Sep. 5, 2024 @ Salt Lake City

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Ultra-low-power, microwave-multiplexed qubit controller using adiabatic quantum-flux-parametron logic

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Superconducting quantum processors (QPs)

Circuit-based QP

- 1000+ qubits
- Integer factorization
- Quantum simulation
- Machine learning

https://www.ibm.com/quantum/blog/quantum-roadmap-2033

Annealing QP

- 5000+ qubits
- Combinatorial optimization

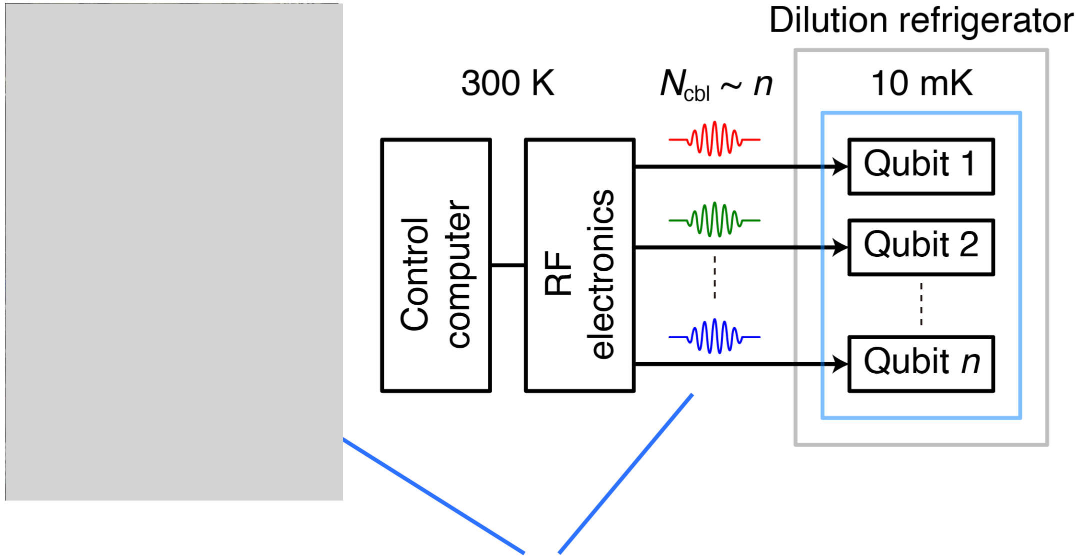
https://www.dwavesys.com/solutions-and-products/systems/

Large-scale superconducting QPs under development worldwide

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

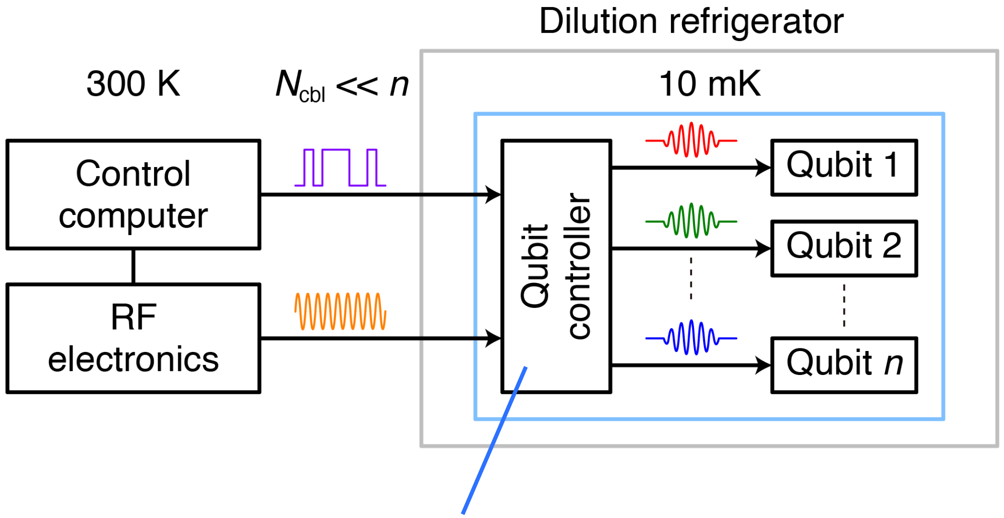
Scalability of superconducting QPs

Current control



😢 Qubit count limited by cable count

Future control

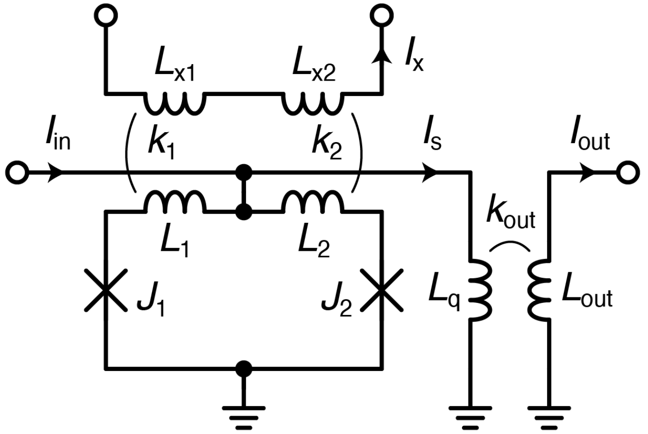


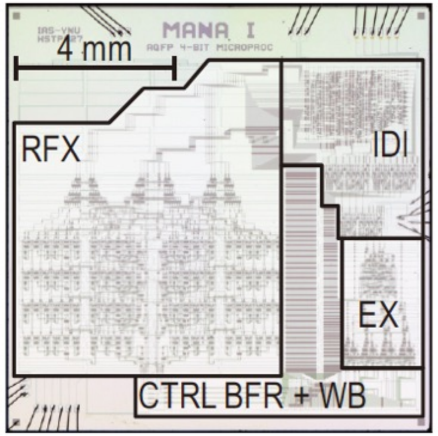
😄 Controls qubits directly at 10 mK
😢 But cooling power too small (< 10 µW)

Ultra-low-power, cryogenic qubit controller (µwave generator) required to build large-scale QP

Purpose of this study

Energy-efficient supercond. logic: Adiabatic QFP (AQFP)

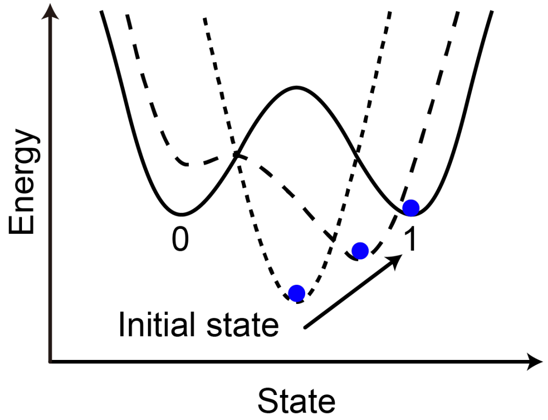




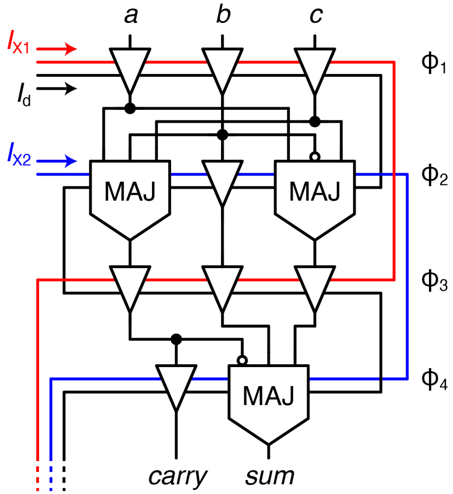
N. Takeuchi et al., Supercond. Sci. Tech. **26** (2013).
C. L. Ayala et al., IEEE J. Solid-State Circ. **56** (2021).

Features for qubit controller

Ultra-low energy:
~10^{-21} J per JJ



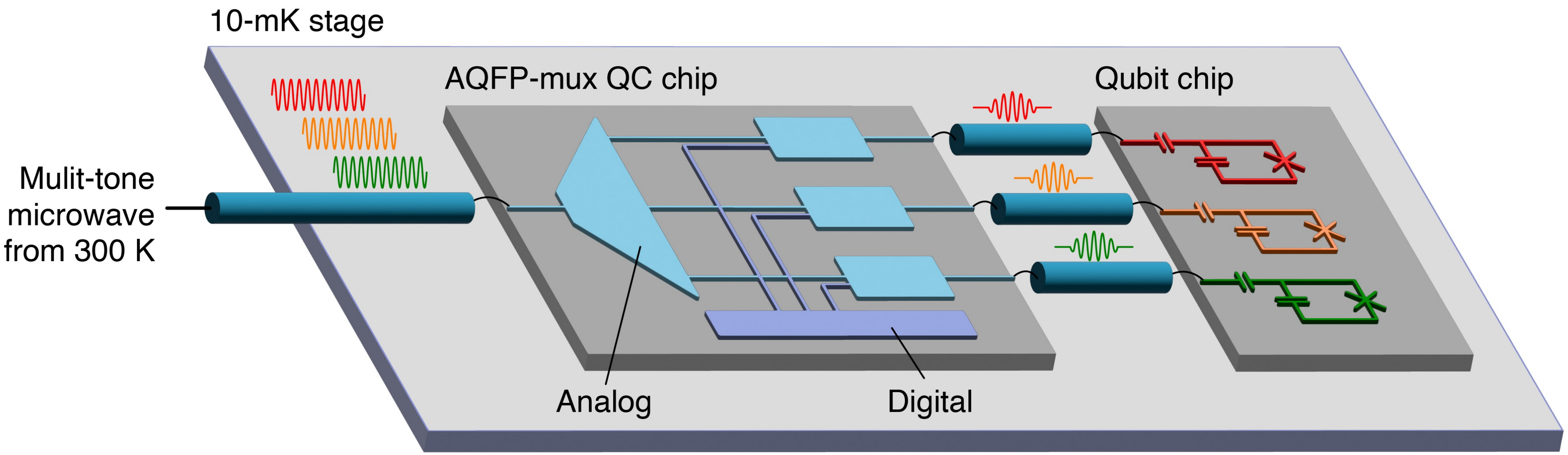
Microwave-based clocking



Develop ultra-low-power qubit controller using AQFP logic

Microwave-pulse generator using AQFP

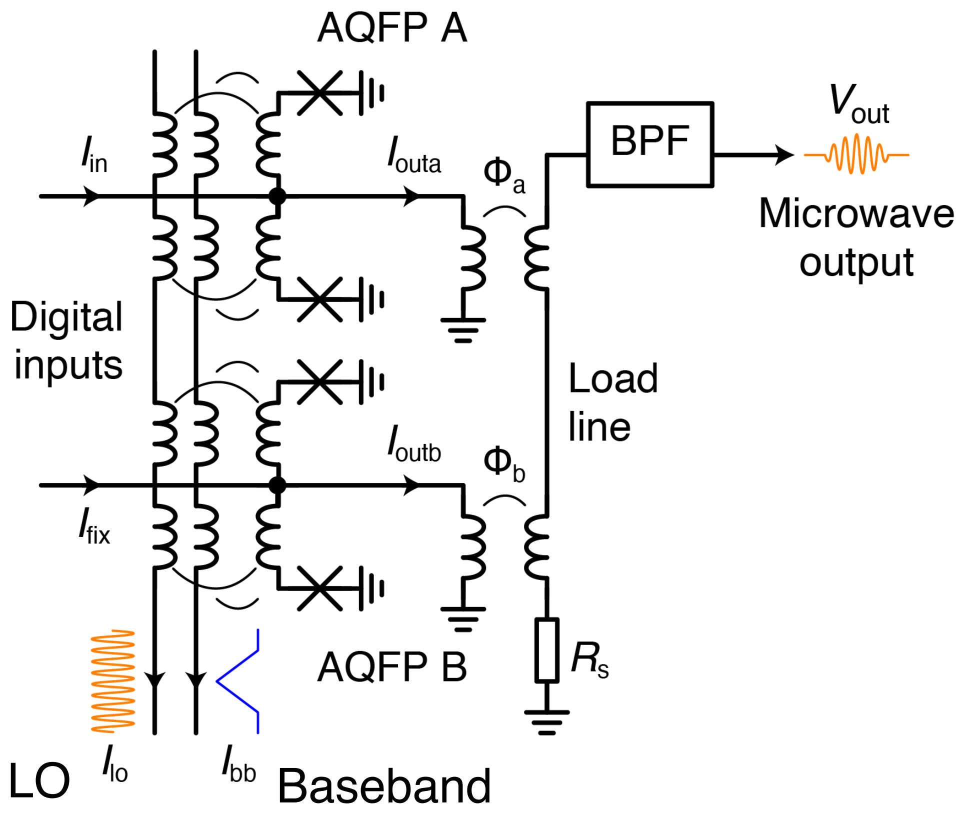
AQFP-multiplexed qubit controller (AQFP-mux QC)

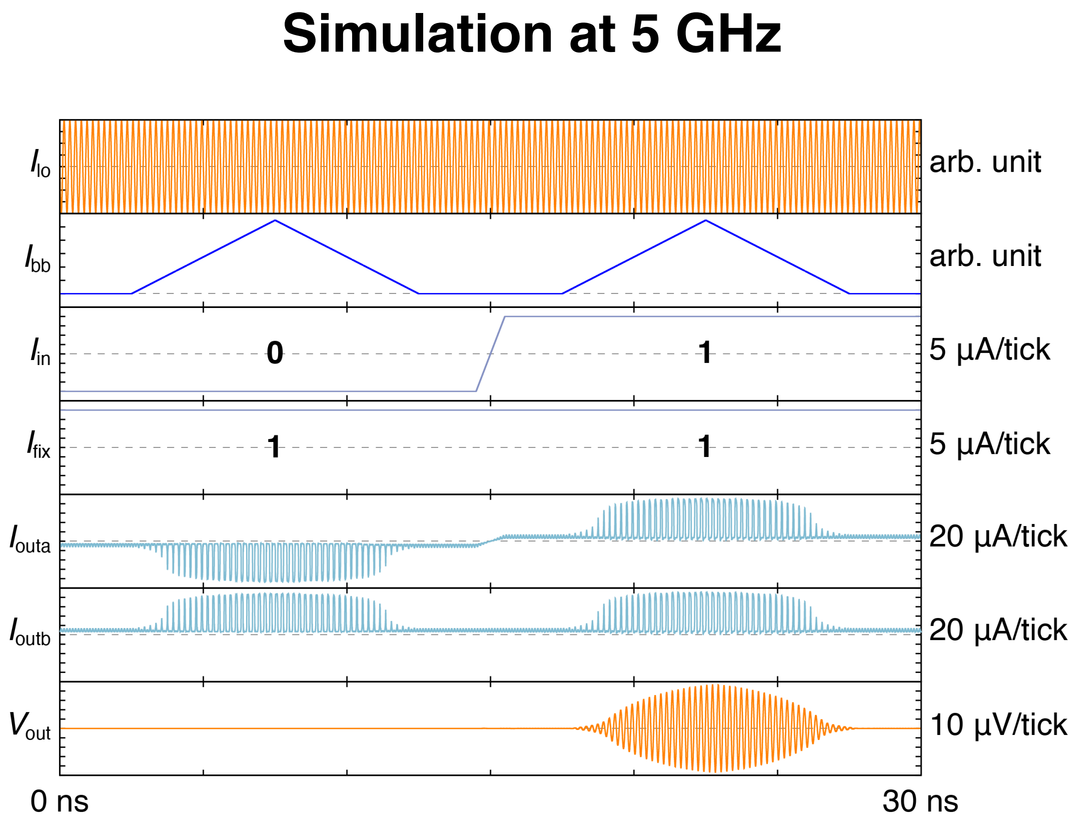


N. Takeuchi et al., npj Quantum Inf. **10** (2024).

- ✓ AQFP and microwave engineering combined for high scalability
- ✓ Ultra-low-power qubit control using AQFP (81.8 pW per qubit)
- ✓ Driven by a single coaxial cable owing to microwave multiplexing

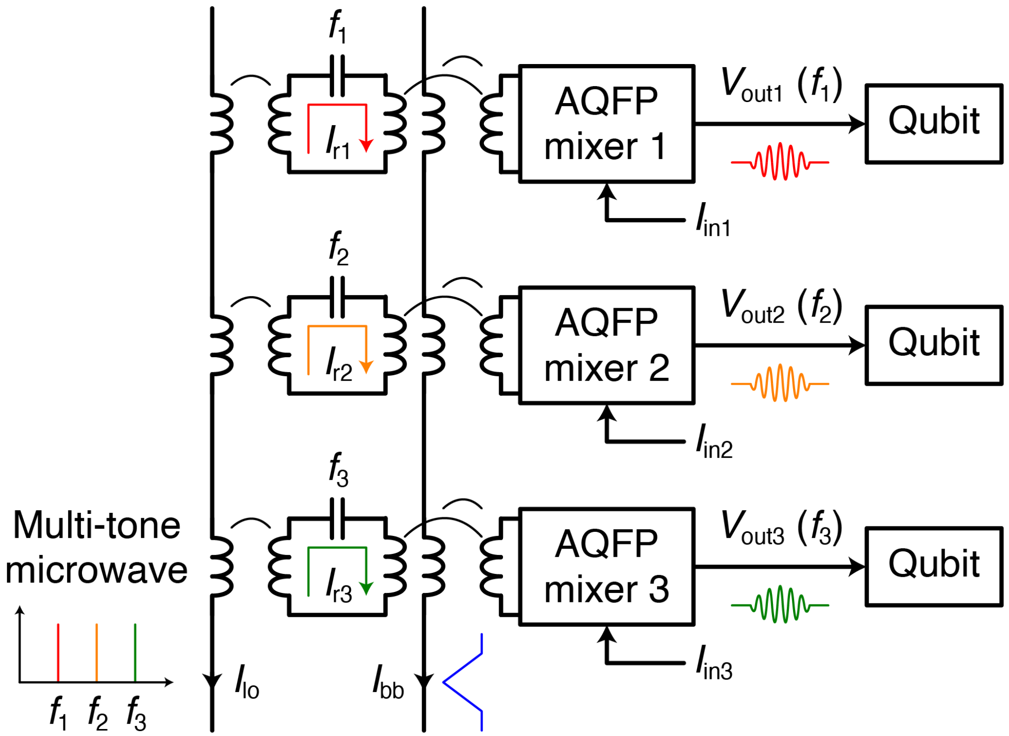
Core tech: AQFP mixer



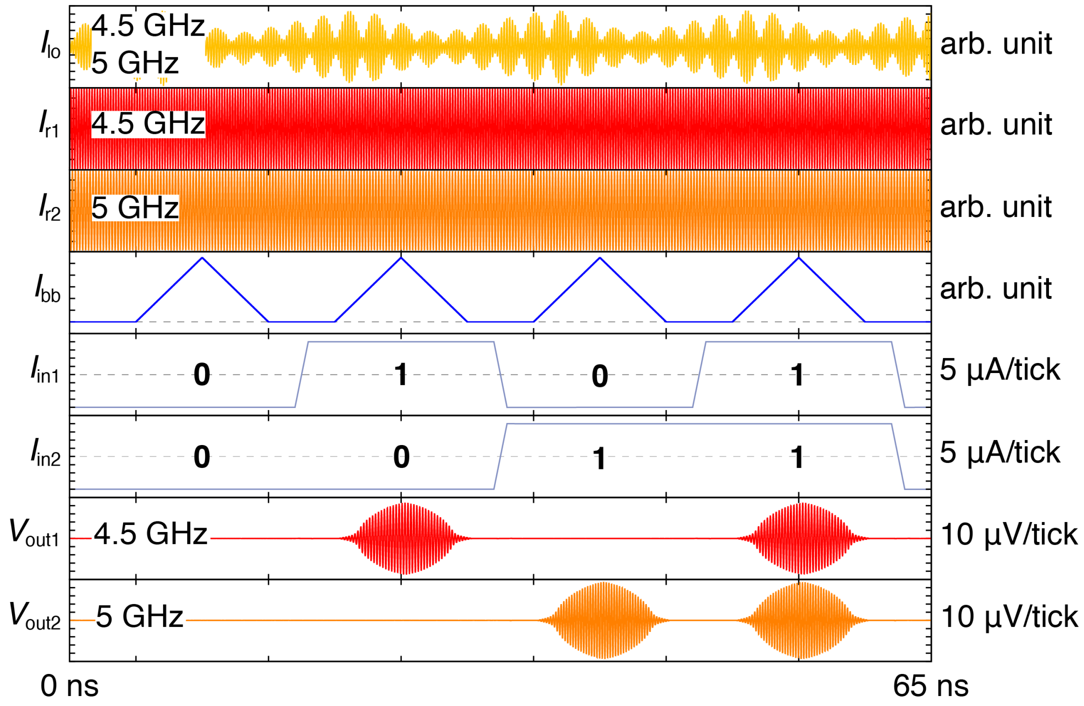


- Switching and mixing of microwave using the nonlinearity of AQFPs
- V_{out} generated by mixing I_{lo} and I_{bb}; and switched on/off by I_{in} and I_{fix}

AQFP-mux QC

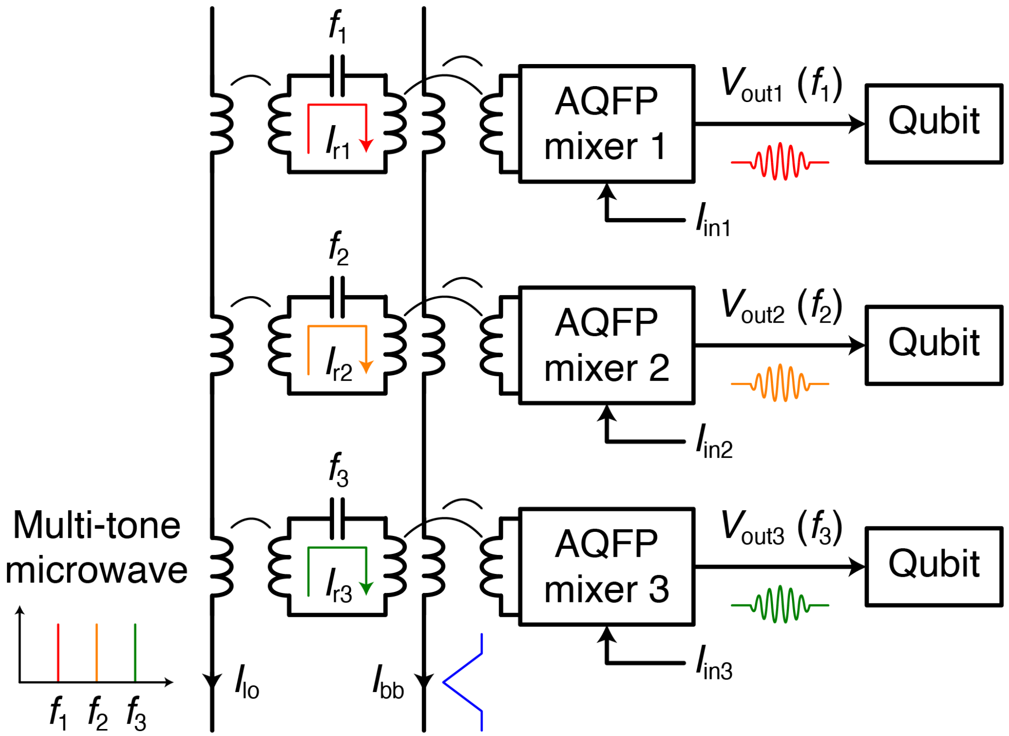


Simulation at 4.5 and 5 GHz



- ✓ Cable # does not increase with qubit # due to μwave muxing
- ✓ Parallel qubit control available, unlike TDM

AQFP-mux QC: Power estimation



Circuit spec. @ 5 GHz

Item	Value
Max output power	−76.6 dBm
Max power diss.	81.8 pW per qubit (27% for AQFPs)
Standby power	2.82 pW per qubit (81% for AQFPs)
# of multiplexing	~2,000 per 1 GHz for resonators with $Q \sim 10^4$

- ✓ Cable # does not increase with qubit # due to µwave muxing
- ✓ Parallel qubit control available, unlike TDM
- ✓ Extremely low-power; frequency-efficient than FDM (mux #: 32)

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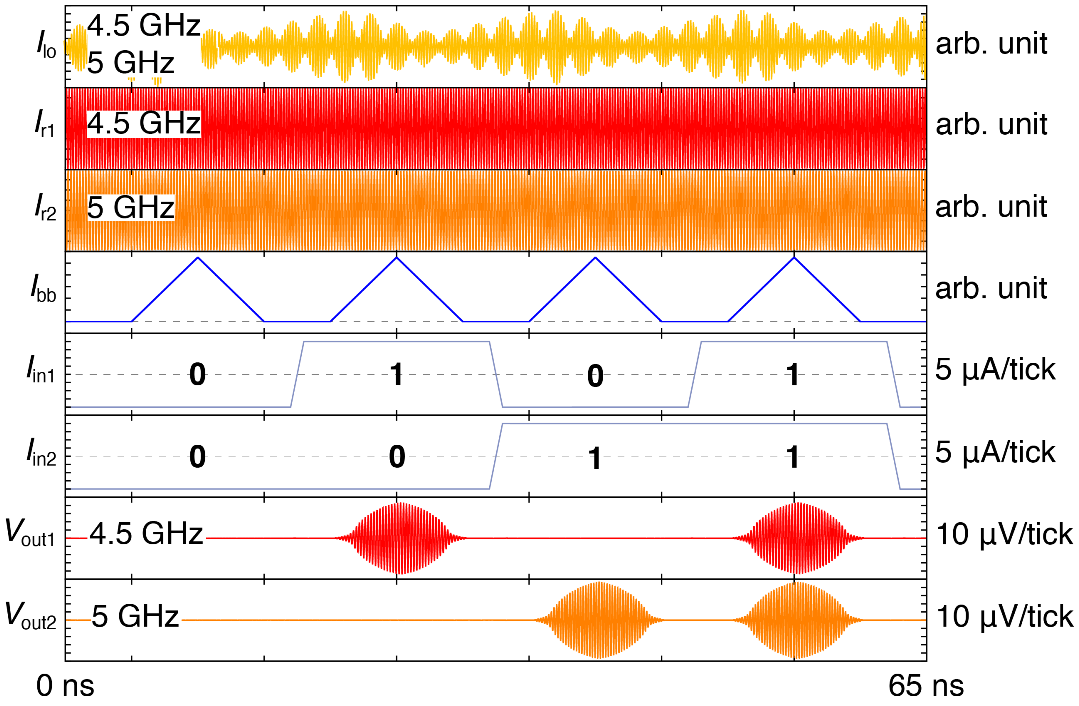
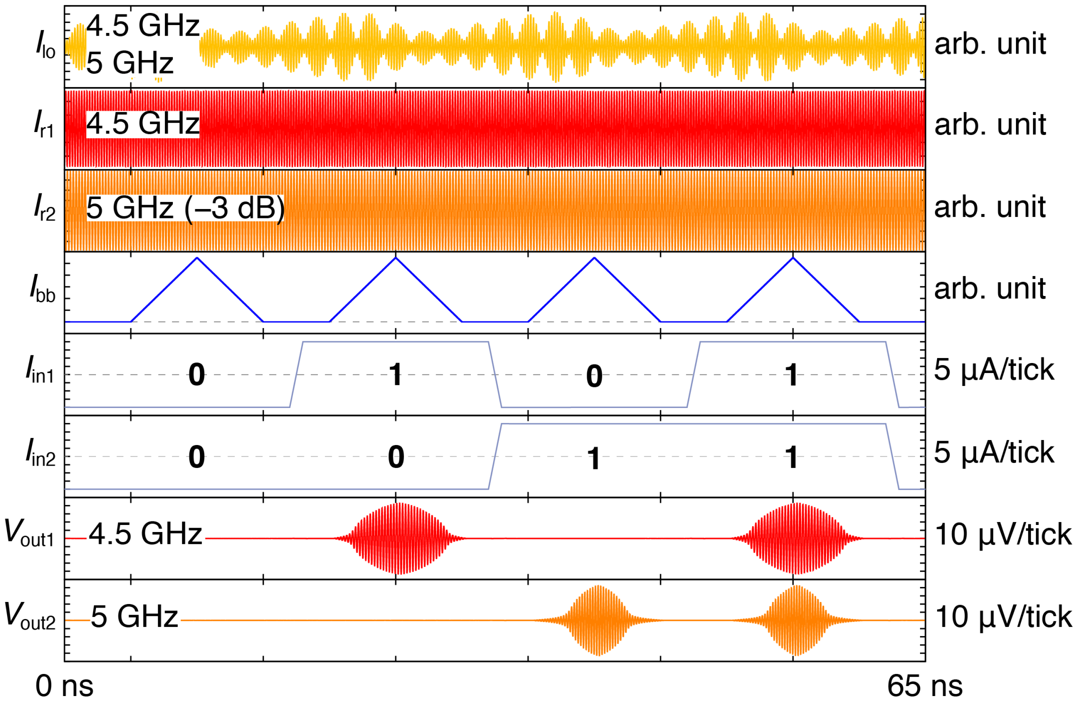
Individual power calibration

4.5 GHz: –57 dBm, 5 GHz: –56 dBm



4.5 GHz: –57 dBm, 5 GHz: –59 dBm



Each output power can be individually calibrated by microwave tone

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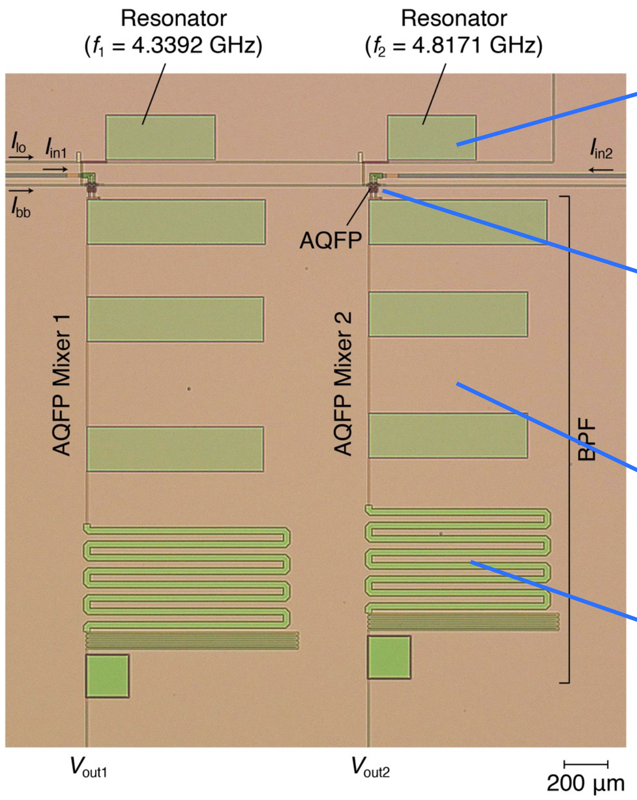
AQFP-mux QC chip



Lumped *LC* resonator

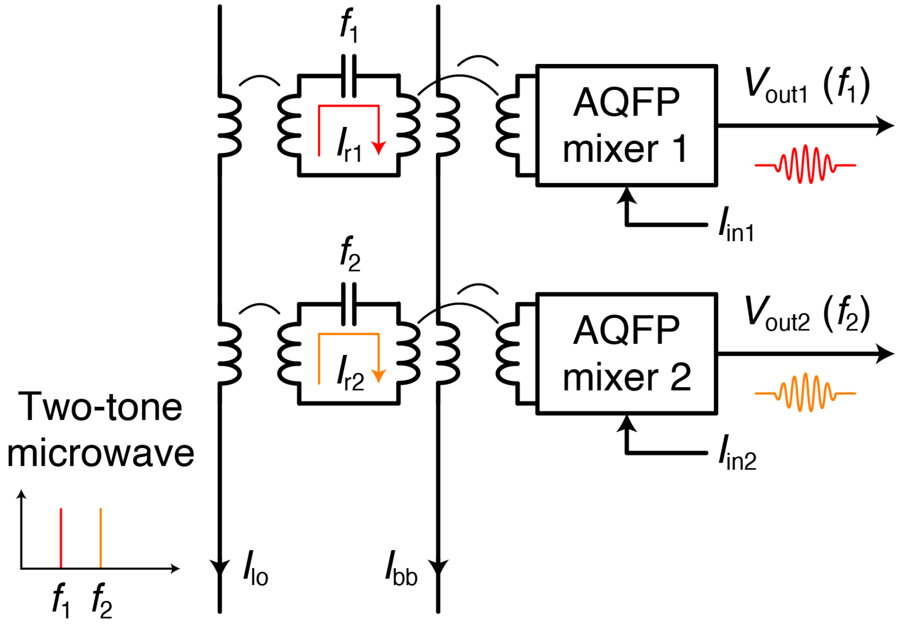
- External *Q*: ~200
- Current increase: ~80

AQFP x 2

LPF

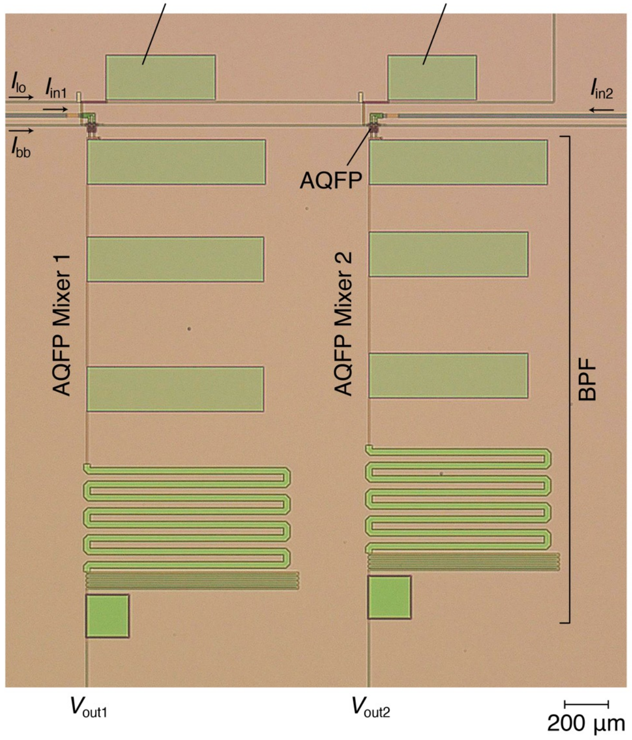
Impedance matching circuit

Circuit diagram

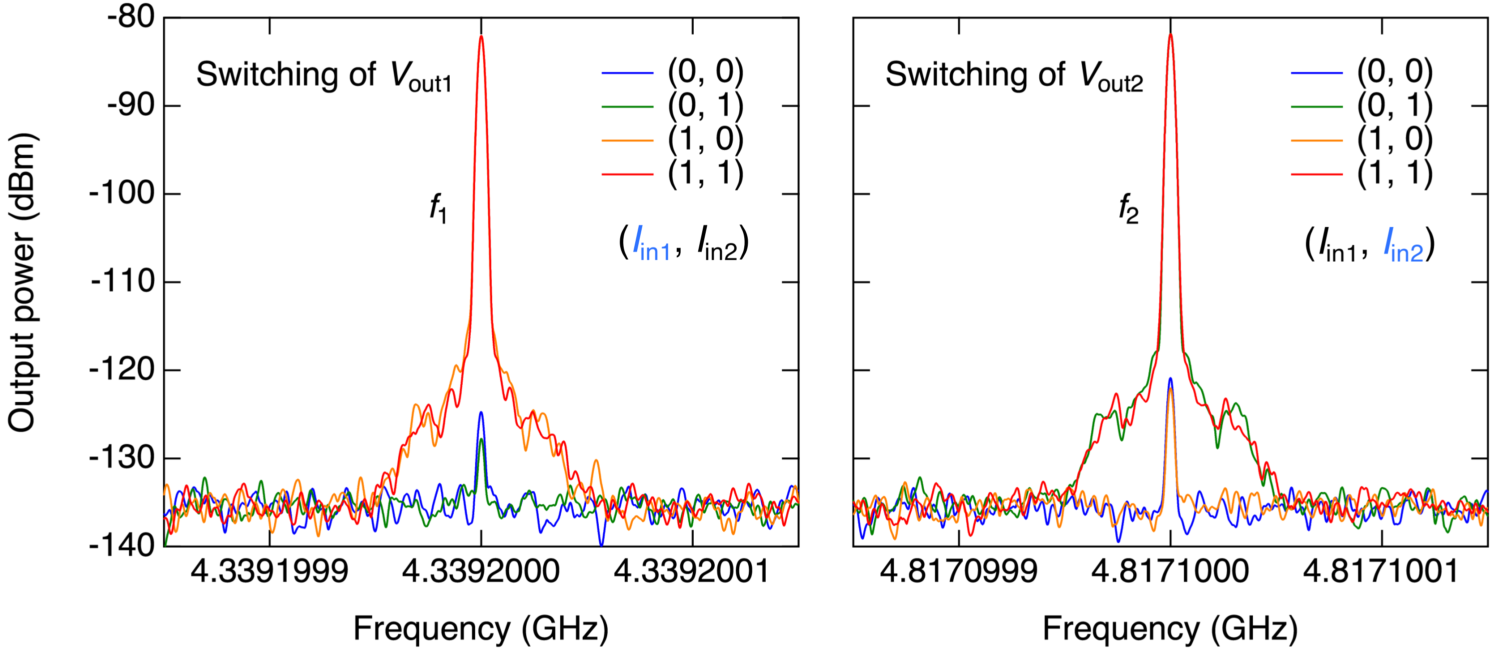


Designed an AQFP-mux chip comprising two mixers;
Fundamental microwave control tested at 4.2 K

Experiment @ 4 K: Microwave switching



Output power vs digital inputs



Each output switched on/off by digital signal
(Output power: –82 dBm, on/off ratio: ~40 dB)

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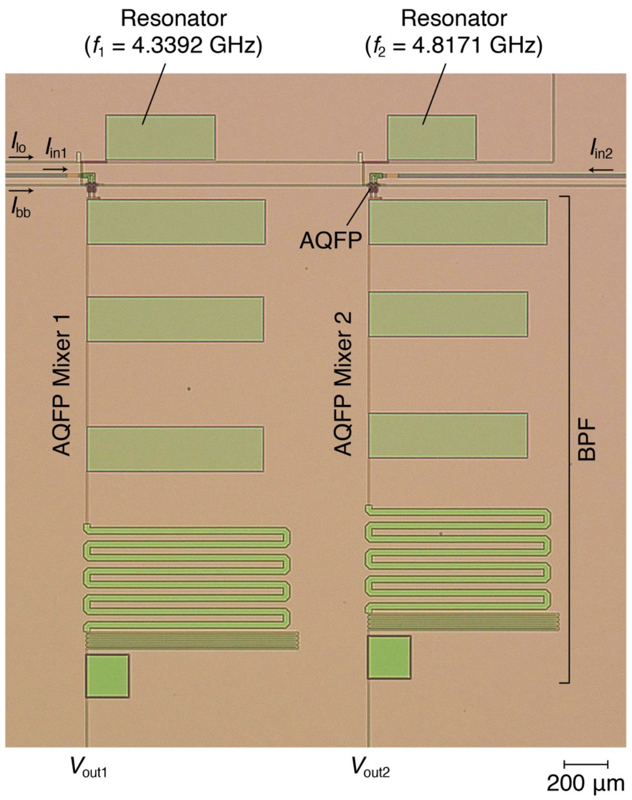
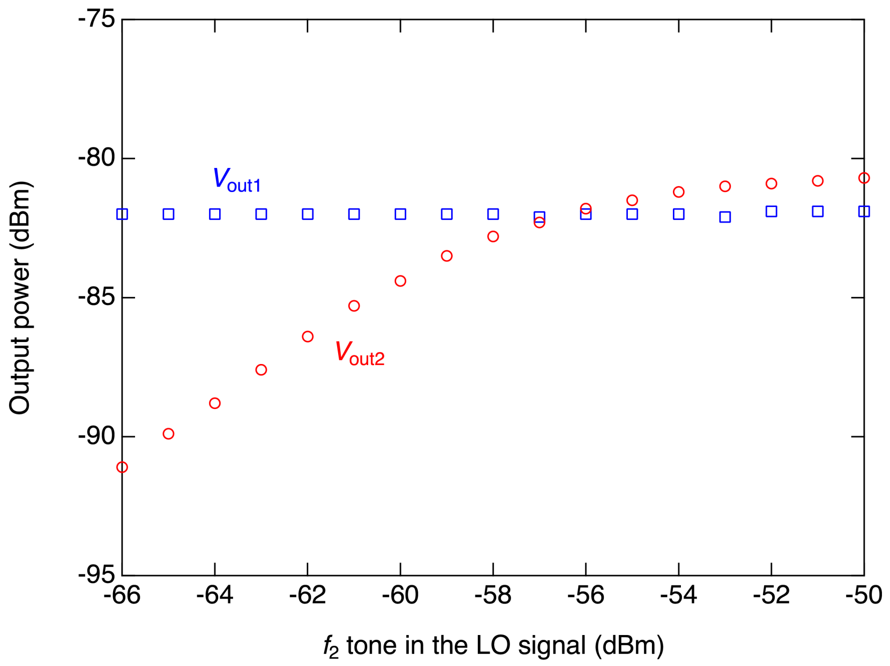
Experiment @ 4 K: Individual power calibration



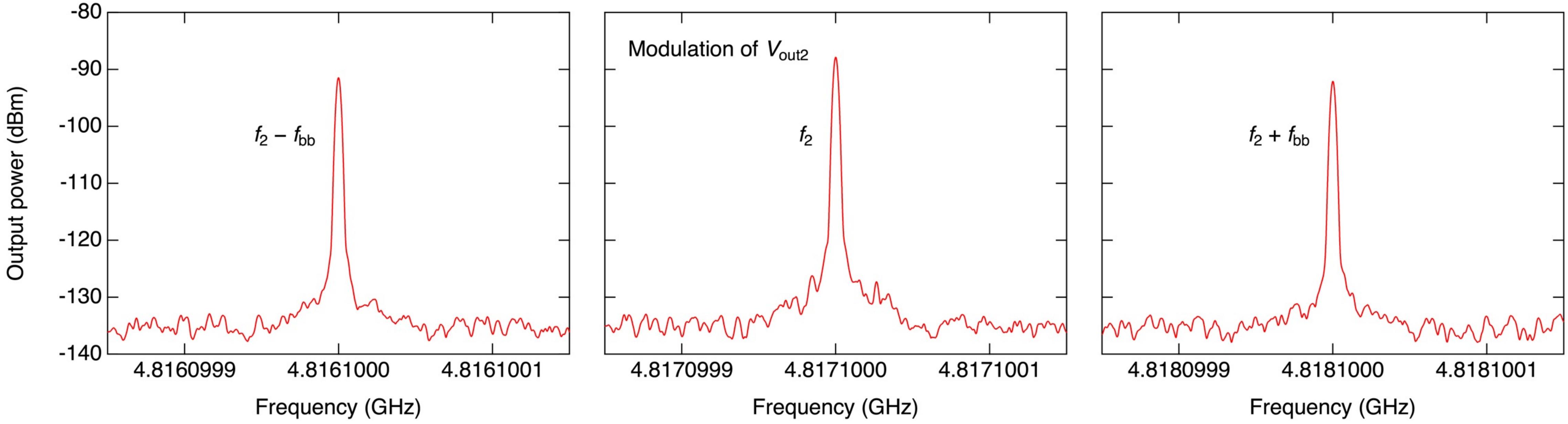
Output power vs f_2 tone



Power of V_{out2} individually calibrated by f_2 tone power, while keeping V_{out1} almost constant

Experiment @ 4 K: Modulation

Power at LO and sidebands
(1-MHz square pulse added to baseband)



Baseband signal upconverted by AQFP mixer

Qubit controller comparison

Technology	Cryo-CMOS [1]	Cryo-CMOS [2]	SFQ [3]	SFQ [4]	AQFP (this study)
Circuit	Microwave-pulse generator	Microwave DEMUX	Microwave-pulse generator	Pulse-train generator	Microwave-pulse generator
Power dissipation	12 mW/qubit	180 nW/qubit	51.7 µW/qubit	1.6 µW/qubit	81.8 pW/qubit
Op. temperature	3 K	10 mK	3 K[a]	3 K	10 mK[a]
Cable count[b]	$N_{qubit}/32$	$\log_2(N_{qubit}) + 1$	N_{qubit}	N_{qubit}	$\sim N_{qubit}/4{,}000$
Multiplexing	TDM + FDM	TDM			Microwave muxing
Parallel qubit op.	(✓)[c]		✓	✓	✓
X gate ($X_{\pi/2}$)	✓	✓	✓	✓	✓
Z gate (T)	✓	✓			
Digital controller	✓				

[a]So far demonstrated at 4.2 K in liquid He
[b]Cable count between 10-mK and 3-K stages
[c]Limited to 2 operations per cable

[1] J. P. G. Van Dijk et al., IEEE J. Solid-St. Circ. **55** (2020).
[2] R. Acharya et al., Nat. Electron. **23** (2023).
[3] H. Shen et al., Supercond. Sci. Tech. **36** (2023).
[4] L. Howe et al., PRX Quantum **3** (2022).
[5] N. Takeuchi et al., TEION KOGAKU **59** (2024).

Conclusion

- **AQFP-mux QC: Scalable qubit controller for large-scale QPs**
  - Based on AQFP, an energy-efficient supercond. logic element
  - Generates multi-tone microwave pulses by the non-linearity of AQFPs
  - Highly scalable
    - Ultra-low-power dissipation: 81.8 pW per qubit
    - A few control lines owing to microwave multiplexing: ~N_{qubit}/4,000
  - Individual power calibration by adjusting each tone level
  - (Precise pulse shaping, with AQFPs' non-linearity taken into account)
  - Proof-of-concept experiments successfully performed at 4.2 K

- **More details can be found in:**
  - N. Takeuchi et al., npj Quantum Inf. **10** 53 (2024).

Acknowledgements

- **This study was supported by**
  - JST FOREST (Grant No. JPMJFR212B)
  - JSPS KAKENHI (Grants No. JP19H05614 and No. JP19H05615).

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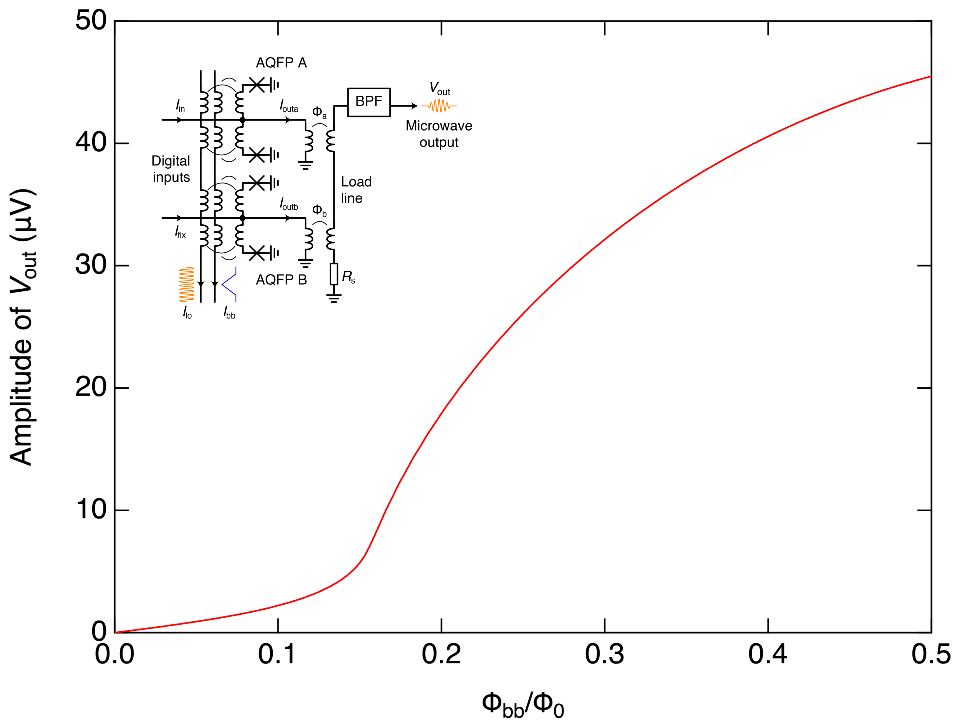
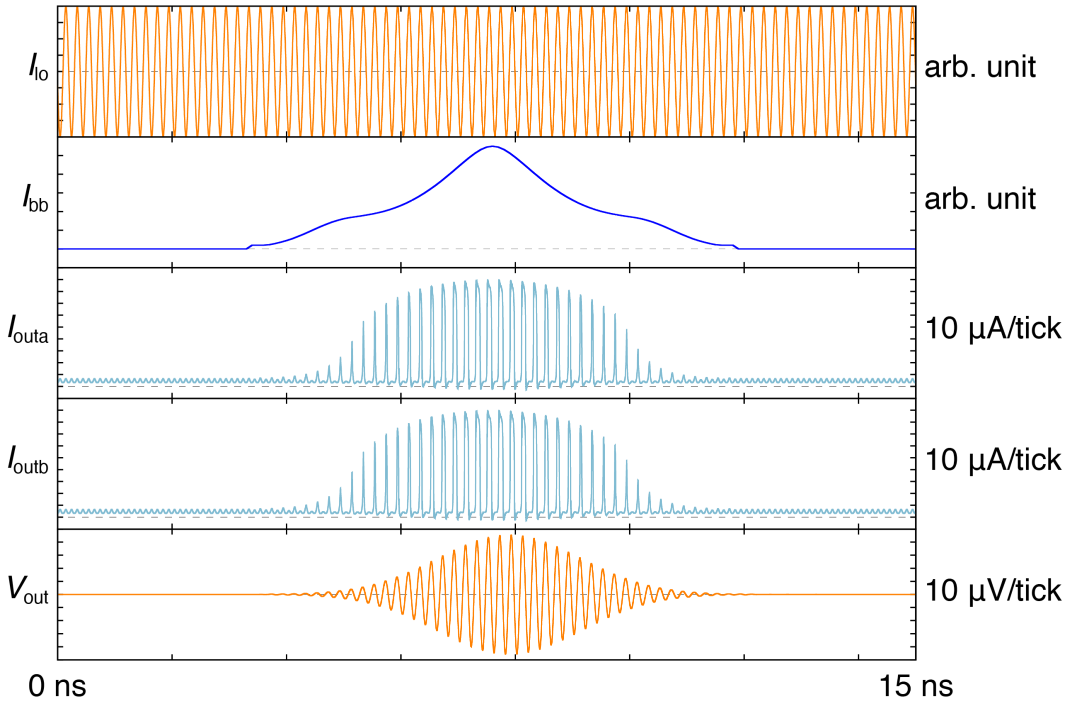
Pulse shaping

Nonlinearity btw. BB and output



Numerical simulation



Precise pulse shaping possible by considering the nonlinearity of AQFP mixer