ASPIRE Kickoff Meeting 2025
June 6, 2025@U. Ulm

Diamond Spin Qubits for Quantum Computing and Communication

Hideo Kosaka

Professor, Yokohama National University
Director, Quantum Information Research Center
Research fellow, The University of Tokyo
Japan

YNU
YOKOHAMA National University
QIC
UTokyo

MIC
JPMI00316
MOONSHOT
JPMJMS2062

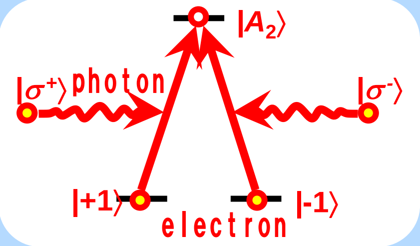
MIC

JPMI00316

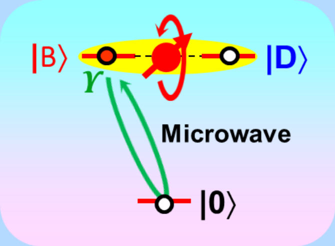
Diamond NV center for Quantum Repeater

Under zero magnetic field at relatively high temperature (10K)

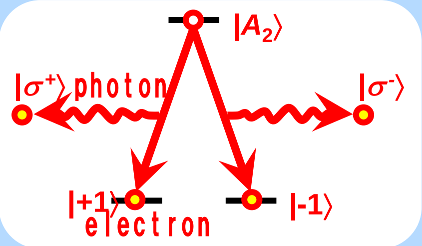
Long coherence time>0.1s, fast operation>400MHz→high fidelity>99.97%



Physical Review Letters, 114, 053603 (2015)



Nature Communications, 7, 11668 (2016)

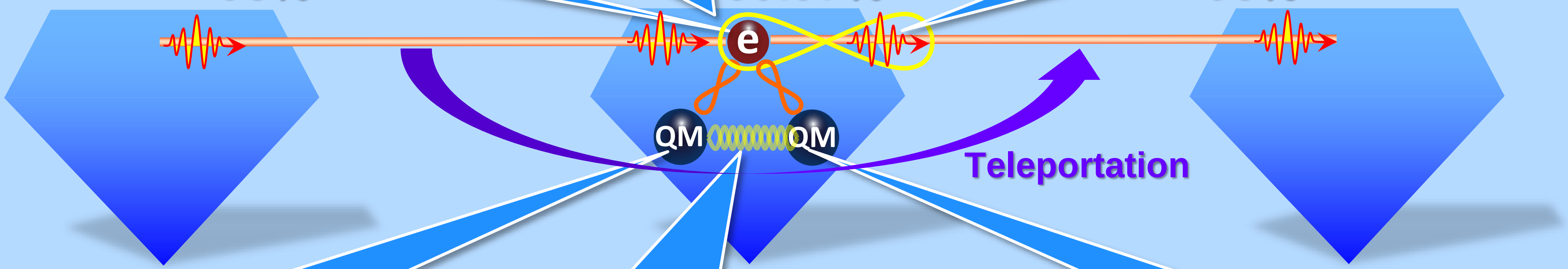


Communications Physics, 4, 264 (2021)

Q. State Transfer 98%

Fault-tolerant Q. Gate 99.97%

Entangled Emission 98%



Initialization & Readout 99.7%

Appl. Phys. Lett. 120, 194002 (2022)

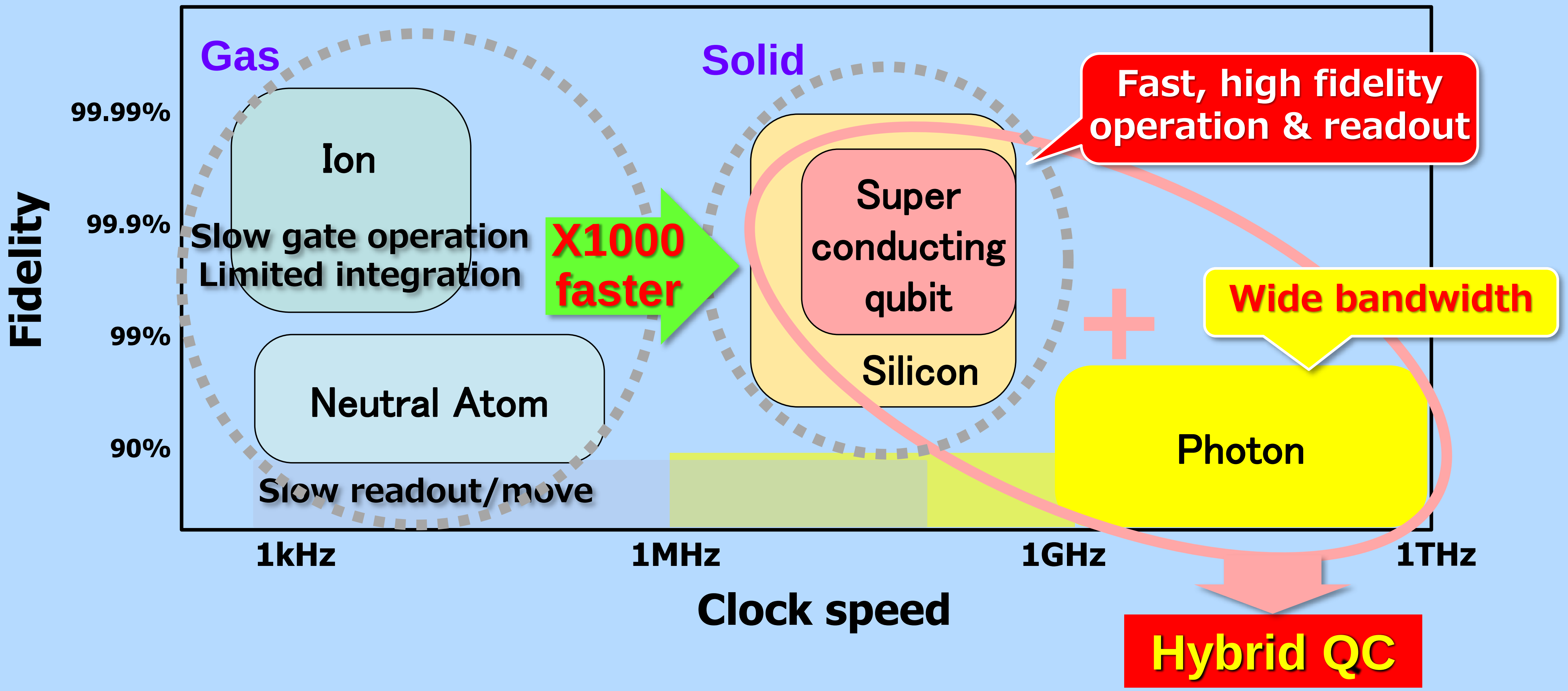
Bell State Meas. 90%

Appl. Phys. Lett. 120, 194002 (2022)
npj Quantum Information 9, 101 (2023)

Q. Error Correction 86%

Communications Physics 5, 102 (2022)

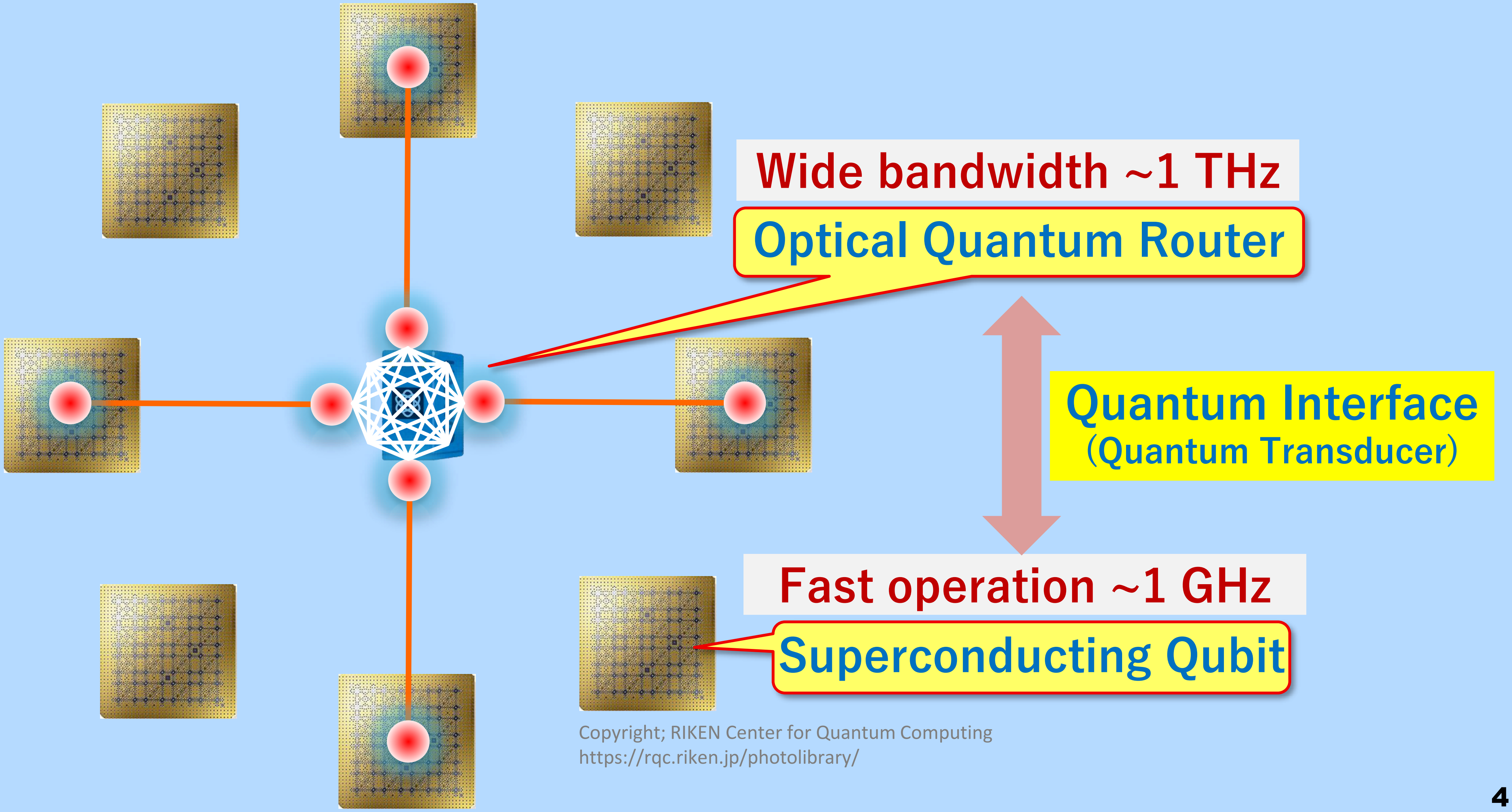
Various Qubits for Quantum Computing



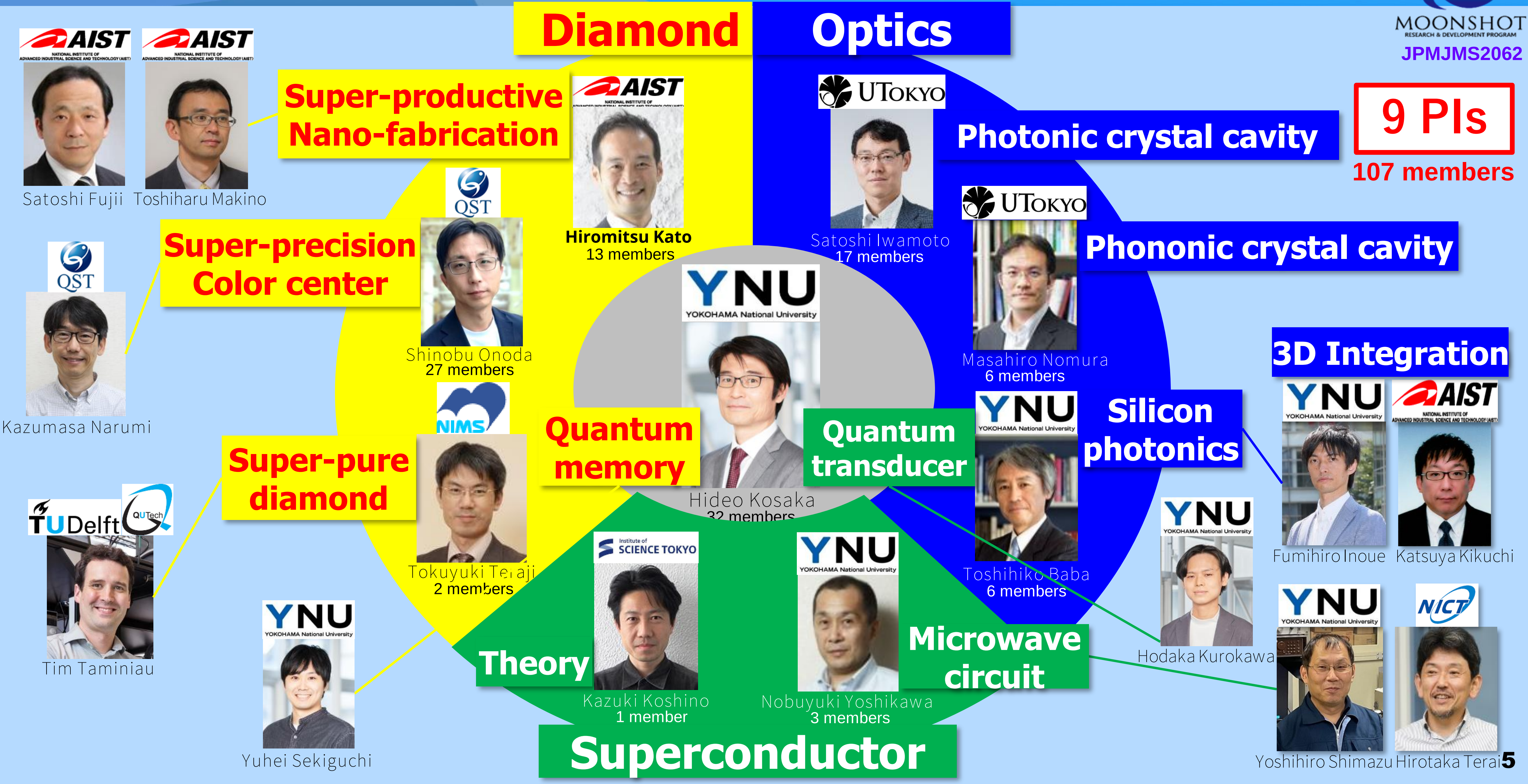
Kosaka Moonshot Project

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM
JPMJMS2062

Superconducting-optical Hybrid Quantum Computer



Kosaka Moonshot Project

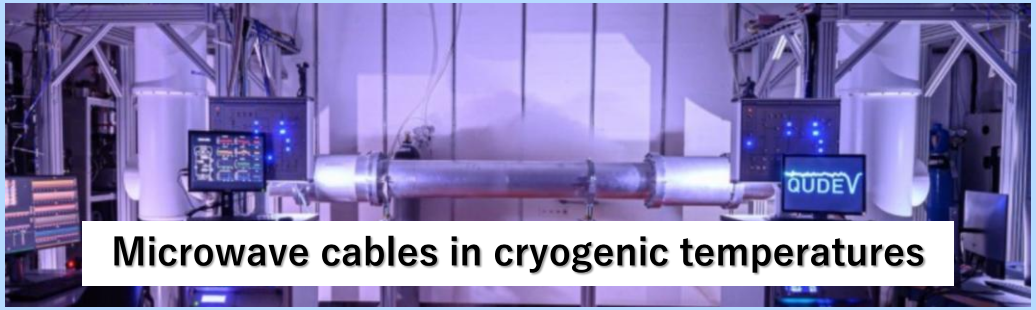


Motivation

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM
JPMJMS2062

Super Computer

理研HP: www.riken.jp/pr/news/2021/20210309_2/index.html

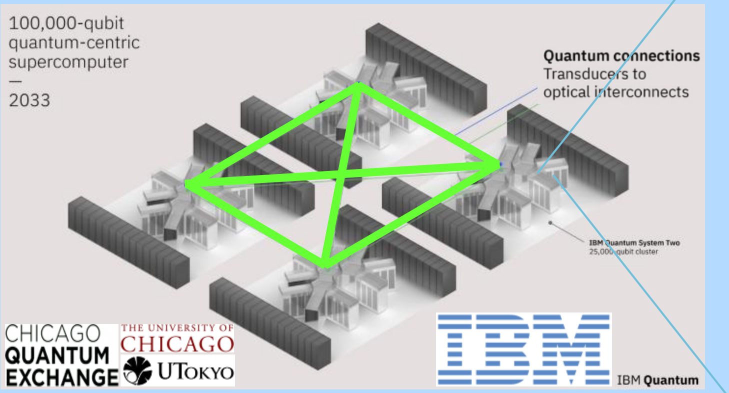


Wallraff ETH
P. Magnard et al., Phys. Rev. Lett. 125, 260502 (2020).

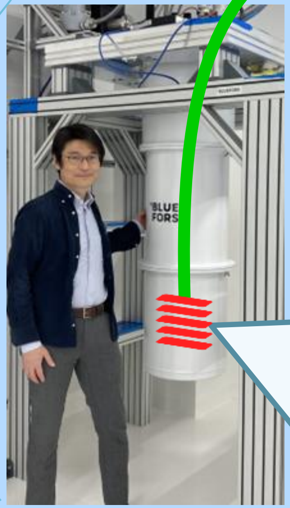
Replaced by fiber optics at room temperature

Flexible, high-speed optical connectivity

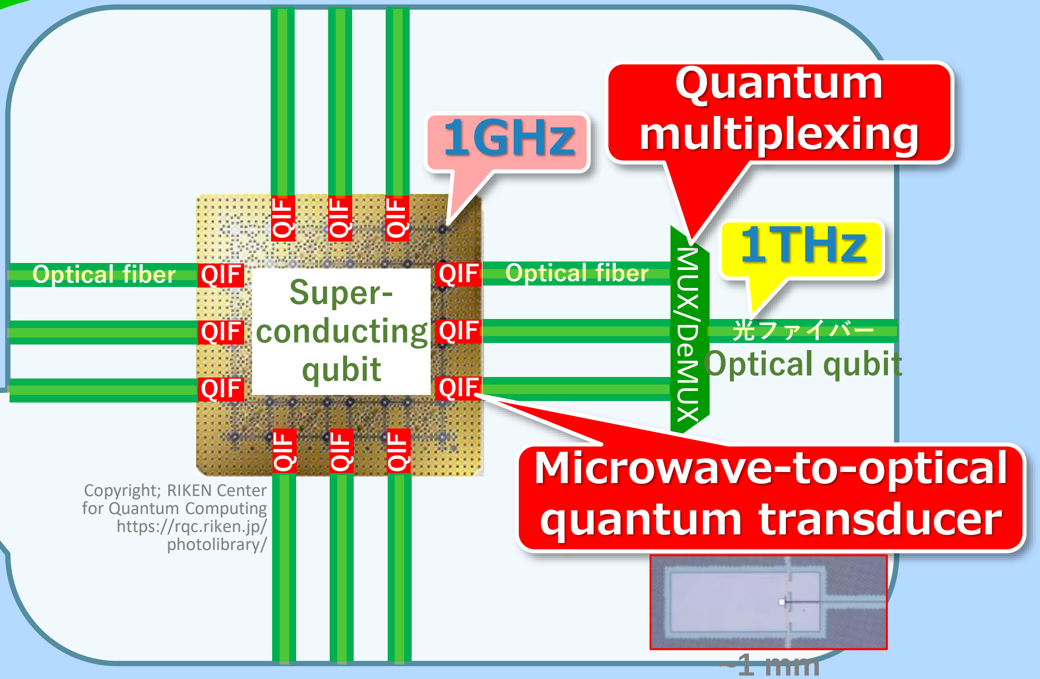
Super Quantum Computer

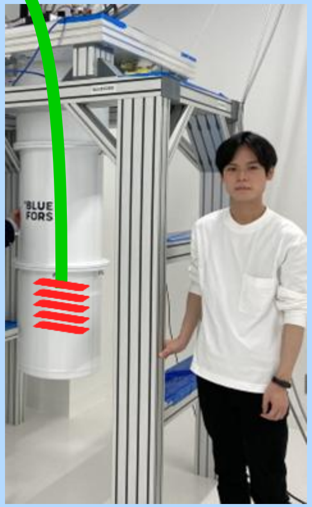


IBM社HP: newsroom.ibm.com/2023-05-21-IBM-Launches-100-Million-Partnership-with-Global-Universities-to-Develop-Novel-Technologies-Towards-a-100,000-Qubit-Quantum-Centric-Supercomputer



Dilution fridge～10mK）





Dilution fridge（～10mK）

Modulator to Quantum Transducer

Quantum frequency converter from a microwave photon (~10GHz) to a visible photon (~500THz)

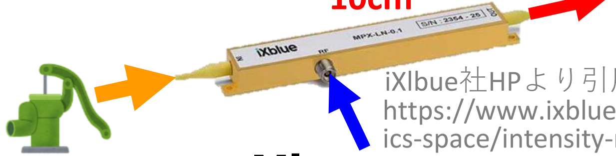
Conventional modulator
W–class pump light

Bulk resonator
mW–class pump light

Nano cavity
μW class pump light

Color center nanocavity
pW–class pump light

EO modulator



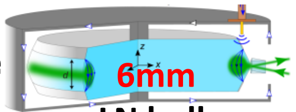
iXlbue社HPより引用
https://www.ixblue.com/photonics-space/intensity-modulators/

AO modulator

Gooch&Housego社HPより引用
https://gandh.com/products/acoustooptics/modulators

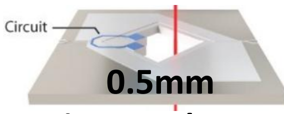
Bulk EO resonator

ISTA
Heterodyne detection



A. Rueda et al., npj Quantum Information, 5, 108 (2019).

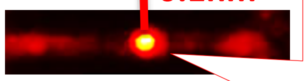
Bulk AO resonator

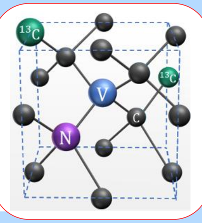


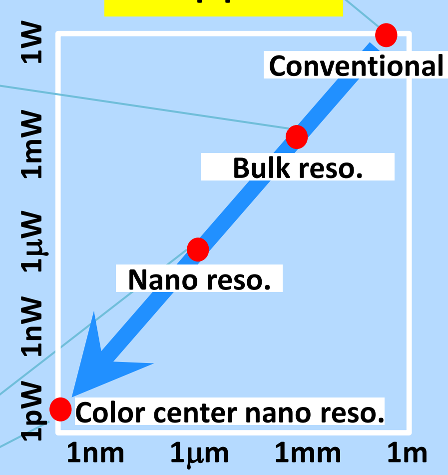
JILA
Carrier freq. ω_0~1MHz

A. P. Higginbotham et al., Nature Physics 14, 1038 (2018)

Nano EO・EOM・OM(opto-mecha) Resonator

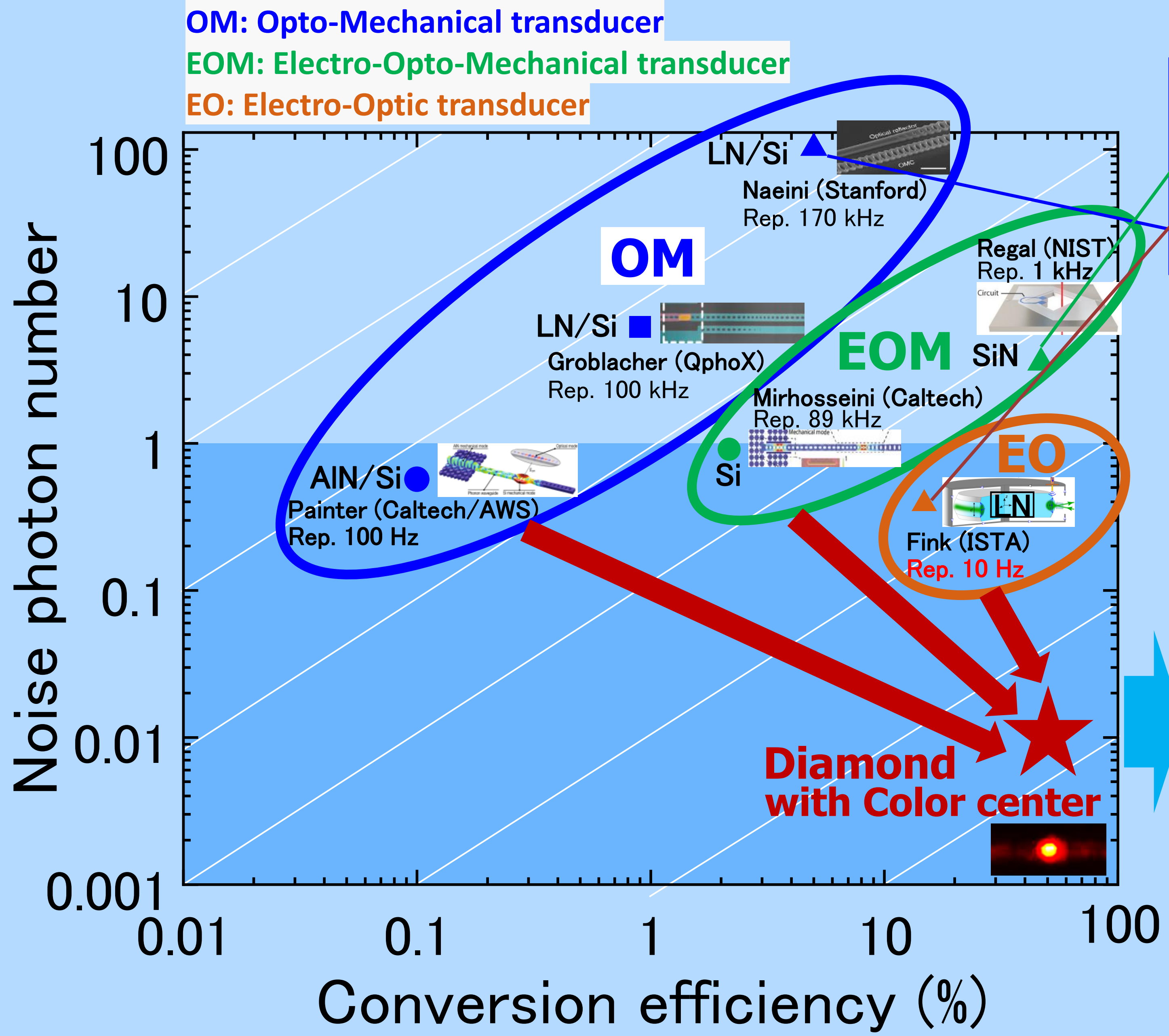






Noise Photon Reduction

Trends in Quantum Transducer

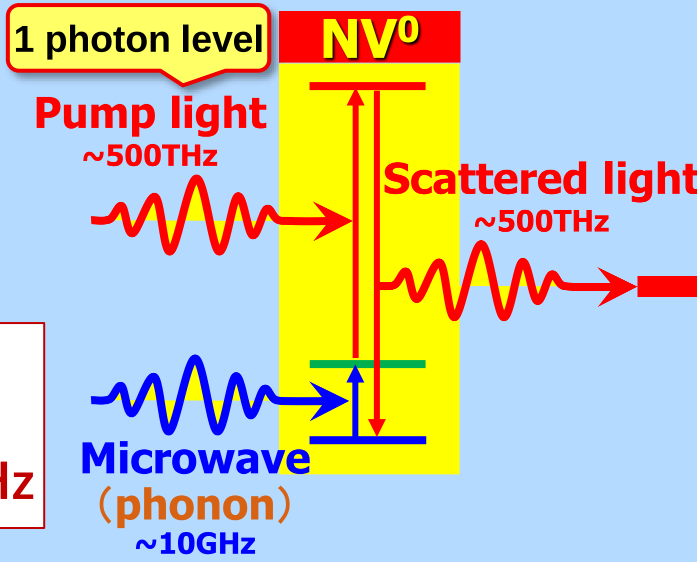


Current top data

- Conversion efficiency 50%
- Noise photon 0.3 (F = 80%)
- Rep. Rate ($\propto 1/\sqrt{\text{pump}}$) 170 kHz

Efficiency~50%
Noise <0.01
Rep. Rate~1MHz

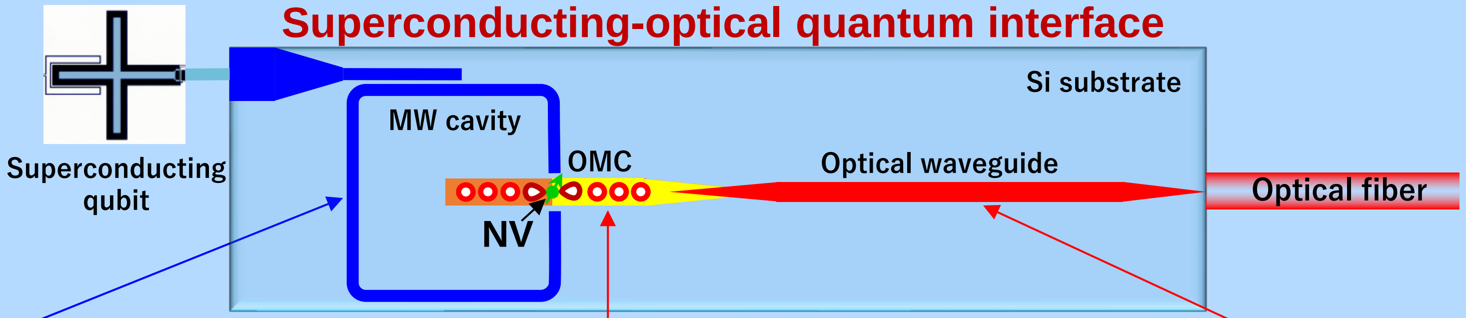
Double resonant sum frequency generation by three-level system



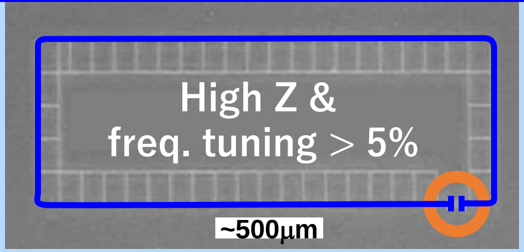
● Mirhosseini & **Painter**, Nature 588, 599 (2020)
▲ Sahu & **Fink**, Nat. Commun. 13, 1276 (2022)
▲ Brubaker & **Regal**, Phys. Rev. X 12, 021062 (2022)
▲ Jiang & **Naeini**, Nature Physics 19, 1423 (2023)
■ Weaver, **Groblacher** & Stockill, Nat. Nano. 19, 166 (2024)
● Zhao & **Mirhosseini**, arXiv:2406.02704 (2024)

Development Status of Elemental Components

Core elements for superconducting – optical quantum interface



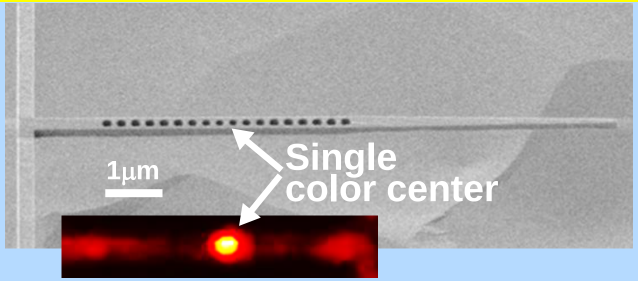
Superconducting microwave resonator



NbTiN Nanowire on Si

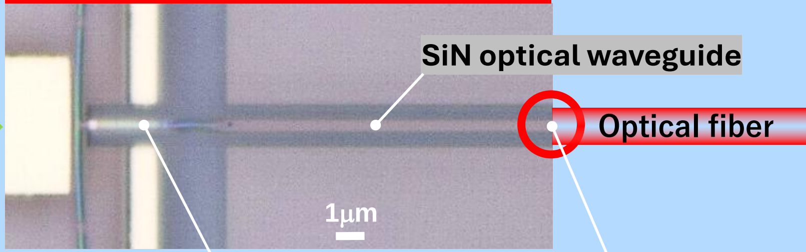
MW photon

Diamond color center opto-mechanical crystal



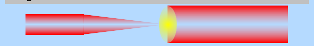
Optical photon

Silicon photonics optical circuit



Diamond color center nano cavity

Spot-size conversion



Hirotaka Terai

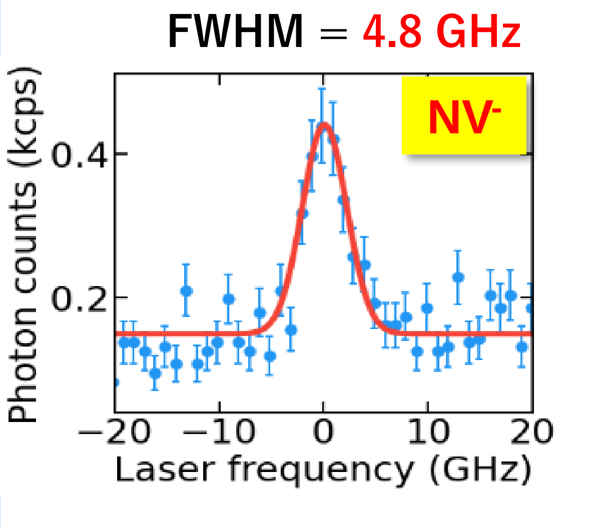
Satoshi Iwamoto Masahiro Nomura

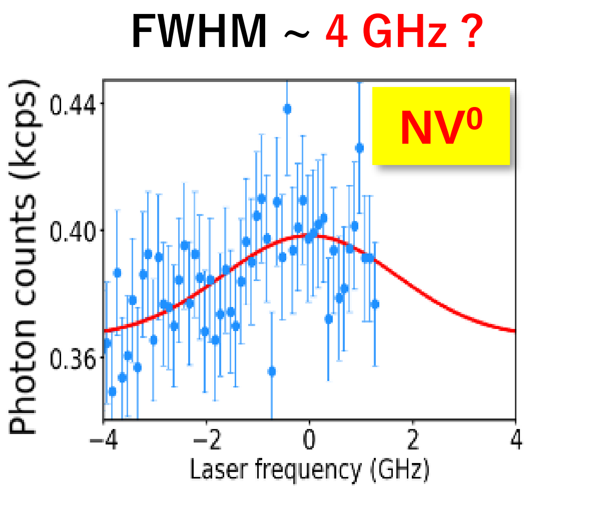
Shinobu Onoda

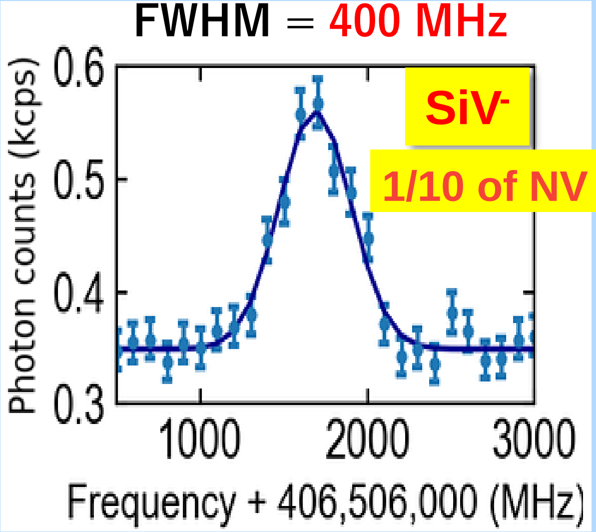
Toshihiko Baba

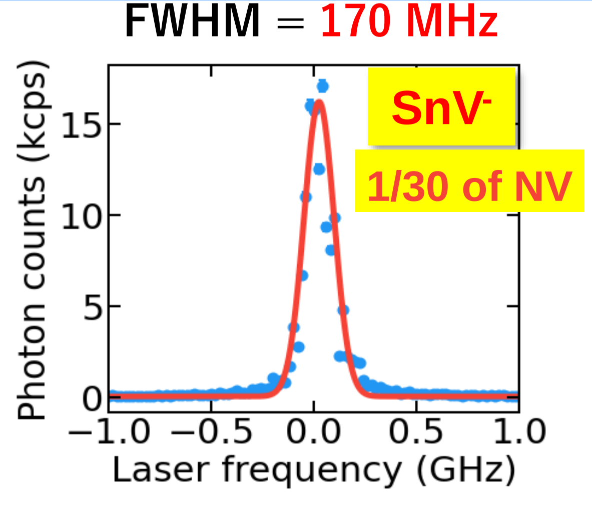
Candidates of color centers

Spectral diffusion of color centers in a photonic nano structure

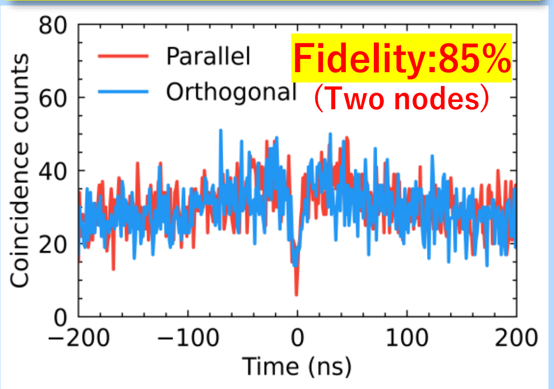


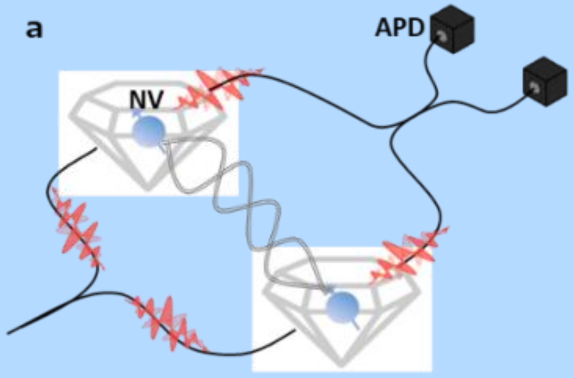




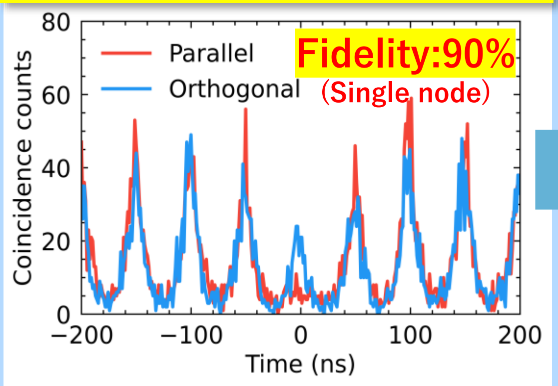


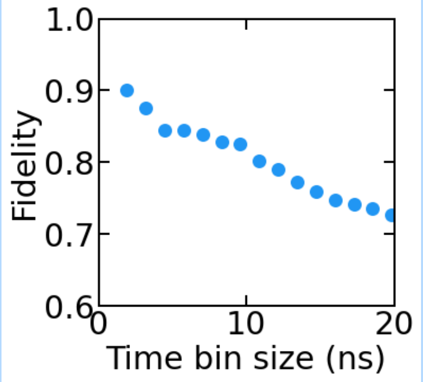
NV- HOM interference





SnV- HOM interference

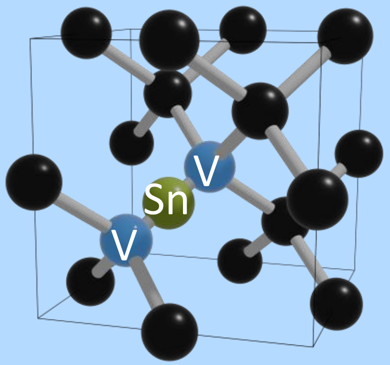


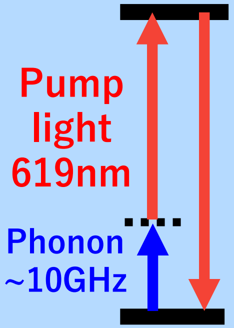


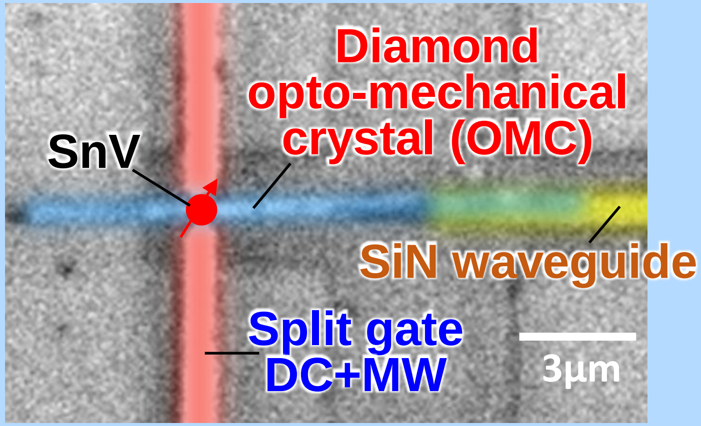
Proof-of-principle demonstration of quantum conversion

Microwave-to-photon conversion in diamond opto-mechanical crystal (OMC) with a SnV center

SnV



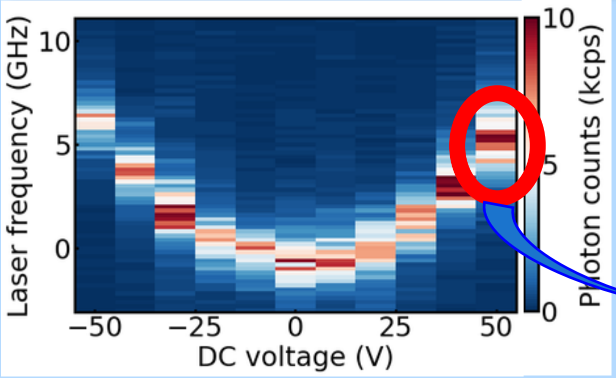




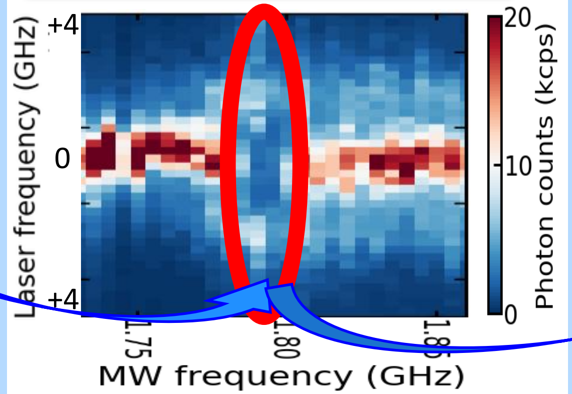
Preliminary

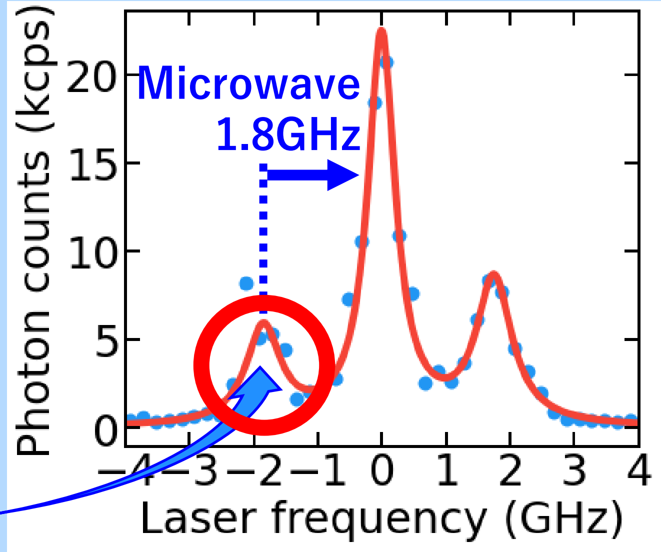
Microwave-assisted optical transition via phonons resonant to diamond OMC

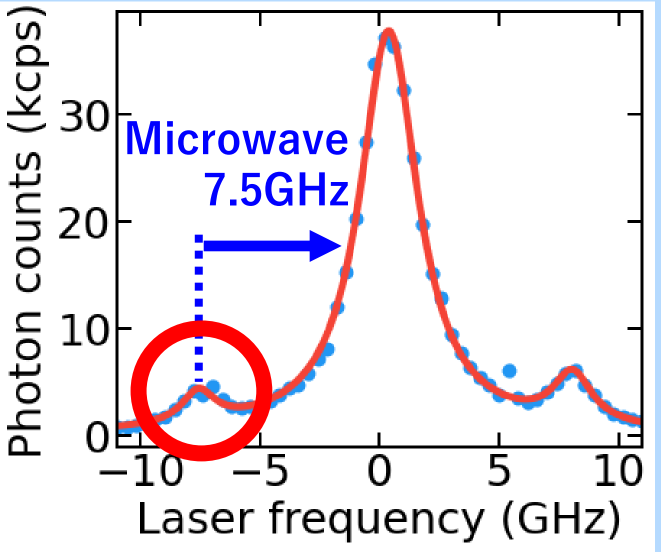
Optical transition frequency shifts with DC E-field



The frequency splits with DC + Microwave

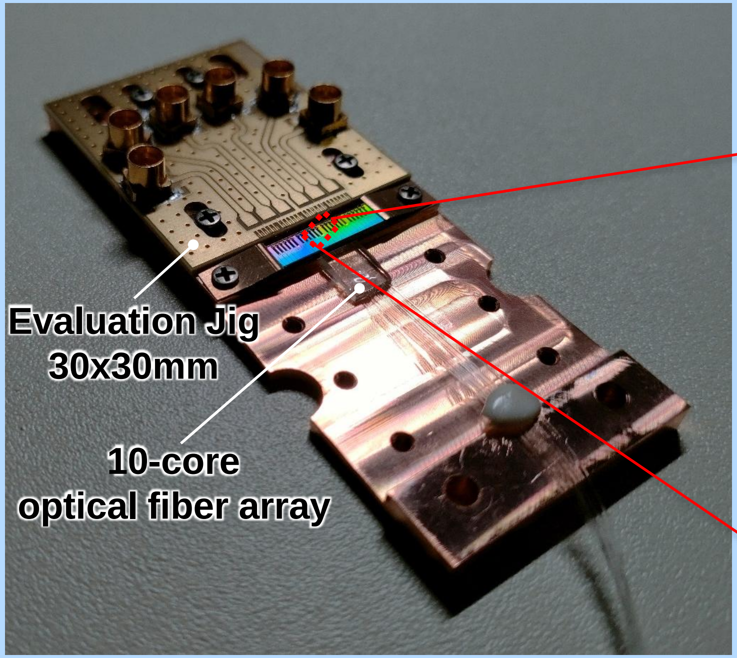




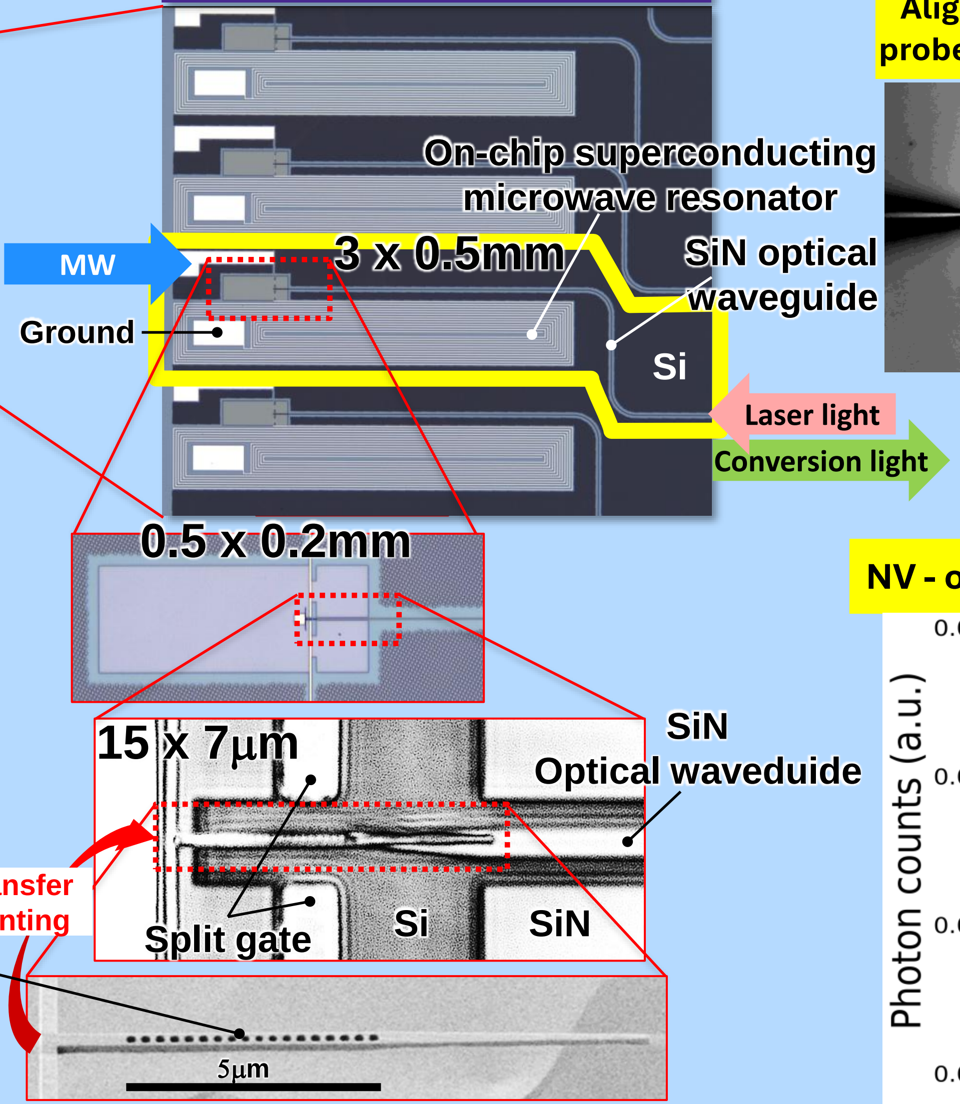


Electrostatic coupling (field-enhanced piezoelectric effect)

Chip Integration



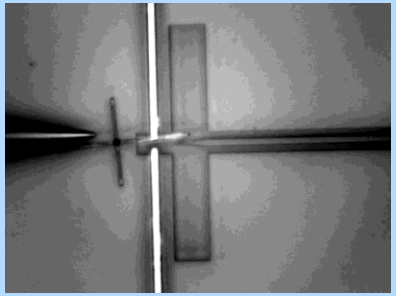
Microwave-optical quantum transducer chip



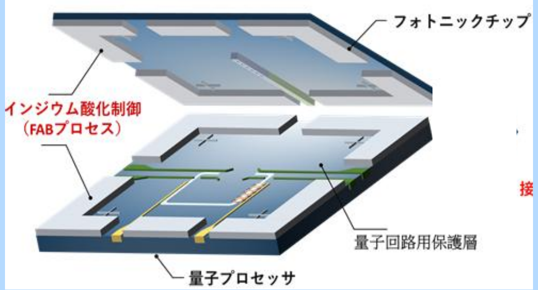
Diamond color center nano resonator

Mounting accuracy

Alignment accuracy by prober after P&P ~100 nm

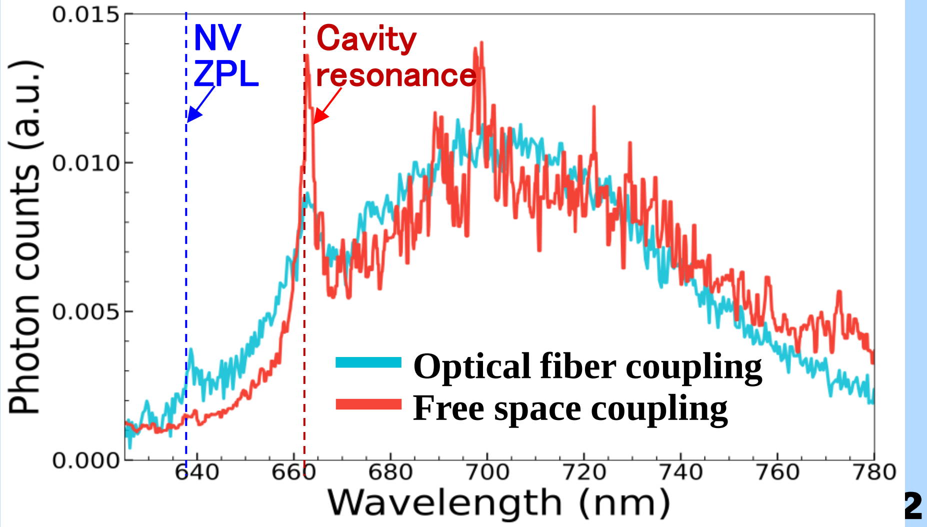


3D chiplet integration process (Indium BEOL wiring)



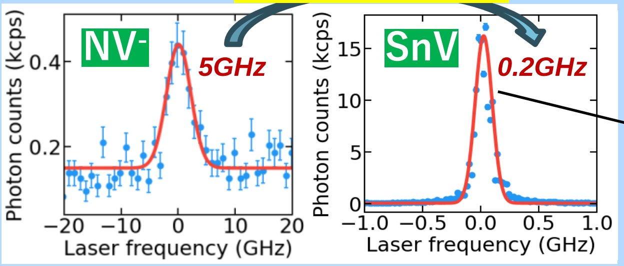
Optical fiber coupling

NV - optical resonator - optical waveguide - optical fiber



color center spectral diffusion

Reduced to 1/30



Issues and Measures

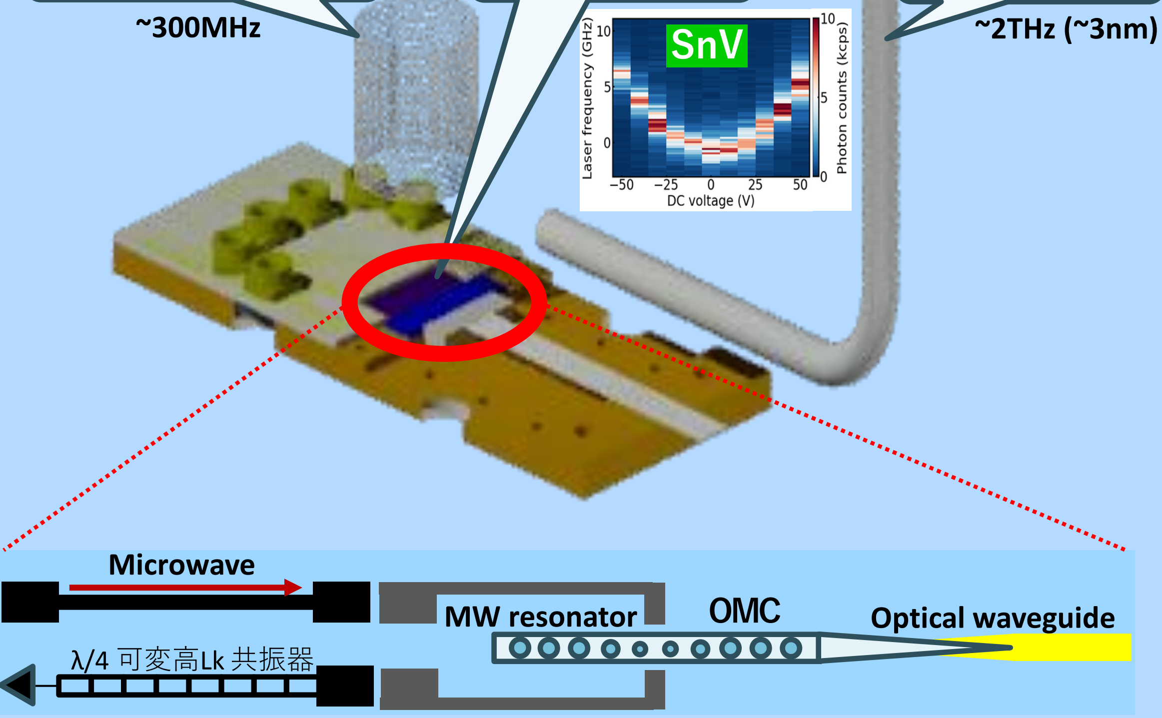
Frequency matching

Frequency control of MW resonator → **Frequency control of color center** → **Frequency control of optical resonator**

Magnetic field applied by S.C. coil
~300MHz

Electric field applied by split gate
~7GHz

Gas adsorption applied by gas line
~2THz (~3nm)



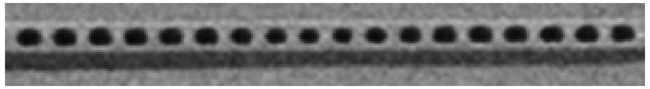
Coupling of microwave to mechanical mode (phonon)

Piezo coupling method: ~1 MHz (AlN 30nm, L_k~500)
Electrostatic coupling: ~0.4 MHz/100V @Si

Compatibility of opto-mechanical resonators

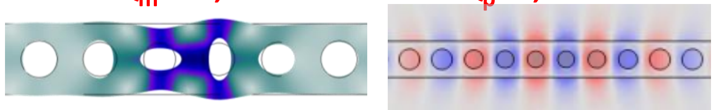
Plan A

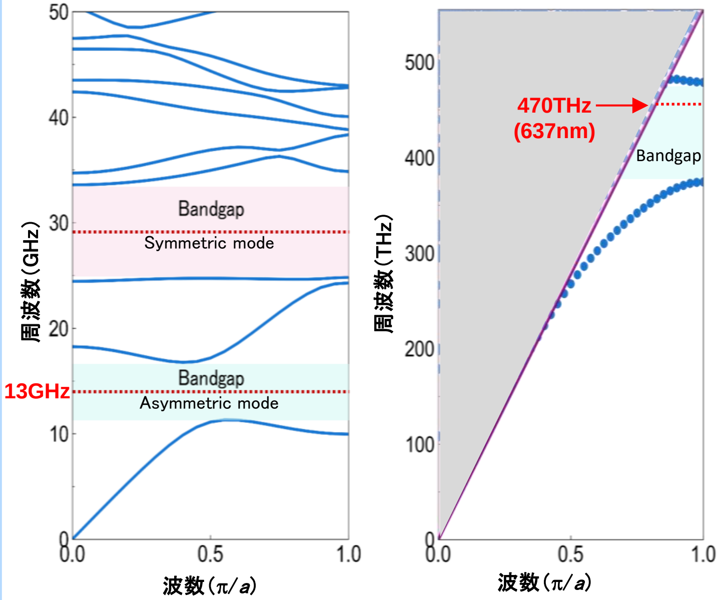
Diamond OMC



Phononic crystal
Q_m=30,000

Photonic crystal
Q_p=6,200

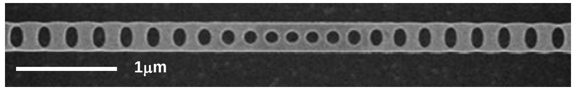




Symmetric mode having higher Q and piezoelectric coupling is available with elliptical holes.

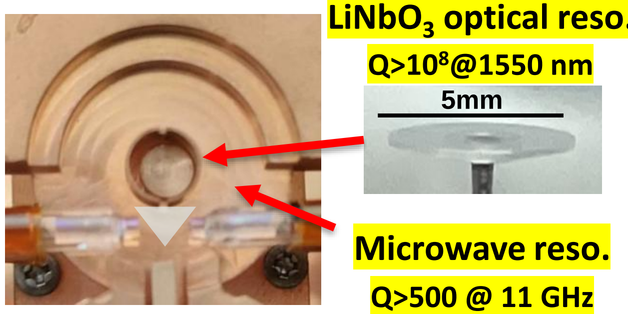
Plan B

Silicon OMC



Plan C

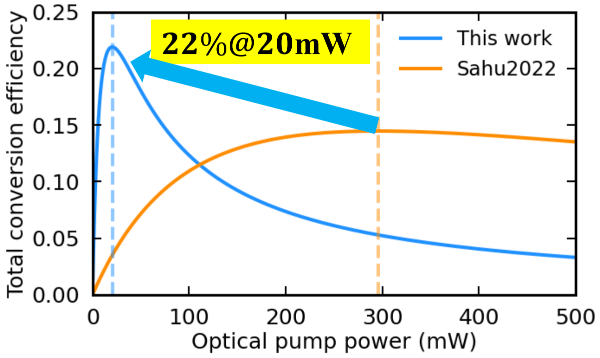
LN bulk EO



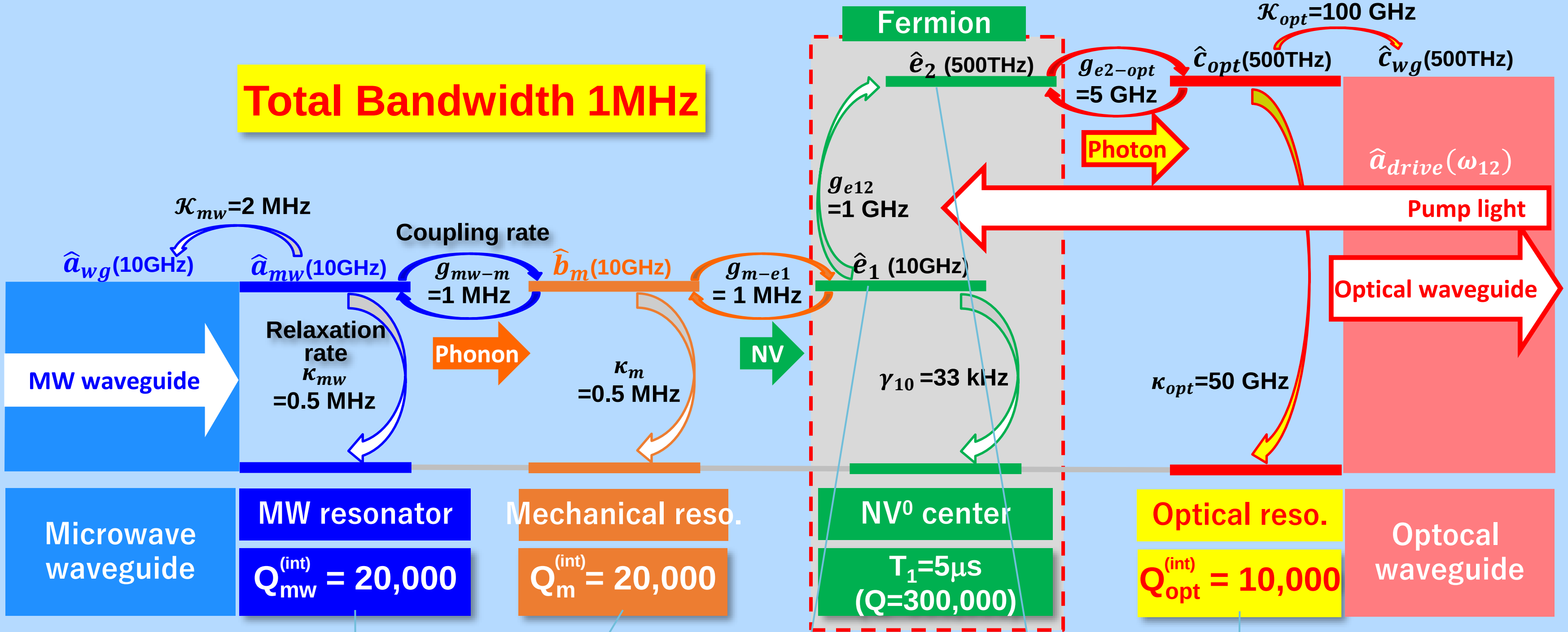
$LiNbO_3$ optical reso.
$Q>10^8$@1550 nm

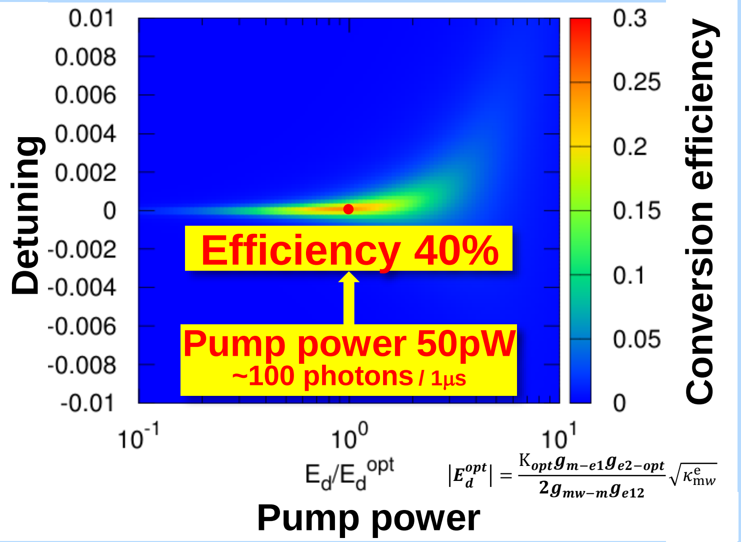
Microwave reso.
Q>500 @ 11 GHz

Pump power - conversion efficiency

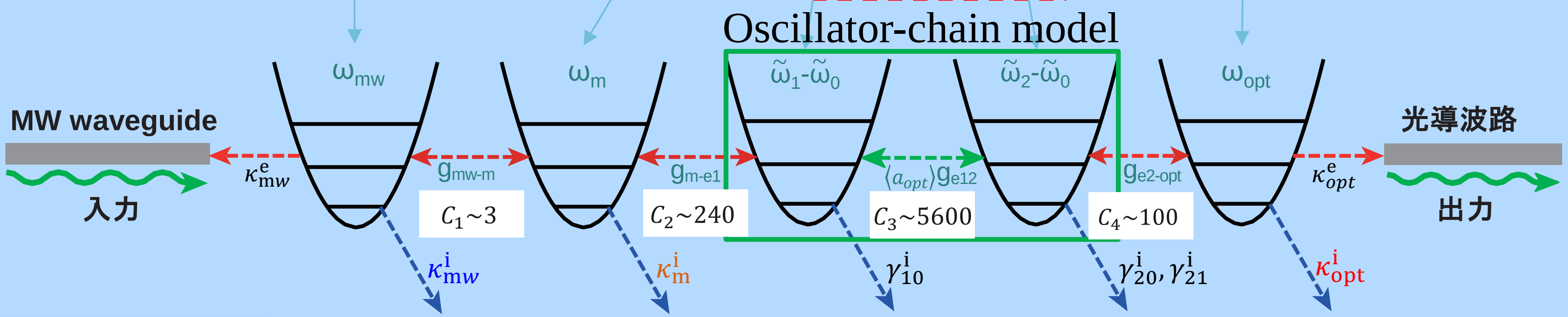


Simulation of Conversion Efficiency





Pump light reduced to ~100 photons with NV^0



Conversion efficiency

$$\eta = \frac{\kappa^{in}_{ex}}{\kappa^{in}_{tot}} \frac{4C_1C_2C_3C_4}{\{(1+C_1+C_2)(1+C_4)+C_3(1+C_1)\}^2} \frac{\kappa^{out}_{ex}}{\kappa^{out}_{tot}}$$

Critical condition $(1+C_1+C_2)(1+C_4) = C_3(1+C_1)$

JC Model + Input-Output Theory

$$H_0 = \omega_{mw} a^\dagger a + \omega_m b^\dagger b + \omega_{e1} e_1{}^\dagger e_1 + \omega_{e2} e_2{}^\dagger e_2 + \omega_{opt} c^\dagger c$$

$$H_{int} = g_{mw-m}(a^\dagger b + b^\dagger a) + g_{m-e1}(b^\dagger e_1 + e_1{}^\dagger b) + g_{e2-opt}(e_2{}^\dagger c + c^\dagger e_2) + \langle a_{opt}\rangle g_{e12}(e_2{}^\dagger e_1 c + c^\dagger e_1{}^\dagger e_2)$$
$$+ \sqrt{\mathcal{K}_{mw}}(a^\dagger a_{wg} + a_{wg}{}^\dagger a) + \sqrt{\mathcal{K}_{opt}}(c^\dagger c_{wg} + c_{wg}{}^\dagger c)$$

Quantum Information Center (QIC)

Management

PM
Center Director
Hideo Kosaka

International collaboration
Assistant Professor
Anton Myalitsin

International PR
Adjunct Teaching Staff
Annelies Volders

IP Strategy
Intellectual Property Producer
Kinya Kumazawa

Management
Assistant Professor
Teruyuki Kinno

Japanese Universities

Professor — Toshihiko Baba
Professor — Nobuyuki Yoshikawa
Professor — Tomoyuki Horikiri
Professor — Daisuke Akamatsu
Professor — Akihiro Minamino

Associate Professor — Yoshiaki Nishijima
Associate Professor — Yuki Yamanashi
Associate Professor — Akira Ozawa
Associate Professor — Fumihiro Inoue
Associate Professor — Yoshihiro Shimazu

Assistant Professor — Yuhei Sekiguchi
Assistant Professor — Hodaka Kurokawa
Assistant Professor — Akira Kamimaki
Assistant Professor — Abdul Nasir Kuzhiyan Thadathil
Assistant Professor — Jowesh Avisheik Goundar

YNU YOKOHAMA National University

Center Vice Director — Satoshi Iwamoto (UTokyo)
Visiting Professor — Masahiro Nomura (UTokyo)
Visiting Associate Professor — Kazuki Koshino (Institute of SCIENCE TOKYO)

National Institutes

Visiting Professor — Toshiharu Makino (AIST)
Visiting Professor — Hiromitsu Kato (AIST)
Visiting Professor — Tokuvuki Teraji (NIMS)
Visiting Associate Professor — Shinobu Onoda (QST)
Visiting Professor — Hirotaka Terai (NICT)
Visiting Professor — Shigehito Miki (NICT)

International

Visiting Professor — Fedor Jelezko (uulm)
Visiting Professor — Christoph Becher (SAARLAND UNIVERSITY)
Visiting Professor — Jonathan Finley (TUM)
Visiting Professor — Kai Mueller (TUM)

Company

Visiting Professor — Yu Mimura (FURUKAWA ELECTRIC)
Visiting Associate Professor — Mamiko Kujiraoka (TOSHIBA)

Partnership

UTokyo-IIS
RIKEN
QST
universität uulm
University of Stuttgart Germany

Joint Research

NICT
FURUKAWA ELECTRIC
QUTech