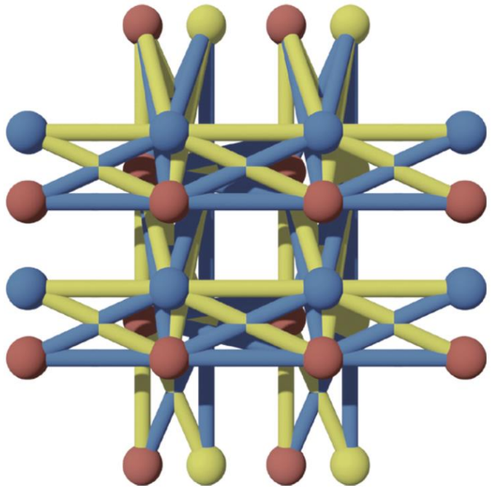


Development of
Large-scale
Fault-tolerant
Universal
Optical
Quantum
Computers

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

MS6 公開シンポジウム
March 27, 2024

誤り耐性型大規模汎用光量子コンピューターの研究開発

Akira Furusawa

Department of Applied Physics
School of Engineering
The University of Tokyo

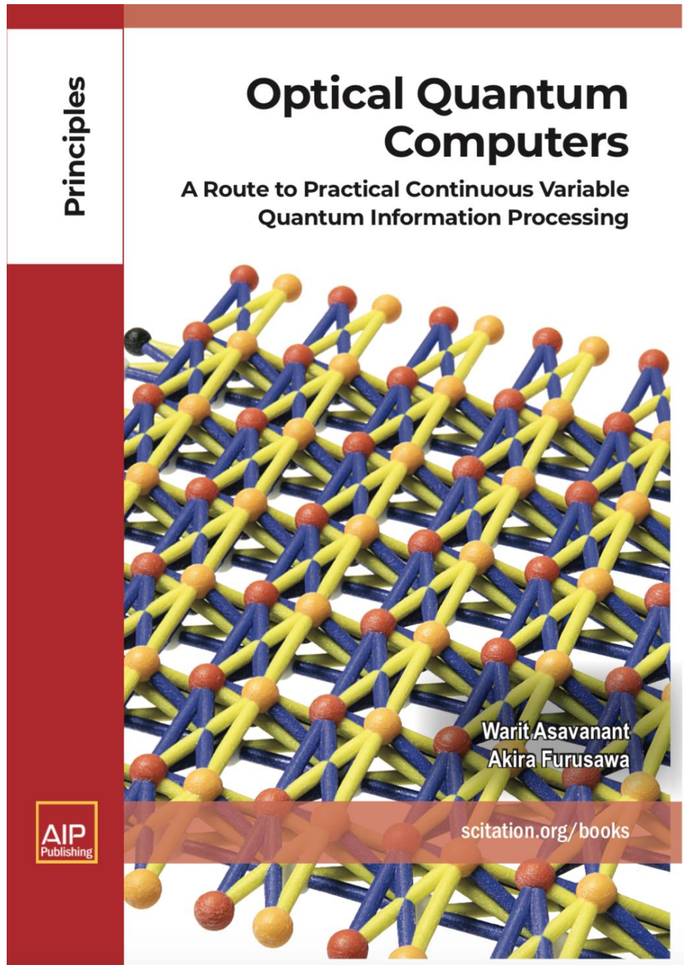
RIKEN
QUANTUM
COMPUTING

Caltech

Unconditional Quantum Teleportation

A. Furusawa, J. L. Sørensen, S. L. Braunstein, C. A. Fuchs,
H. J. Kimble,* E. S. Polzik

23 OCTOBER 1998 VOL 282 SCIENCE www.sciencemag.org



QUIC Caltech/MIT/USC 1997

古澤　明

1984年　東京大学工学
1986年　東京大学大学
（株）ニコ
1988-1990年　東京大学
1996-1998年　カリフ
2000年　東京大学大学
2007年　東京大学大学
2021年　理化学研究所

SPIE Photonics West | #P
@PhotonicsWest

フォロー

Akira Furusawa, plenary speaker and self-described “crazy windsurfer,” talks about the work his team is doing to build a real machine of optical quantum computers based on quantum teleportation technology. 🥼💥

@UTokyo_News_en @RIKEN_JP
#PhotonicsWest

ポストを翻訳

Collaborators

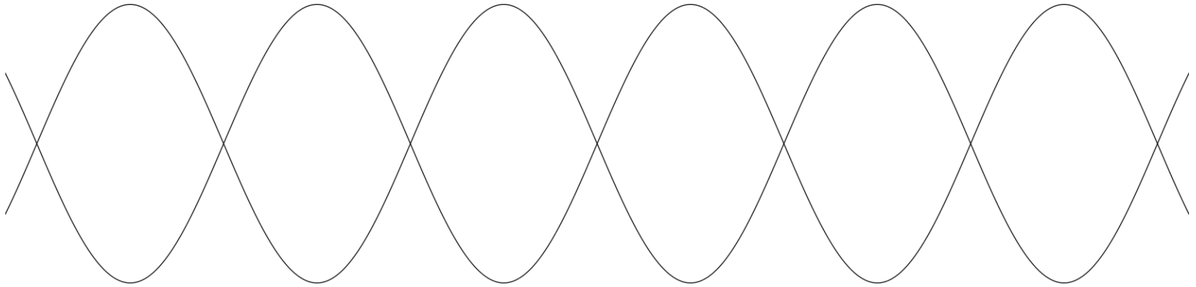
A. Furusawa The University of Tokyo, RIKEN
M. Endo, W. Asavanant, K. Takase, K. Fukui, B. Charoensombutamon, T. Yamashima,
T. Nakamura, A. Kawasaki, T. Sonoyama, F. Hanamura, B. Jeong, H. Nagayoshi,
T. Nomura, K. Takahashi, R. Ide, T. Suzuki, T. Sano, M. Nakashima, K. Hirota,
T. Hoshi, A. Sakaguchi (RIKEN), J. Yoshikawa (RIKEN), S. Yokoyama (RIKEN),
H. Yonezawa (RIKEN),

P. van Loock (Mainz), R. Filip (Palacky), P. Marek (Palacky), E. H. Huntington (ANU),
N. Menicucci (RMIT), R. Alexander (Xanadu), S. Miki (NICT), M. Yabuno (NICT),
F. China (NICT), H. Terai (NICT), D. Fukuda (AIST)
H. Takahashi (UTokyo), S. Takeda (UTokyo),
T. Hashimoto (NTT), T. Kashiwazaki (NTT), T. Kazama (NTT), K. Enbutsu (NTT),
R. Kasahara (NTT), T. Umeki (NTT), A. Inoue (NTT)

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

Conventional qubits = standing wave

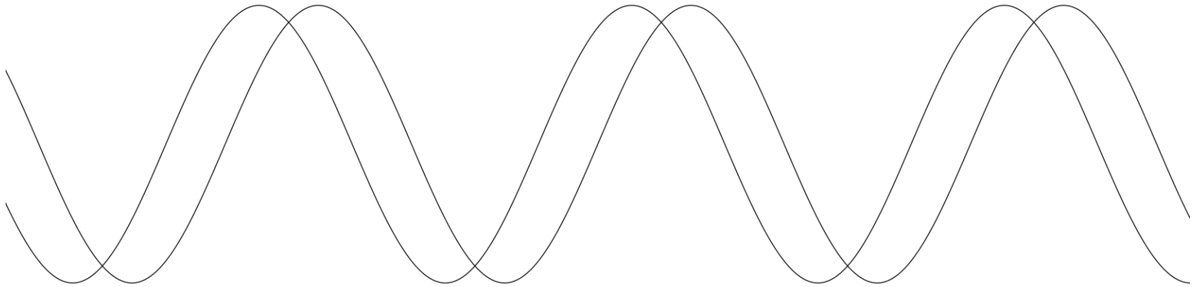
Life time (decoherence)
Need a chip, many cables (spatial-domain multiplexing)



1GHz clock frequency
Single core
Need quantum algorithms

Photonic qubits = traveling wave

No life time (measurement within coherence time)
No need a chip, 4 cables (time-domain multiplexing)

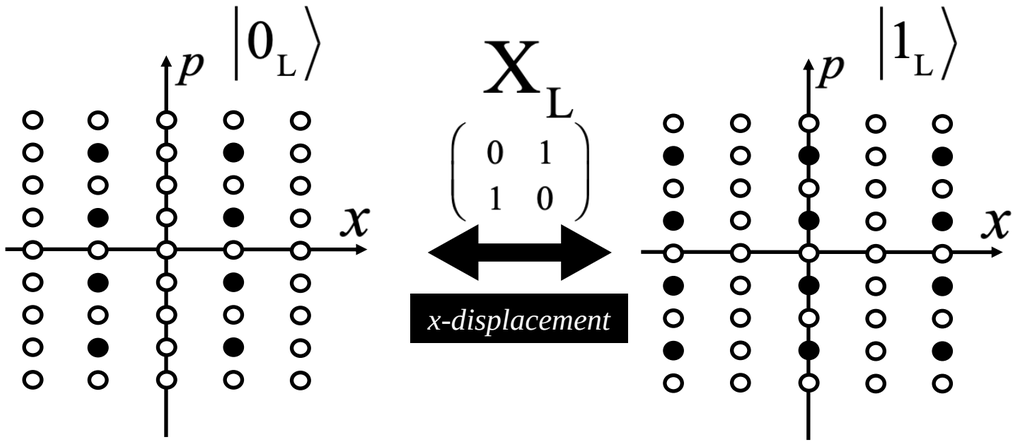


With 5G/6G technology
100GHz clock frequency
100 multi-core
Super quantum computer
No need quantum algorithms

Fault-tolerant quantum computing

GKP qubits & Logical operations

Logical qubits for Quantum error correction



D. Gottesman et al. PRA **64,** 012310 (2001)

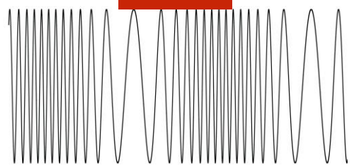
Complex amplitude

$$\hat{a} = \hat{x} + i\hat{p}$$

$$\left[\hat{x}, \hat{p}\right] = \frac{i}{2}$$

$$\hbar = \frac{1}{2}$$

FM $\hat{p}$

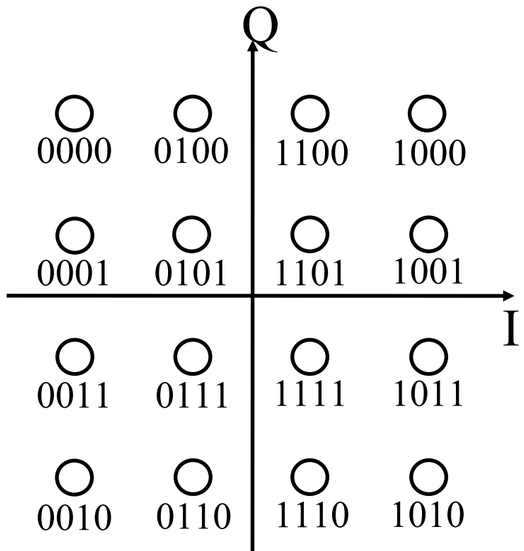


5G technology

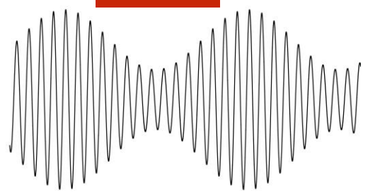
Quadrature Amplitude Modulation
QAM

Coherent communication

Radio AM FM



AM $\hat{x}$



Fault-tolerant quantum computing

GKP qubits & Logical operations

○ $+\infty$

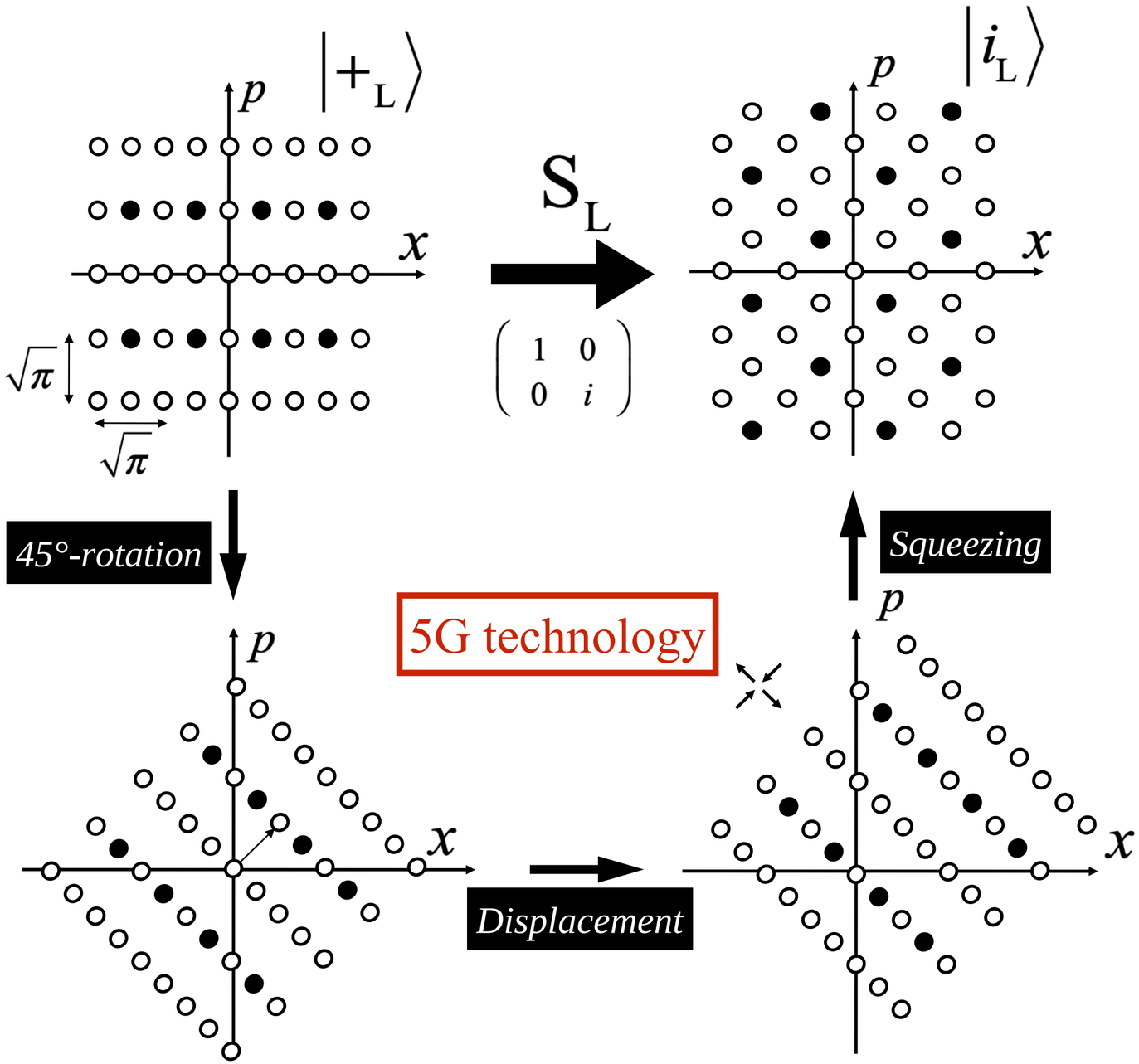
● $-\infty$

Complex amplitude

$$\hat{a} = \hat{x} + i\hat{p}$$

$$\left[\hat{x}, \hat{p}\right] = \frac{i}{2}$$

$$\hbar = \frac{1}{2}$$

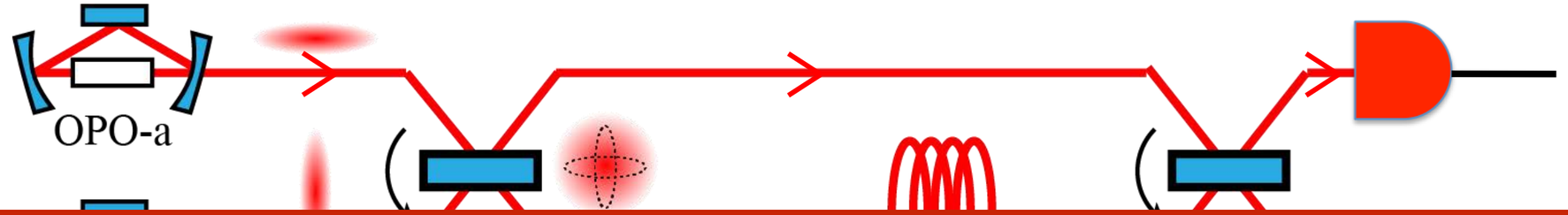


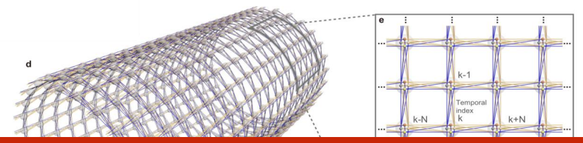
Clifford

Gaussian

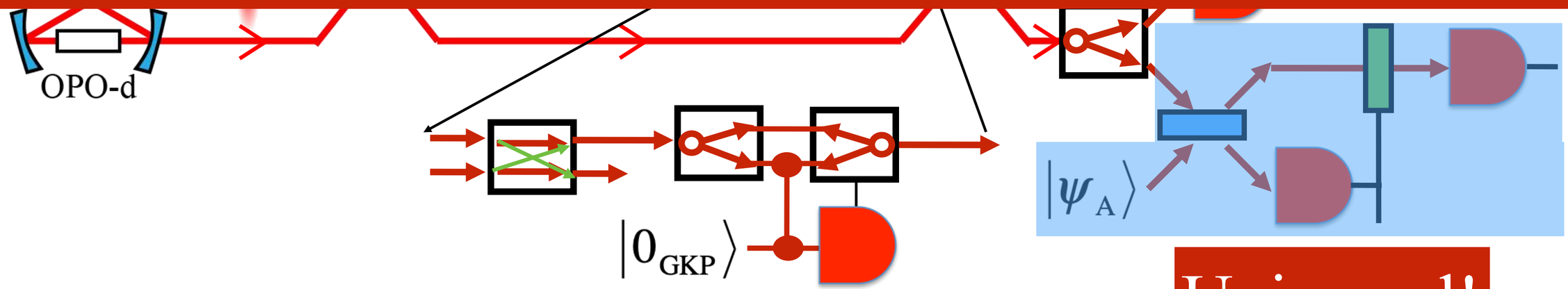
Goal

Optical parametric amplifier





All-optical quantum computer with 10THz clock frequency

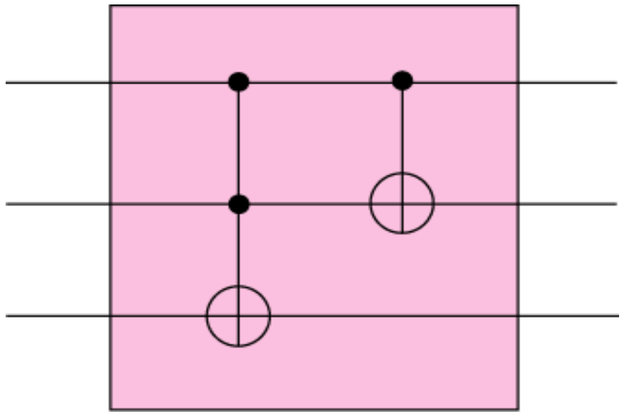


Fault tolerant!

Universal!

Quantum computing

Quantum circuit model



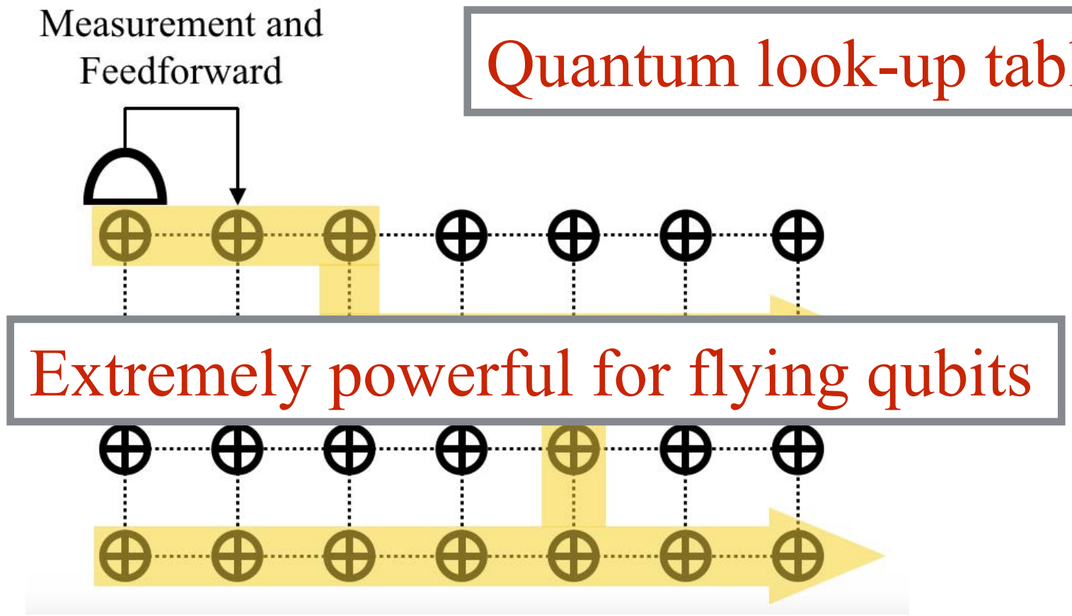
Qubit
R. P. Feynman (1980)

Continuous variable
S. Lloyd and S. L. Braunstein (1999)

Measurement-based model (one-way quantum computing)

Large-scale entangled state (Cluster state)
Measurement and Feedforward

Sequential teleportation



Qubit
R. Raussendorf and H. J. Briegel (2001)

$$\oplus = \left(|0\rangle + |1\rangle\right)/\sqrt{2}$$

Continuous variable
N. C. Menicucci and P. van Loock et al. (2006)

$$\oplus = \int_{-\infty}^{+\infty} dx\,|x\rangle$$

Changing measurement bases = changing operation

The age of standing-wave qubit is over!!

Traveling wave → Measurement within laser coherence time

No decoherence!!

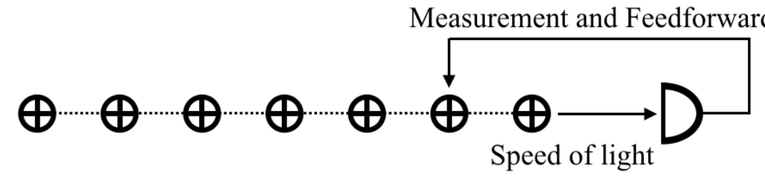
We can do it forever!!

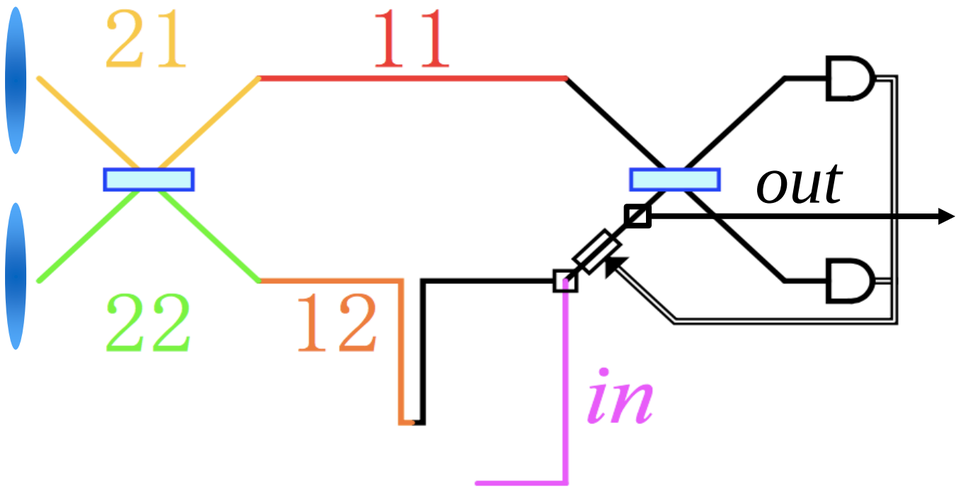
No flex ng)

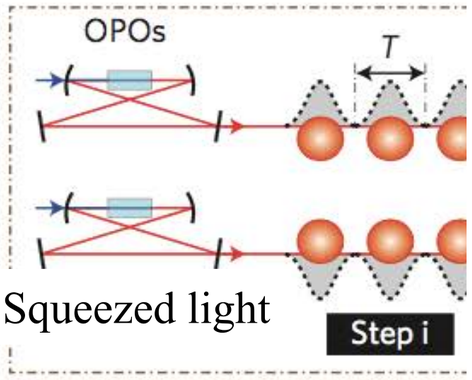
Measurement-based m

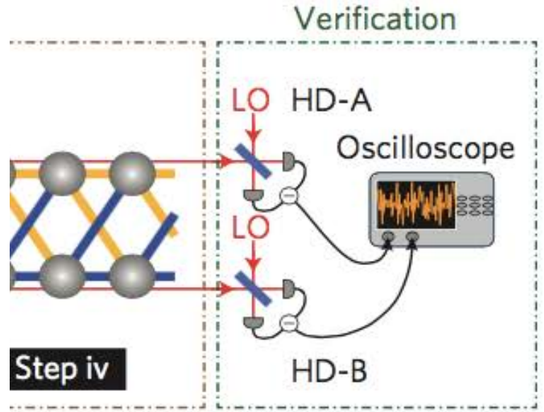
One-way quantum cor

CV cluster state!!







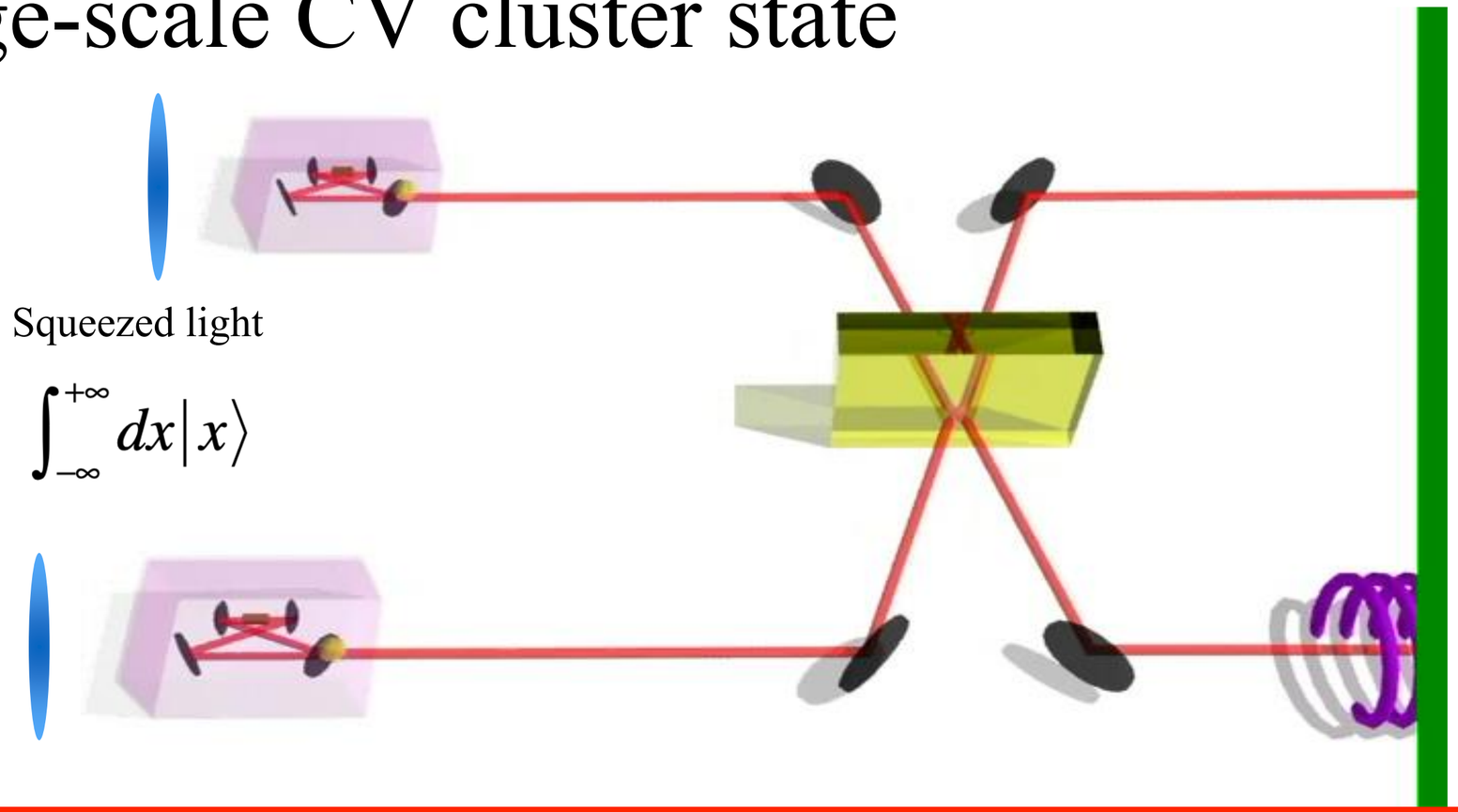


10000-wave-pa

Large-scale quantum computing = fixed-size of the setup

Programmable

Ultra-large-scale CV cluster state



Unlimited time-domain multiplexing technology

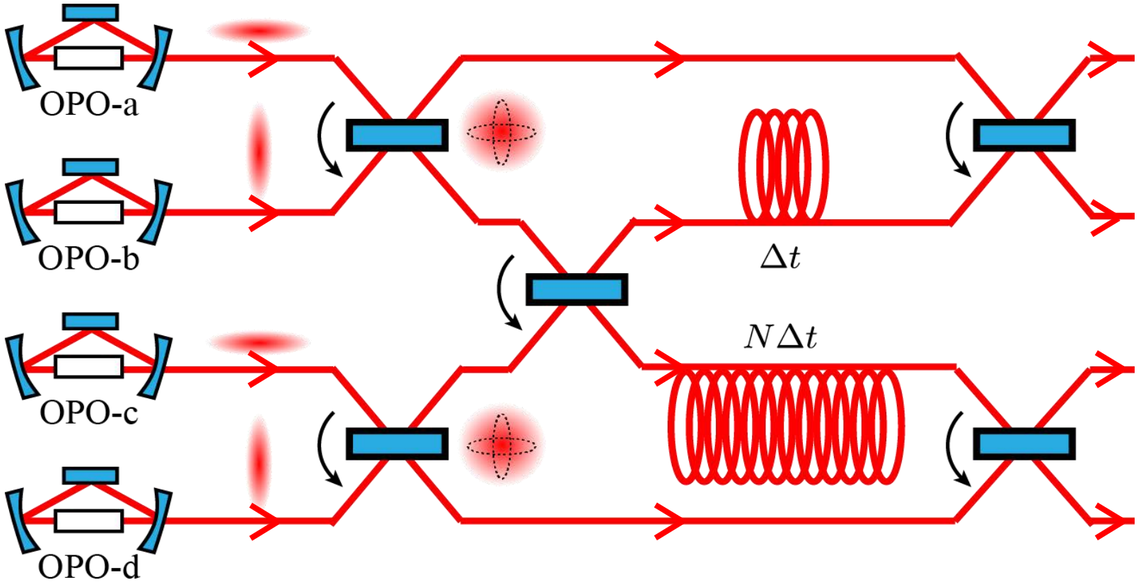
One-million wave-packet entanglement!!

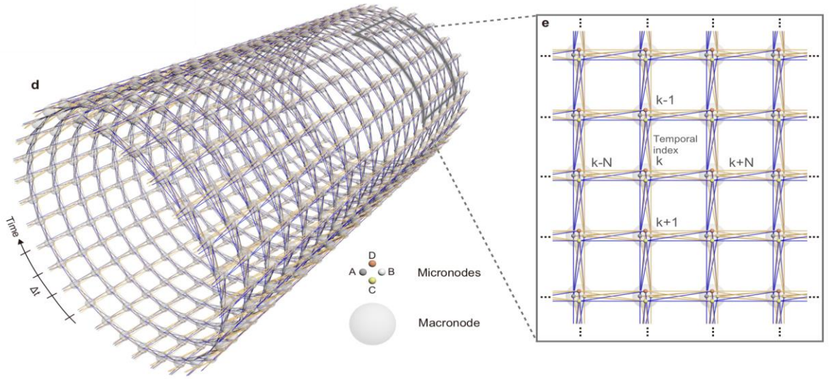
S. Yokoyama, R. Ukai, S. C. Armstrong, C. Sornphiphatphong, T. Kaji, S. Suzuki, J. Yoshikawa, H. Yonezawa, N. C. Menicucci, and A. Furusawa, Nature Photonics 7, 982 (2013).

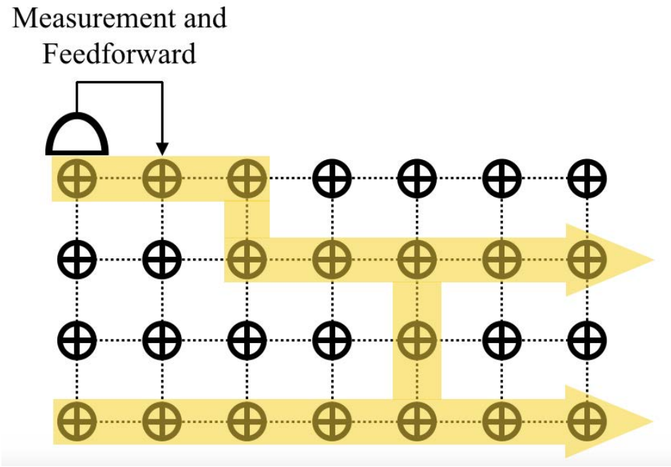
J. Yoshikawa, S. Yokoyama, T. Kaji, C. Sornphiphatphong, Y. Shiozawa, K. Makino, and A. Furusawa, APL Photonics 1, 060801 (2016).

Time-domain multiplexed 2D cluster state

Quantum look-up table







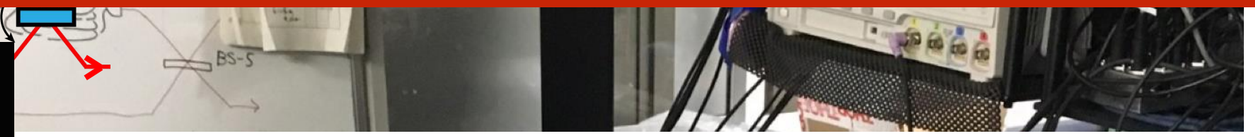
QUANTUM COMPUTING

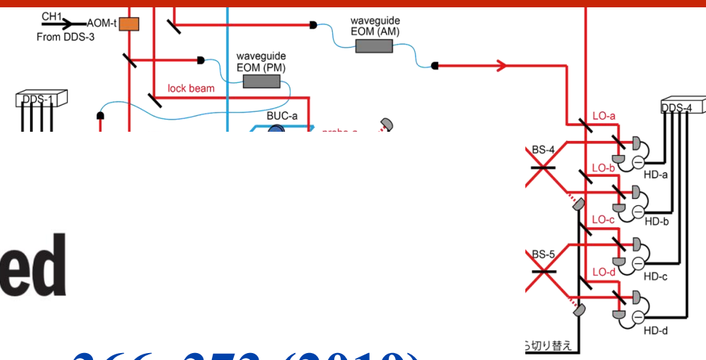
Generation of time-domain-multiplexed two-dimensional cluster state

Science 366, 373 (2019)

Warit Asavanant[1], Yu Shiozawa[1], Shota Yokoyama[2], Baramee Charoensombutamon[1], Hiroki Emura[1], Rafael N. Alexander[3], Shuntaro Takeda[1,4], Jun-ichi Yoshikawa[1], Nicolas C. Menicucci[5], Hidehiro Yonezawa[2], Akira Furusawa[1]*

We succeeded in creation of a 2D cluster state of 5 x 5000 !!





QUANTUM COMPUTING

Generation of time-domain-multiplexed two-dimensional cluster state

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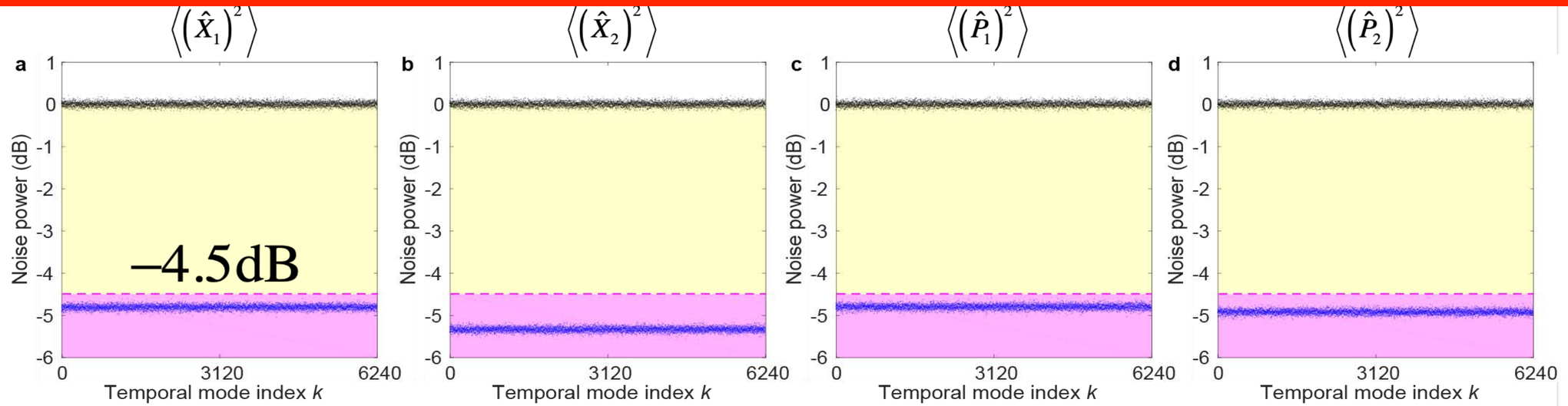
Warit Asavanant[1], Yu Shiozawa[1], Shota Yokoyama[2], Baramee Charoensombutamon[1], Hiroki Emura[1], Rafael N. Alexander[3], Shuntaro Takeda[1,4], Jun-ichi Yoshikawa[1], Nicolas C. Menicucci[5], Hidehiro Yonezawa[2], Akira Furusawa[1]*

P. van Loock & A. Furusawa, Phys. Rev. A 67, 052315 (2003)

The van loock - Furusawa criteria



Goal

Homodyne measurement

OPO-a

OPO-b

OPO-c

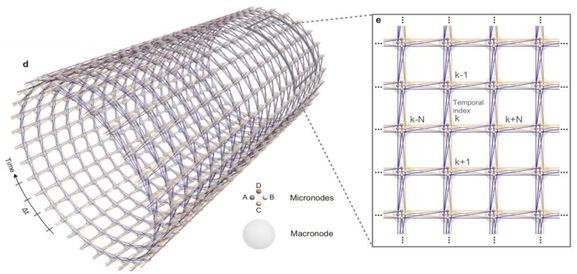
OPO-d

Δt

$N\Delta t$

$|0_{GKP}\rangle$

$|\psi_A\rangle$



Large scale!

Fault tolerant!

Universal!

Fault-tolerant quantum computing

GKP qubits & Logical operations

○ $+\infty$

● $-\infty$

Complex amplitude

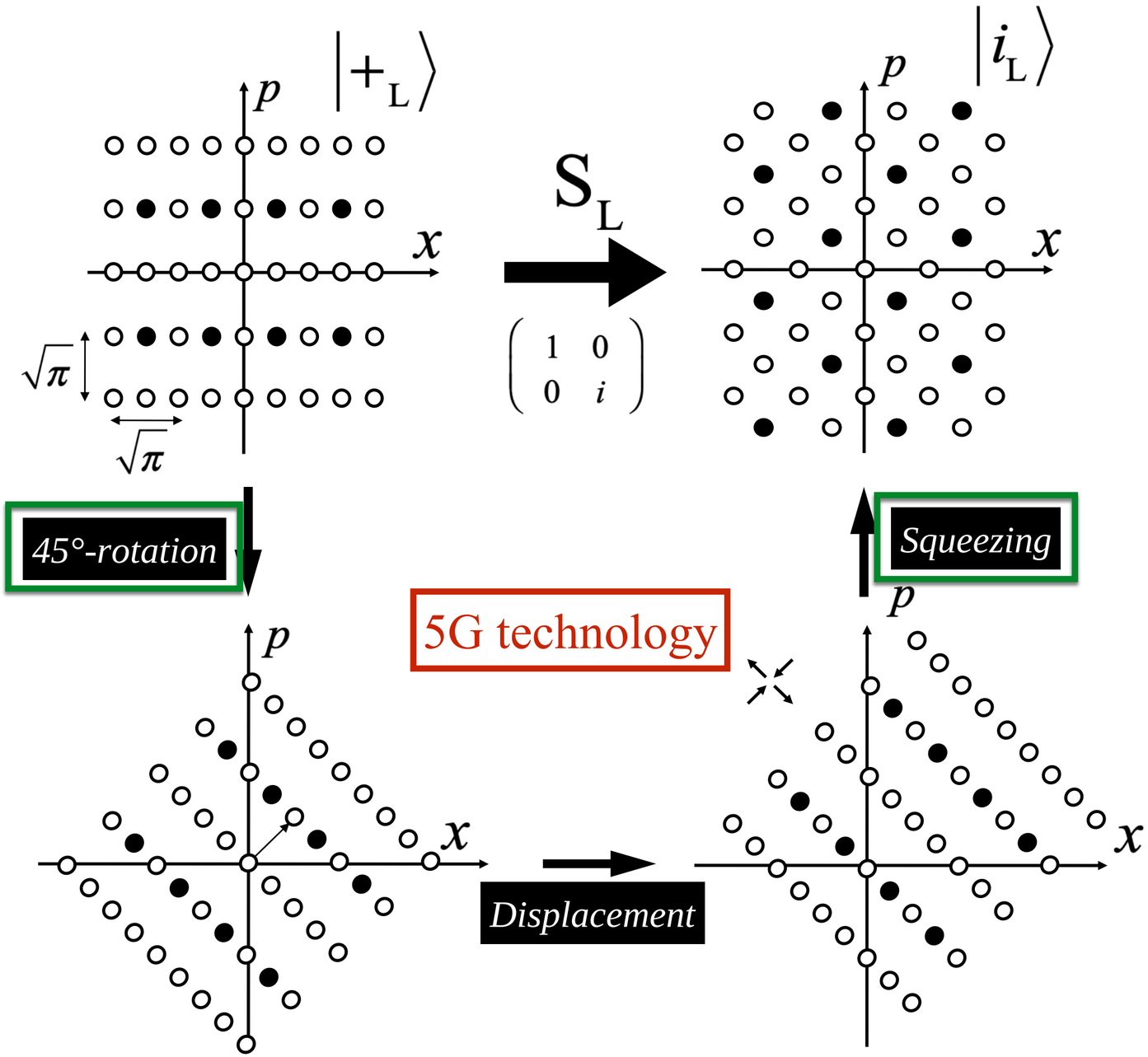
$$\hat{a} = \hat{x} + i\hat{p}$$

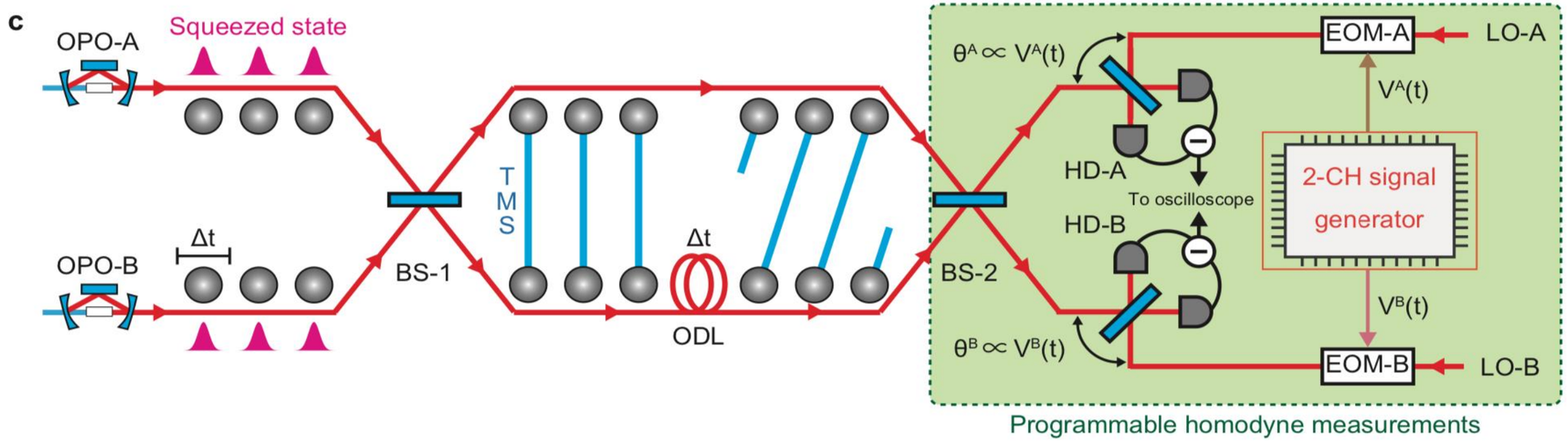
$$\left[\hat{x}, \hat{p}\right] = \frac{i}{2}$$

$$\hbar = \frac{1}{2}$$

Clifford

Gaussian





Phase rotation

$$\begin{pmatrix} \cos\theta & \sin\theta \\ \cdots & \cdots \end{pmatrix}$$

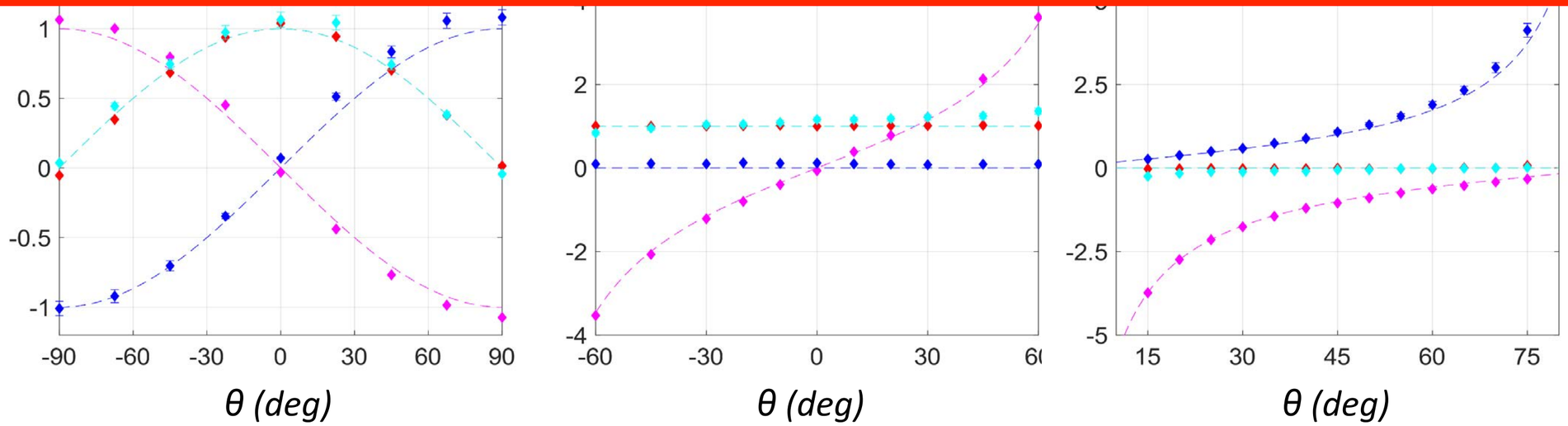
Shear

$$\begin{pmatrix} 1 & 0 \\ \cdots & \cdots \end{pmatrix}$$

Squeezing

$$\begin{pmatrix} 0 & \tan\theta \\ \cdots & \cdots \end{pmatrix}$$

Clifford universality!!

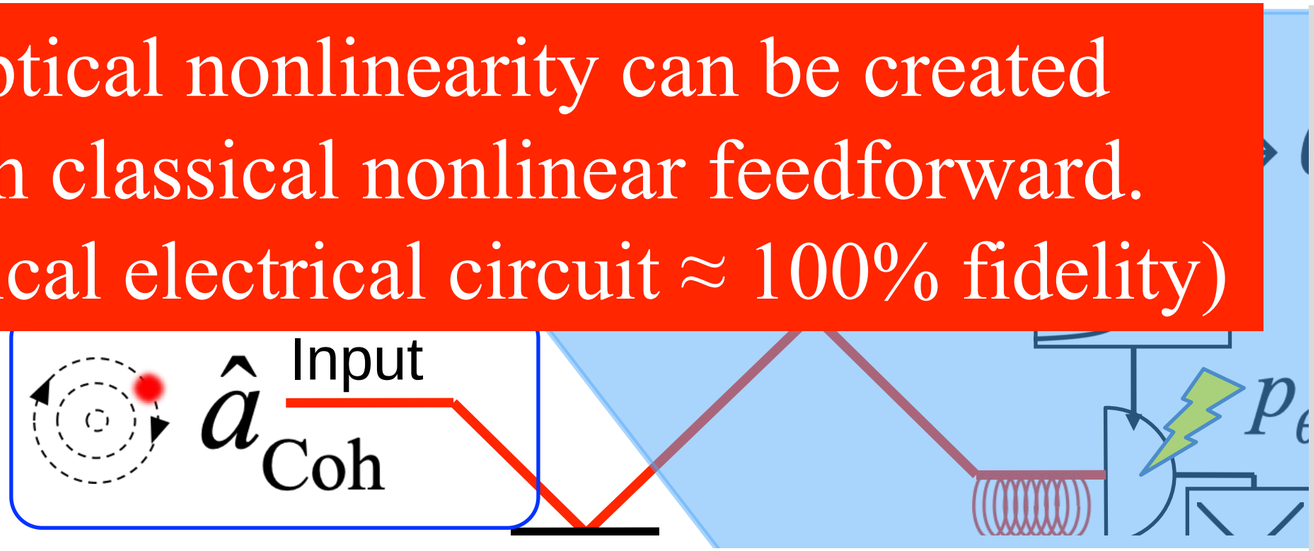


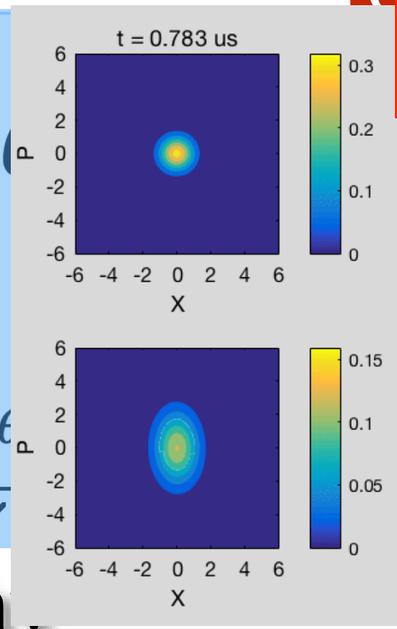
W. Asavanant et al., Phys. Rev. Applied 16, 034005 (2021).

Nonlinear measurement

5G technology

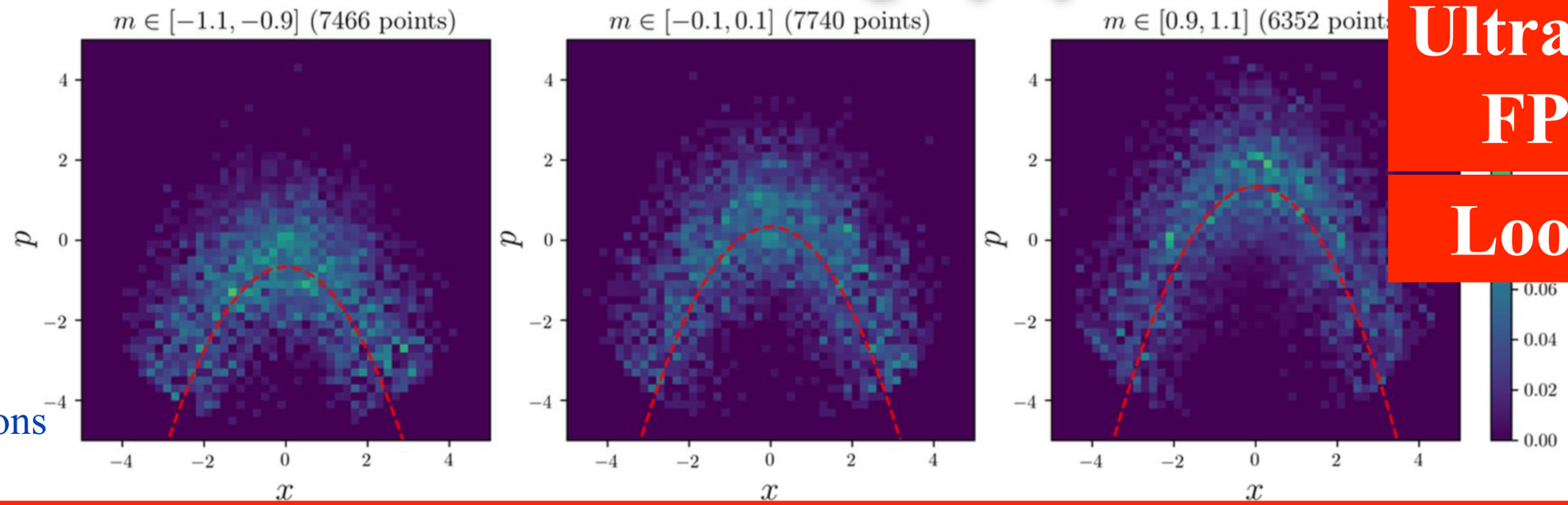
Optical nonlinearity can be created
with classical nonlinear feedforward.
(classical electrical circuit ≈ 100% fidelity)





20GHz ASIC!!

Detector tomography



Ultra-low-latency
FPGA board

Lookup table!!

A. Sakaguchi et al.,
Nature Communications
14, 3817 (2023).

We succeeded in projection onto a cubic phase state!!

Goal

Homodyne measurement

OPO-a

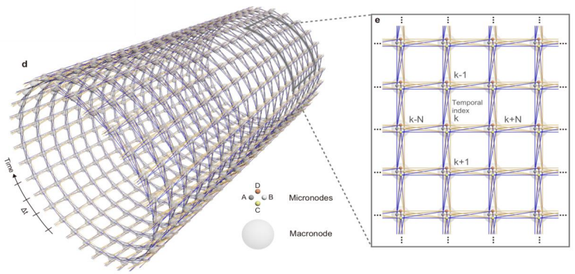
OPO-b

OPO-c

OPO-d

Δt

$N\Delta t$



Large scale!

$|0_{GKP}\rangle$

Fault tolerant!

$|\psi_A\rangle$

Universal!

GKP qubit generation

H. M. Vasconcelos et al., Opt. Lett. 35, 3261 (2010).
D. J. Weigand & B. M. Terhal, PRA 97, 022341 (2018).

RESEARCH ARTICLE

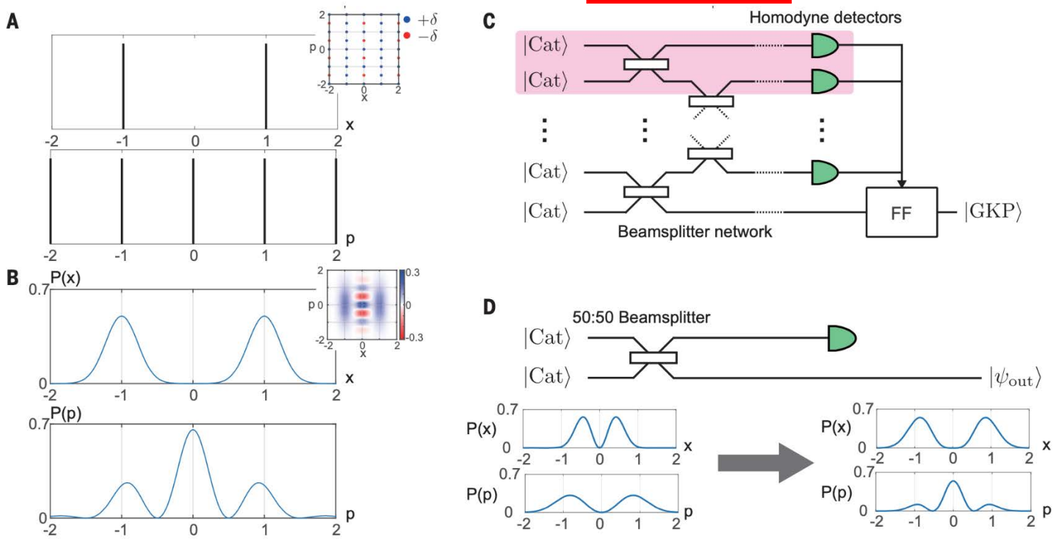
QUANTUM OPTICS

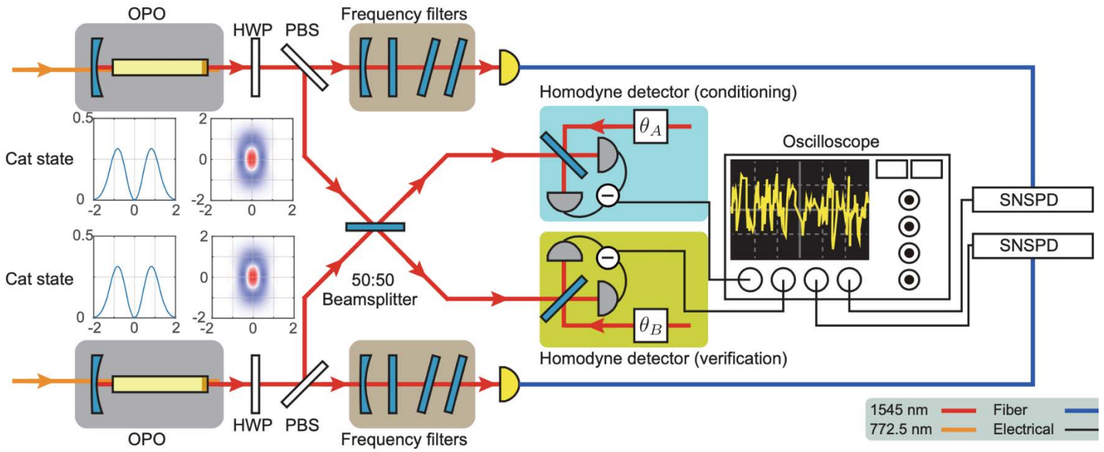
Logical states for fault-tolerant quantum computation with propagating light

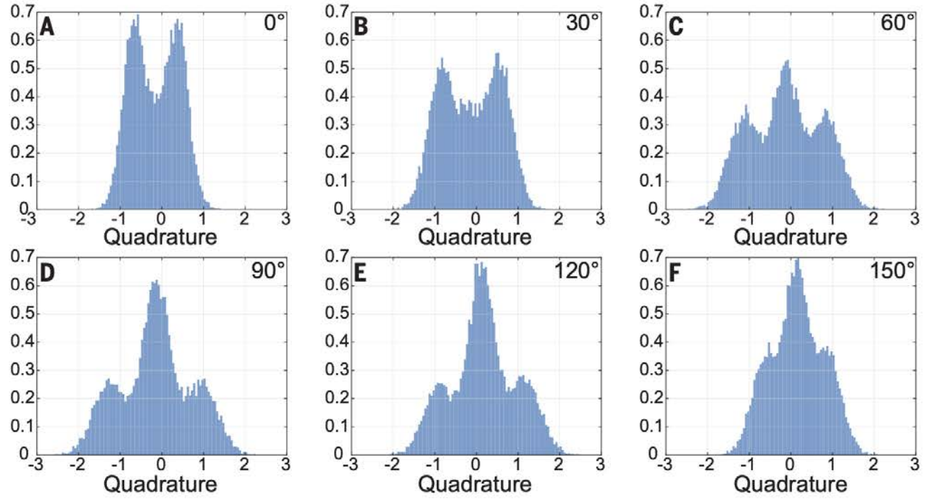
Shunya Konno[1]†, Warit Asavanant[1,2]*, Fumiya Hanamura[1], Hironari Nagayoshi[1], Kosuke Fukui[1], Atsushi Sakaguchi[2], Ryuhoh Ide[1], Fumihiro China[3], Masahiro Yabuno[3], Shigehito Miki[3,4], Hirotaka Terai[3], Kan Takase[1,2], Mamoru Endo[1,2], Petr Marek[5], Radim Filip[5], Peter van Loock[6], Akira Furusawa[1,2]*

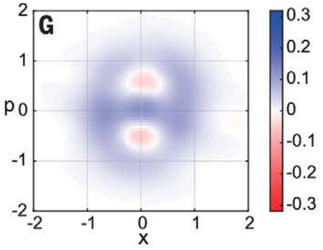
Science 383, 289 (2024)

Breeding



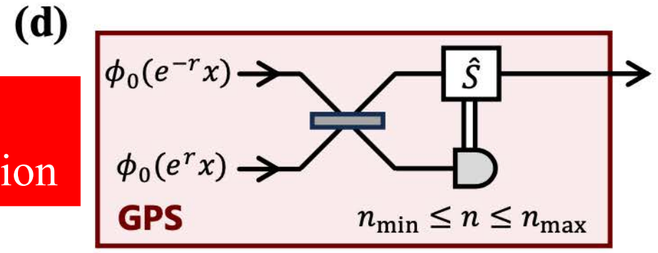


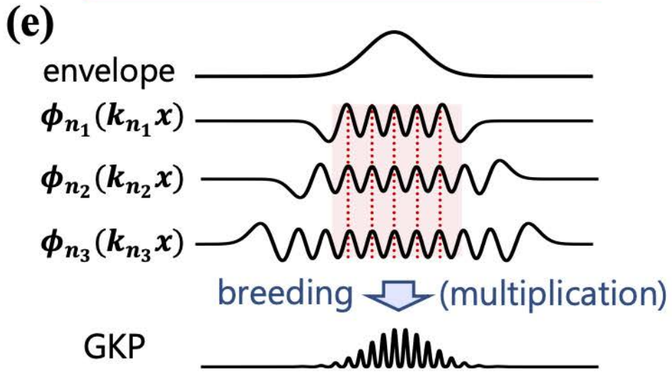


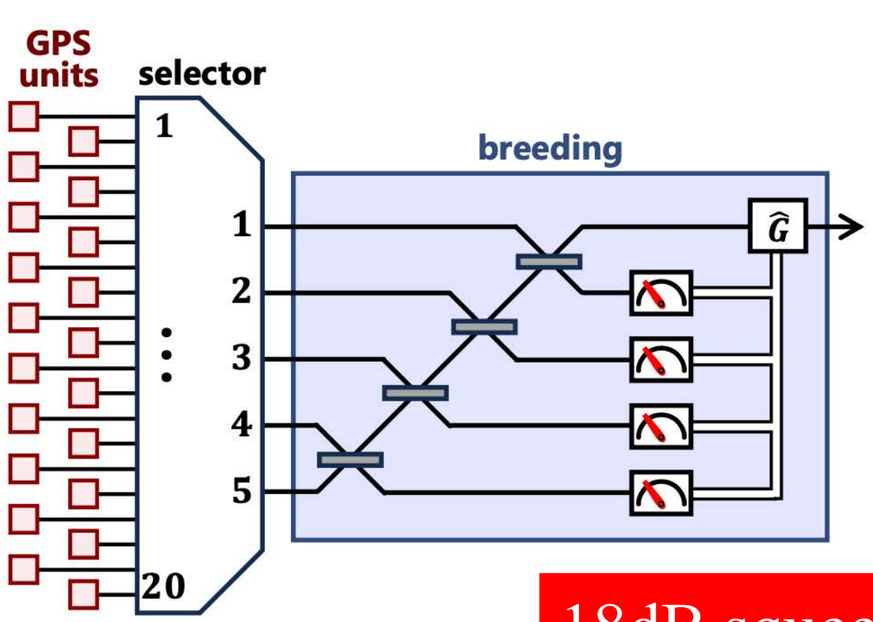


GKP qubit generation

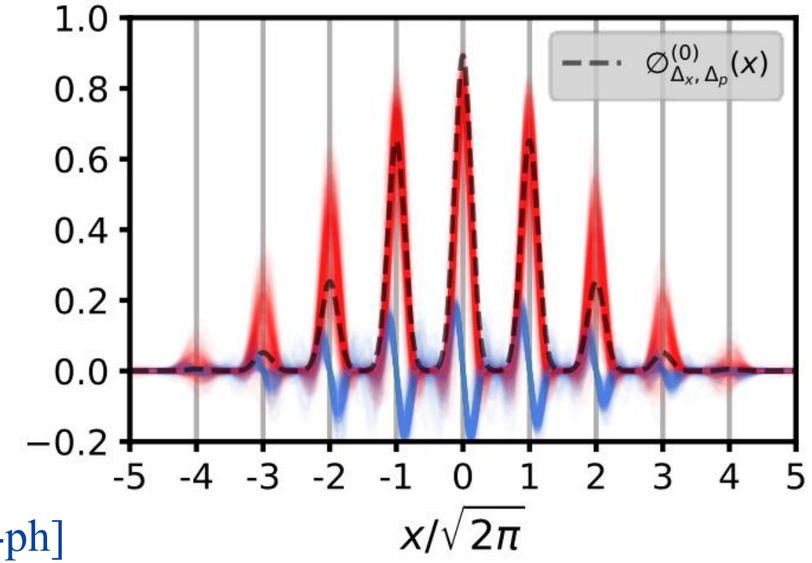
Generalized Photon Subtraction







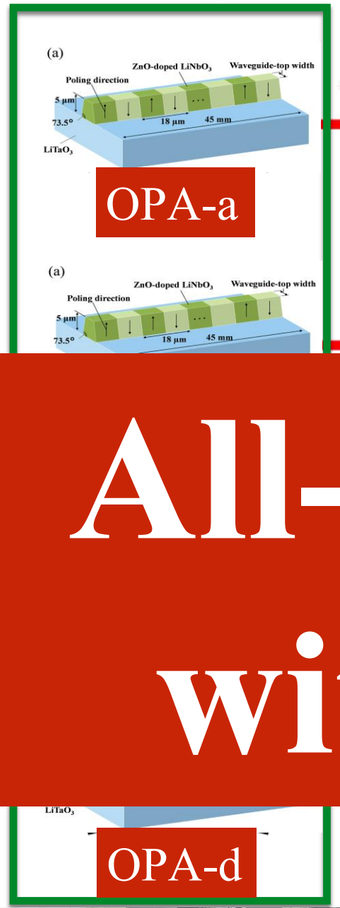
18dB squeezed vacuum
n = 10 – 20
Success probability 10%



K. Takase et al., arXiv:2401.07287 [quant-ph]

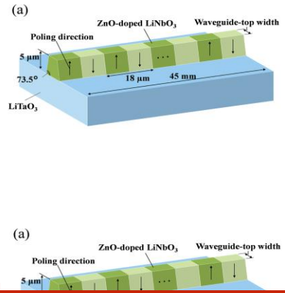
Goal

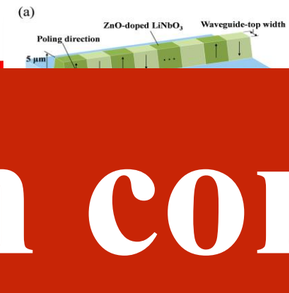
Optical parametric amplifier

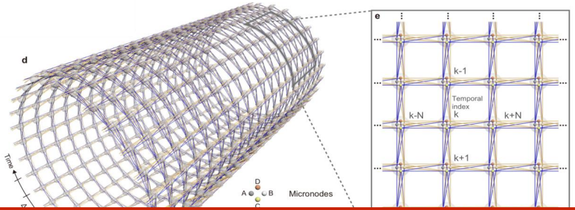


OPA-a

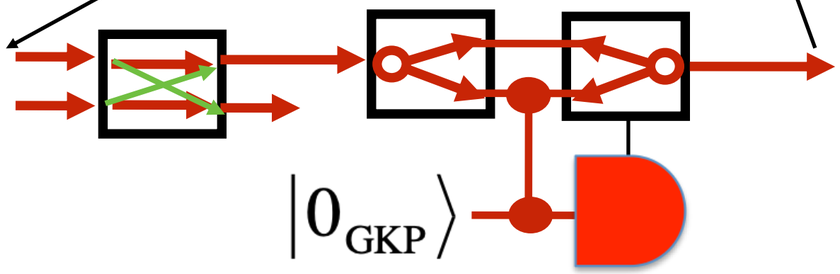
OPA-d



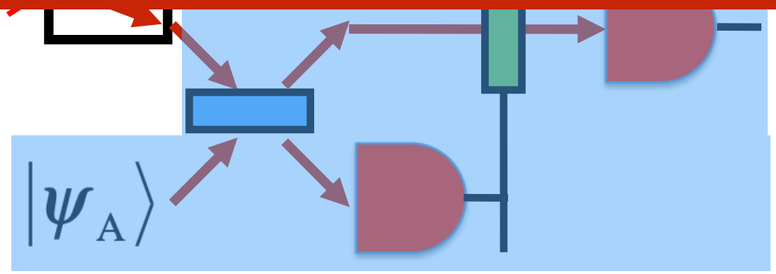




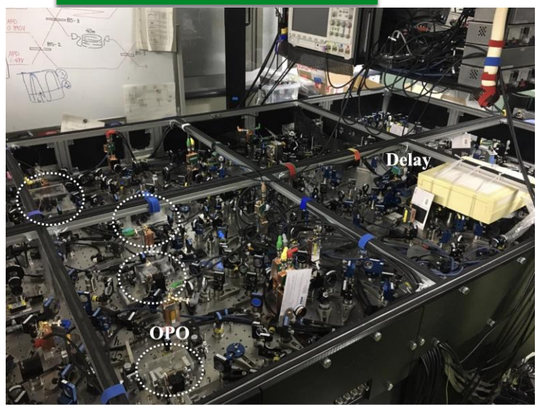
All-optical quantum computer with 10THz clock frequency



Fault tolerant!



Universal!



Applied Physics Letters ARTICLE pubs.aip.org/aip/apl

Over-8-dB squeezed light generation by a broadband waveguide optical parametric amplifier toward fault-tolerant ultra-fast quantum computers

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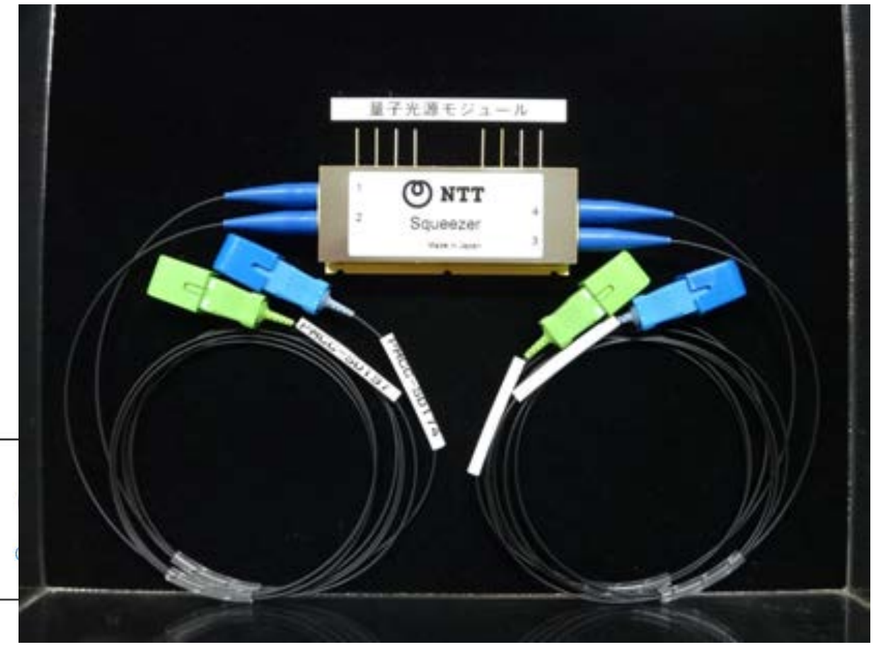


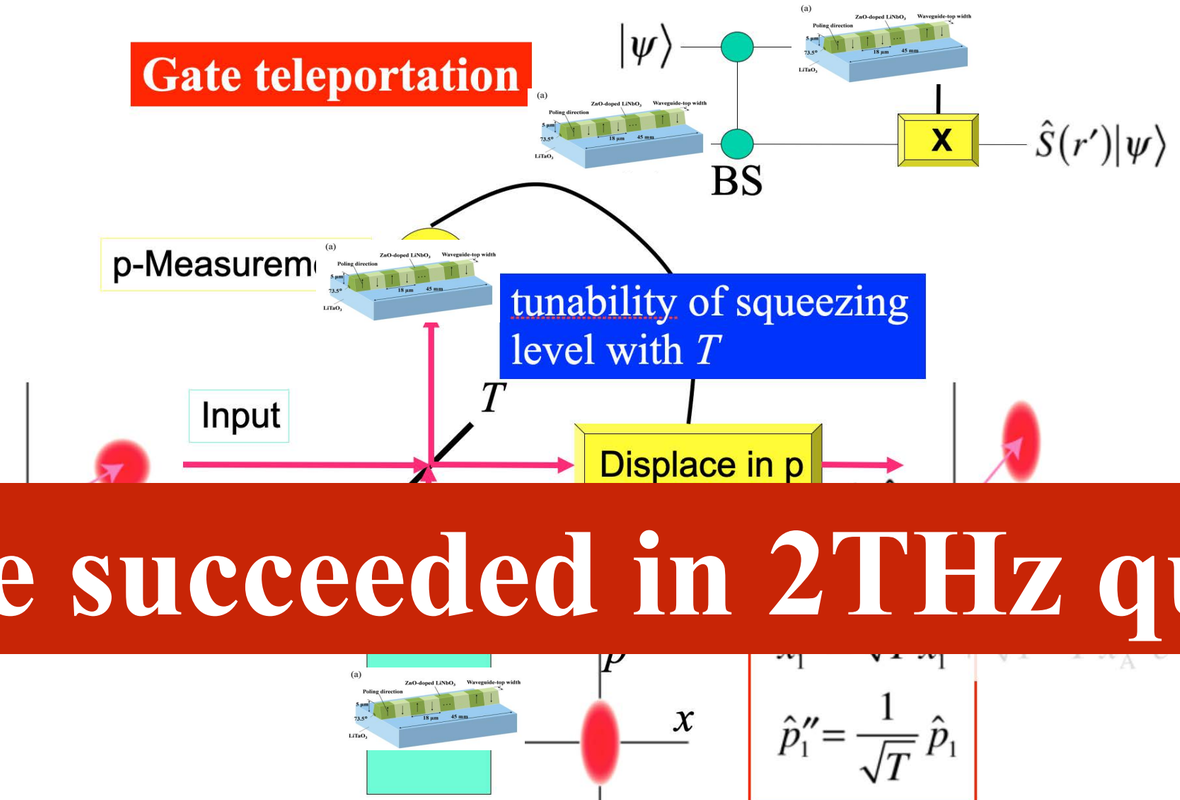
Above a fault-tolerant threshold!!

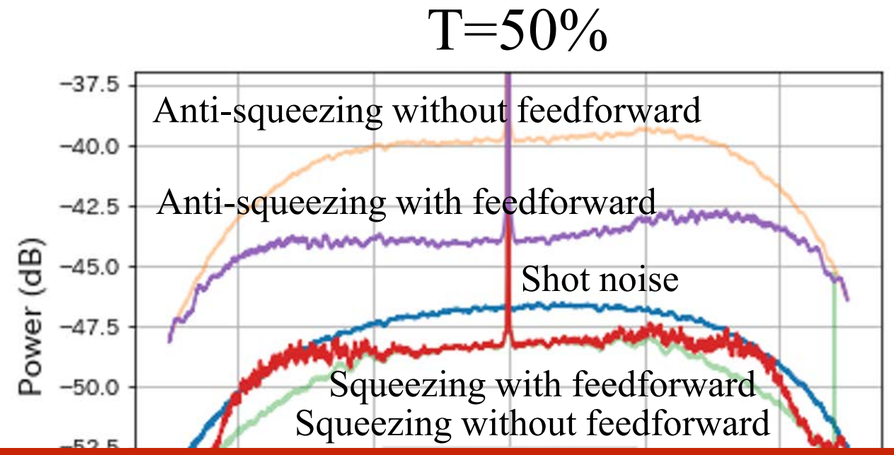
8.3 dB squeezing

6 THz bandwidth

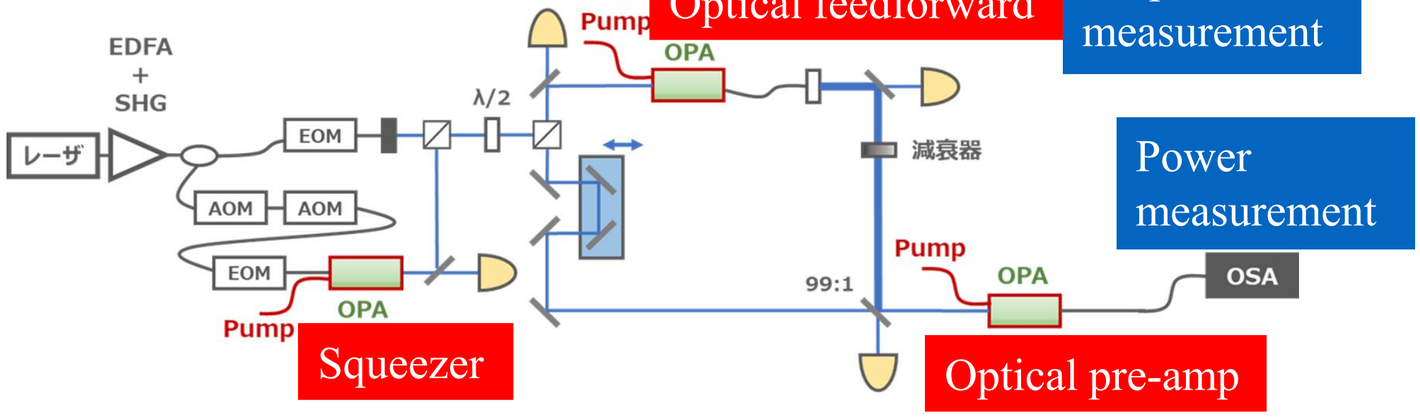
K. Fukui, Phys. Rev. A 107, 052414 (2023)

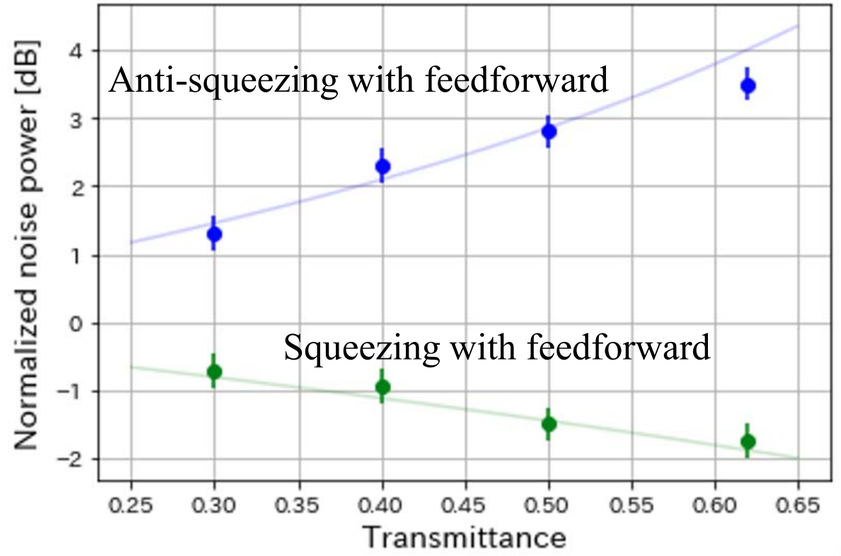
2THz-bandwidth universal squeezer





We succeeded in 2THz quantum operation!!

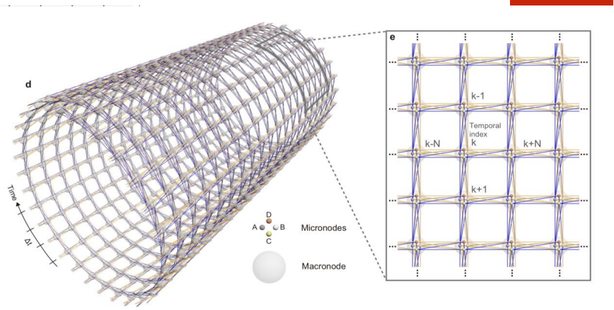




PHYSICAL REVIEW RESEARCH 1, 033063 (2019)

CV-Quantum Neural Networks

Continuous-variable quantum neural networks



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[1]*Xanadu, Toronto, Ontario, Canada M5G 2C8*
[2]*Massachusetts Institute of Technology, Department of Mechanical Engineering*
77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA

CV-QAOA

$$y = f(x_1, x_2, \cdots, x_n)$$

A Quantum Approximate Optimization Algorithm for continuous problems

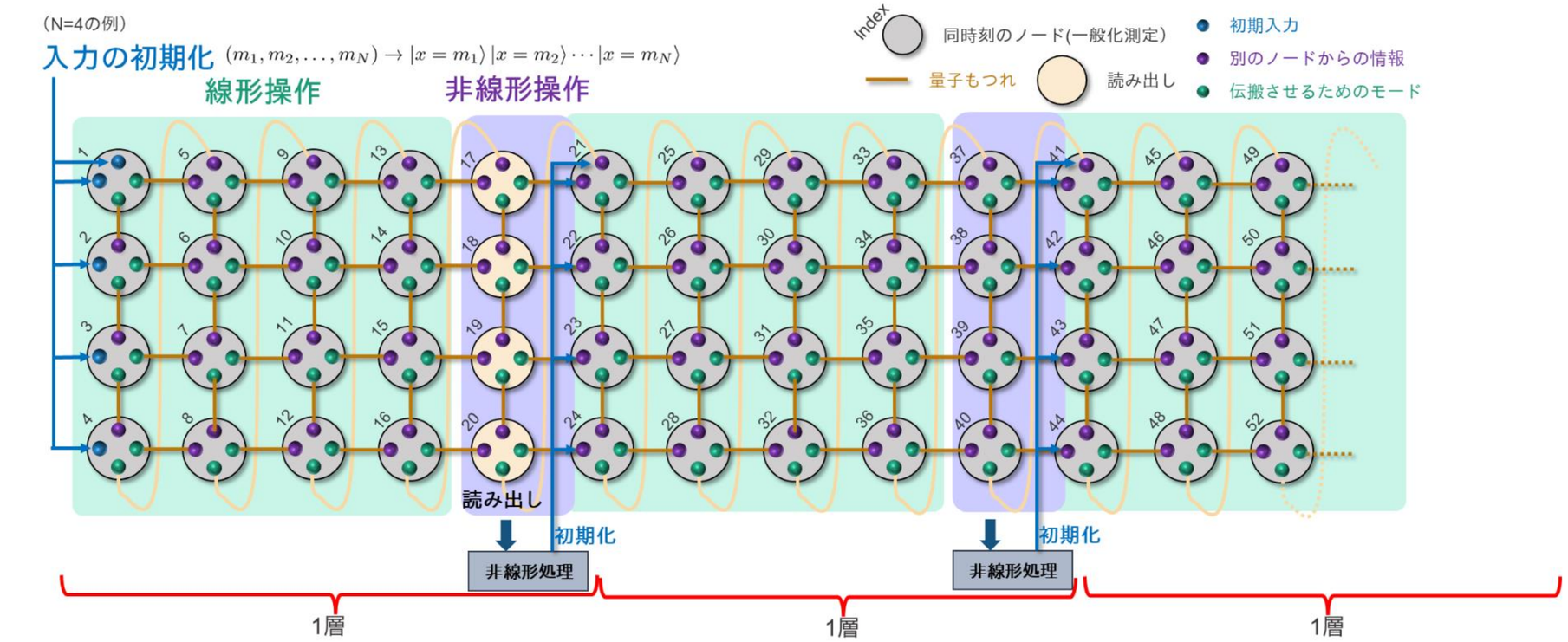
Guillaume Verdon,[1,2,3,*] Juan Miguel Arrazola,[4,†] Kamil Brádler,[4] and Nathan Killoran[4]
[1]*Department of Applie… …terlo… …rio, N2L 3G1, Canada*
[2]*Institute for Quantu… …erloo… …o, N2L 3G1, Canada*
[3]*Perimeter In… …Water… …2Y5, Canada*
[4]*Xanadu, 777 Bay Street, Toronto, Ontario, M5G 1S5, Canada*

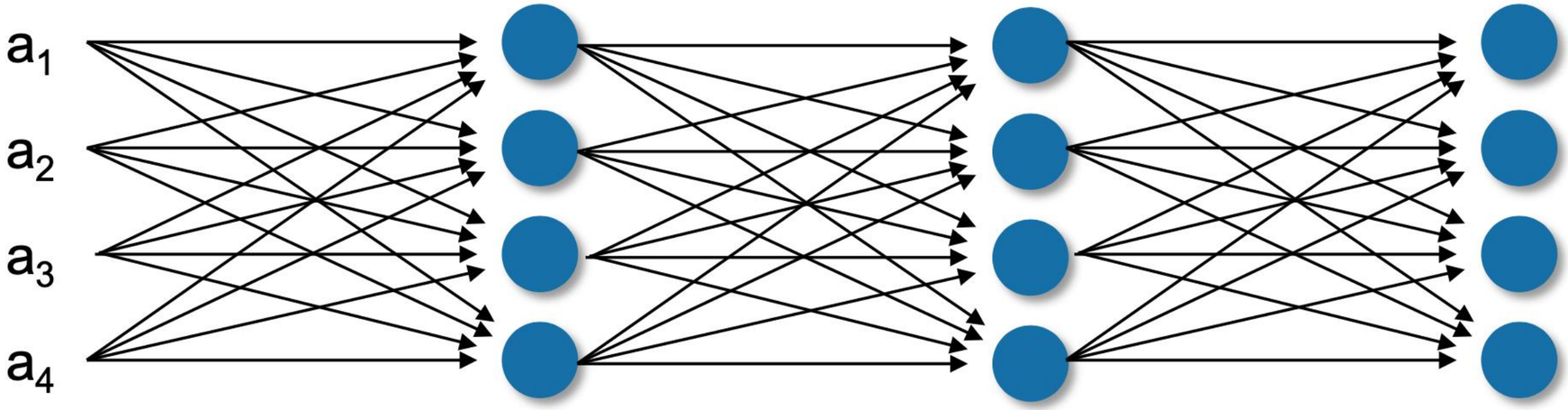
Real machine **Cloud**

100MHz→10GHz→100GHz Clock

5G technology

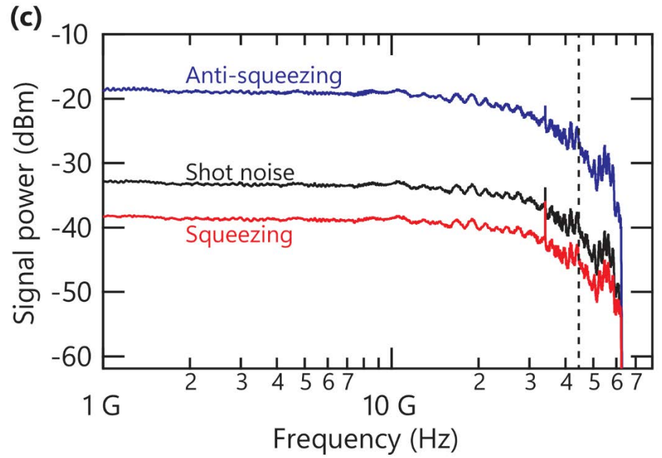
CV-Quantum Neural Networks

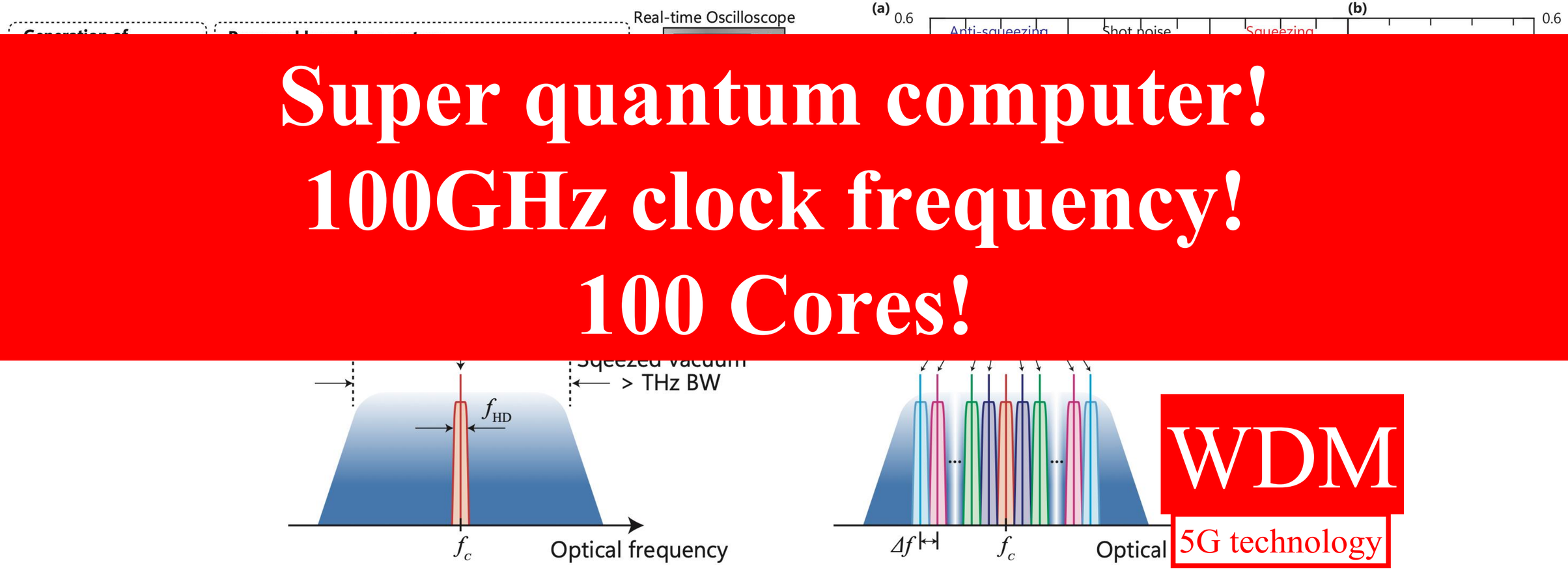




Applied Physics Letters ARTICLE scitation.org/journal/apl

Toward a multi-core ultra-fast optical quantum processor: 43-GHz bandwidth real-time amplitude measurement of 5-dB squeezed light using modularized optical parametric amplifier with 5G technology

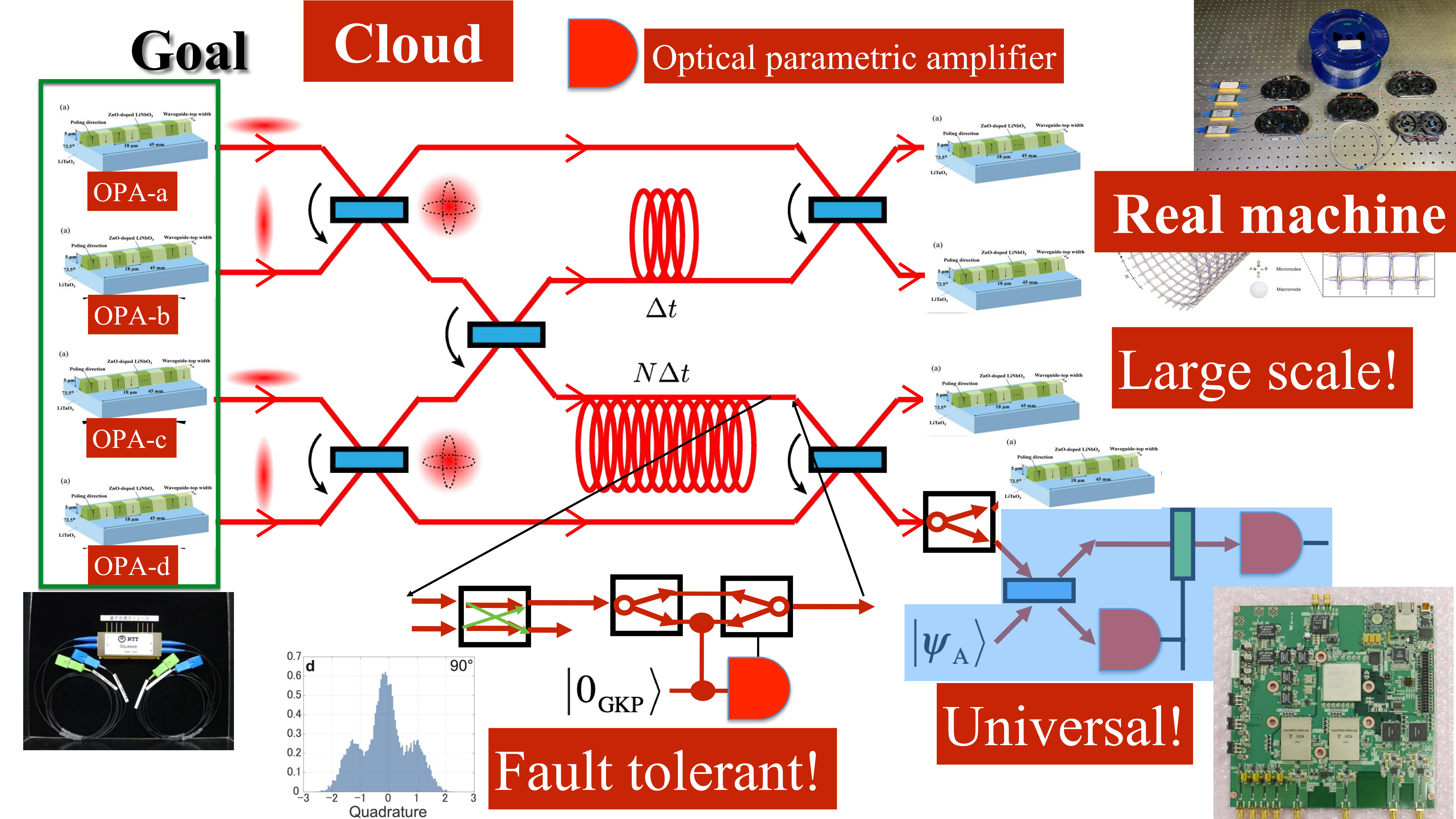




Super quantum computer!
100GHz clock frequency!
100 Cores!

WDM
5G technology

A. Inoue et al., Apple. Phys. Lett. 122, 104001 (2023).


Goal
Cloud
Optical parametric amplifier
Real machine
Large scale!
Fault tolerant!
Universal!
OPA-a
OPA-b
OPA-c
OPA-d
(a)
Poling direction
ZnO-doped LiNbO$_3$
Waveguide-top width
5 µm
73.5°
18 µm
45 mm
LiTaO$_3$
Δt
$N\Delta t$
$|0_{\mathrm{GKP}}\rangle$
$|\psi_{\mathrm{A}}\rangle$
d
90°
Quadrature
Micronodes
Macronode
NTT
Squeezer

This book is a current and rare treatment of the theoretical and experimental aspects of one of the most promising approaches to quantum computation—continuous-variable (CV) quantum computation using optical systems. In addition to its pedagogical value to those new to quantum computing, it is also a practical handbook for both experimentalists and theorists working in the field. ***Optical Quantum Computers: A Route to Practical Continuous Variable Quantum Information Processing*** summarizes many recent experimental developments

Researchers, graduate students, and those working in the quantum computing industry and its related fields will find this an invaluable resource.

Warit Asavanant, Ph.D., is an Assistant Professor of Applied Physics at The University of Tokyo, Japan. He earned his Ph.D. at the Furusawa–Yoshikawa Laboratory with research topics centering the usage of continuous-variable optical entanglement in quantum computation. He received an award for his outstanding M.S. thesis from the Department of Applied Physics, Graduate School of Engineering, The University of Tokyo.

Akira Furusawa, Ph.D., is a Professor of Applied Physics at The University of Tokyo and a Deputy Director of RIKEN Center for Quantum Computing, Japan. He is a pioneer in quantum teleportation and his research has ensured great progress toward the realization of optical quantum computers using quantum teleportation techniques. He is the recipient of numerous awards, including the Ryogo Kubo Memorial Award in 2006, the JSPS Prize and Japan Academy Medal in 2007, the International Quantum Communication Award in 2008, the Toray Science and Technology Prize in 2014, and the Medal of Honor with Purple Ribbon in 2016.

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Principles

Principles

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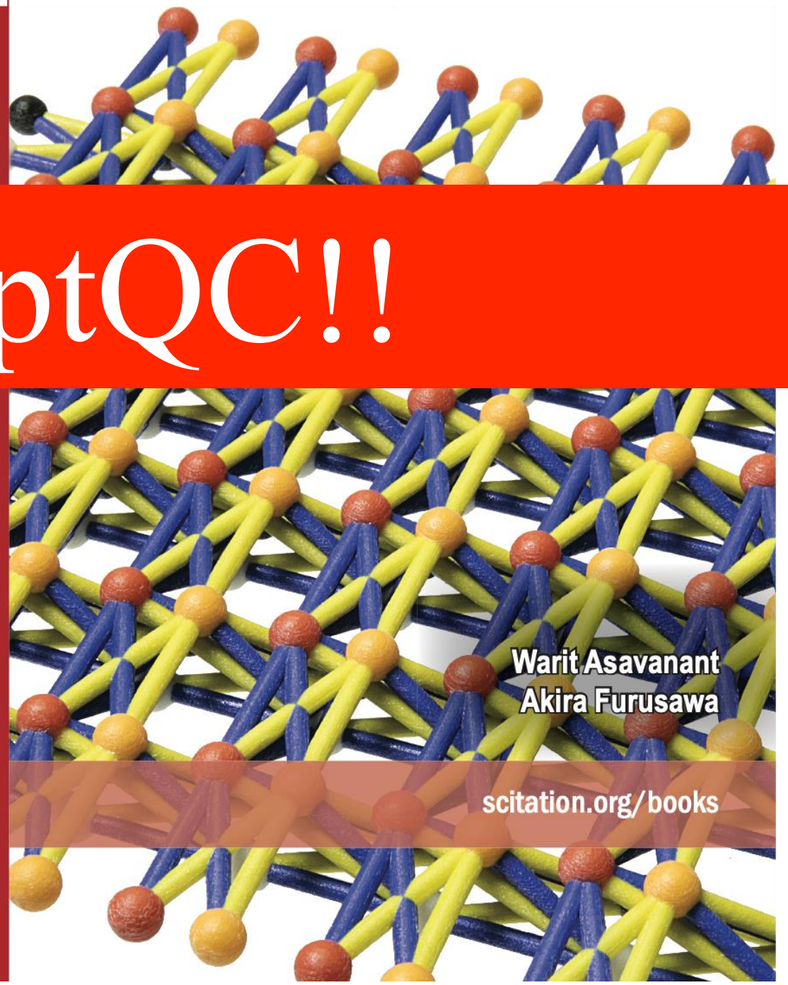
Optical Quantum Computers

A Route to Practical Continuous Variable Quantum Information Processing



We will launch OptQC!!