22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems
Hotel Santa Fe, Santa Fe, NM 87505, April 6, 2025 - April 10, 2025

US Committee for SCE

2025 Workshop Sante Fe New Mexico

Current Status of Superconducting Electronics (SCE) in Japan

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YOKOHAMA National University YNU

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

Outline

- Japan's national projects on quantum computing
- Superconducting electronics projects related to quantum computing
- Superconducting digital electronics projects

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Japan's National Projects on Quantum Computers

- Moonshot R&D Program 6 (JST Japan Science and Technology Agency)
  - Title: Realization of a fault-tolerant universal quantum computer by 2050
  - Sponsor: Cabinet Office, Japan Science and Technology Agency (JST)
  - Duration: Phase 1: 2020-2025, Phase 2: 2026-2030
  - Institutions: NEC, Hitachi, AIST, RIKEN, NICT, NTT, U Tokyo, Osaka U, YNU etc.
- NEDO – Post-5G Project (NEDO New Energy and Industrial Technology Development Organization)
  - Title: Research and development of quantum computing and Ising computing systems
  - Sponsor: New Energy and Industrial Technology Development Organization (NEDO)
  - Duration: 2018-2027
  - Institutions: AIST, NEC, Toshiba, NII, Waseda U, TIT, YNU etc.
- Q-LEAP (JST Japan Science and Technology Agency)
  - Title: Quantum Leap Flagship Program (Q-LEAP)
  - Sponsor: MEXT, JST
  - Duration: 2018-2029
  - Institutions: RIKEN, U Tokyo, NII、Osaka U, etc.

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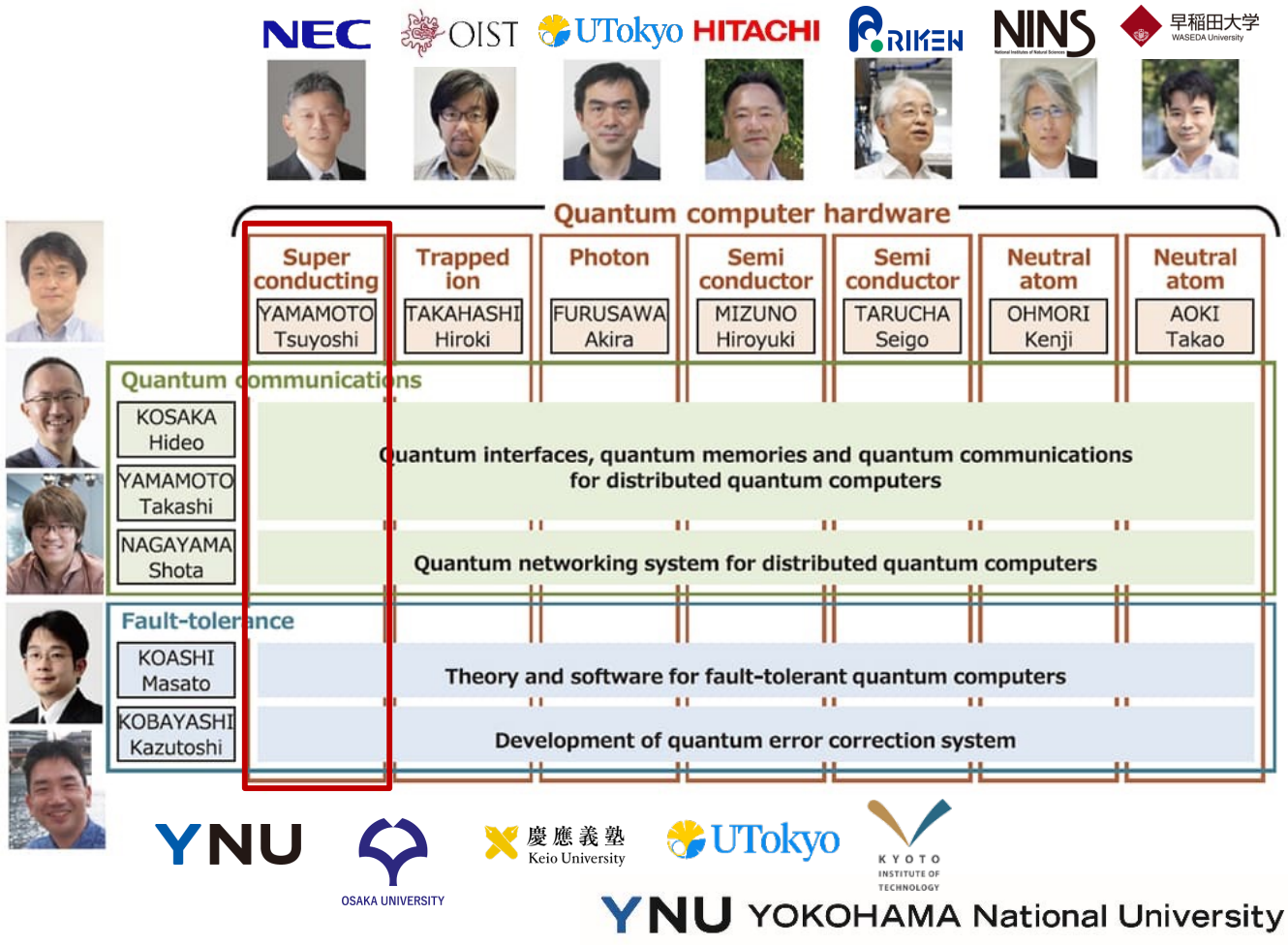
Moonshot R&D Program 6

- Aim: Development of basic technologies for a fault-tolerant universal quantum computer.

Research Area	Details
Hardware	Superconducting qubits, spin qubits, photonics, neutral atoms
Error Correction	Surface codes, topological codes, cat codes
Algorithms	Applications in chemistry, optimization, machine learning
System Integration	Scalable quantum processor design, cryogenic electronics, quantum control infrastructure



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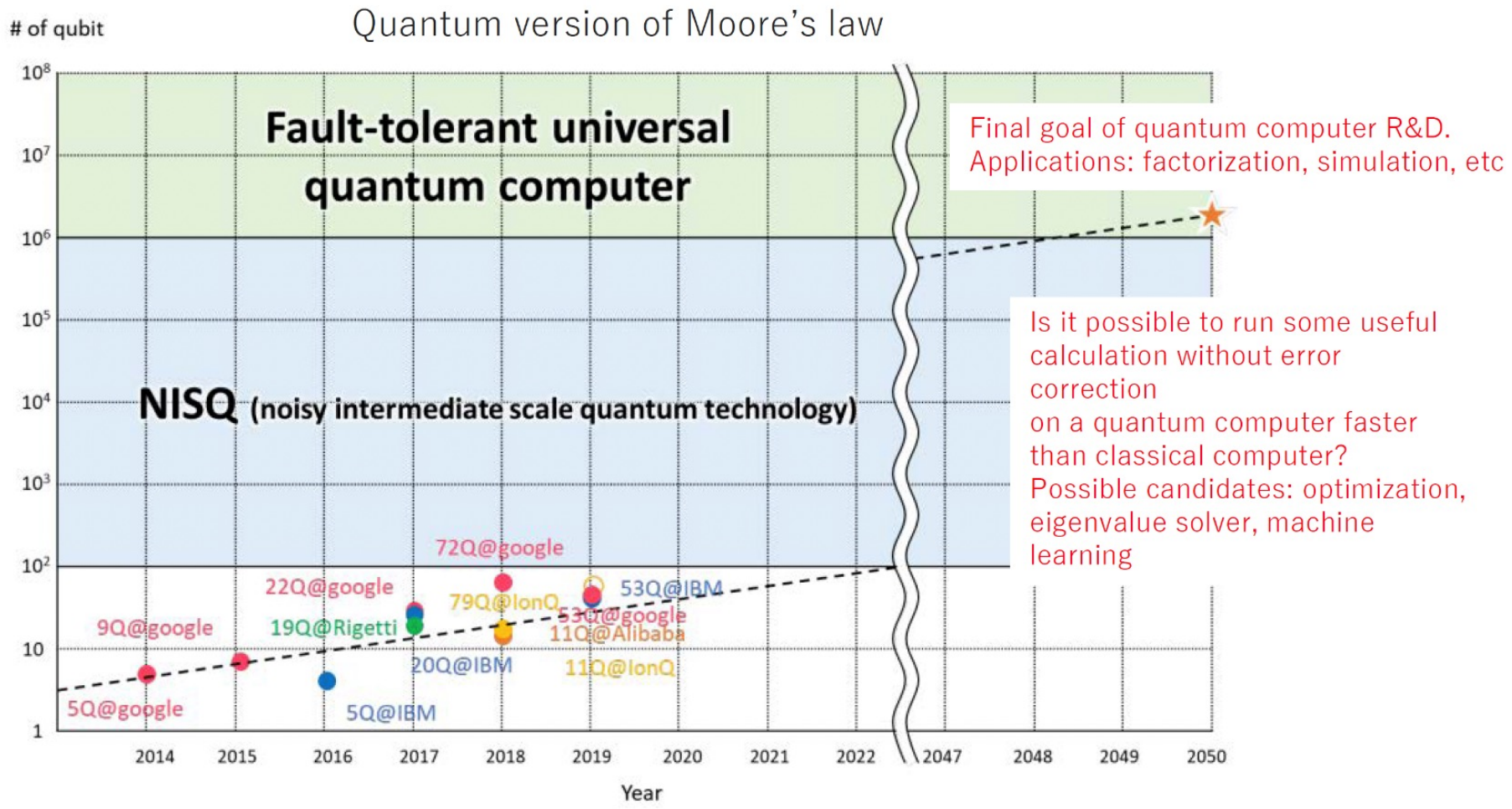
Development of Integration Technologies for Superconducting Quantum Circuits

- Reader:
  Tsuyoshi Yamamoto (NEC)

- Goal: Realize a large-scale superconducting quantum computer by developing key hardware technologies.
- Approach:
  - Solve wiring bottlenecks using cryo electronics (e.g., SFQ circuits, flip-chip interconnects)
  - Reduce hardware demands via high-coherence qubits and bosonic error-correcting codes

beyond NISQ



https://www.jst.go.jp/moonshot/sympo/20240327/pdf/05_yamamoto_tsuyoshi.pdf

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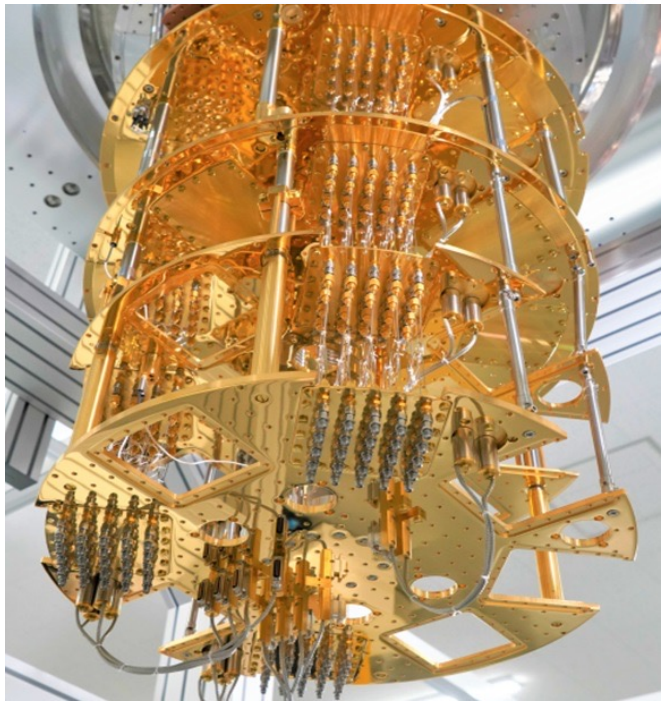
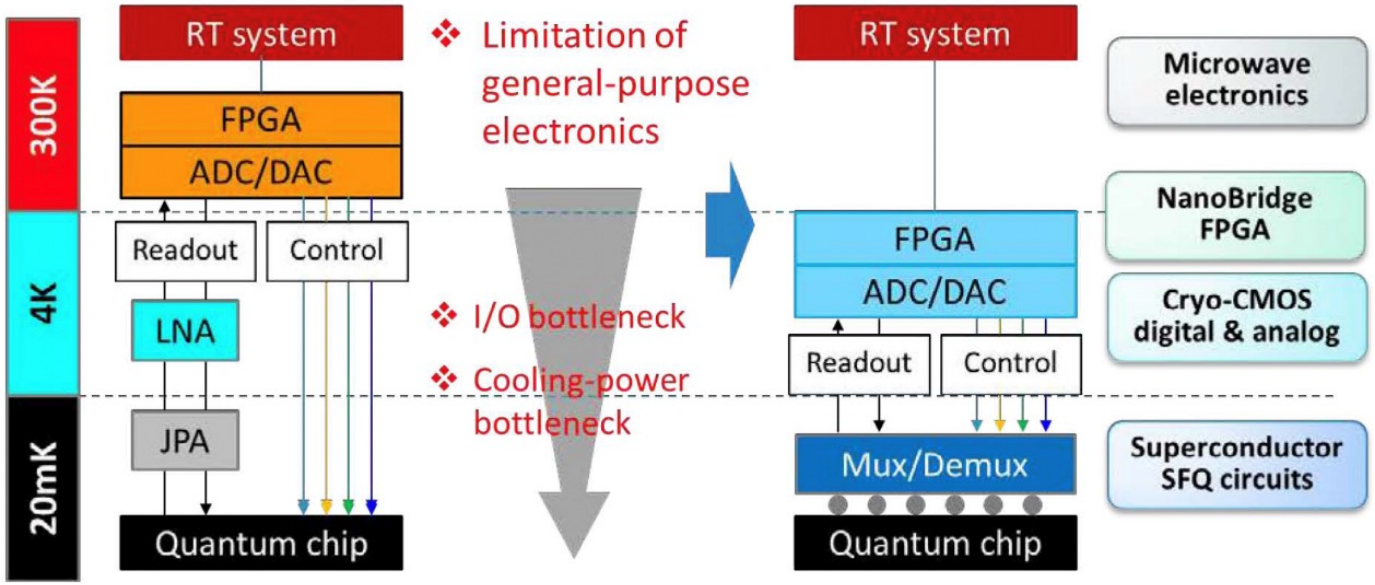
Cryo-electronics

- Cryo-CMOS, SFQ, AQFP etc.
- Potentially reduces the number of physical interconnects (coaxial lines) between the quantum–classical interface and room-temperature electronics





https://www.jst.go.jp/moonshot/sympo/20240327/pdf/05_yamamoto_tsuyoshi.pdf

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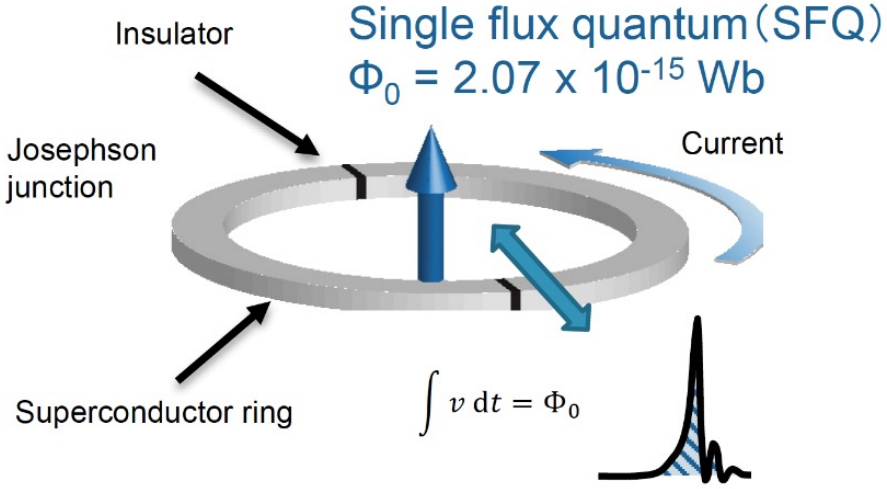
Single-Flux-Quantum Logic Circuits

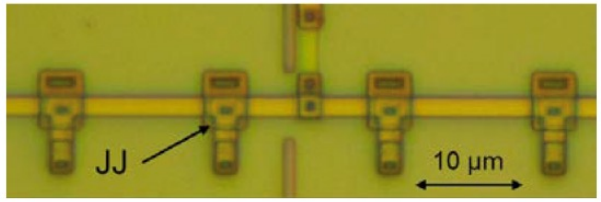
NAGOYA UNIVERSITY

NEC

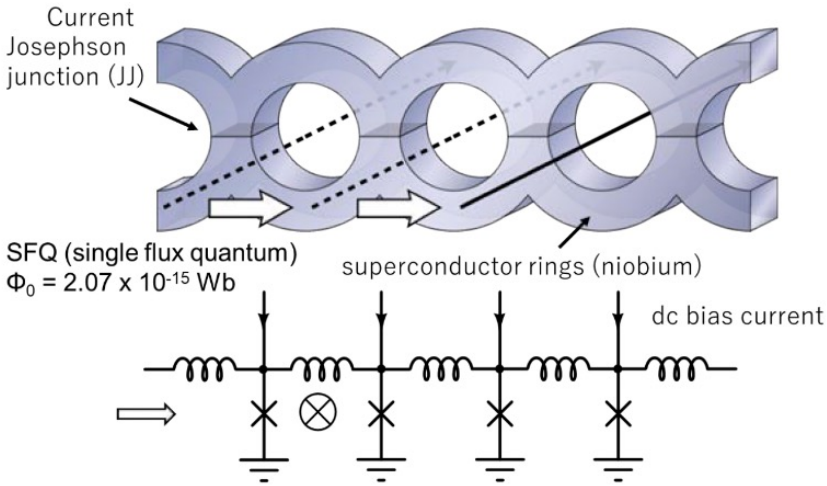
M. Tanaka

T. Yamamoto





Josephson transmission line (JTL)



High-speed digital LSIs using quantized magnetic flux

- Voltage pulse-driven logic
- 10+ GHz, low-power operation
- Transmission line interconnects

K. K. Likharev and V. K. Semenov, IEEE Trans. Appl. Supercond. **1** (1991).

https://www.jst.go.jp/moonshot/sympo/20240327/pdf/05_yamamoto_tsuyoshi.pdf

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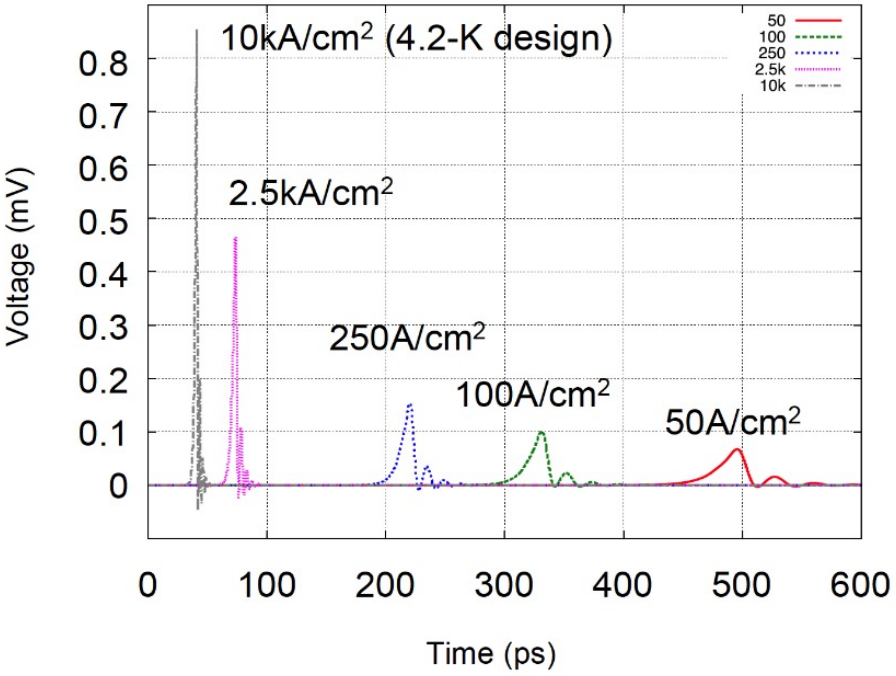
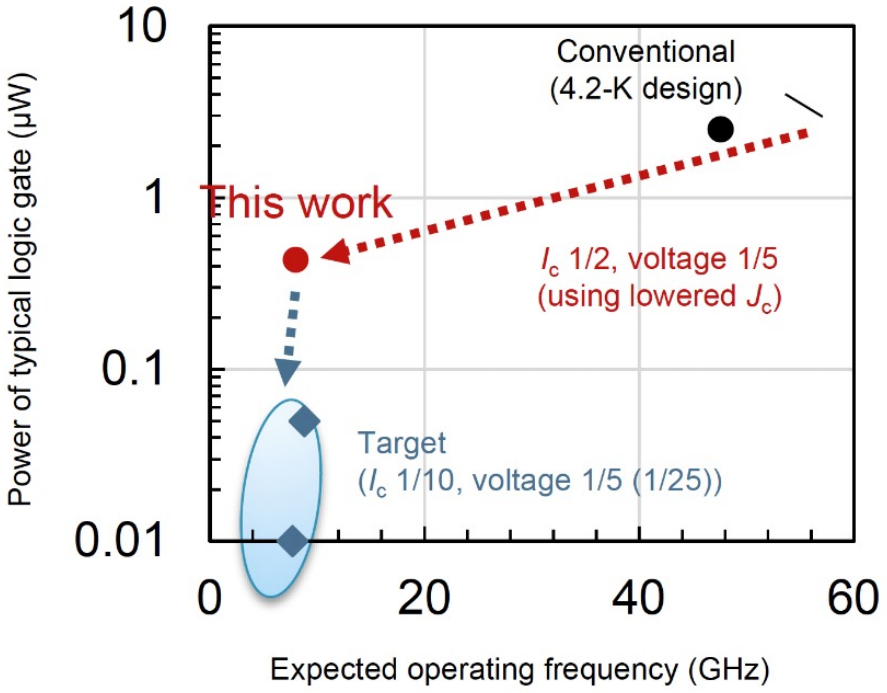
Selection of Critical Current Density (J_c)

- Easy to fabricated small I_c JJs (2–10 μA)
- Acceptable operating frequency (10GHz)

M. Tanaka et al.,
IEEE Trans. Appl. Supercond. 33, 1700805 (2023).

J_c = 250 A/cm²





https://www.jst.go.jp/moonshot/sympo/20240327/pdf/05_yamamoto_tsuyoshi.pdf

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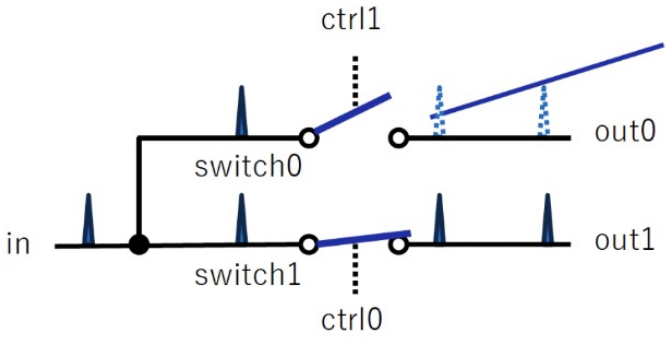
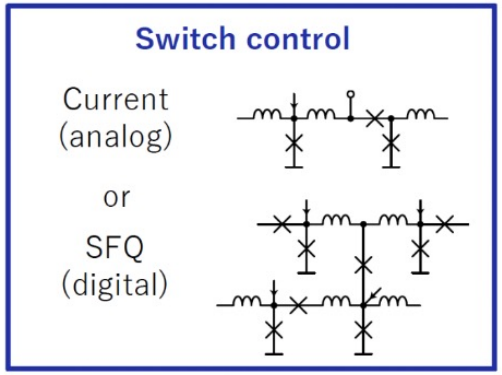
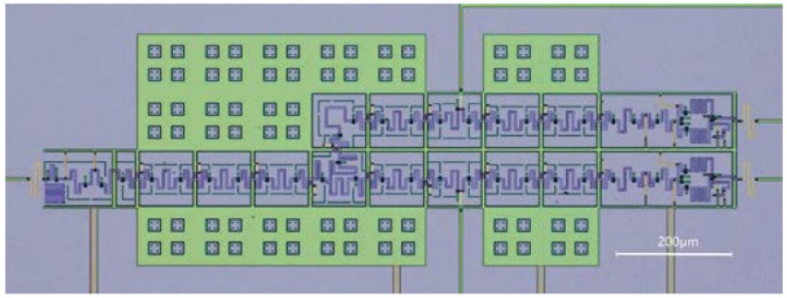
1:2 Demux (Demultiplexer) Demo

- Demux forwards the input signal (SFQ pulse trains) to one of the outputs based on the control signals.

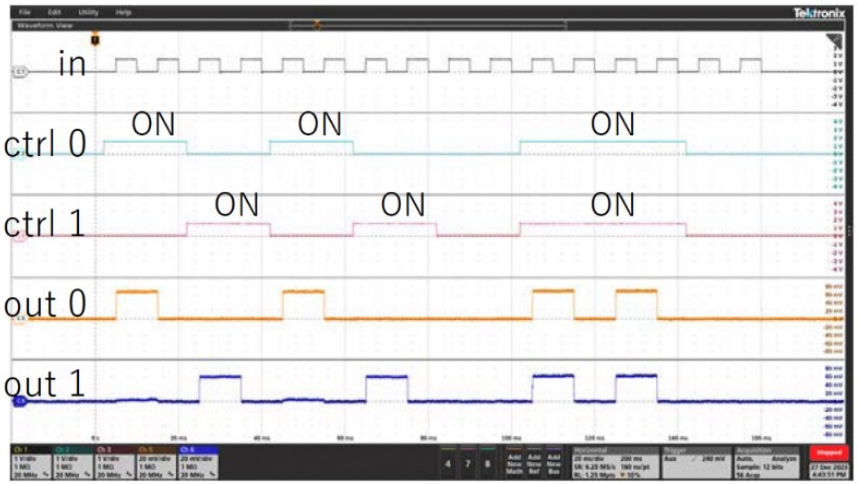






- JJ count: 29
- Bias current: 418 μA
- Area: 0.32 mm2
- Power: 41.8 nW
- Latency: 319.0 ps

Demonstration of current-controlled 1:2 demux



https://www.jst.go.jp/moonshot/sympo/20240327/pdf/05_yamamoto_tsuyoshi.pdf

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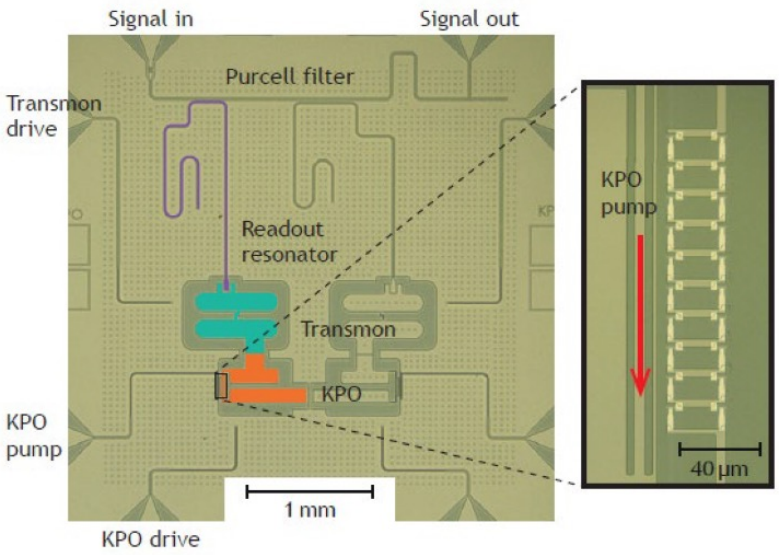
Generation of Kerr cat qubit

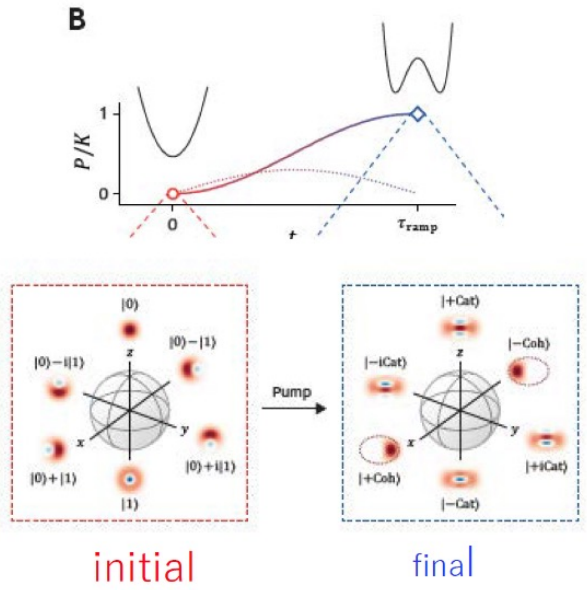
Device picture



Iyama et al., Nature Commun. **15**, 86 (2024).

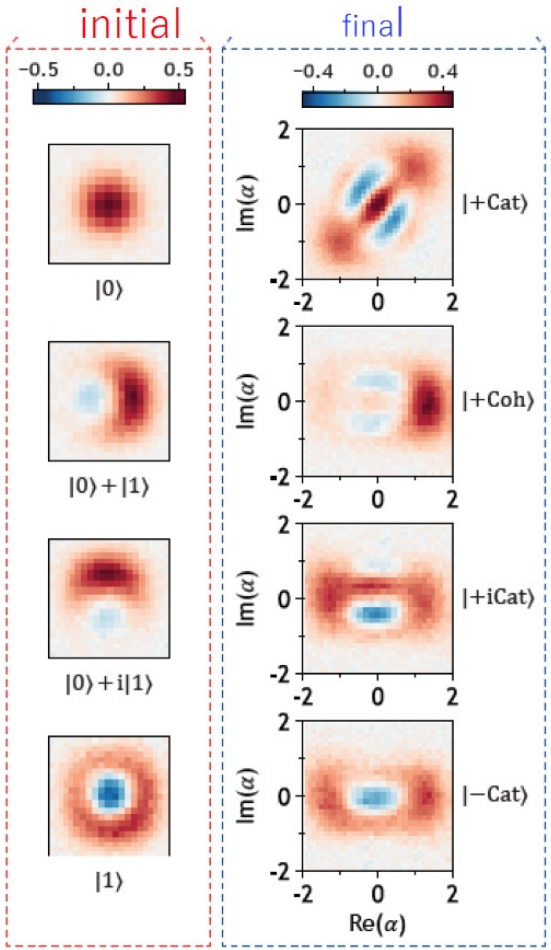
adiabatic pumping

(with counter diabatic pump)



c.f.
Z. Wang et al., Phys. Rev. X **9**, 021049 (2019).

Wigner tomography



https://www.jst.go.jp/moonshot/sympo/20240327/pdf/05_yamamoto_tsuyoshi.pdf

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NEDO – Post-5G Project

- Title: Research and development of quantum computing and Ising computing systems
- Sponsor: New Energy and Industrial Technology Development Organization (NEDO)
- Duration: 2018-2027
- Institutions: AIST, NEC, Toshiba, Fujitsu, U Tokyo, Waseda U, YNU etc.

Task 1: R&D of Generic Software for Ising Machines

- R&D of common software for quantum annealing
- Optimization of architecture
  - Exploration od application
  - Comparison with classical computer.

Task 2: R&D of Quantum-Classical Interface

- R&D of control and readout interfaces using
  - Cryo-CMOS IC
  - Superconducting IC

Task 3: R&D of Quantum processor

- R&D of a JPO-based quantum annealer
- R&D of 3D integration technology

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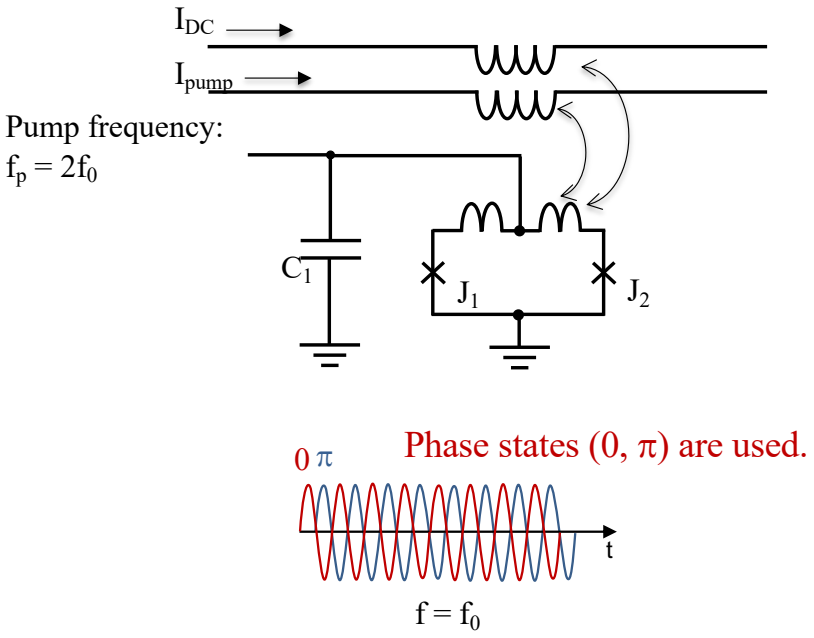
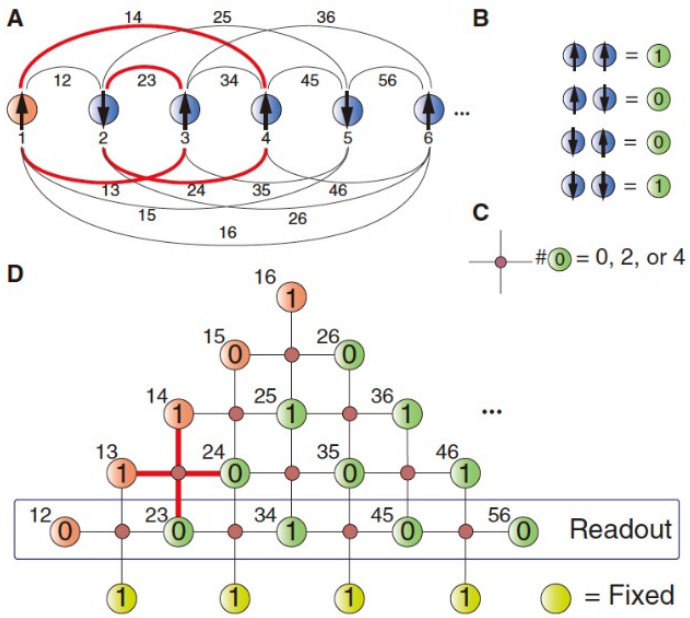
All-to-All Connected JPO Ising Machine

- Build a quantum annealer using Josephson parametric oscillators (JPOs).
- Employ the LHZ scheme for all-to-all qubit connections.

Josephson parametric oscillator (JPO) used as a qubit



LHZ architecture for all-to-all qubit connections



- All-to-all connections are formed using 4-bit JPO cells with four-body interaction.
- N(N-1)/2 physical bits are necessary for N logical bits.

Constraint: the number of 1 in the 4-bit JPO cells has to be even.

Lechner, Hauke, Zoller Sci. Adv. 2015.

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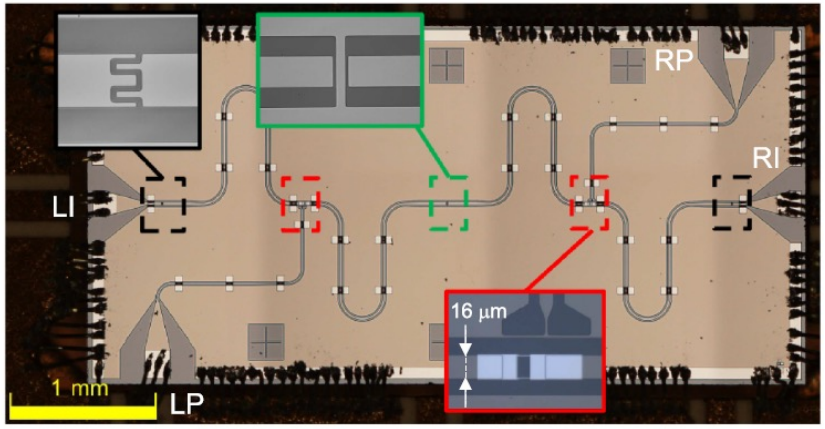
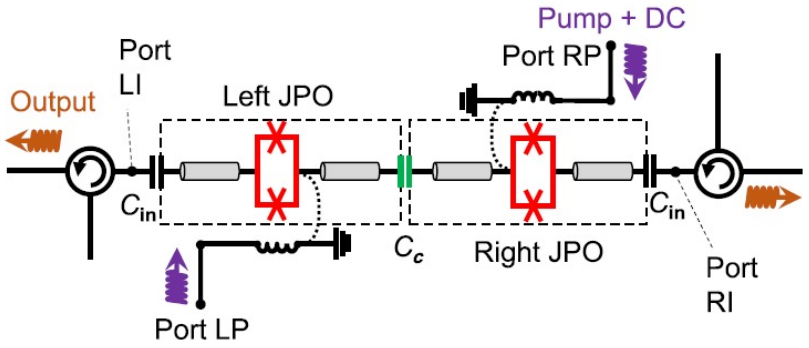
Correlated Oscillations in Coupled JPOs

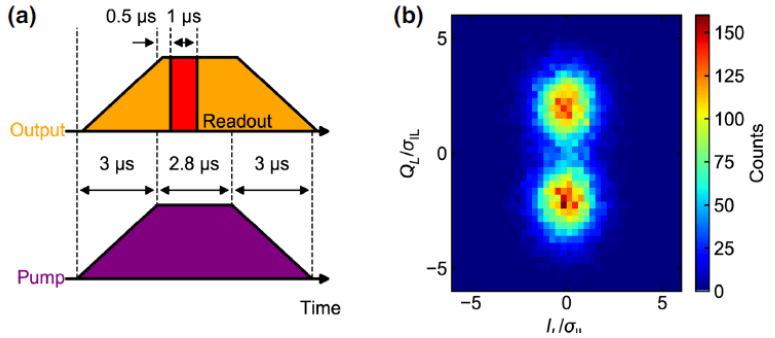
Optical image and circuit schematic of a device chip contain two JPOs



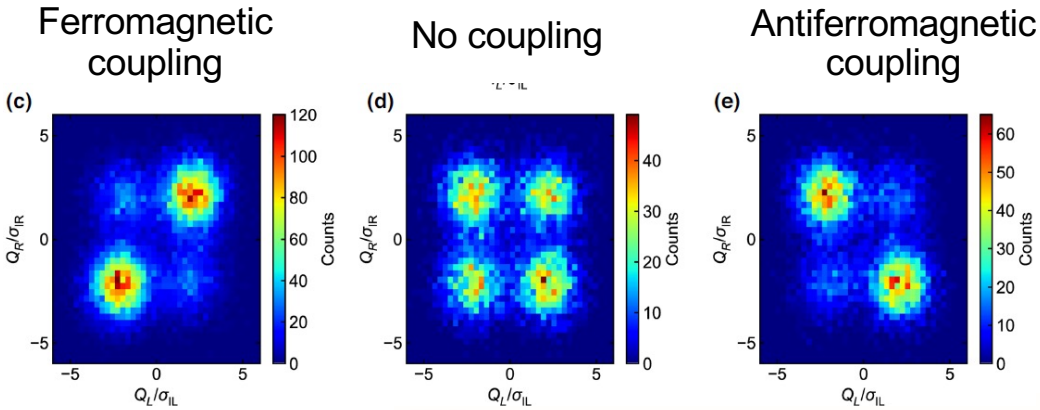


T. Yamaji et al., Phys Rev Appl 20 014057 (2023).

Output signal from the *left* JPO plotted in the *IQ* plane



Oscillation amplitudes of two JPOs



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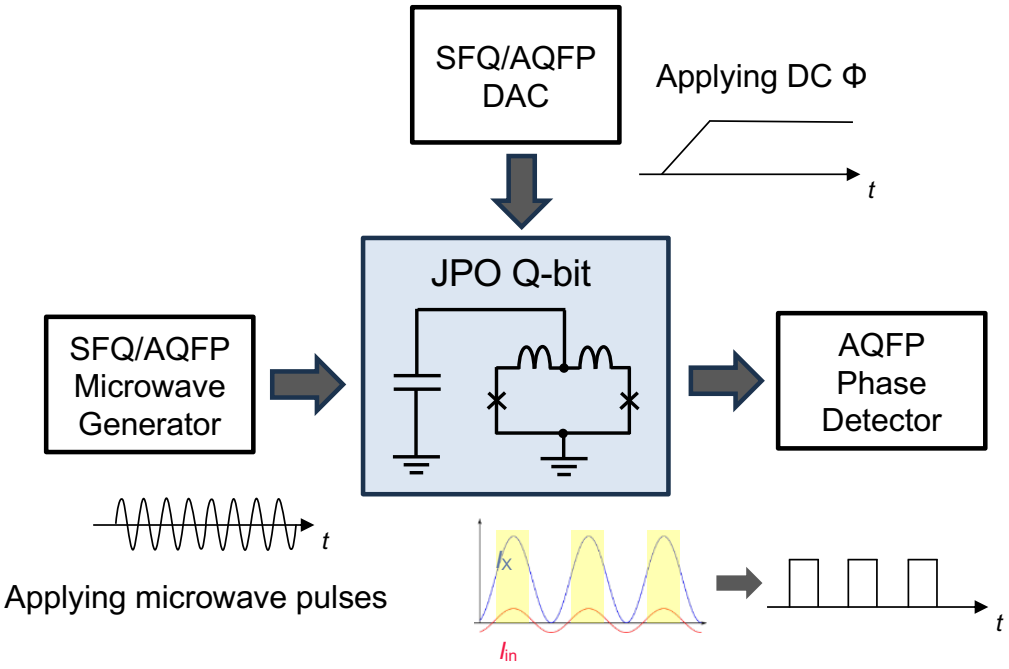
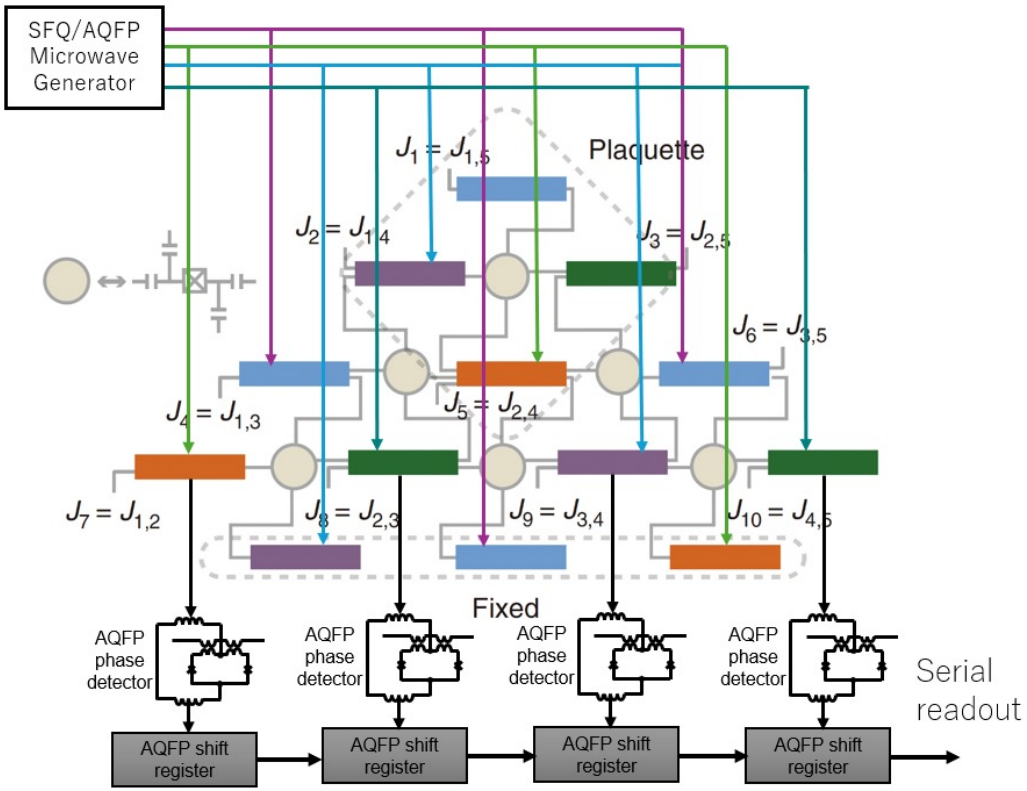
Project in YNU

Control and detection of JPO states by SFQ and AQFP circuits at low temperatures





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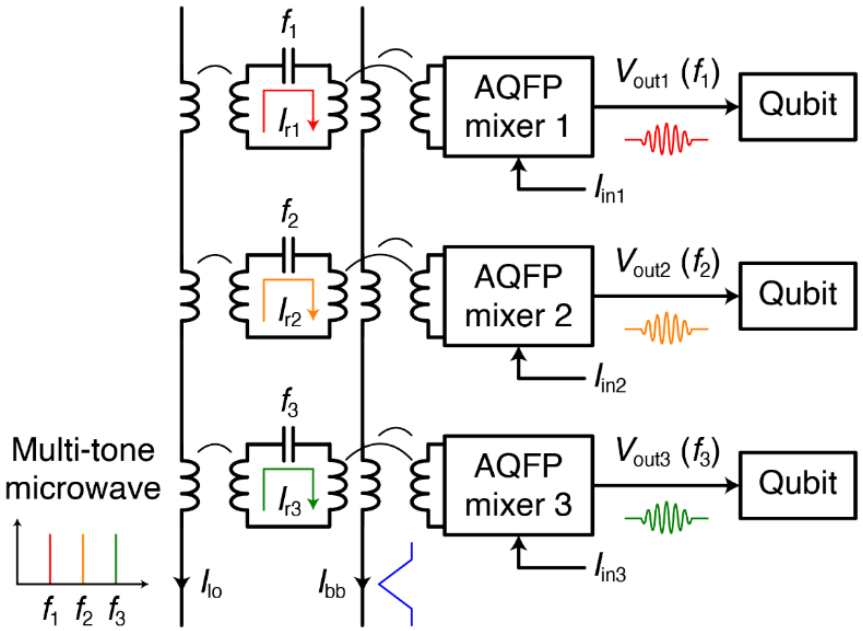
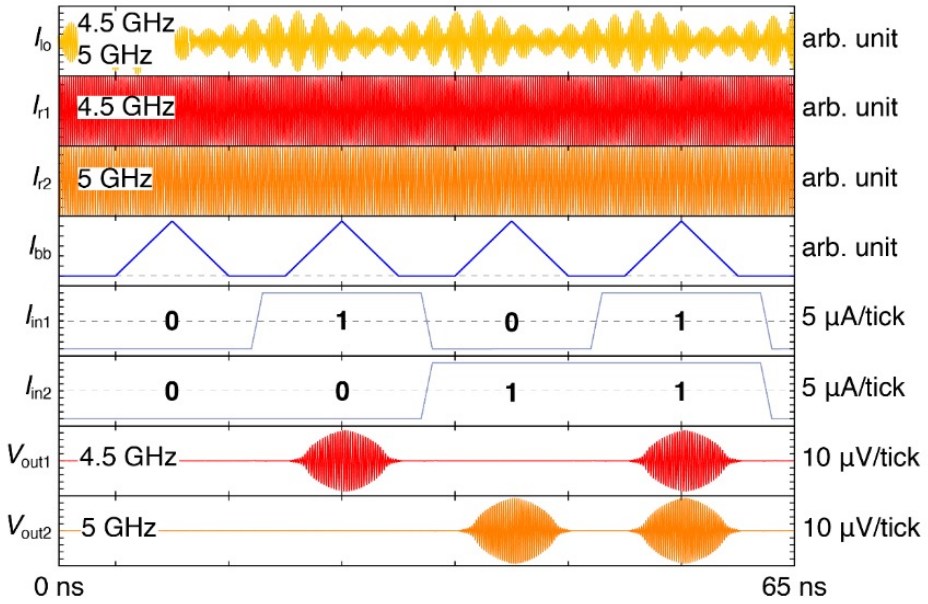
Operation Principle of AQFP-mux QC



Simulation at 4.5 and 5 GHz



- ✓ Cable # does not increase with qubit # due to microwave multiplexing
- ✓ Parallel qubit control available.

N. Takeuchi, *et al. npj Quantum Inf* **10**, 53 (2024).

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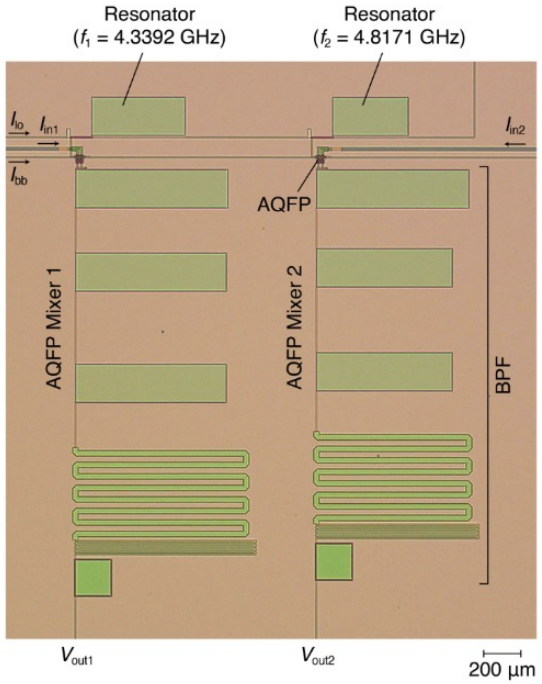
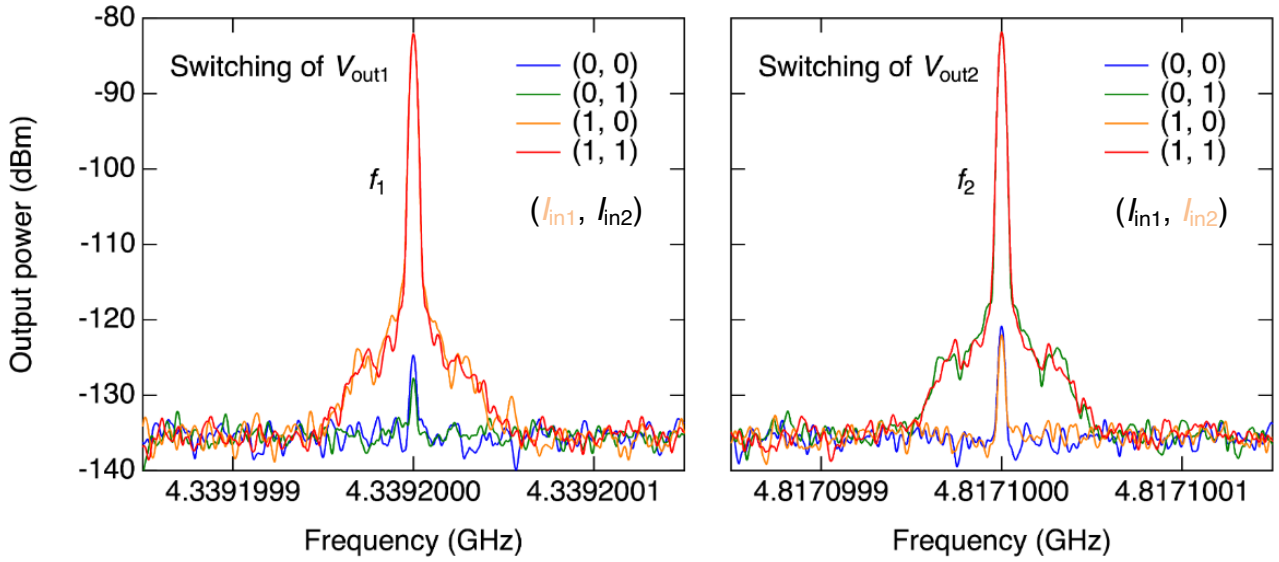
Experiment @4.2K: Microwave Switching



Output power: –82 dBm
On/off ratio: ~40 dB
power dissipation: 81.8 pW per qubit

Output power vs. digital inputs



Each output switched on/off by digital signals

N. Takeuchi, *et al. npj Quantum Inf* **10**, 53 (2024).

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Superconducting digital electronics projects in Japan

- Research on ultra-low power sub-terahertz superconducting quantum digital systems based on pulse-driven circuits
  - Sponsor: Japan Society for the Promotion of Science (JSPS)
  - Research category: Grant-in-Aid for Specially Promoted Research
  - Leader: Akira Fujimaki (Nagoya University)
  - Duration: 2018-2024
  - Institutions: Nagoya U, Kyoto U, AIST, Tohoku U, YNU
- Creation and development of superconducting computing technology for post-Moore era
  - Sponsor: Japan Society for the Promotion of Science (JSPS)
  - Research category: Grant-in-Aid for Scientific Research (S)
  - Leader: Koji Inoue (Kyusyu University)
  - Duration: 2022-2027
  - Institutions: Kyusyu U, Tokyo U, Osaka U
- Creation of Ultra-Low Power High-Density Adiabatic Quantum Flux Logic
  - Sponsor: Japan Society for the Promotion of Science (JSPS)
  - Research category:
  - Research category: Grant-in-Aid for Scientific Research (A)
  - Leader: Nobuyuki Yoshikawa (YNU)
  - Duration: 2024-2027
  - Institutions: YNU, Kobe U

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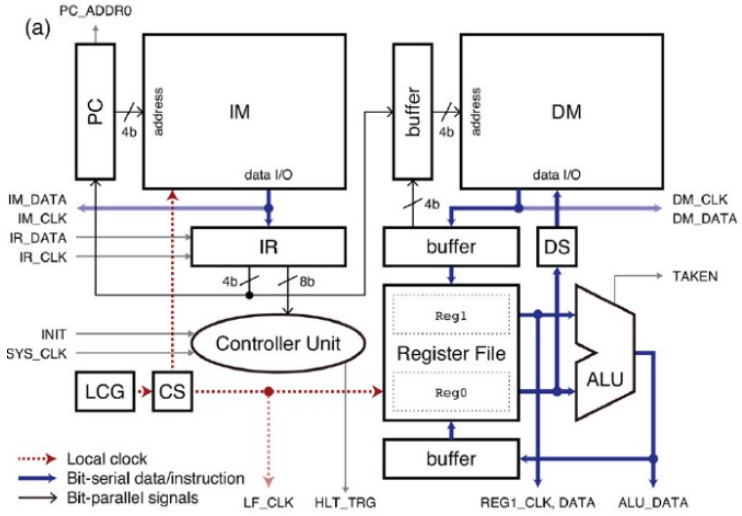
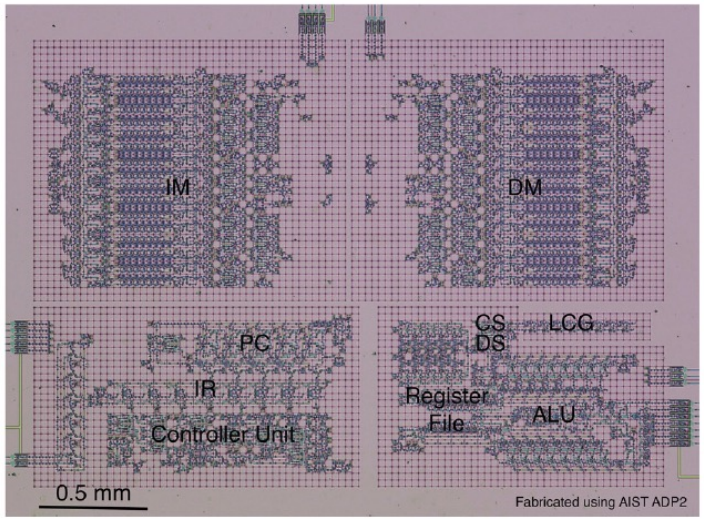
Research on ultra-low power sub-terahertz superconducting quantum digital systems based on pulse-driven circuits

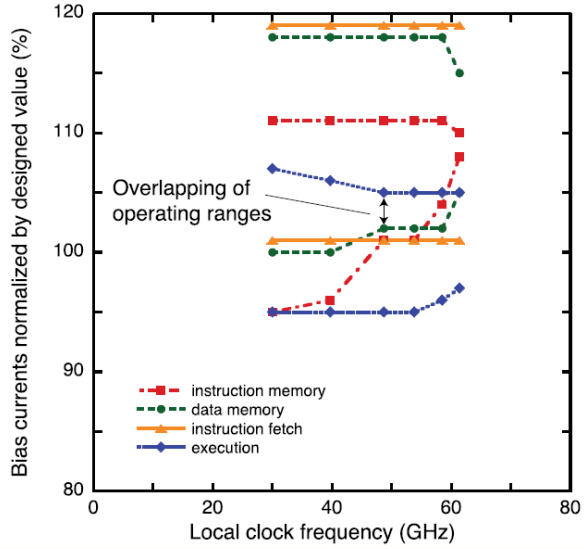
Project goal:

- Development of a 100 GHz-class SFQ microprocessor
- Demonstration application of half-flux quantum circuits and their RAM application

Execution of stored programs by an SFQ RAM embedded bit-serial microprocessor at 50 GHz clock frequency







M. Tanaka, *et al. Appl. Phys. Lett.* **122**, 192601 (2023).

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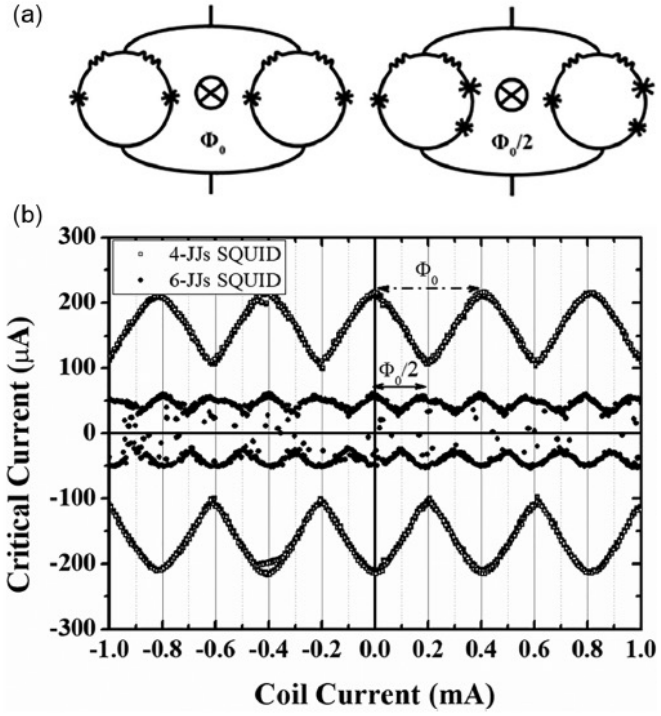
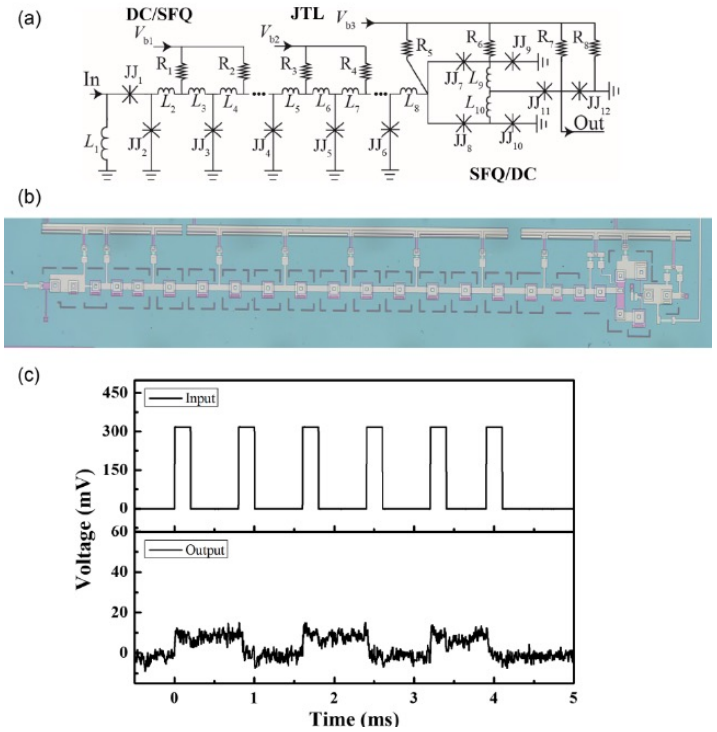
Research on ultra-low power sub-terahertz superconducting quantum digital systems based on pulse-driven circuits

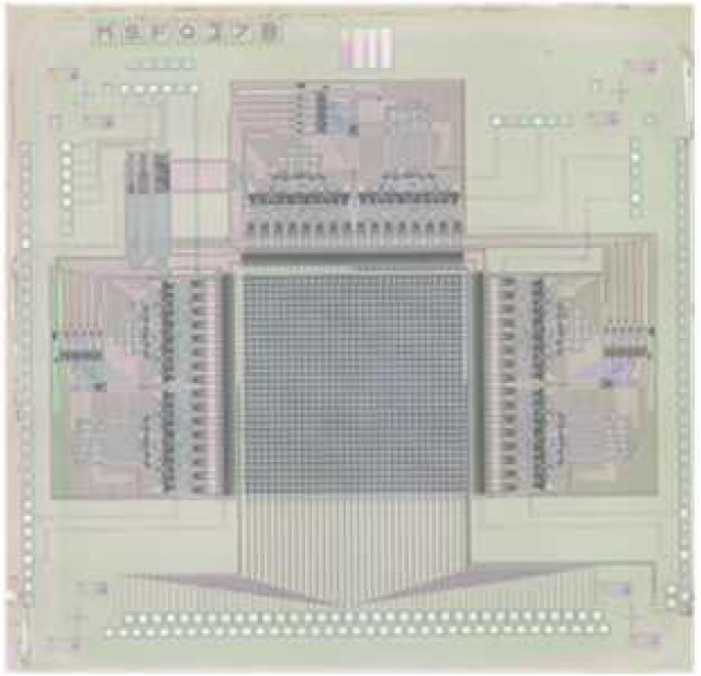
Half-flux quantum (HFQ) circuits using π junctions





F. Li, *et al. Appl. Phys. Lett.* **122**, 162601 (2023).

1-kb impulse-driven HFQ RAM



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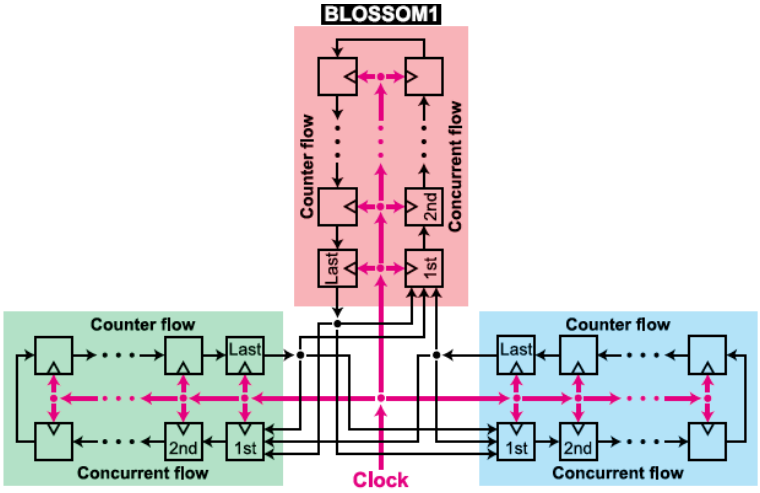
Creation and development of superconducting computing technology for post-Moore era

Project goal:

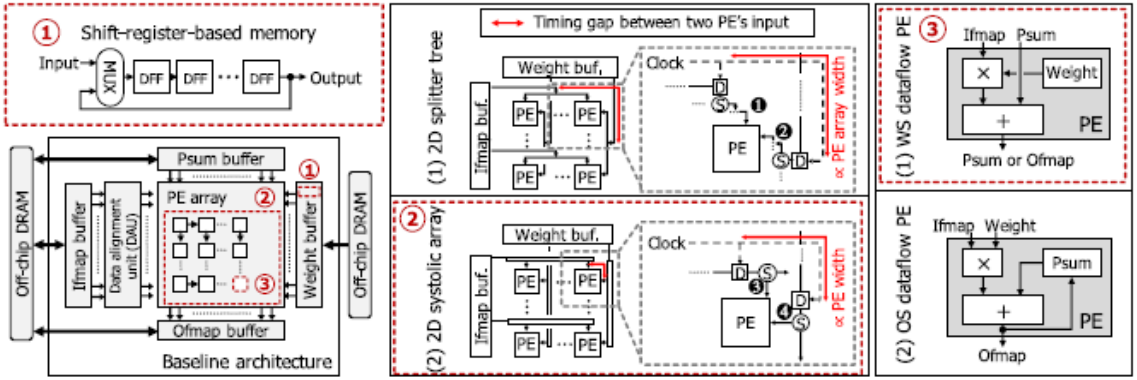
- Investigation of novel superconducting device technologies, including novel optical, memory, and SFQ devices.
- Development of superconducting computer system architectures and OS technologies.

A 57.2GHz 8-bit superconductor microprocessor with dual-clocking scheme



Nagaoka *et al.*, *2022 IEEE Asian Solid-State Circuits Conference (A-SSCC)*

Superconductor computing for neural networks



K. Ishida *et al.*, *et al. IEEE Micro.* **41**, 19-26 (2021).

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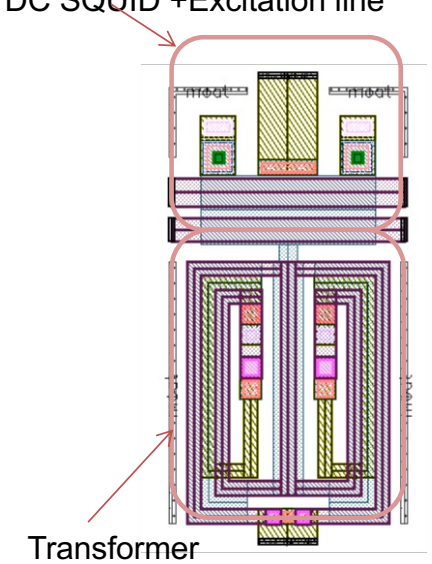
Creation of Ultra-Low Power High-Density Adiabatic Quantum Flux Logic

Project goal:

- Investigation of high integration density adiabatic superconducting logic

Layout of Conventional AQFP buffer

DC SQUID +Excitation line

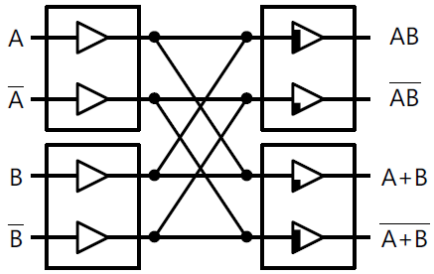


Transformer

Designed by AIST HSTP

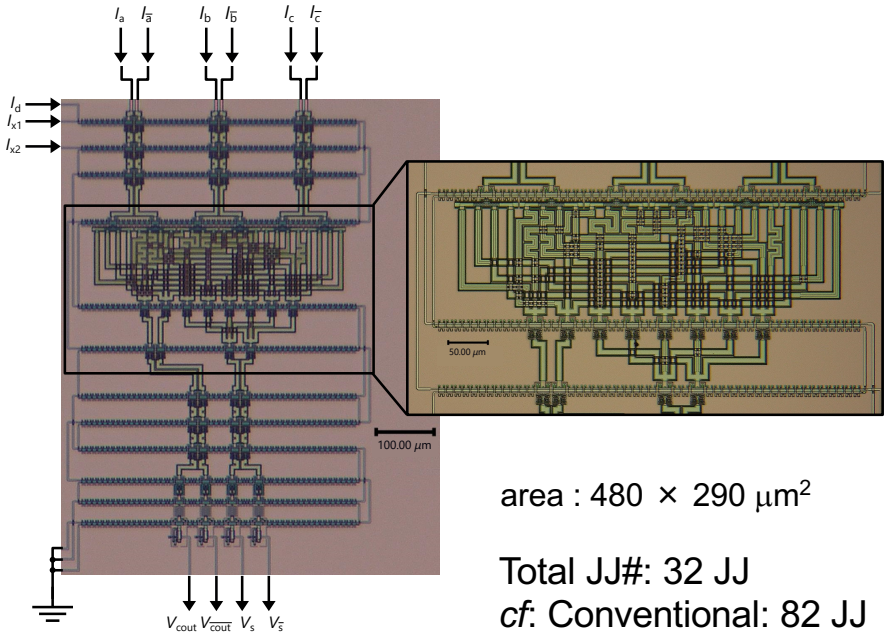
Dual-Rail Direct-Coupled AQFP (D^2QFP) Logic

D^2QFP AND-OR



Tota JJ#I: 16 JJ
Cf. Conventional: 16 JJ)

D^2QFP FA



area : 480 × 290 μm^2

Total JJ#: 32 JJ
cf: Conventional: 82 JJ

N. Yoshikawa, *et al. ASC2024, Salt Lake City*.

YNU YOKOHAMA National University

Summary

- The current status of Japan's superconducting (SC) electronics projects was reviewed.
- Most large-scale funding is rerated to quantum computing.
  - Superconducting circuits, such as an RSFQ and AQFP, are used for qubit control and readout.
- Some small-scale projects on SC digital electronics are ongoing, supported by JSPS.

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