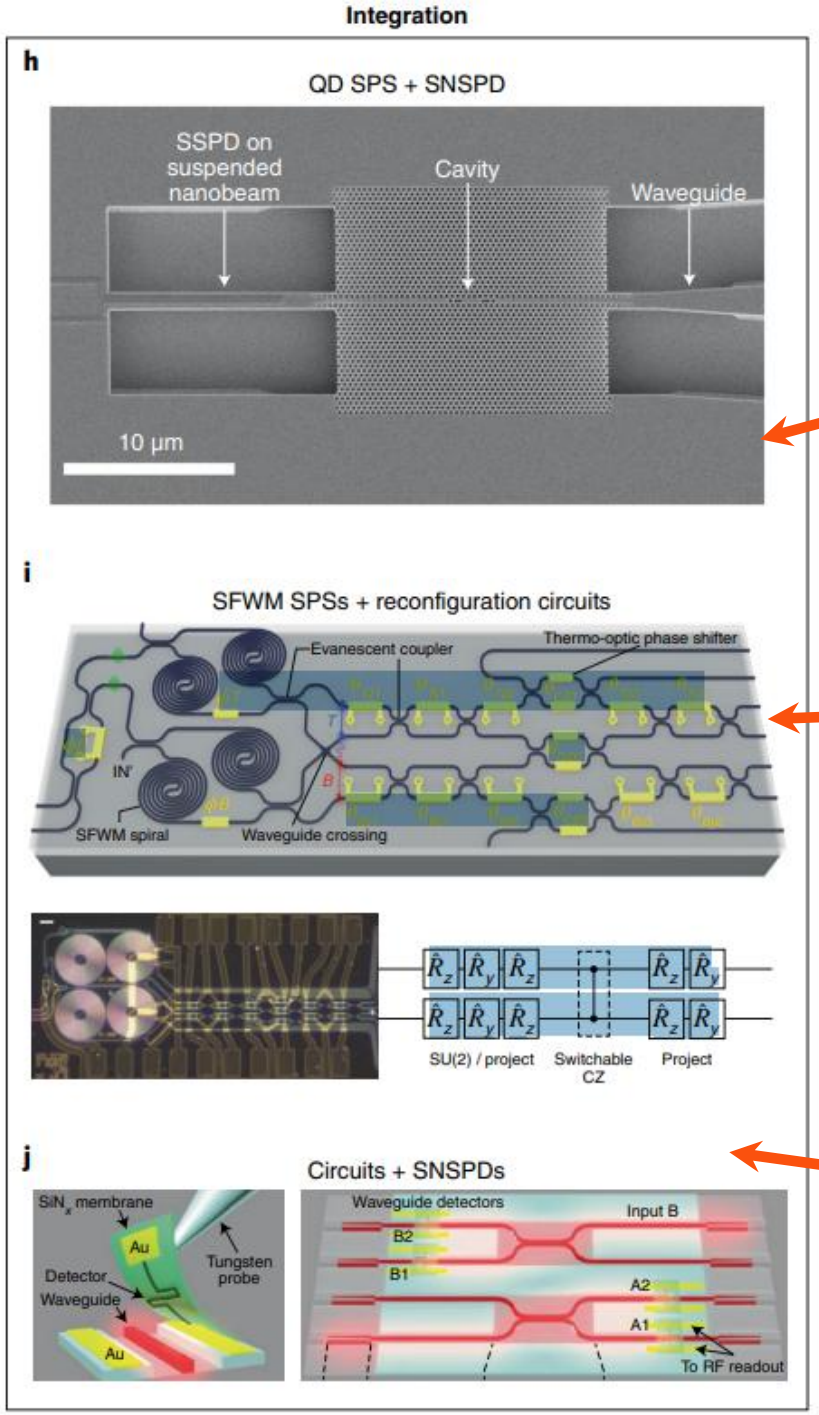


An integrated TES PNR detector that is evanescently coupled to silica waveguides




An integrated SNSPD atop of a Si waveguide that can absorb and detect photons with >90% efficiency



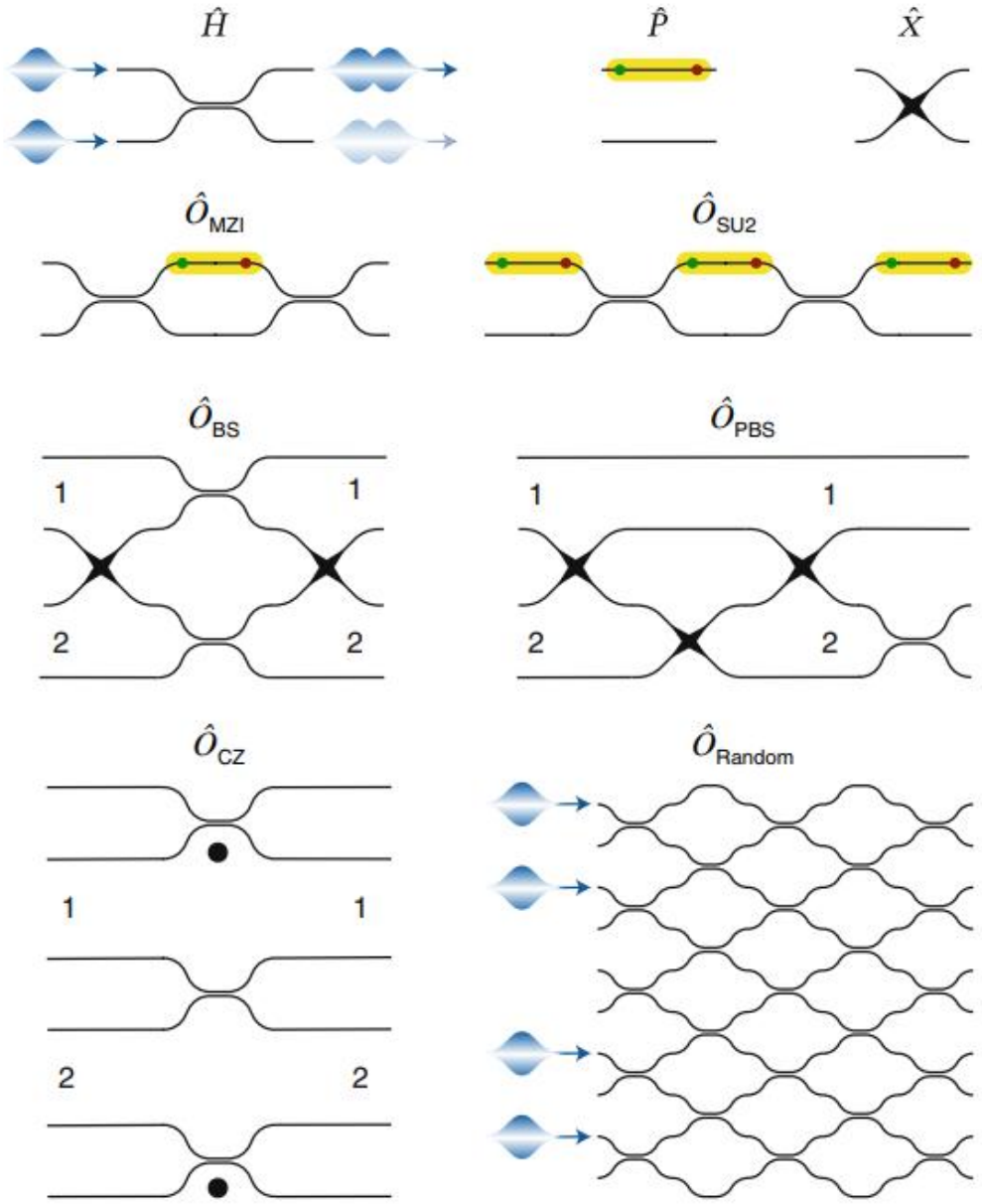



An integration of a QD source with two SNSPDs in the GaAs photonic-crystal waveguide system that enables the on-chip detection of QD luminescence

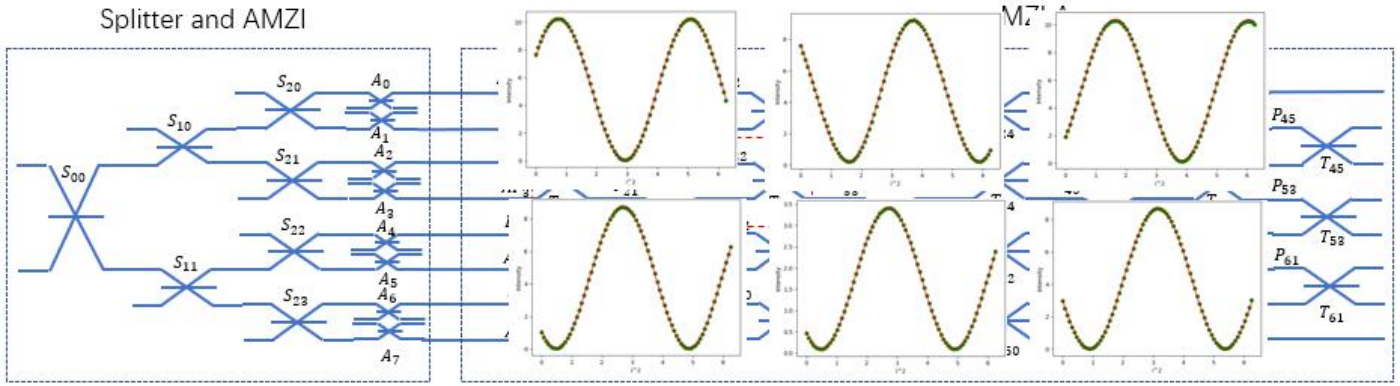
An integration of four SFWM SPSs with re-programmable quantum photonic circuits in Si that allows the on-chip preparation, manipulation and measurement of photonic qubits $T$ and $B$. $R_i$ $(i = 1,2,3)$ are rotation operators implemented by the phase shifters (θ, φ).

An integration of Si photonic circuits with SNSPD

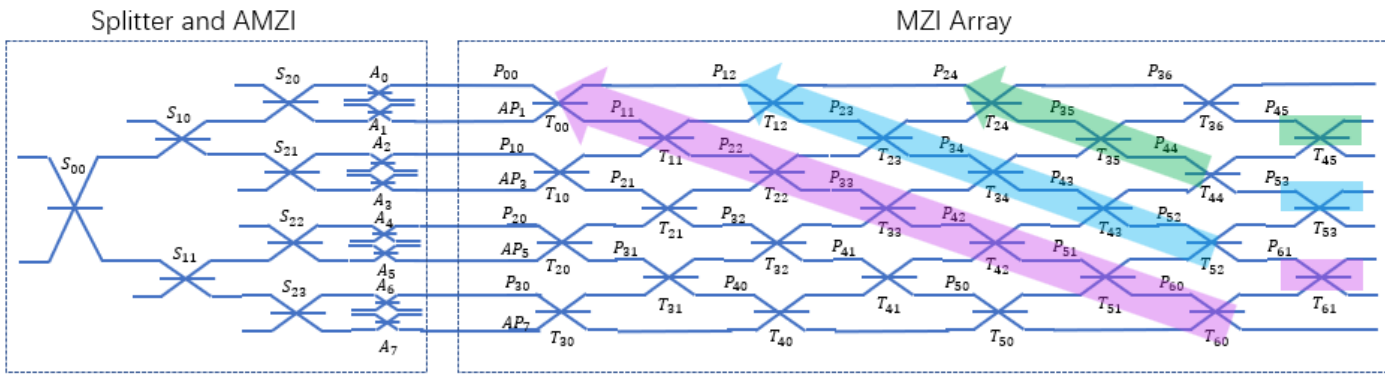
# Gates and Calibration



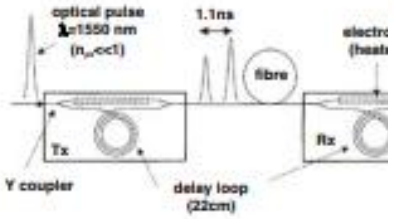

## Chip Characterization - Phase Programming




## Chip Characterization - Amplitude Programming



# Quantum Key Distribution

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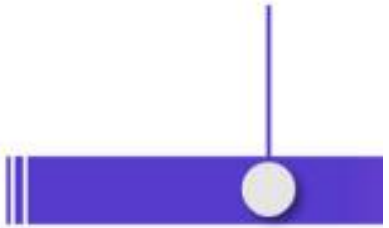

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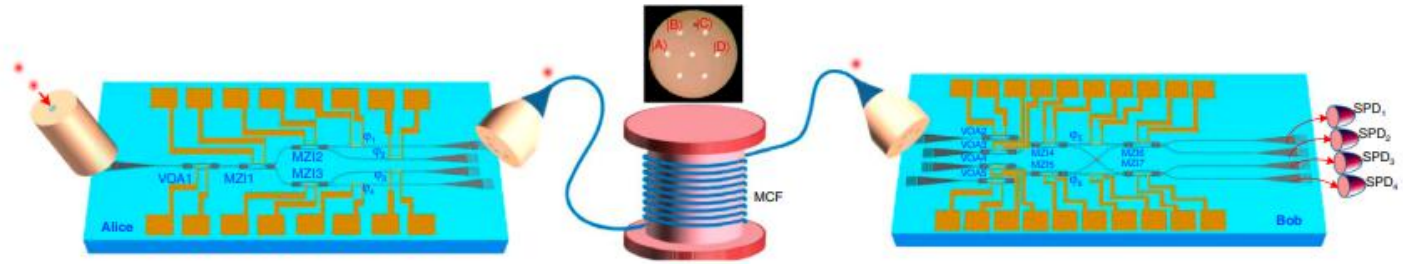


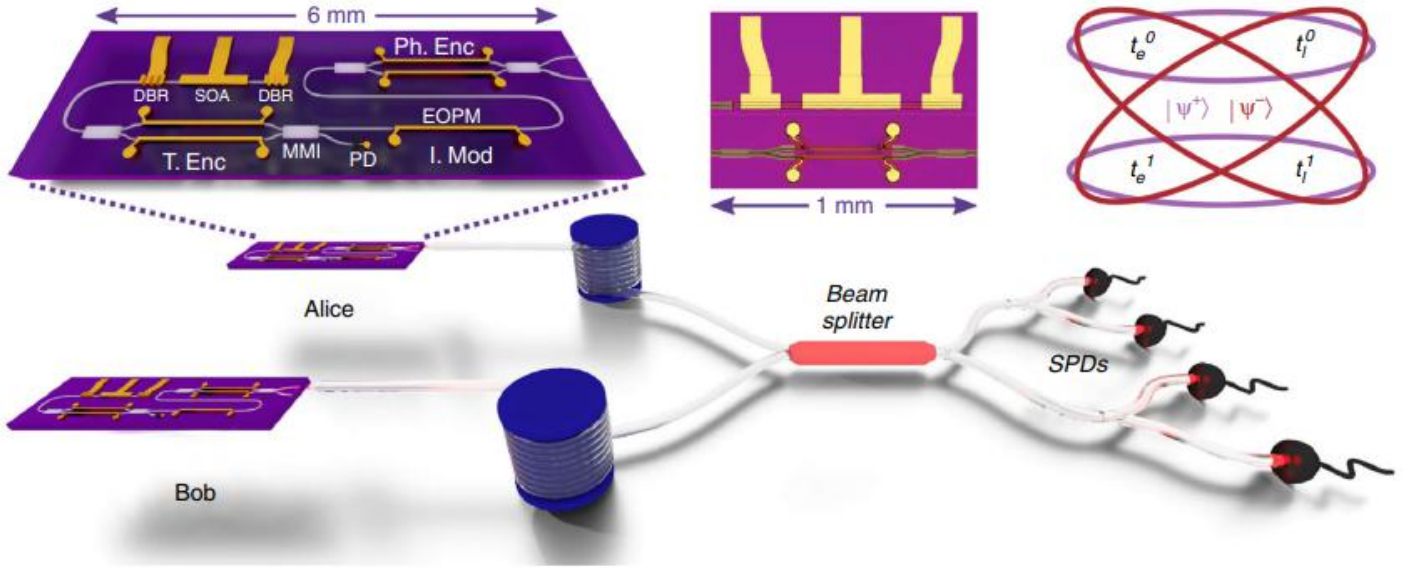


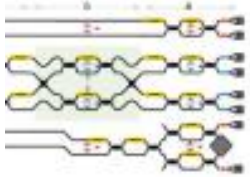

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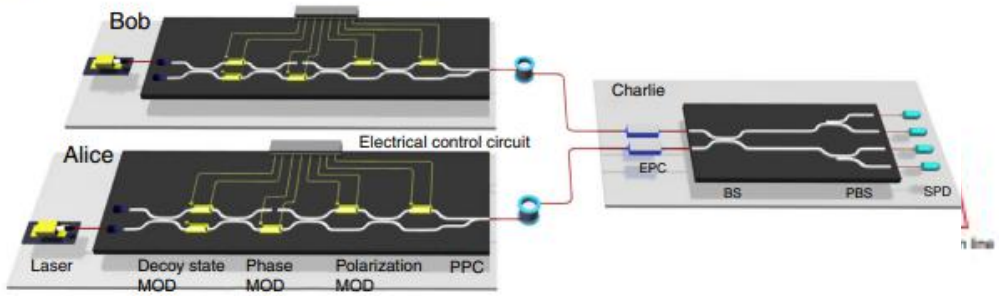
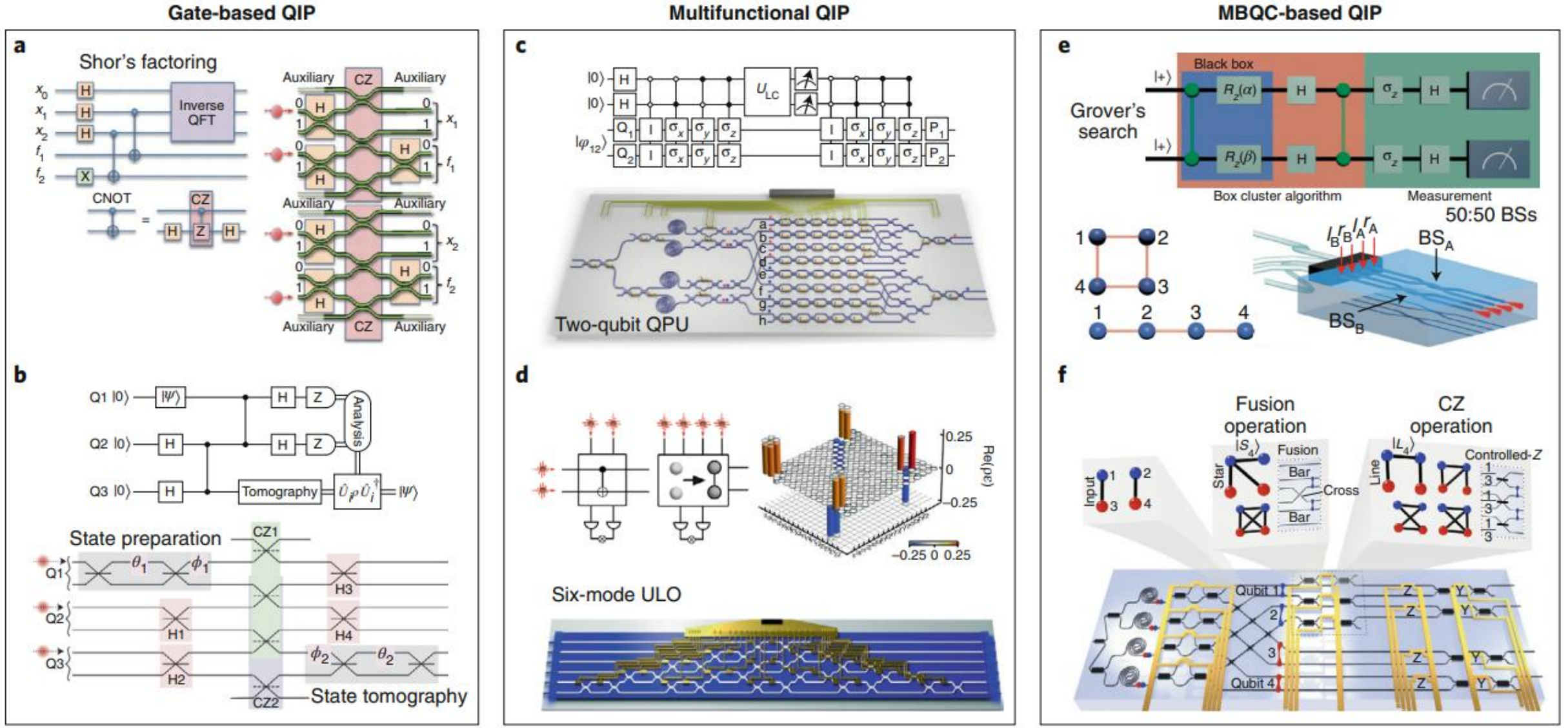


# Quantum Processing



What we have done….

nature photonics

LETTERS

https://doi.org/10.1038/s41566-019-0504-5

# An integrated silicon photonic chip platform for continuous-variable quantum key distribution

G. Zhang[1,2], J. Y. Haw[3], H. Cai[2], F. Xu[4*], S. M. Assad[3], J. F. Fitzsir
J. Wu[7], W. Ser[1], L. C. Kwek[8*] and A. Q. Liu[1*]

**Quantum key distribution (QKD) is a quantum communication technology that promises unconditional communication security. High-performance and cost-effective QKD systems are essential for the establishment of quantum communication networks[1–3]. By integrating all the optical components (except the laser source) on a silicon photonic chip, we have realized a**

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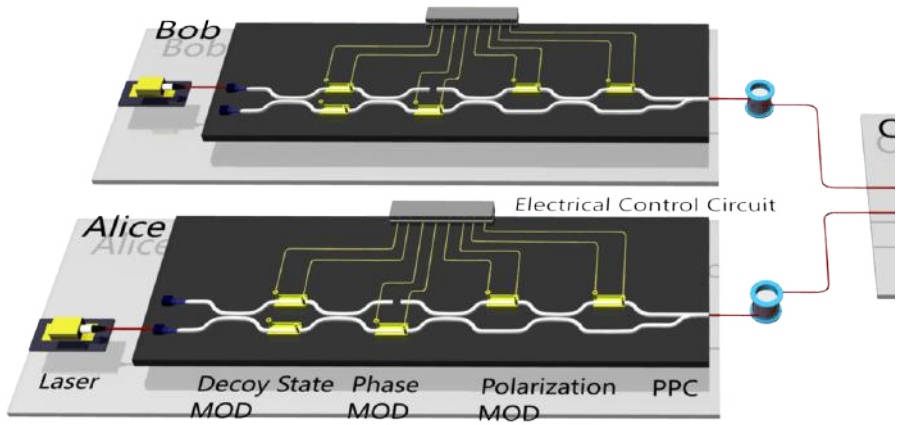


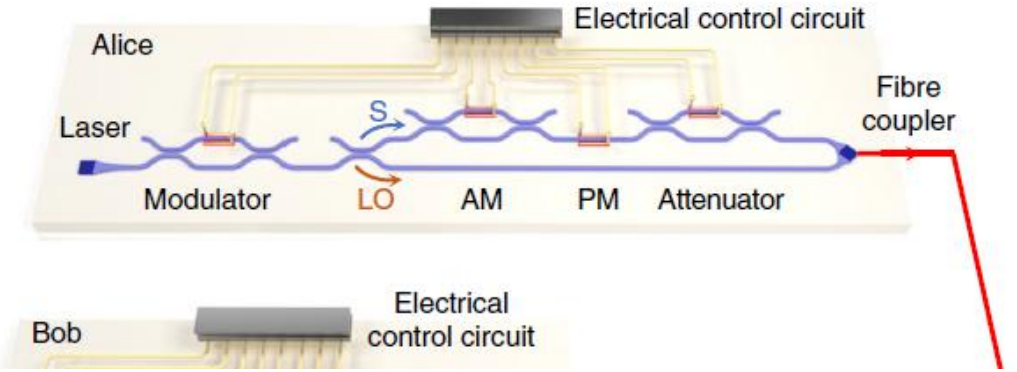


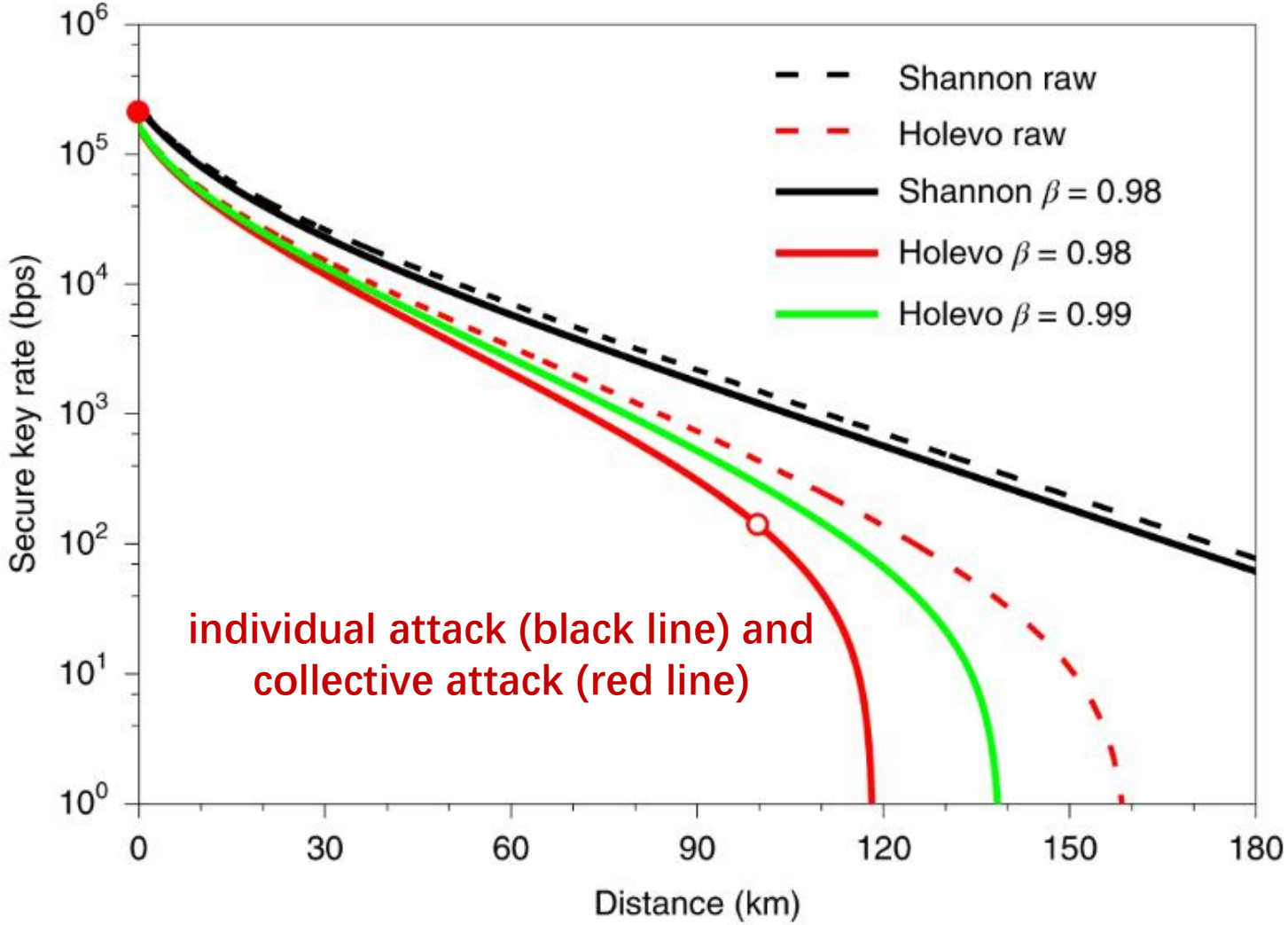


PHYSICAL REVIEW APPLIED 14, 011001 (2020);
238-242 2020; Physical Review X, 10(3), 0310

# Quantum Key Distribution

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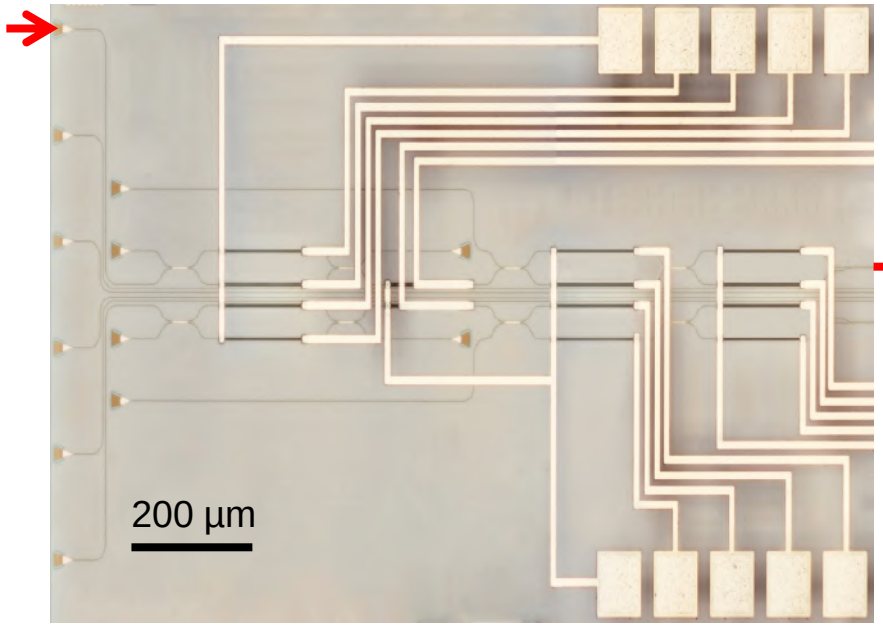
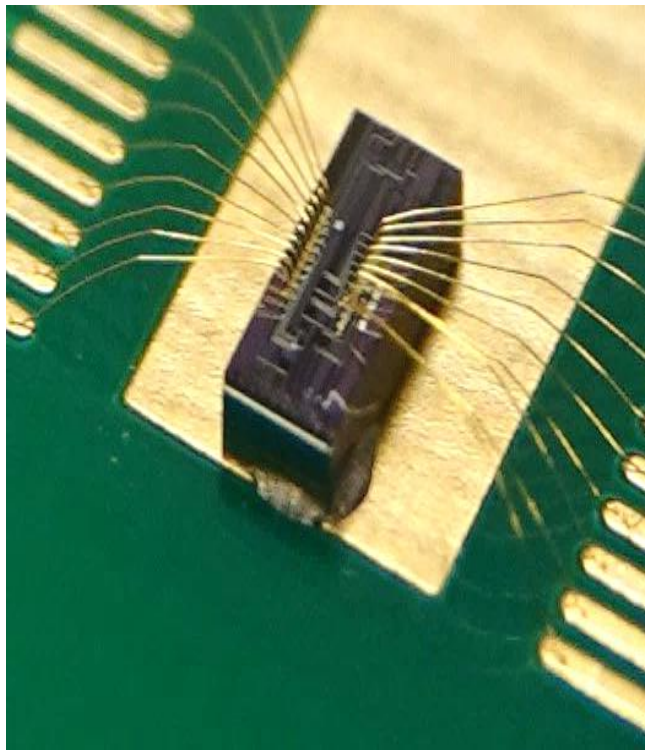
Review Article | Open access | Published: 14 July 2023

## Recent progress in quantum photonic chips for quantum communication and internet

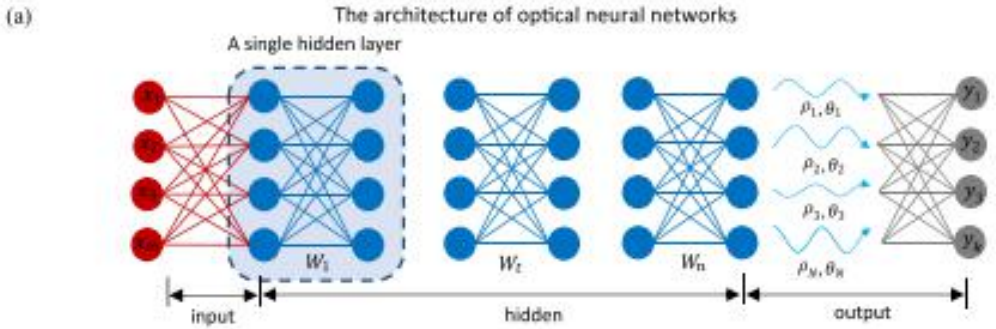
Wei Luo, Lin Cao, Yuzhi Shi ✉, Lingxiao Wan, Hui Zhang, Shuyi Li, Guanyu Chen, Yuan Li, Sijin Li, Yunxiang Wang, Shihai Sun, Muhammad Faeyz Karim ✉, Hong Cai ✉, Leong Chuan Kwek ✉ & Ai Qun Liu ✉

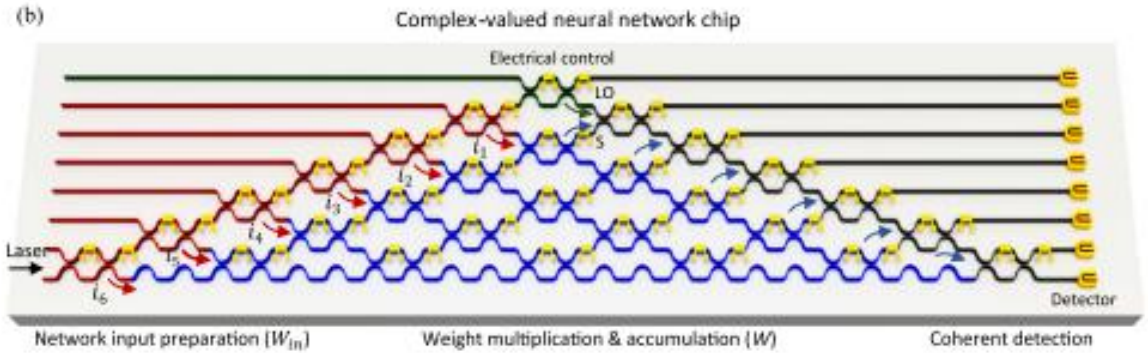


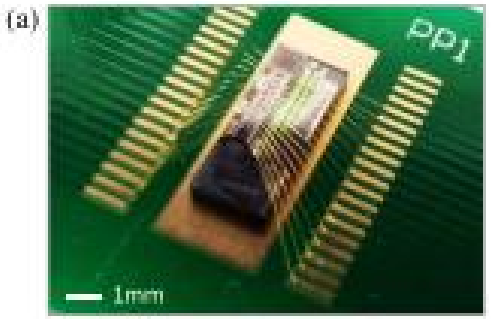

Transmitter chip

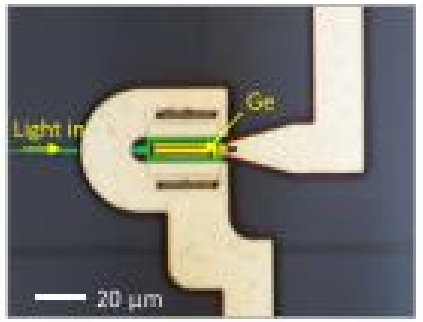


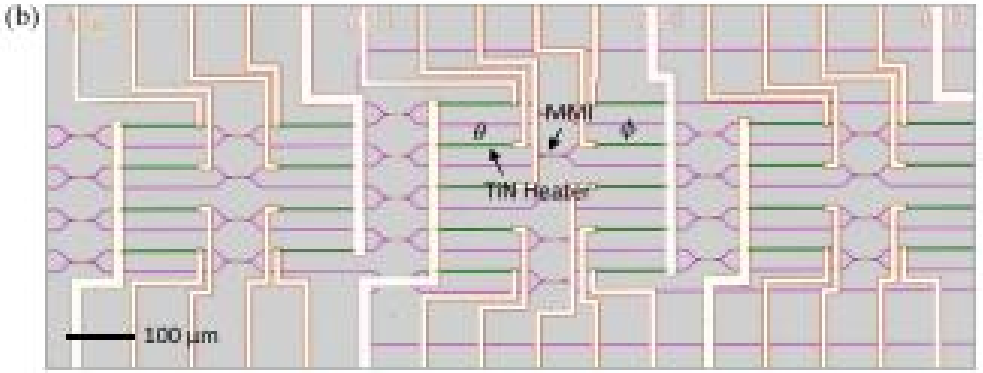
# Integrated photonic chips for Artificial Intelligence

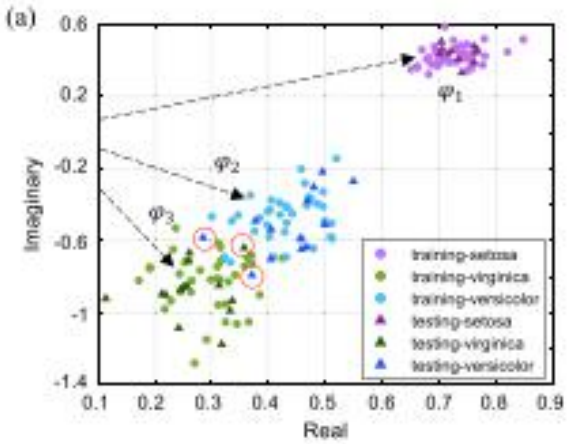


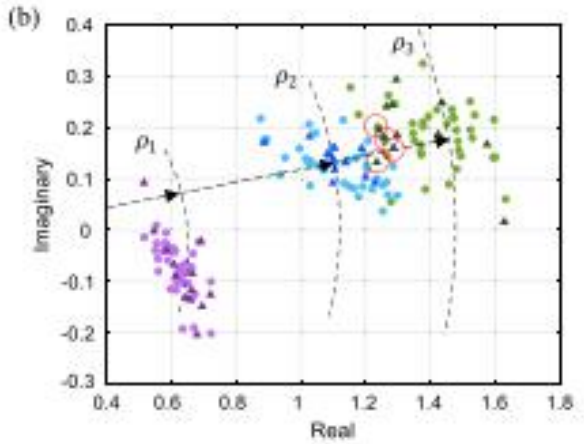



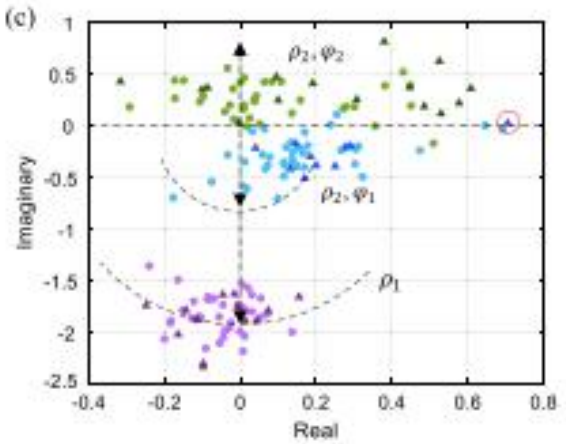



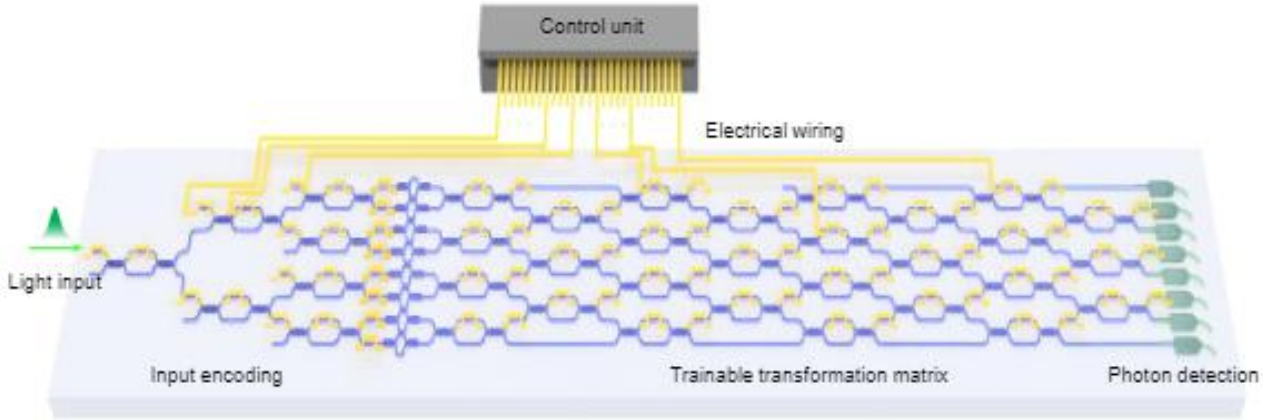



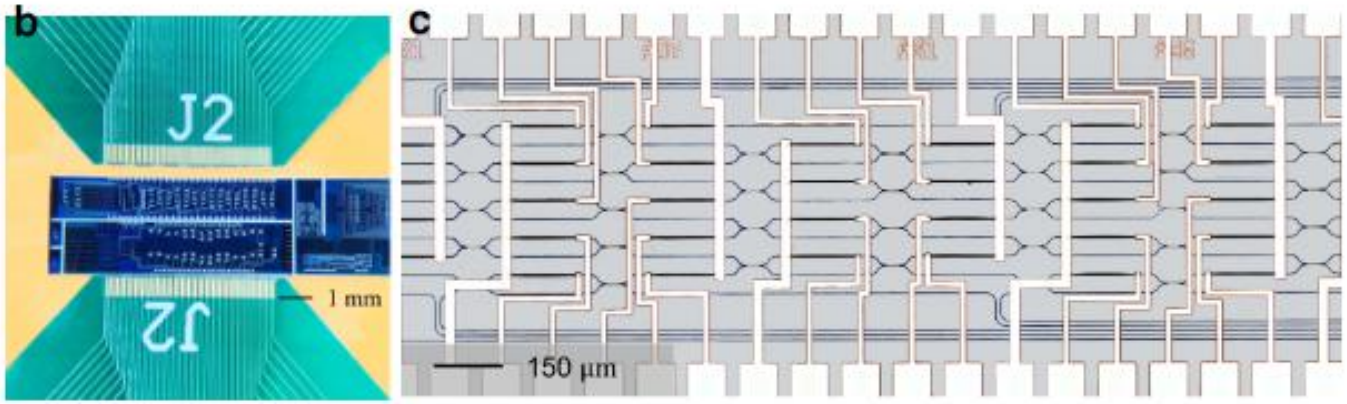



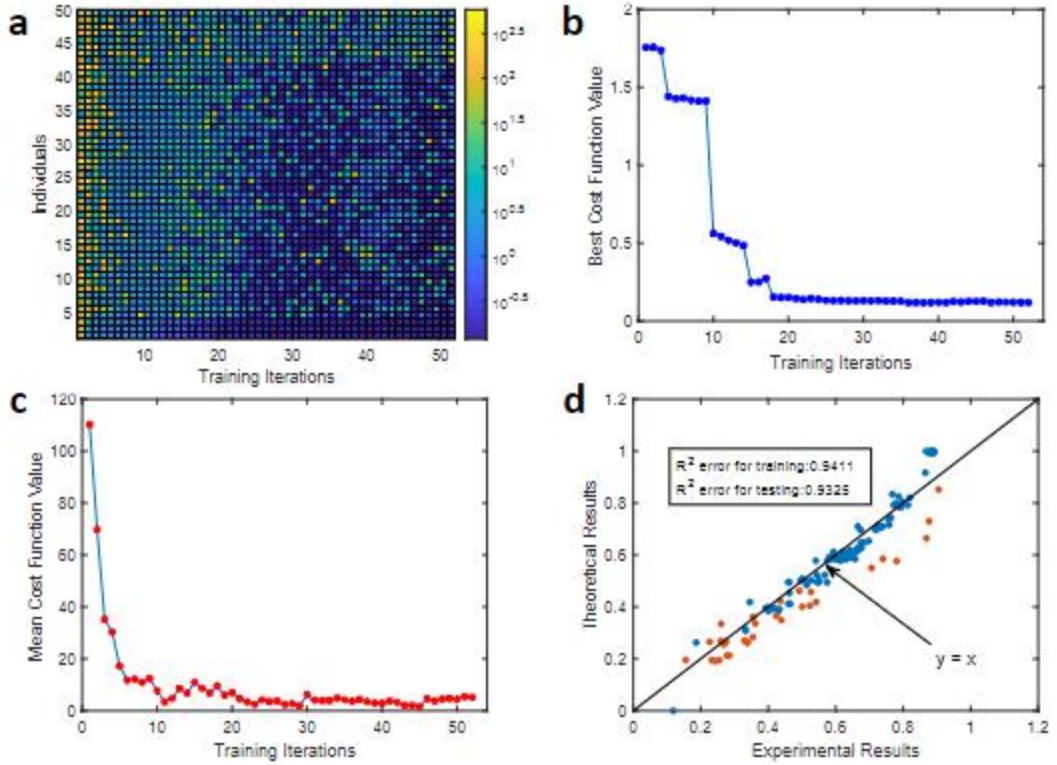

Zhu, H. H., *et al*. (2022). Space-efficient optical computing with an integrated chip diffractive neural network. *Nature communications*, *13*(1), 1-9.; Zhang, H., et al. (2021). An optical neural chip for implementing complex-valued neural network. *Nature Communications*, *12*(1), 1-11.

# Integrated photonic chips for Computational Chemistry




The regression quality is measured by the coefficient of determination $R^2$ score (the best regression has a $R^2$ score of 1). The training $R^2$ of our trained model on chip is 0.9411, and the testing score is 0.9325.



nature COMMUNICATIONS

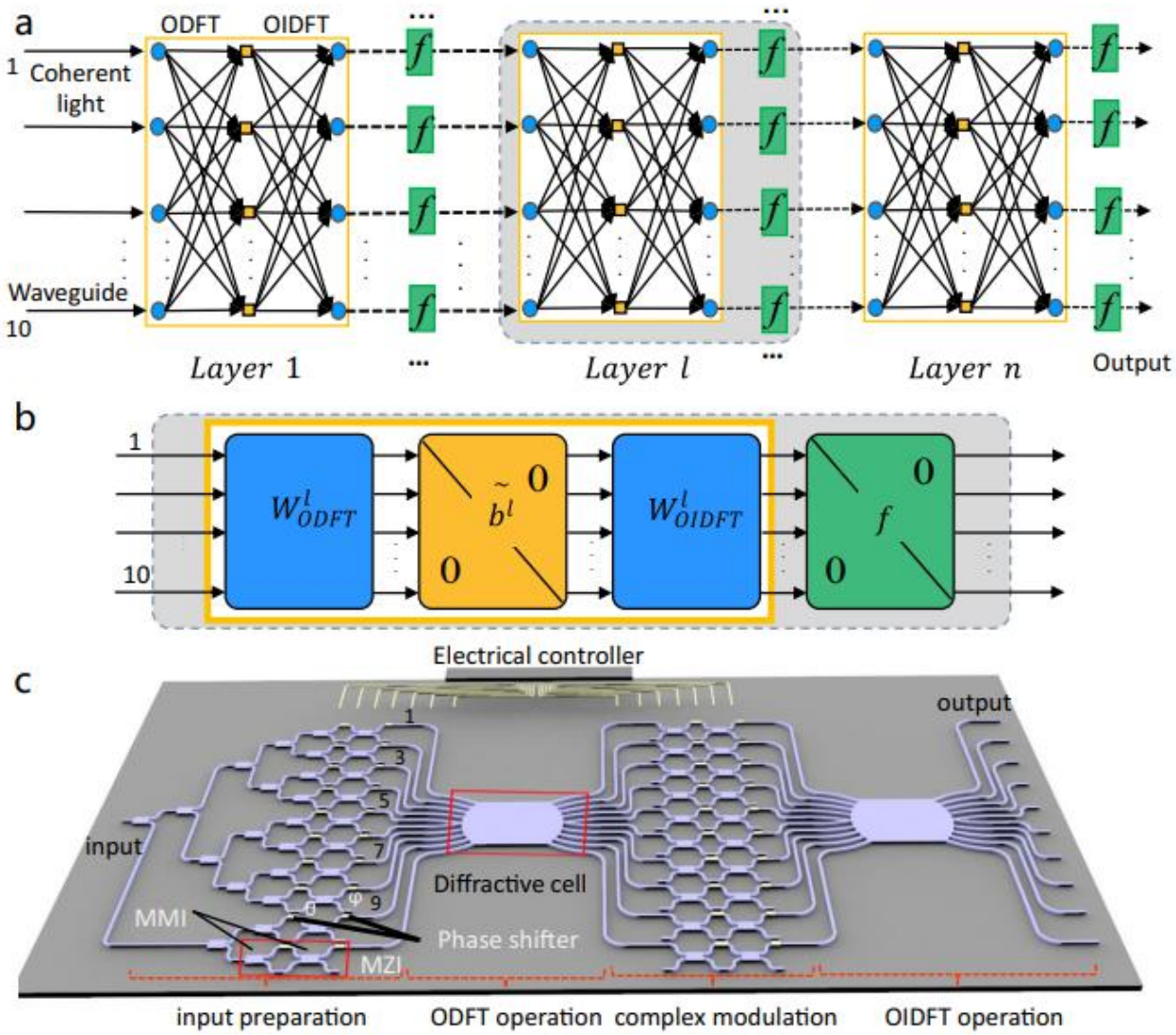
ARTICLE

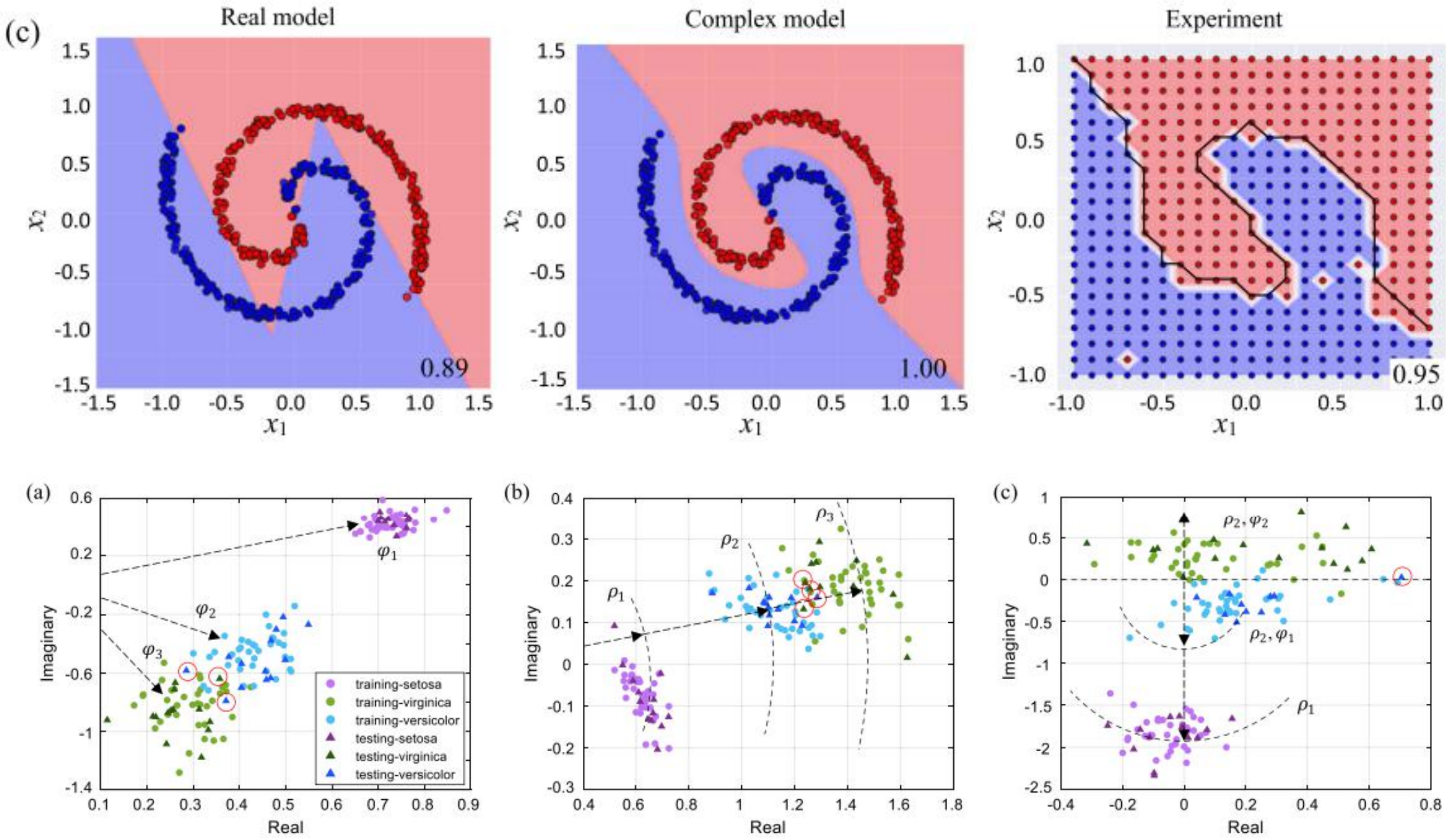
https://doi.org/10.1038/s41467-022-28702-0 OPEN

# Space-efficient optical computing with an integrated chip diffractive neural network

H. H. Zhu[1], J. Zou[1], H. Zhang[1], Y. Z. Shi[2], S. B. Luo[1], N. Wang[3], H. Cai[3], L. X. Wan[1], B. Wang[1], X. D. Jiang[1✉], J. Thompson[4], X. S. Luo[5], X. H. Zhou[6✉], L. M. Xiao[7✉], W. Huang[8], L. Patrick[5], M. Gu[9✉], L. C. Kwek[1,4✉] & A. Q. Liu[1✉]

Large-scale, highly integrated and low-power-consuming hardware is becoming progressively more important for realizing optical neural networks (ONNs) capable of advanced optical computing. Traditional experimental implementations need $N^2$ units such as Mach-Zehnder interferometers (MZIs) for an input dimension $N$ to realize typical computing operations (convolutions and matrix multiplication), resulting in limited scalability and consuming excessive power. Here, we propose the integrated diffractive optical network for imple-

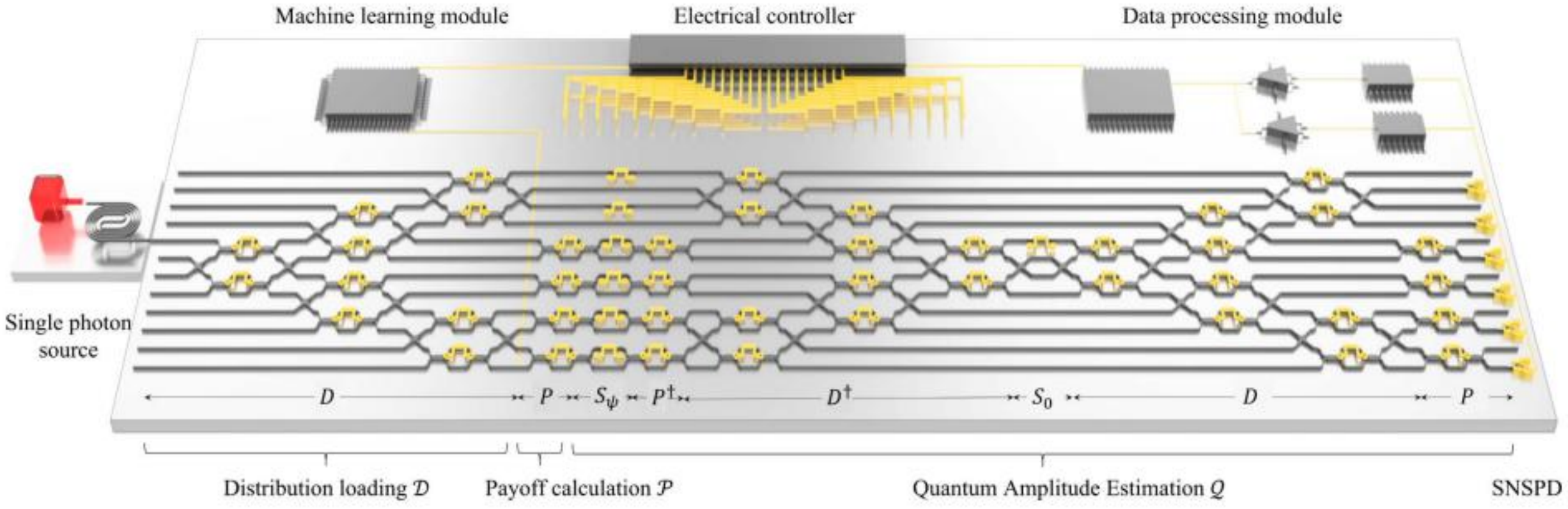


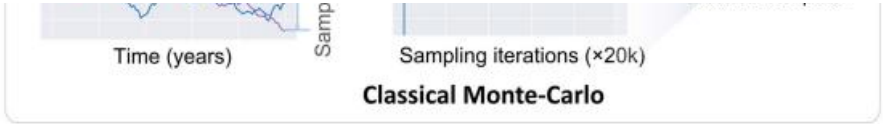

(c)
Real model
Complex model
Experiment
0.89
1.00
0.95
$x_1$
$x_2$
(a)
(b)
(c)
Imaginary
Real
$\varphi_1$
$\varphi_2$
$\varphi_3$
$\rho_1$
$\rho_2$
$\rho_3$
$\rho_2, \varphi_2$
$\rho_2, \varphi_1$
training-setosa
training-virginica
training-versicolor
testing-setosa
testing-virginica
testing-versicolor

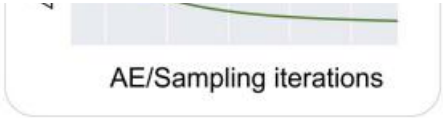
Research Article Vol. 11, No. 10 / October 2023 / Photonics Research 1703

PHOTONICS Research

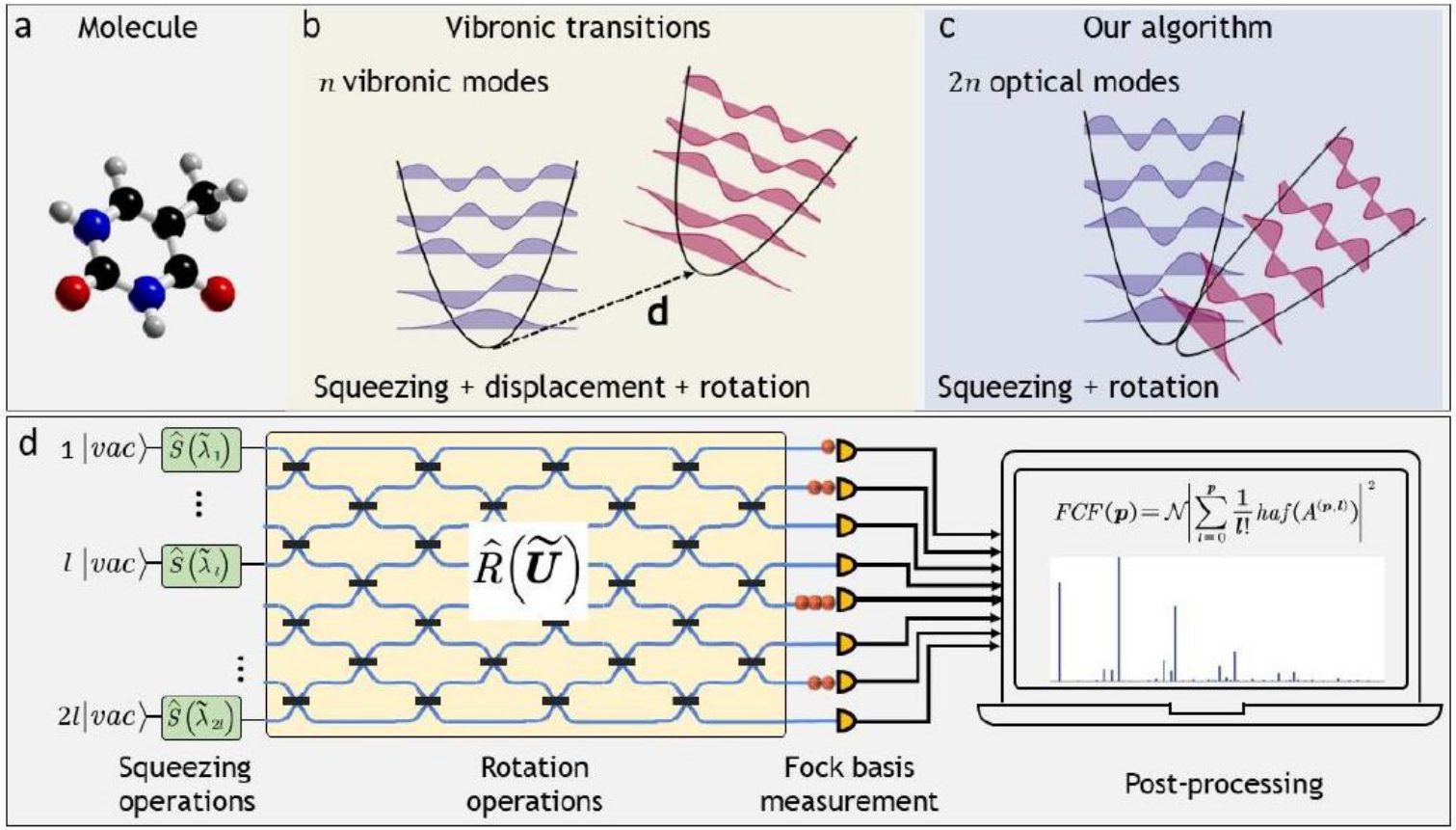
# Efficient option pricing with a unary-based photonic computing chip and generative adversarial learning

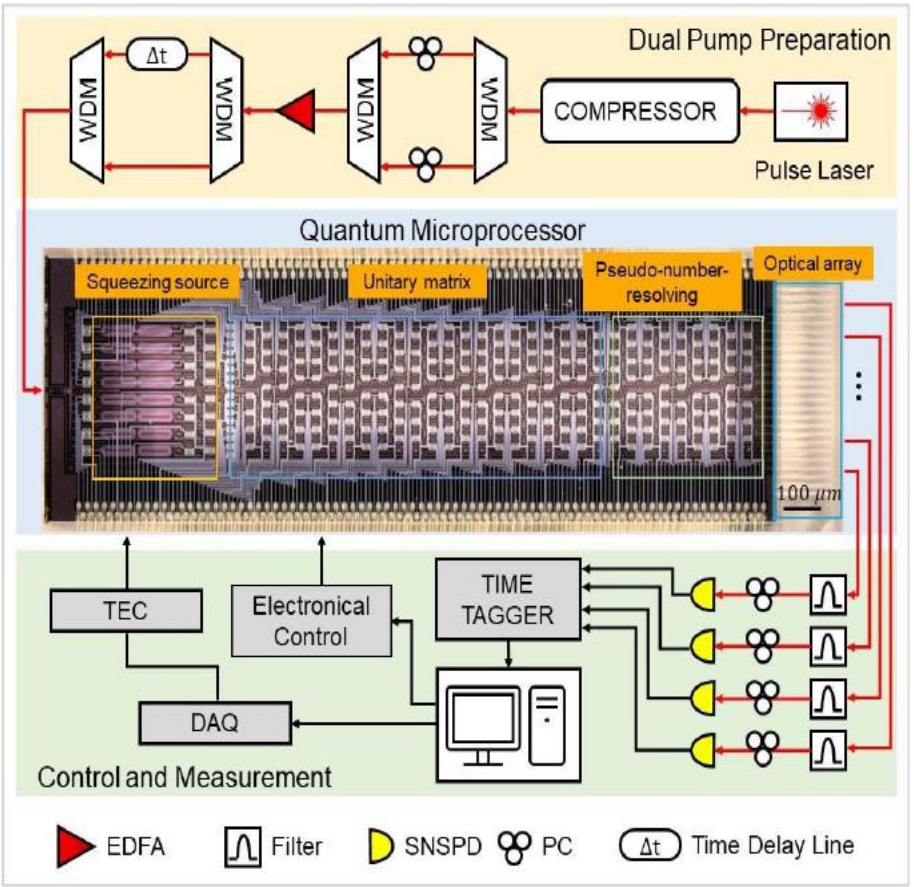


# Large-scale photonic network with squeezed vacuum states for molecular vibronic spectroscopy

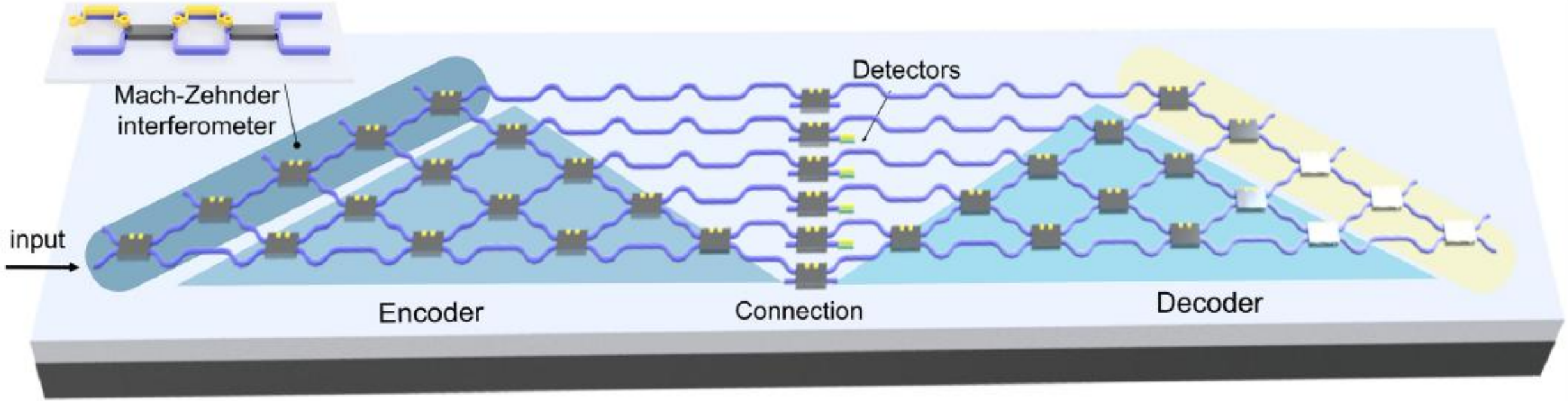



$$FCF(\boldsymbol{p}) = \mathrm{N}\left|\sum_{l=0}^{p} \frac{1}{\boldsymbol{l}!} haf\left(A^{(\boldsymbol{p},\boldsymbol{l})}\right)\right|^2$$

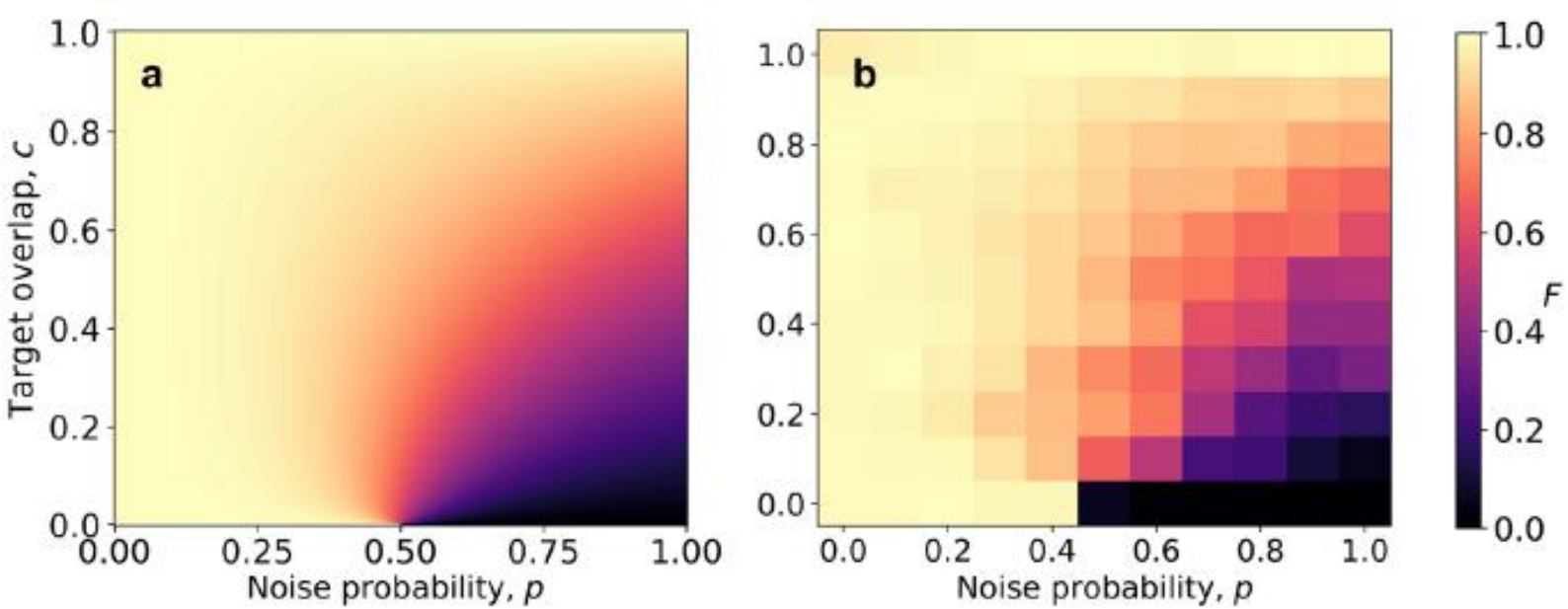
The photonic quantum circuit model, by translating the Doktorov operator to squeezing operators and rotation operator.

**Zhu, Hui Hui, et al. "Large-scale photonic network with squeezed vacuum states for molecular vibronic spectroscopy." Nature Communications 15.1 (2024): 6057.**

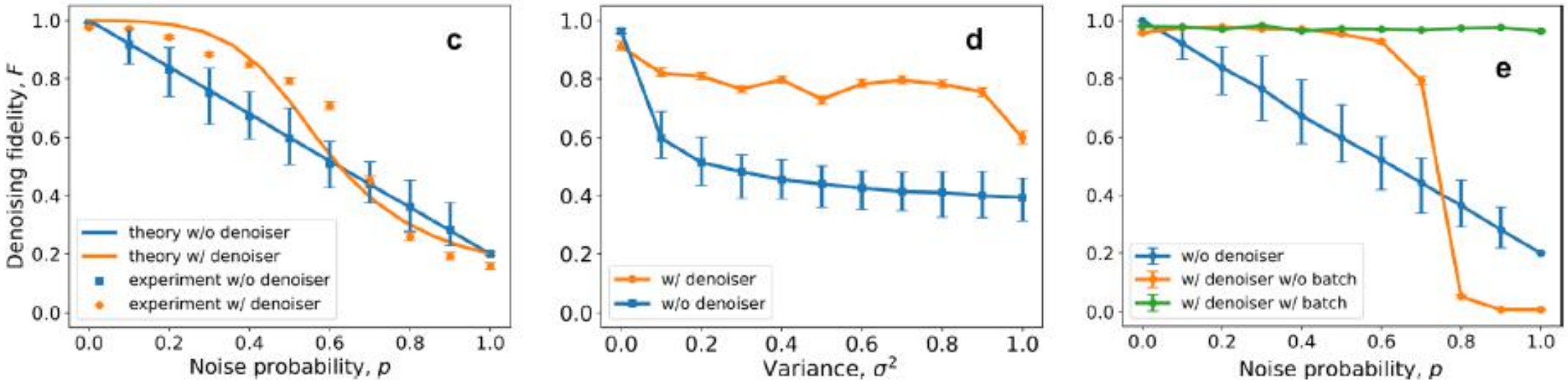



The entire autoencoder network is manufactured on the silicon-on-insulator (SOI) platform, featuring a 220-nm-thick silicon top layer and a 2-$\mu$m-thick buried oxide layer. A thin layer of titanium nitride (TiN) is deposited as the resistive layer for heating elements. A thin aluminum film is patterned to realize the electrical connection for the heaters. Isolation trenches are etched in the $SiO_2$ top cladding and Si substrate.

Theory




Experiment




$$\mathscr{E}(\rho) = (1-p)\rho + p\rho_{\text{noise}}$$

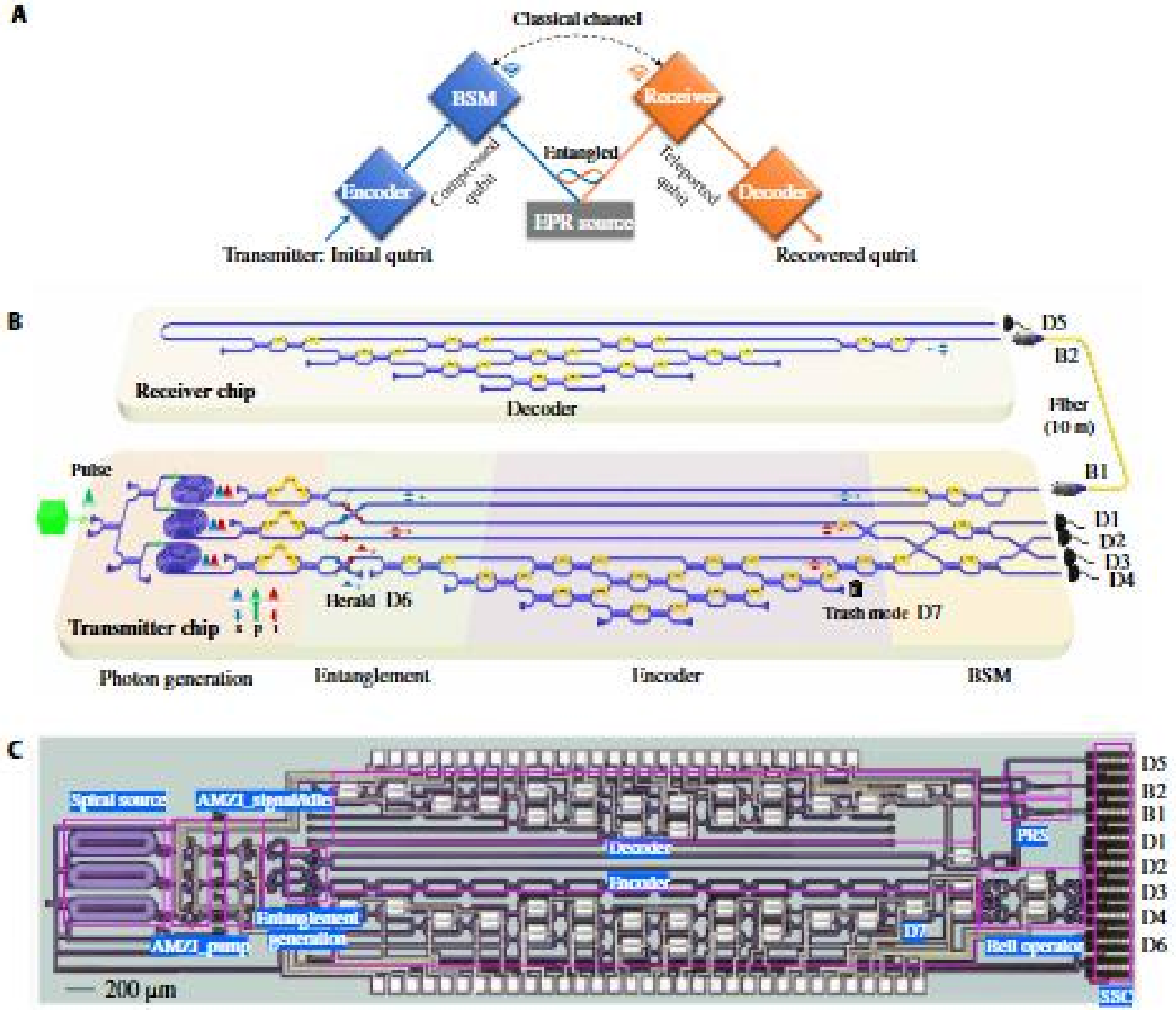
SCIENCE ADVANCES | RESEARCH

OPTICS

# Resource-efficient high-d teleportation with a quan

Hui Zhang[1]†, Lingxiao Wan[1]†, Tobias Haug[2], Hong Cai[7], Lip Ket Chin[1], Muhammad Faeyz Bin Dong[9], Syed Assad[10], M. S. Kim[2], Anthon

Quantum autoencoders serve as efficient means for their use to reduce resource costs for quantum tele quantum autoencoder in a compress-teleport-deco using an integrated photonic platform for future sc input states by erasing redundant information and pervised machine learning is applied to train the on- of any state from a high-dimensional subspace. Unkr



Rigorous noise
autoencoders

Cite as: AVS Quantum Sci. **6**, 023
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Published Online: 31 May 2024

Wai-Keong Mok,[1,2] Hui Zhang
M. S. Kim,[5] Ai Qun Liu,[3,4] and

AFFILIATIONS

[1]California Institute of Technology, Pa
[2]Centre for Quantum Technologies, N

# Rigorous noise reduction with quantum autoencoders

Wai-Keong Mok*,[1,2] Hui Zhang*,[3,4] Tobias Haug*,[5] Xianshu Luo,[6] Guo-Qiang Lo,[6] Hong Cai,[7] M. S. Kim,[5] Ai Qun Liu,[3,4] and Leong-Chuan Kwek[2,8,9,4]

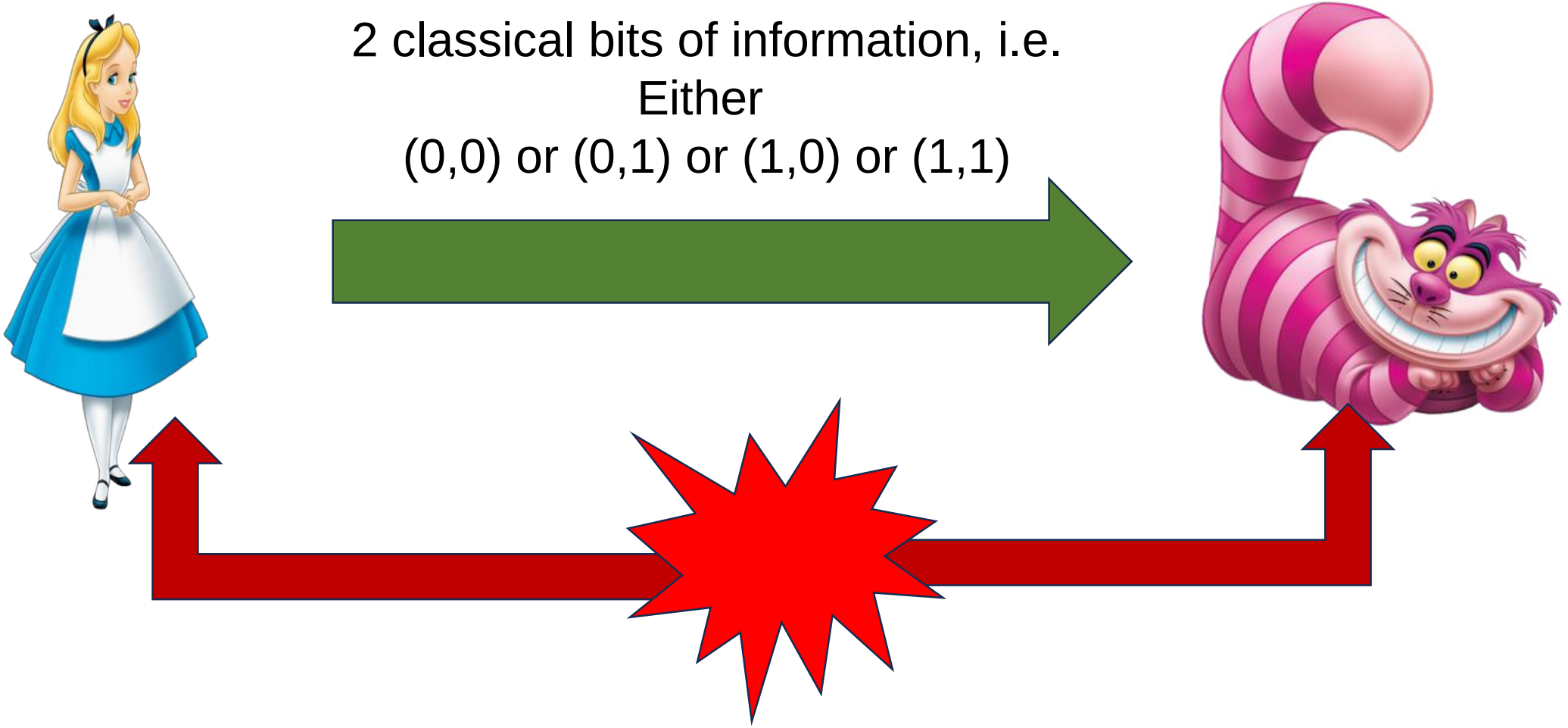
[1]*California Institute of Technology, Pasadena, CA 91125, USA*
[2]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543**
[3]*Institute of Quantum Technologies (IQT), The Hong Kong Polytechnic University, Hong Kong*
[4]*Quantum Science and Engineering Centre (QSec), Nanyang Technological University, Singapore**
[5]*QOLS, Blackett Laboratory, Imperial College London SW7 2AZ, UK**
[6]*Advanced Micro Foundry, 11 Science Park Rd, Singapore*
[7]*Institute of Microelectronics, A*STAR (Agency for Science, Technology and Research), Singapore*
[8]*MajuLab, CNRS-UNS-NUS-NTU International Joint Research Unit, Singapore UMI 3654, Singapore*
[9]*National Institute of Education, Nanyang Technological University, Singapore 637616, Singapore*

Reducing noise in quantum systems is a major challenge towards the application of quantum technologies. Here, we propose and demonstrate a scheme to reduce noise using a quantum autoencoder with rigorous performance guarantees. The quantum autoencoder learns to compresses noisy quantum states into a latent subspace and removes noise via projective measurements. We find various noise models where we can perfectly reconstruct the original state even for high noise levels. We apply the autoencoder to cool thermal states to the ground state and reduce the cost of magic state distillation by several orders of magnitude. Our autoencoder can be implemented using only unitary transformations without ancillas, making it immediately compatible with the state of the art. We experimentally demonstrate our methods to reduce noise in a photonic integrated circuit. Our results can be directly applied to make quantum technologies more robust to noise.

Mok, W. K., Zhang, H., Haug, T., Luo, X., Lo, G. Q., Li, Z., ... & Kwek, L. C. (2024). Rigorous noise reduction with quantum autoencoders. *AVS Quantum Science*, *6*(2).

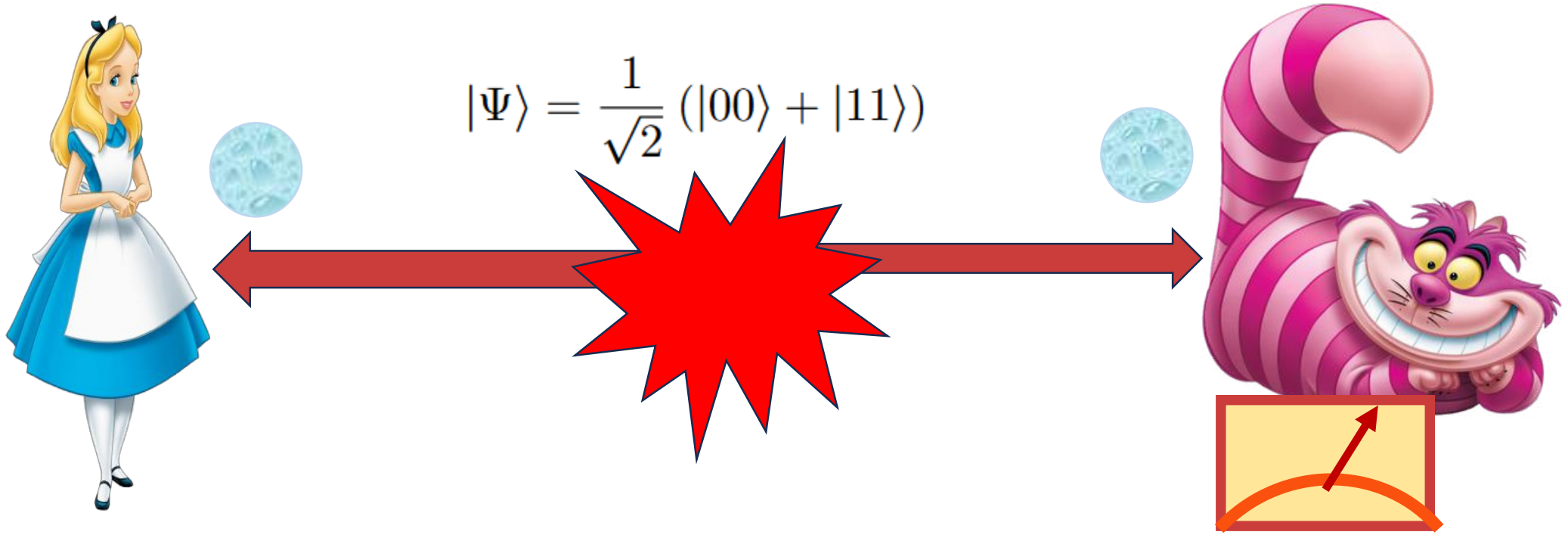
# Superdense Coding

# Superdense coding




Using entanglement $|\Psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

# Superdense coding

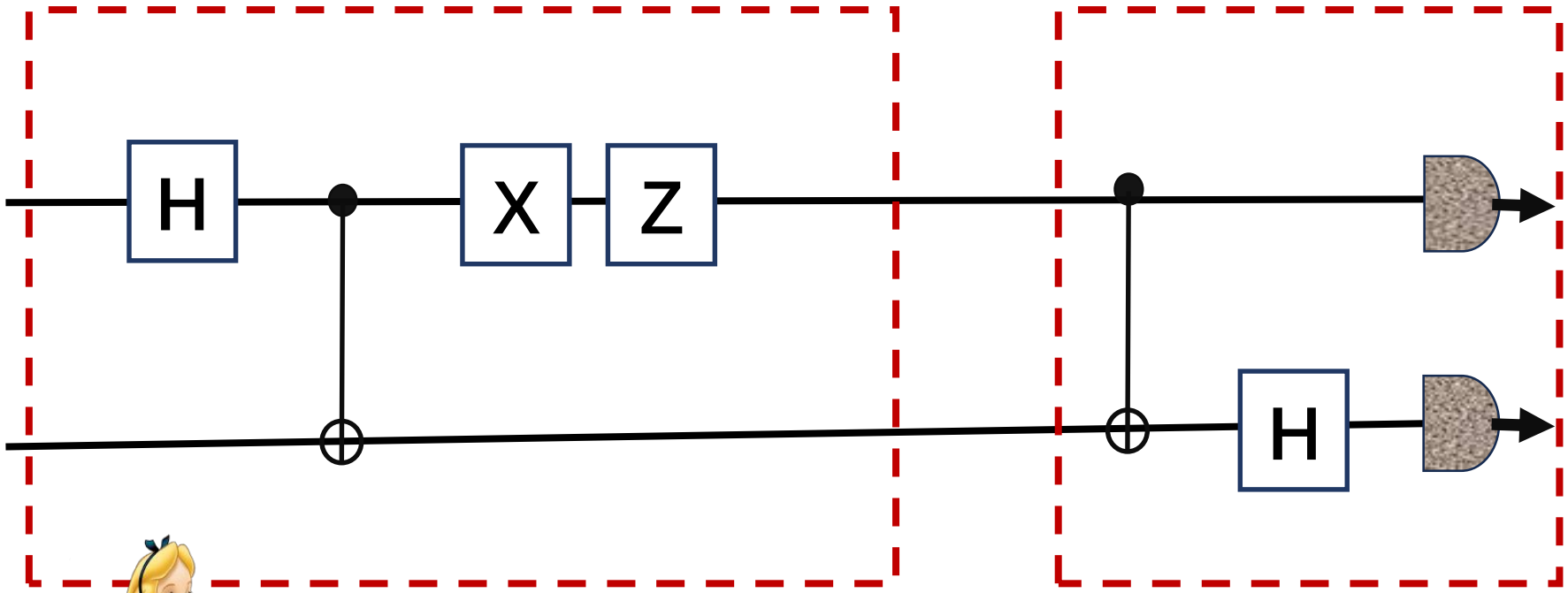



For sending $|00\rangle$, do nothing
For sending $|01\rangle$, apply $X$
For sending $|10\rangle$, apply $Z$
For sending $|11\rangle$, apply $XZ$

## Bell State Measurement

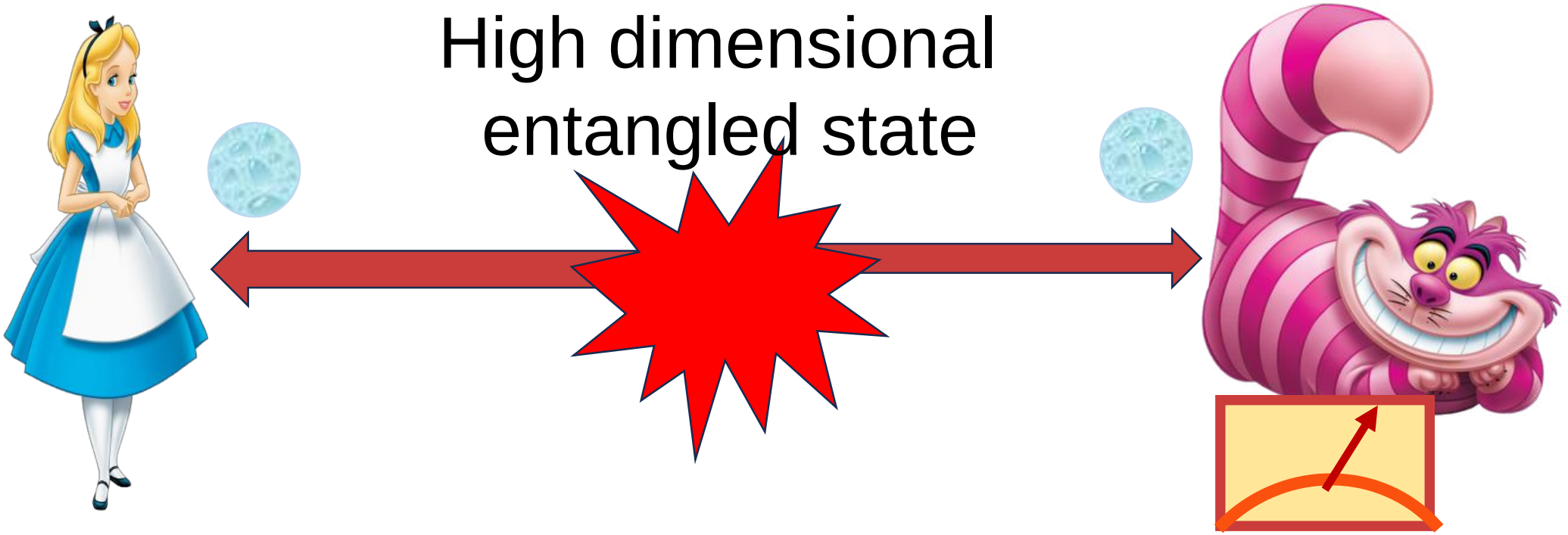
If measurement is $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, Bob concludes that Alice sends 00
If measurement is $\frac{1}{\sqrt{2}}(|10\rangle + |01\rangle)$, Bob concludes that Alice sends 01
If measurement is $\frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$, Bob concludes that Alice sends 10
If measurement is $\frac{1}{\sqrt{2}}(|10\rangle - |01\rangle)$, Bob concludes that Alice sends 11

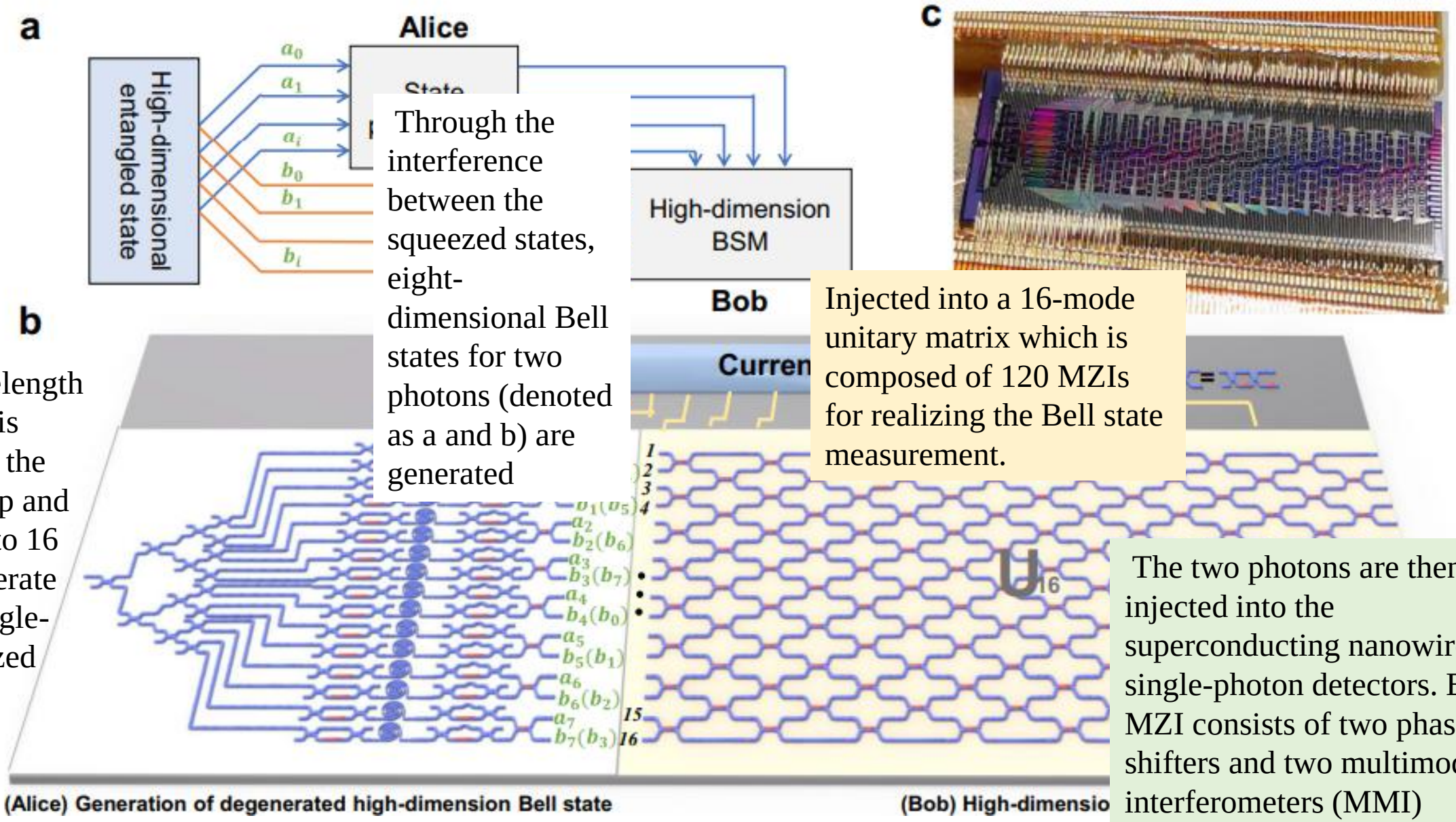
# Circuit model for superdense coding



In higher dimensions?

# Superdense coding






A dual-wavelength pump beam is injected into the photonic chip and separated into 16 paths to generate the weak single-mode squeezed states

Through the interference between the squeezed states, eight-dimensional Bell states for two photons (denoted as a and b) are generated

Injected into a 16-mode unitary matrix which is composed of 120 MZIs for realizing the Bell state measurement.

The two photons are then injected into the superconducting nanowire single-photon detectors. Each MZI consists of two phase shifters and two multimode interferometers (MMI)

# Generation of high dimensional entangled state

A single squeezed state is described as $|\varphi\rangle \approx (|0\rangle_a + p|2\rangle_a)/\sqrt{1+p^2}$ for $p \ll 1$

For the superposition of two adjacent output weak squeezed states labeled as modes $a$ and $b$, described by

$$|\varphi> = \frac{1}{\sqrt{2}}(|20\rangle_{ab} - |02\rangle_{ab}),$$

the evolution after passing through a 50:50 beamsplitter is expressed as

Recall squeezed state is:

$$|\varphi\rangle = \exp(\zeta a^{\dagger 2} - \zeta^* a^2)|0\rangle$$

$$|\varphi\rangle = (|20\rangle_{ab} - |02\rangle_{ab})/\sqrt{2}$$

$$= (a^{\dagger 2} - b^{\dagger 2})|00\rangle/2$$

$$\xrightarrow{50:50\ BS} [(a^\dagger + b^\dagger)^2/2 - (a^\dagger - b^\dagger)^2/2]|00\rangle/2$$

$$= a^\dagger b^\dagger |00\rangle$$

$$= |11\rangle_{ab}$$

For the 8-dimension Bell states, there exists a set of 64 orthogonal Bell states which can be encoded into 16 spatial modes named as $a_0$ to $a_7$ and $b_0$ to $b_7$. But we cannot distinguish all of them with linear optics. So we perform the high-dimension Bell states which can distinguish most of them.

$$\begin{pmatrix} a_{0in} \\ \vdots \\ a_{7in} \\ b_{0in} \\ \vdots \\ b_{7in} \end{pmatrix} \rightarrow U_{16} \cdot \begin{pmatrix} a_{0in} \\ \vdots \\ a_{7in} \\ b_{0in} \\ \vdots \\ b_{7in} \end{pmatrix}.$$

# Eleven “Bell” states:

To generate the eleven orthogonal high-dimension Bell states, Alice needs to perform the local operations in the state

$$|\varphi\rangle = \frac{1}{2\sqrt{2}} \begin{pmatrix} |a_0\ b_0\rangle + |a_1\ b_1\rangle + |a_2\ b_2\rangle \\ +|a_3\ b_3\rangle + |a_4\ b_4\rangle + |a_5\ b_5\rangle \\ +|a_6\ b_6\rangle + |a_7\ b_7\rangle \end{pmatrix}$$

$$|\psi_0\rangle = (|a_0b_0\rangle - |a_1b_1\rangle + |a_2b_2\rangle - |a_3b_3\rangle + |a_4b_4\rangle - |a_5b_5\rangle + |a_6b_6\rangle - |a_7b_7\rangle)/2\sqrt{2}$$

$$|\psi_1\rangle = (|a_0b_0\rangle + |a_1b_1\rangle - |a_2b_2\rangle - |a_3b_3\rangle + |a_4b_4\rangle + |a_5b_5\rangle - |a_6b_6\rangle - |a_7b_7\rangle)/2\sqrt{2}$$

$$|\psi_2\rangle = (|a_0b_0\rangle - |a_1b_1\rangle - |a_2b_2\rangle + |a_3b_3\rangle + |a_4b_4\rangle - |a_5b_5\rangle - |a_6b_6\rangle + |a_7b_7\rangle)/2\sqrt{2}$$

$$|\psi_3\rangle = (|a_0b_0\rangle + |a_1b_1\rangle + |a_2b_2\rangle + |a_3b_3\rangle - |a_4b_4\rangle - |a_5b_5\rangle - |a_6b_6\rangle - |a_7b_7\rangle)/2\sqrt{2}$$

$$|\psi_4\rangle = (|a_0b_0\rangle - |a_1b_1\rangle + |a_2b_2\rangle - |a_3b_3\rangle - |a_4b_4\rangle + |a_5b_5\rangle - |a_6b_6\rangle + |a_7b_7\rangle)/2\sqrt{2}$$

$$|\psi_5\rangle = (|a_0b_0\rangle + |a_1b_1\rangle - |a_2b_2\rangle - |a_3b_3\rangle - |a_4b_4\rangle - |a_5b_5\rangle + |a_6b_6\rangle + |a_7b_7\rangle)/2\sqrt{2}$$

$$|\psi_6\rangle = (|a_0b_0\rangle - |a_1b_1\rangle - |a_2b_2\rangle + |a_3b_3\rangle - |a_4b_4\rangle + |a_5b_5\rangle + |a_6b_6\rangle - |a_7b_7\rangle)/2\sqrt{2}$$

$$|\psi_7\rangle = (|a_0b_4\rangle + |a_1b_5\rangle + |a_2b_6\rangle + |a_3b_7\rangle - |a_4b_0\rangle - |a_5b_1\rangle - |a_6b_2\rangle - |a_7b_3\rangle)/2\sqrt{2}$$

$$|\psi_8\rangle = (|a_0b_4\rangle - |a_1b_5\rangle + |a_2b_6\rangle - |a_3b_7\rangle - |a_4b_0\rangle + |a_5b_1\rangle - |a_6b_2\rangle + |a_7b_3\rangle)/2\sqrt{2}$$

$$|\psi_9\rangle = (|a_0b_4\rangle + |a_1b_5\rangle - |a_2b_6\rangle - |a_3b_7\rangle - |a_4b_0\rangle - |a_5b_1\rangle + |a_6b_2\rangle + |a_7b_3\rangle)/2\sqrt{2}$$

$$|\psi_{10}\rangle = (|a_0b_4\rangle - |a_1b_5\rangle - |a_2b_6\rangle + |a_3b_7\rangle - |a_4b_0\rangle + |a_5b_1\rangle + |a_6b_2\rangle - |a_7b_3\rangle)/2\sqrt{2}$$

$$|\psi_0\rangle' = (|a_0a_1\rangle + |a_2a_3\rangle + |a_4a_5\rangle + |a_6a_7\rangle - |b_0b_1\rangle - |b_2b_3\rangle - |b_4b_5\rangle - |b_6b_7\rangle)/2\sqrt{2}$$

$$|\psi_1\rangle' = (|a_0a_2\rangle + |a_1a_3\rangle + |a_4a_6\rangle + |a_5a_7\rangle - |b_0b_2\rangle - |b_1b_3\rangle - |b_4b_6\rangle - |b_5b_7\rangle)/2\sqrt{2}$$

$|\psi_2\rangle' = (|a_0a_$

$|\psi_3\rangle' = (|a_0a_$

$|\psi_4\rangle' = (|a_0a_$

$|\psi_5\rangle' = (|a_0a_$

$|\psi_6\rangle' = (|a_0a_$

$|\psi_7\rangle' = (|a_0b_$

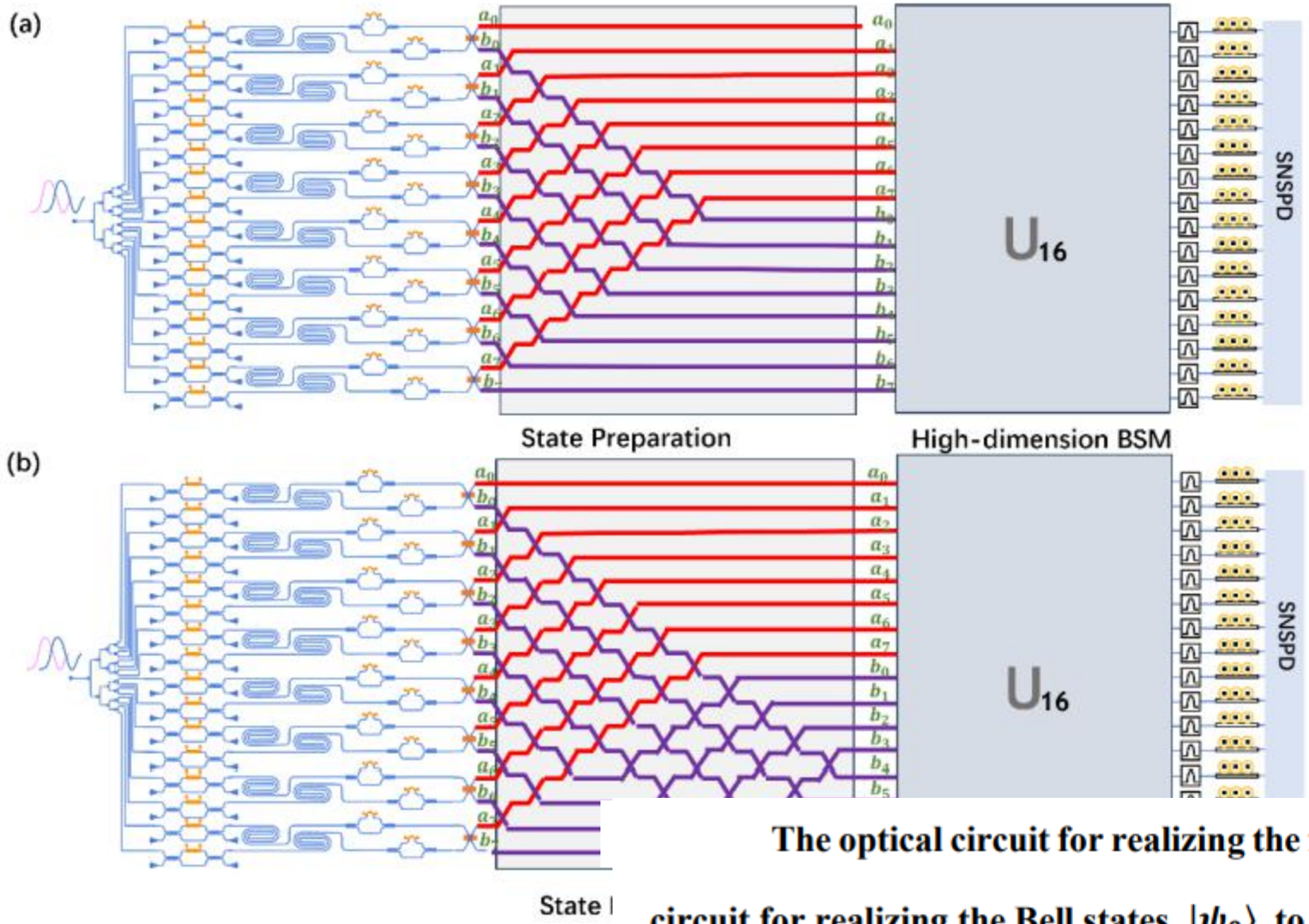
$|\psi_8\rangle' = (|a_0b_$

$|\psi_9\rangle' = (|a_0b_$

$|\psi_{10}\rangle' = (|a_0b_$

$$U_{16} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 & 1 & -1 & -1 & 1 \end{bmatrix} /4$$

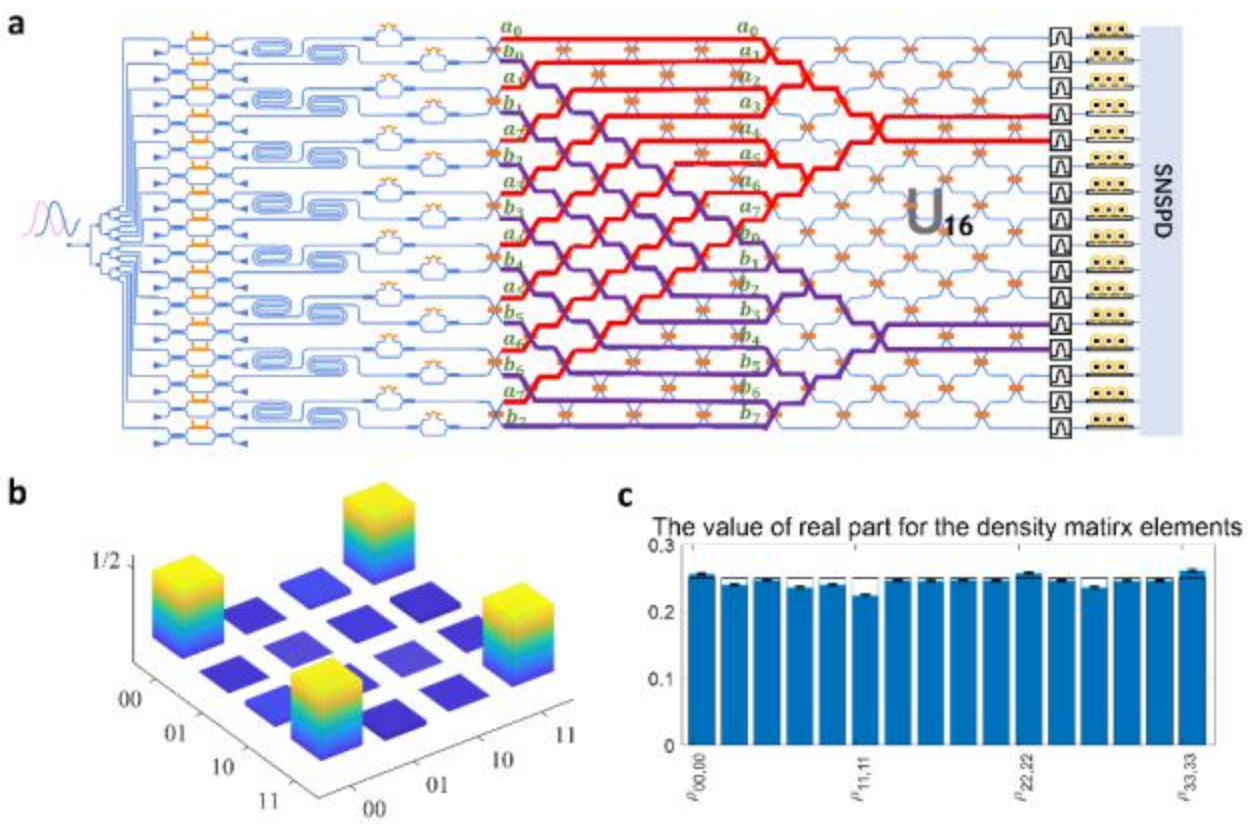
# High dimensional BSM




**The optical circuit for realizing the fully quantum superdense coding protocol. (a) The circuit for realizing the Bell states $|\psi_0\rangle$ to $|\psi_6\rangle$. (b) The circuit for realizing the Bell states $|\psi_7\rangle$ to $|\psi_{10}\rangle$.**

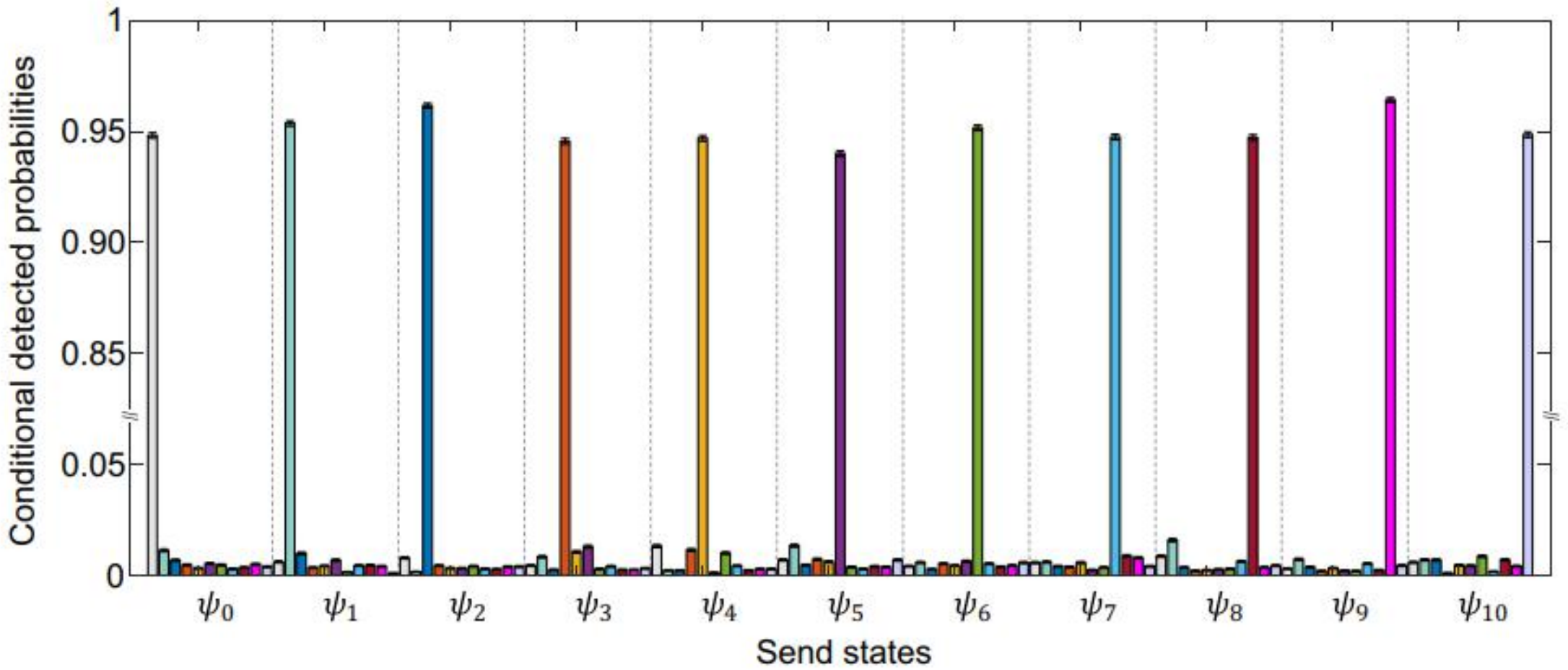
# Scheme for reconstructing the density matrix of the Bell state

a. The circuit for performing the quantum tomography on photonic chip. b. The real part of the density matrix for the reconstructed Bell state. c. The measurement results of the density matrix elements for calculating the fidelity of the four-dimension Bell state.

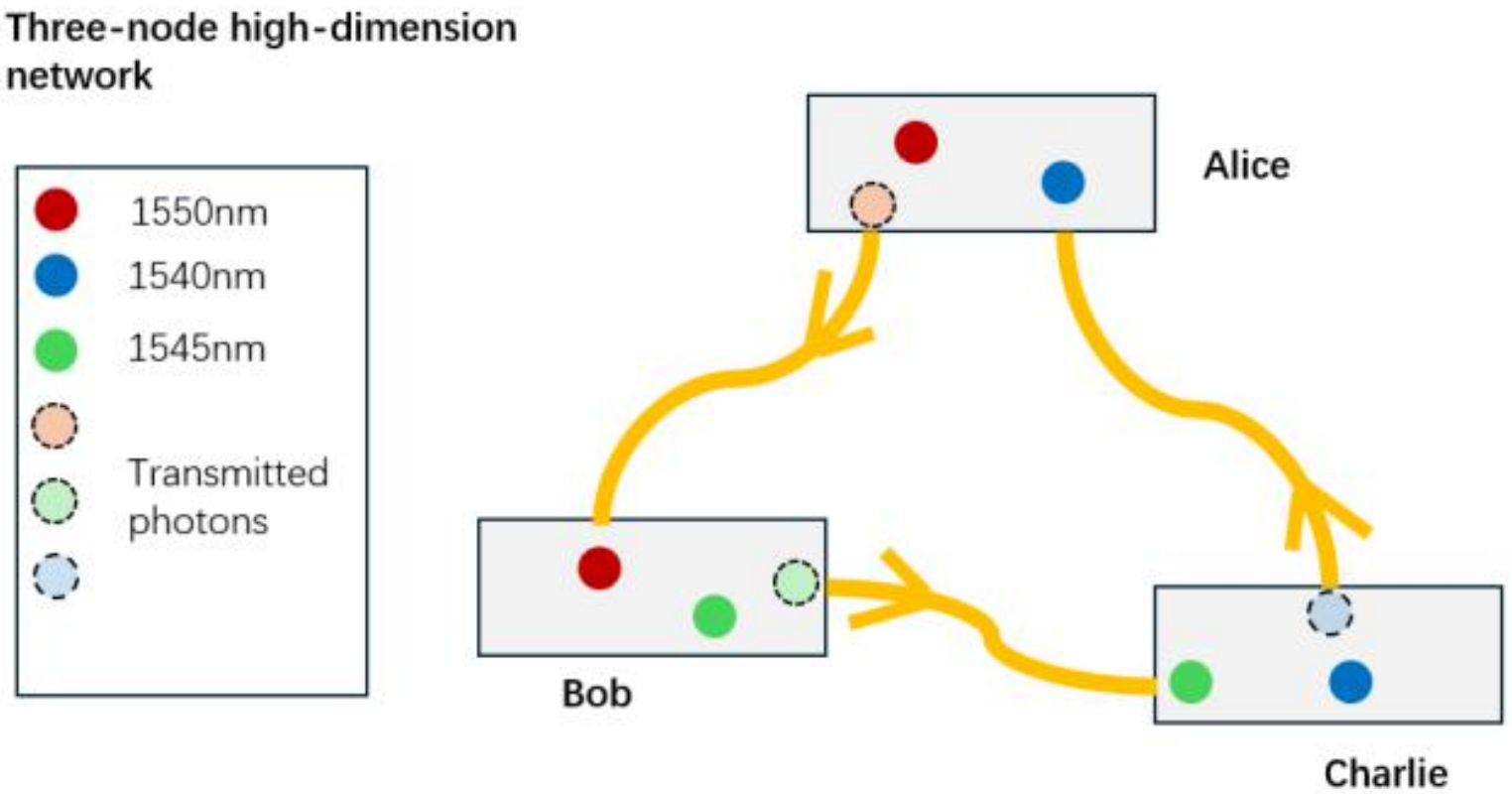


# Measured probabilities

Alice sends the eleven four-dimensional Bell states to Bob, and Bob performs a coincidence measurement on the two photons and obtains the probabilities for each input state.



# Scheme for realizing high-dimensional entangled photons sharing between three nodes in a quantum network



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Thank you very much