量子トランスデューサー

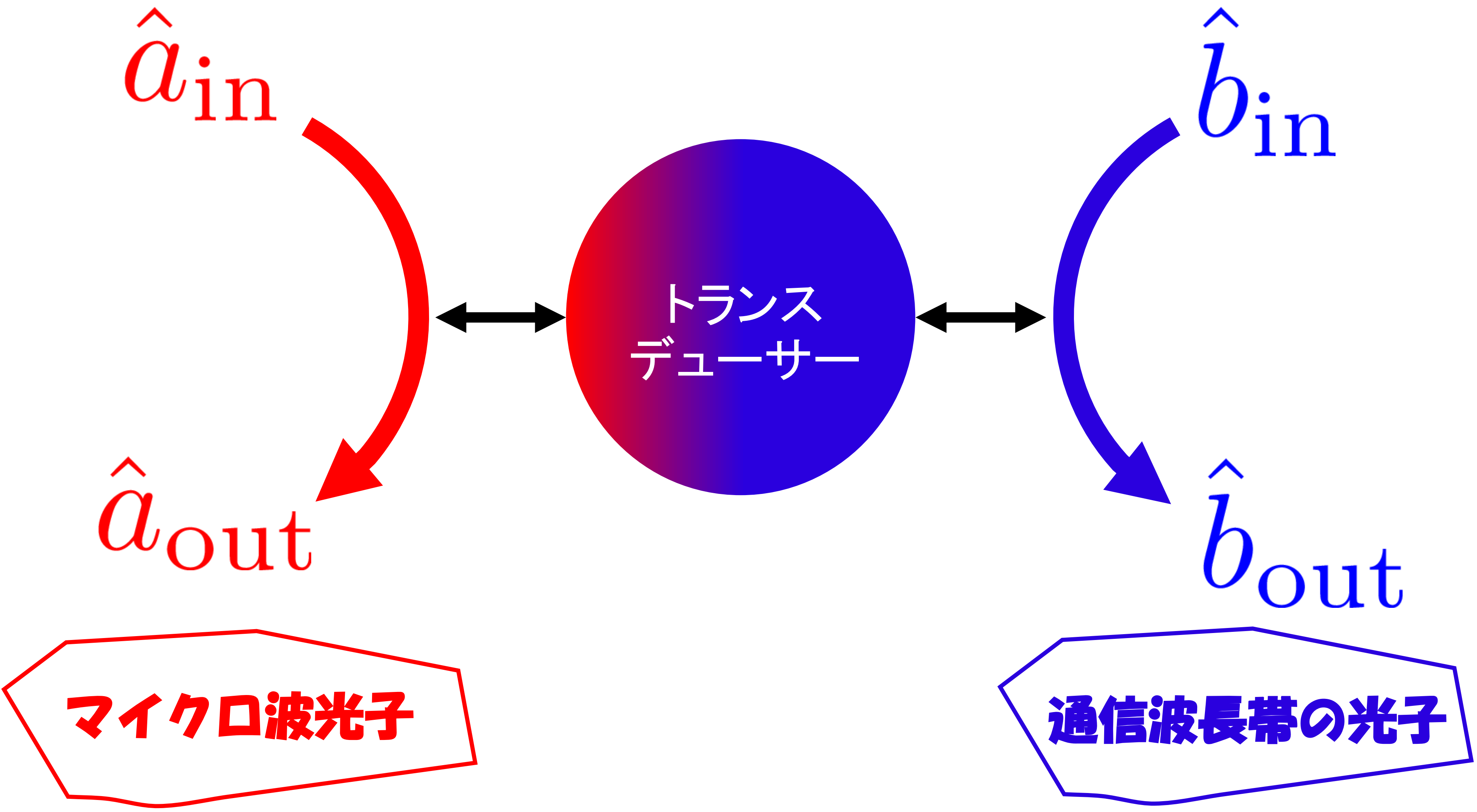
Quantum Transducers

マイクロ波光子 ⟷ 通信波長帯の光子

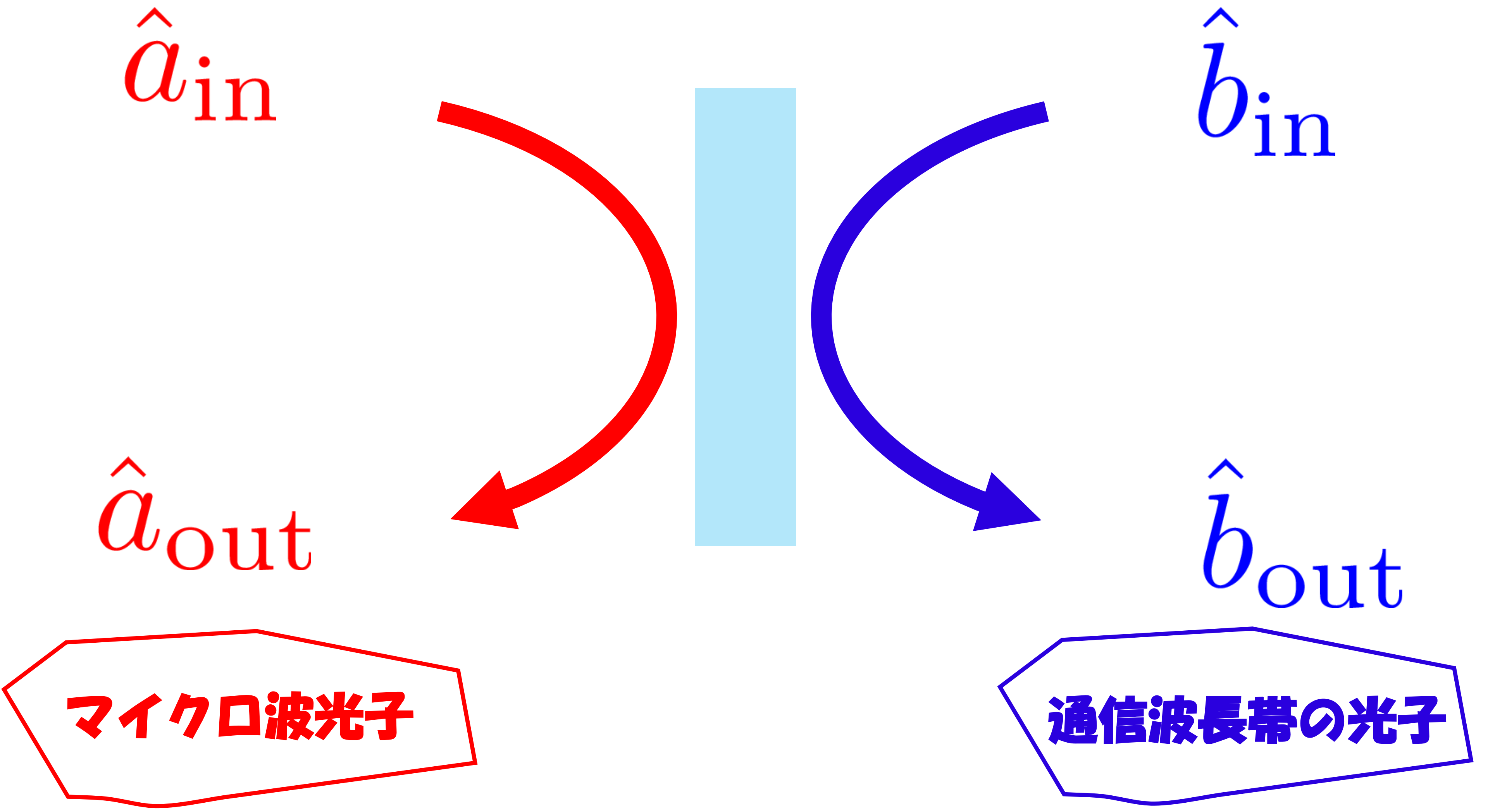
東京大学先端科学技術研究センター
宇佐見康二

RCAST, UTokyo
Koji Usami

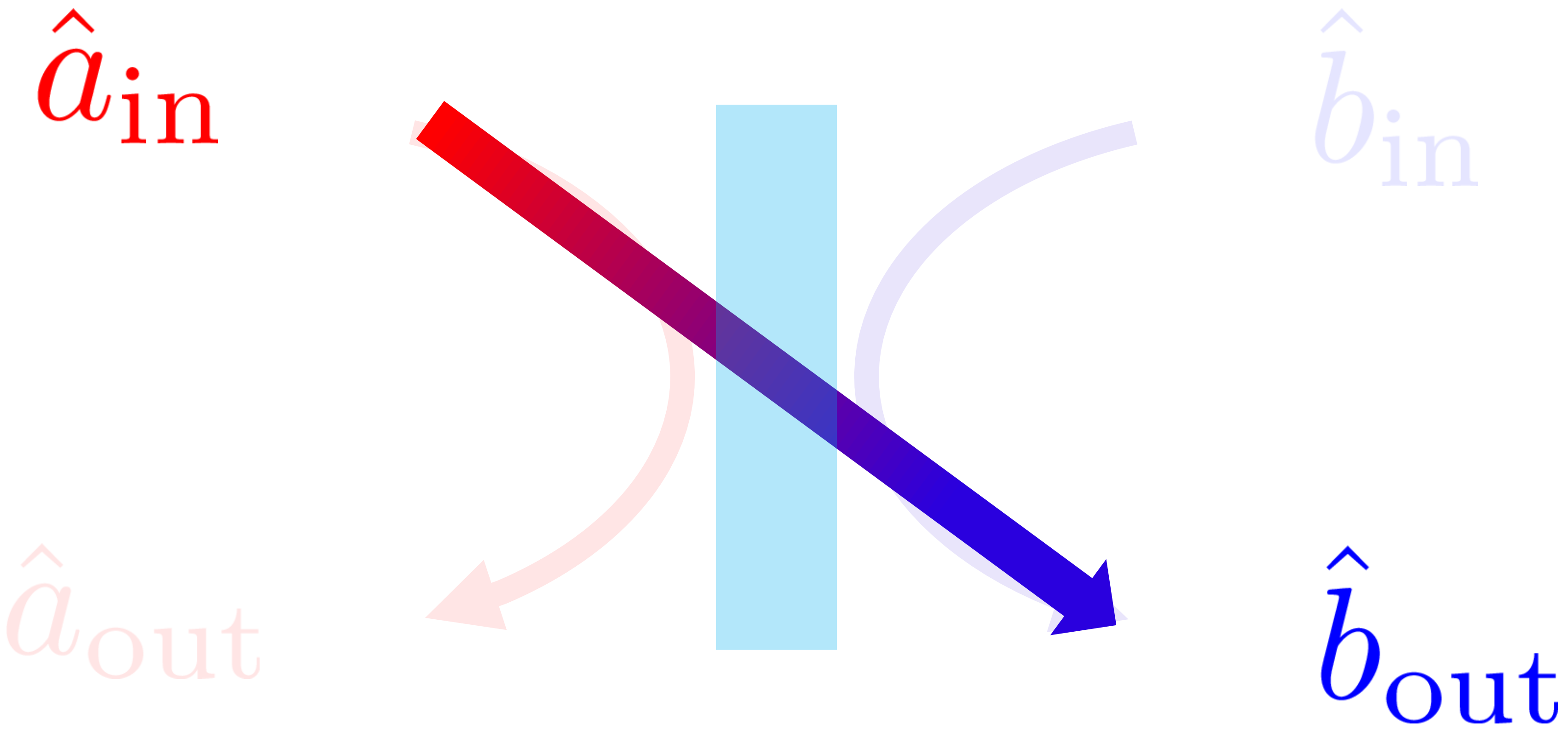
量子トランスデューサーとは？



交換関係


$\hat{a}_{\mathrm{in}}$
$\hat{b}_{\mathrm{in}}$
$\hat{a}_{\mathrm{out}}$
$\hat{b}_{\mathrm{out}}$
マイクロ波光子
通信波長帯の光子

交換関係



$$\left[\hat{a}_{\mathrm{in}}(t), \hat{a}^{\dagger}_{\mathrm{in}}(t')\right] = \delta(t - t')$$

$$\left[\hat{b}_{\mathrm{out}}(t), \hat{b}^{\dagger}_{\mathrm{out}}(t')\right] = \delta(t - t')$$

交換関係

損失: $$\hat{b}_{\mathrm{out}} = \eta \hat{a}_{\mathrm{in}} \qquad (\eta \leq 1)$$

増幅: $$\hat{b}_{\mathrm{out}} = G \hat{a}_{\mathrm{in}} \qquad (G \geq 1)$$

$$\left[\hat{a}_{\mathrm{in}}(t), \hat{a}^{\dagger}_{\mathrm{in}}(t')\right] = \delta(t - t')$$

$$\left[\hat{b}_{\mathrm{out}}(t), \hat{b}^{\dagger}_{\mathrm{out}}(t')\right] \neq \delta(t - t')$$

交換関係

損失: $$\hat{b}_{\mathrm{out}} = \eta\hat{a}_{\mathrm{in}} + \sqrt{1-\eta^2}\,\hat{c}_{\mathrm{in}} \quad (\eta \leq 1)$$

増幅: $$\hat{b}_{\mathrm{out}} = G\hat{a}_{\mathrm{in}} + \sqrt{G^2-1}\,\hat{d}_{\mathrm{in}} \quad (G \geq 1)$$

ノイズ項

$$\left[\hat{a}_{\mathrm{in}}(t), \hat{a}^{\dagger}_{\mathrm{in}}(t')\right] = \delta(t-t')$$

$$\left[\hat{b}_{\mathrm{out}}(t), \hat{b}^{\dagger}_{\mathrm{out}}(t')\right] = \delta(t-t')$$

交換関係

損失: $\hat{b}_{\mathrm{out}} = \eta \hat{a}_{\mathrm{in}}$ 損失なし $(\eta = 1)$

増幅: $\hat{b}_{\mathrm{out}} = G \hat{a}_{\mathrm{in}}$ 増幅なし $(G = 1)$

$$\left[\hat{a}_{\mathrm{in}}(t), \hat{a}^{\dagger}_{\mathrm{in}}(t')\right] = \delta(t - t') \qquad \left[\hat{b}_{\mathrm{out}}(t), \hat{b}^{\dagger}_{\mathrm{out}}(t')\right] = \delta(t - t')$$

ユニティゲインパラメトリック増幅器！

$$\Omega_p = \Omega - \omega$$

ポンプ光子

$$\hat{b}_{\mathrm{out}} \leftrightarrow \hat{a}_{\mathrm{in}}$$

通信波長帯の光子

マイクロ波光子

$\Omega/2\pi \sim 200\ \mathrm{THz}$–$600\ \mathrm{THz}$ $\omega/2\pi \sim 0.1\ \mathrm{MHz}$–$10\ \mathrm{GHz}$

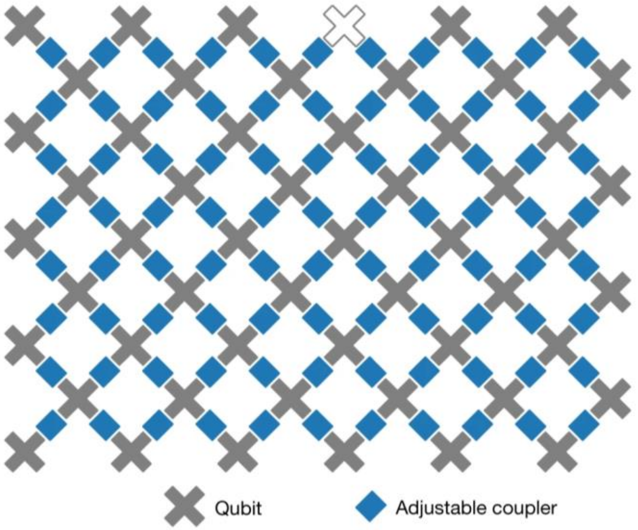
動機

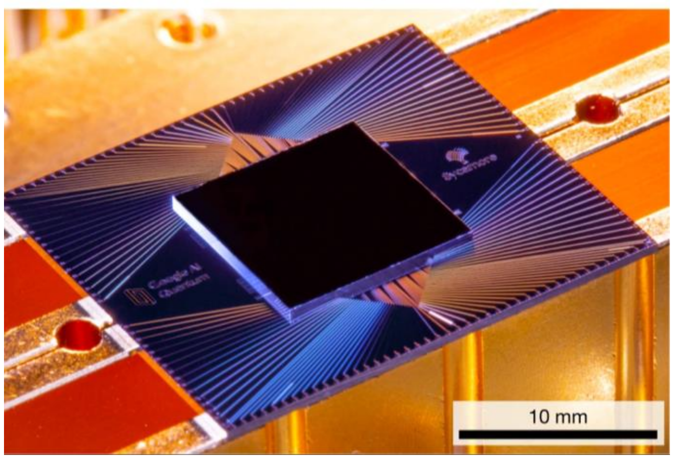
- 量子ビットのネットワーク化

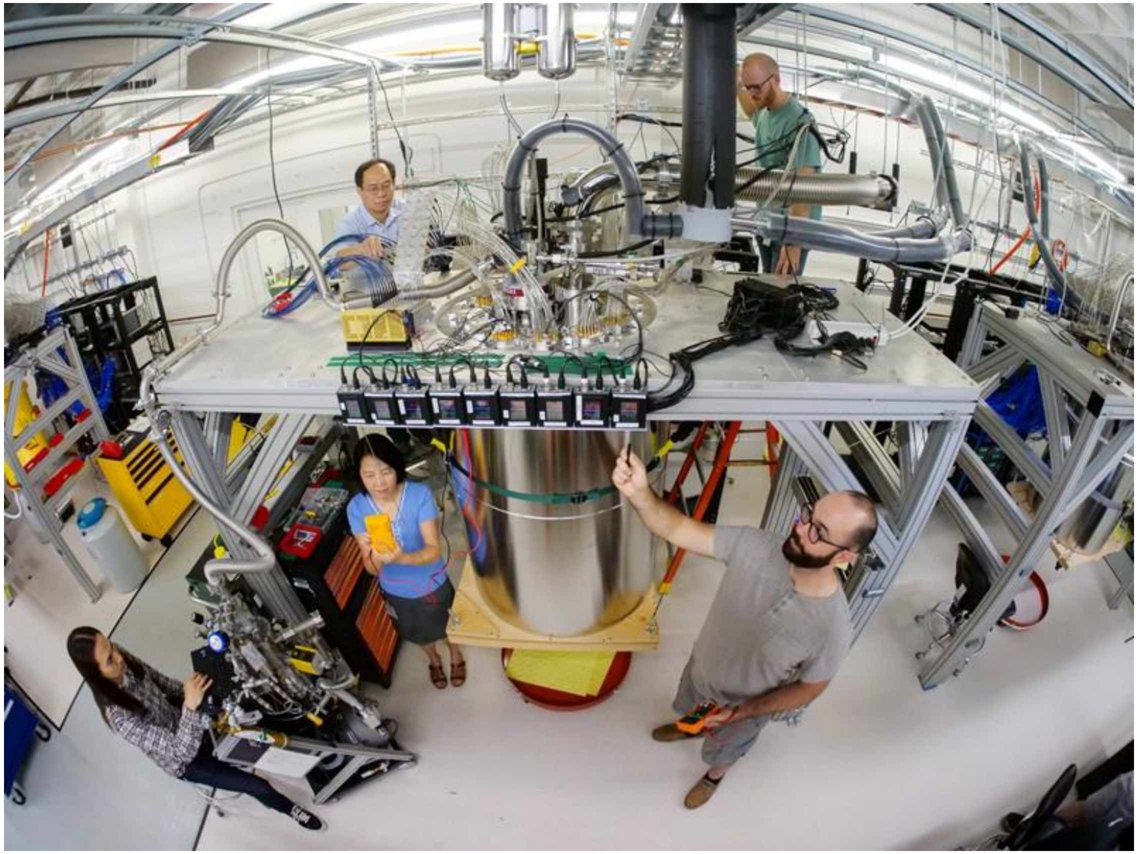
- 熱負荷の緩和

- 微弱ラジオ波信号の光検出

動機１：量子ビットのネットワーク化

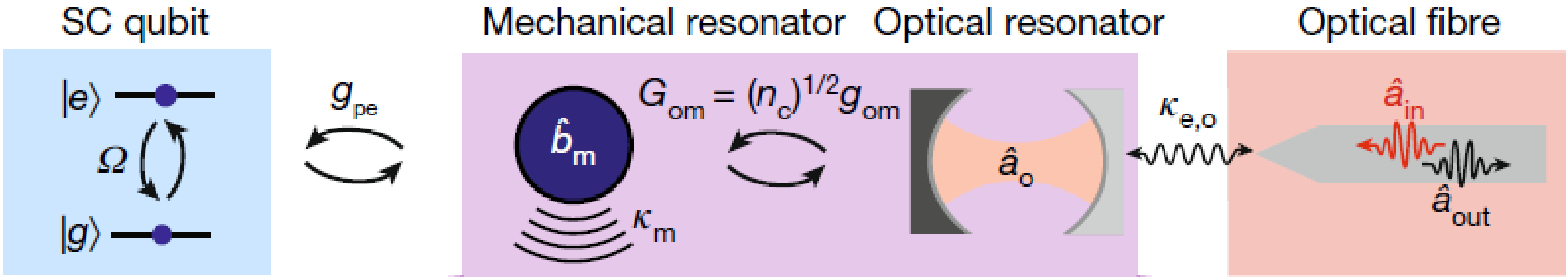




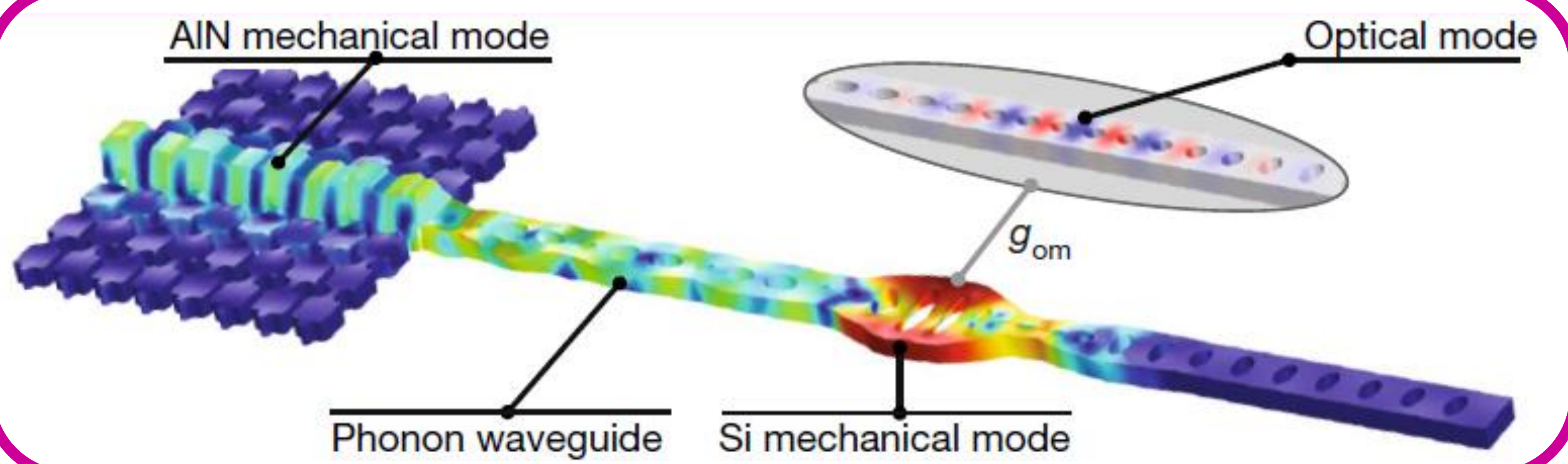


F. Arute *et al*. Nature **574**, 505 (2019)

ラビ振動の光学的検出

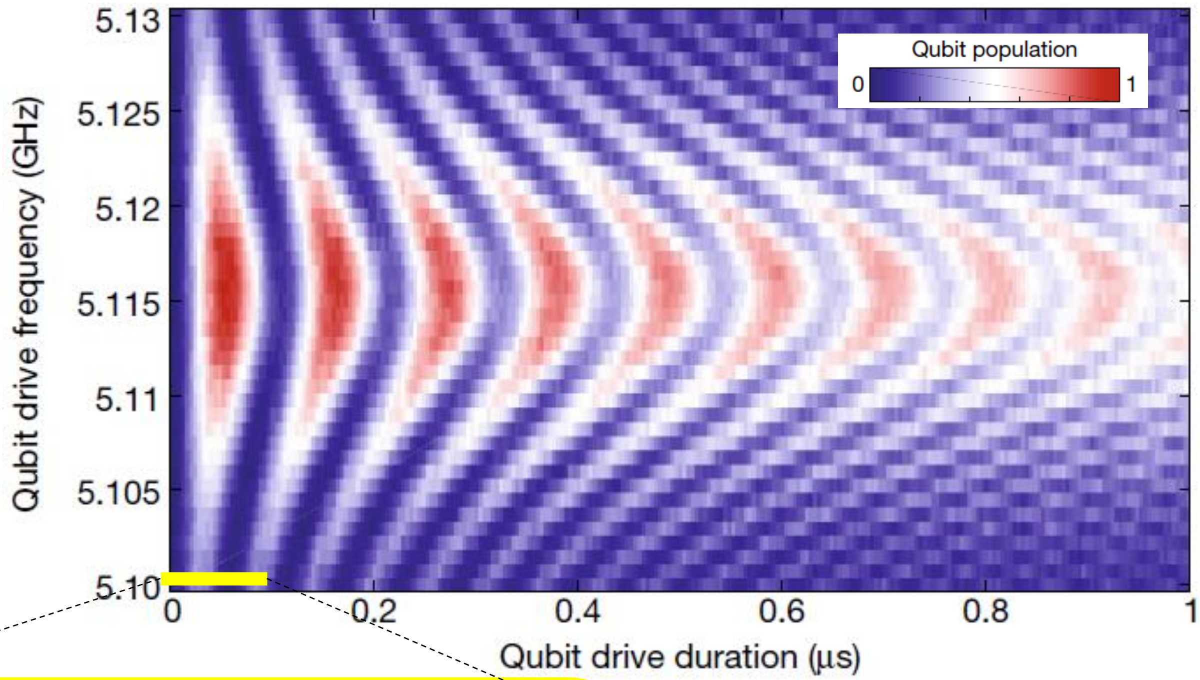


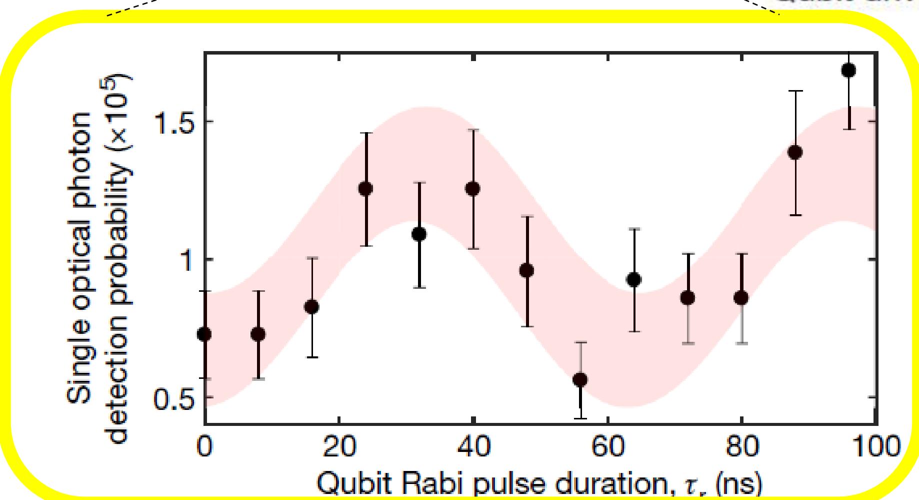
Mechanical “super-mode”

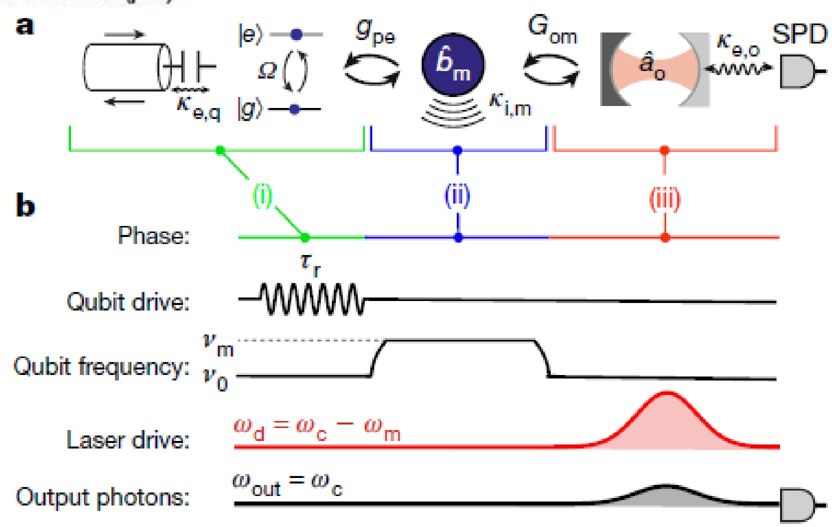


M. Mirhosseini *et al.*, Nature **588,** 599 (2020)

ラビ振動の光学的検出







M. Mirhosseini *et al.,* Nature **588,** 599 (2020)

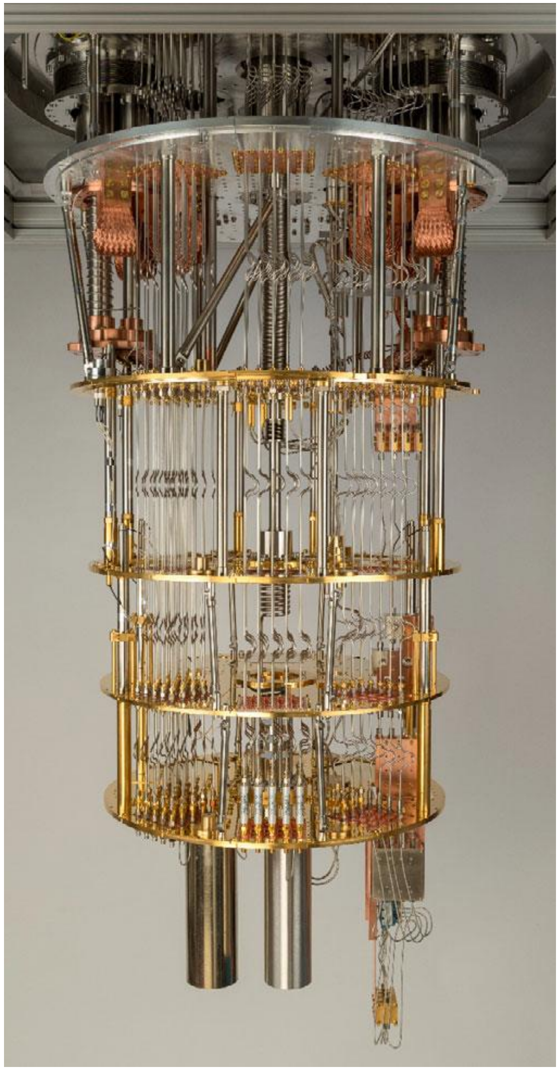
動機

- 量子ビットのネットワーク化

- 熱負荷の緩和

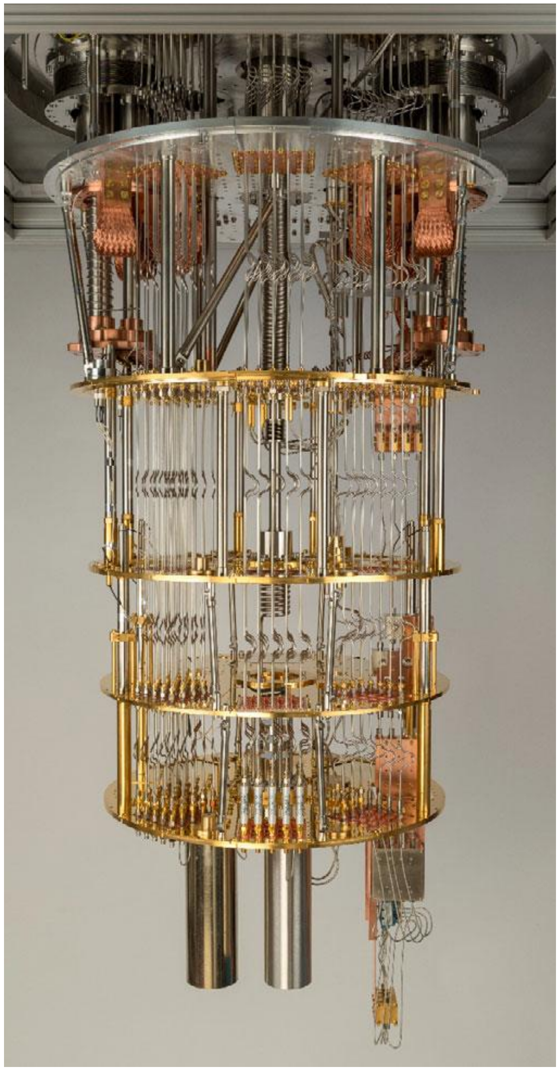
- 微弱ラジオ波信号の光検出

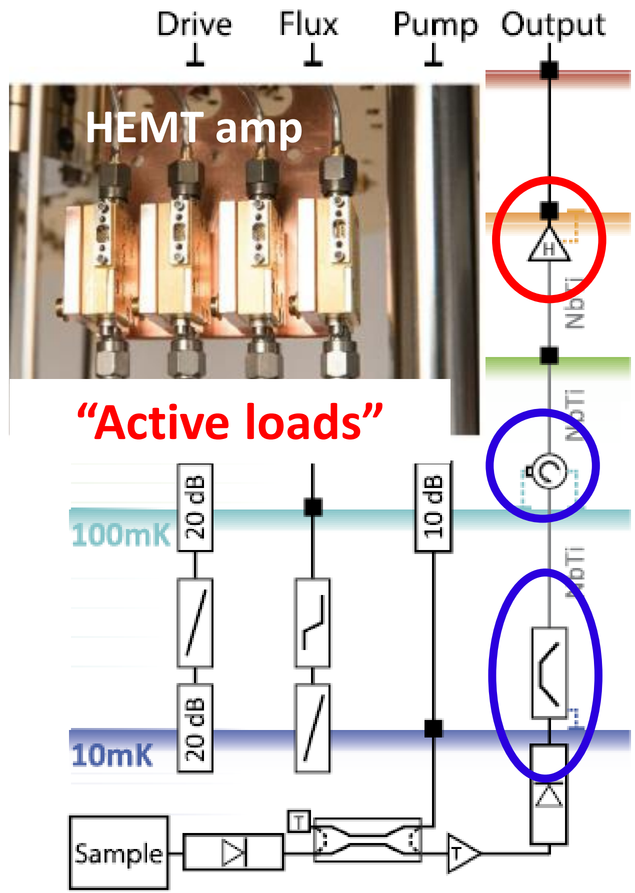
動機２: 熱負荷の緩和

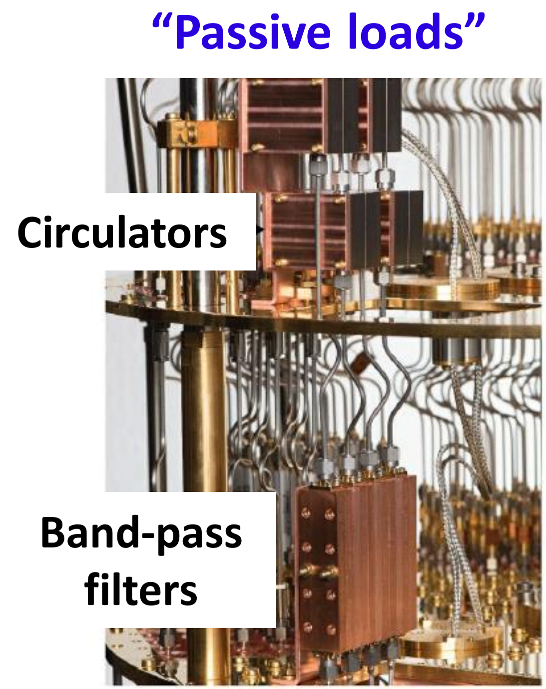


S. Krinner et al., EPJ Quantum Technol. **6**, 2 (2019)

動機 2:熱負荷の緩和

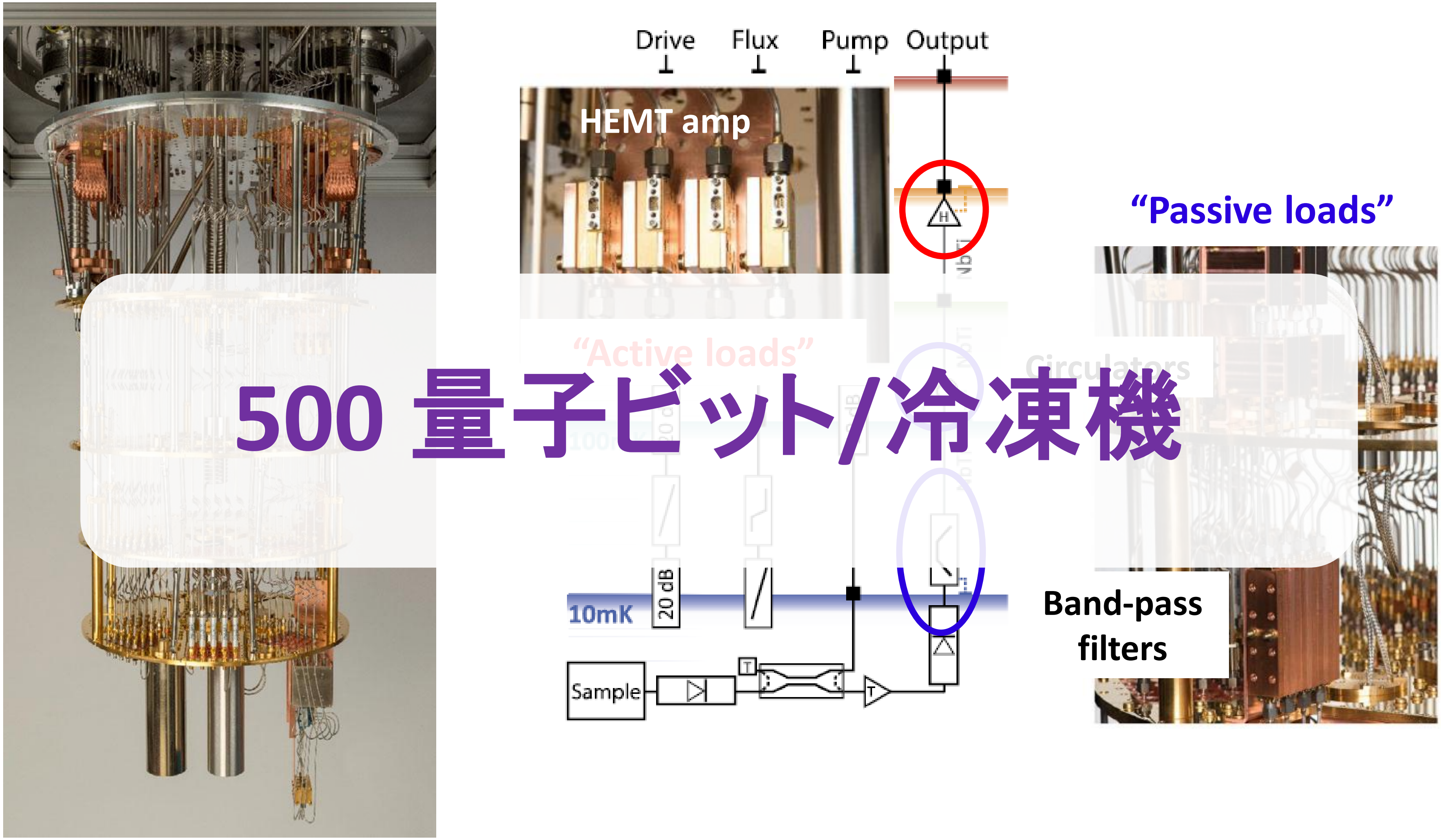






S. Krinner et al., EPJ Quantum Technol. **6**, 2 (2019)

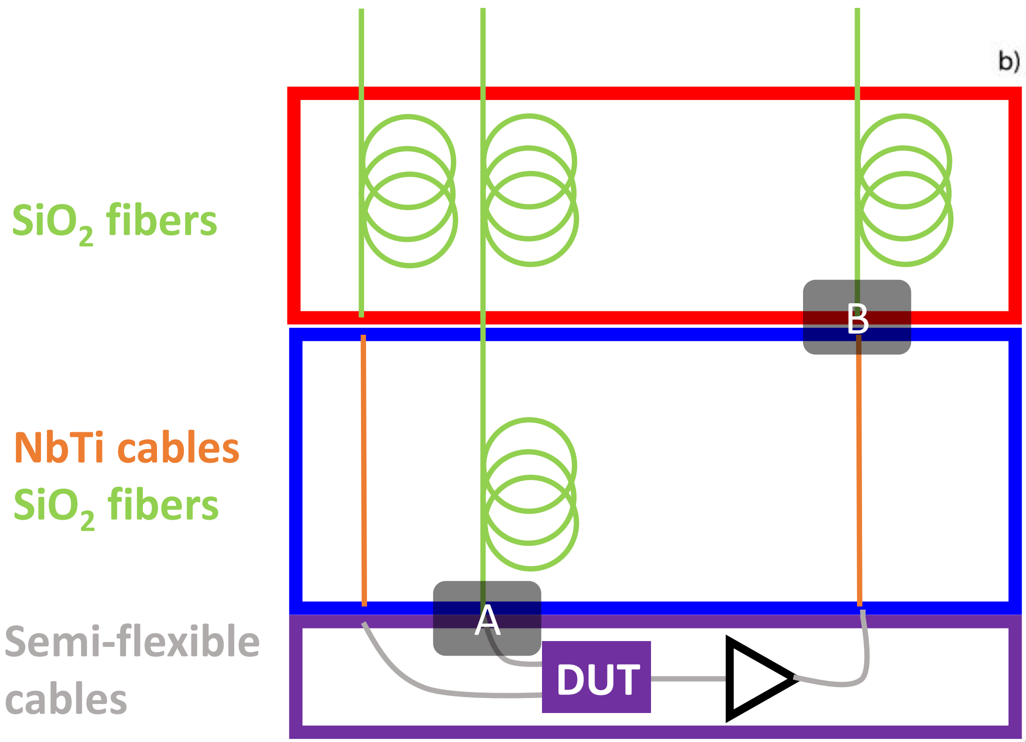
動機２:熱負荷の緩和

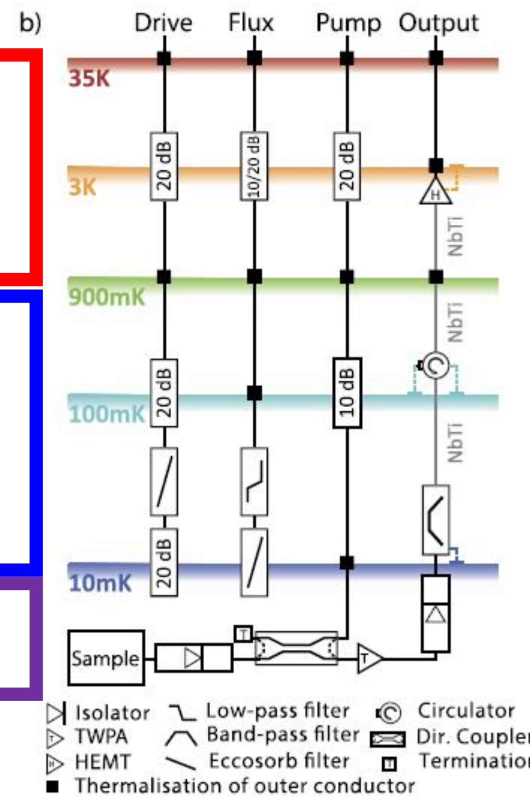


500 量子ビット/冷凍機

S. Krinner et al., EPJ Quantum Technol. **6**, 2 (2019)

イントラフリッジ光リンク





A

Article

Control and readout of a superconducting qubit using a photonic link

https://doi.org/10.1038/s41586-021-03268-x

Received: 3 August 2020

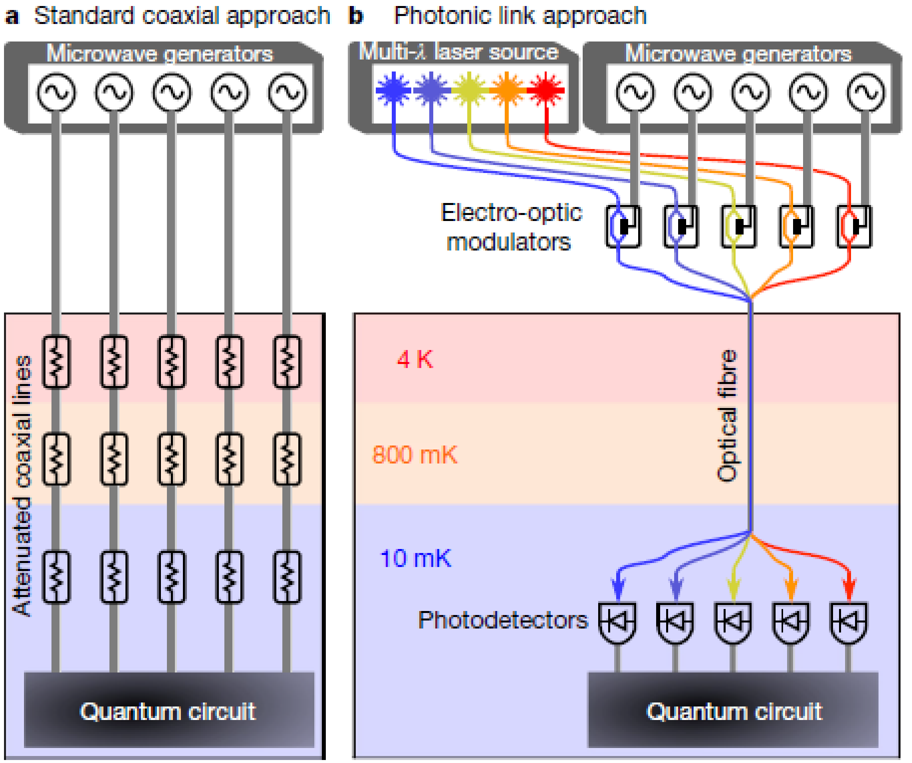
Accepted: 20 January 2021

Published online: 24 March 2021

Check for updates

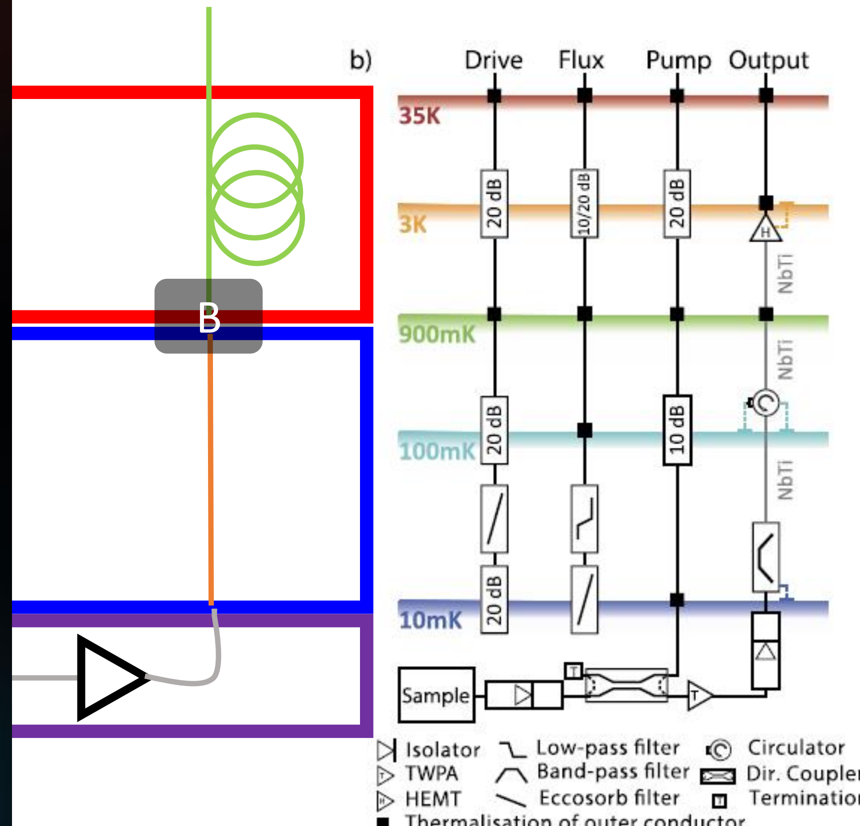
F. Lecocq[1,2]✉, F. Quinlan[1]✉, K. Cicak[1], J. Aumentado[1], S. A. Diddams[1,2] & J. D. Teufel[1]✉

Delivering on the revolutionary promise of a universal quantum computer will require processors with millions of quantum bits (qubits)[1–3]. In superconducting quantum processors[4], each qubit is individually addressed with microwave signal lines that connect room-temperature electronics to the cryogenic environment of the quantum circuit. The complexity and heat load associated with the multiple coaxial lines per qubit limits the maximum possible size of a processor to a few thousand qubits[5]. Here we introduce a photonic link using an optical fibre to guide modulated laser light from room temperature to a cryogenic photodetector[6], capable of delivering shot-noise-limited microwave signals directly at millikelvin temperatures. By demonstrating high-fidelity control and readout of a superconducting qubit, we show that this photonic link can meet the stringent requirements of superconducting quantum information processing[7]. Leveraging the low thermal conductivity and large intrinsic bandwidth of optical fibre enables the efficient and massively multiplexed delivery of coherent microwave control pulses, providing a path towards a million-qubit universal quantum computer.



F. Lecocq et al., Nature **591**, 575 (2021)

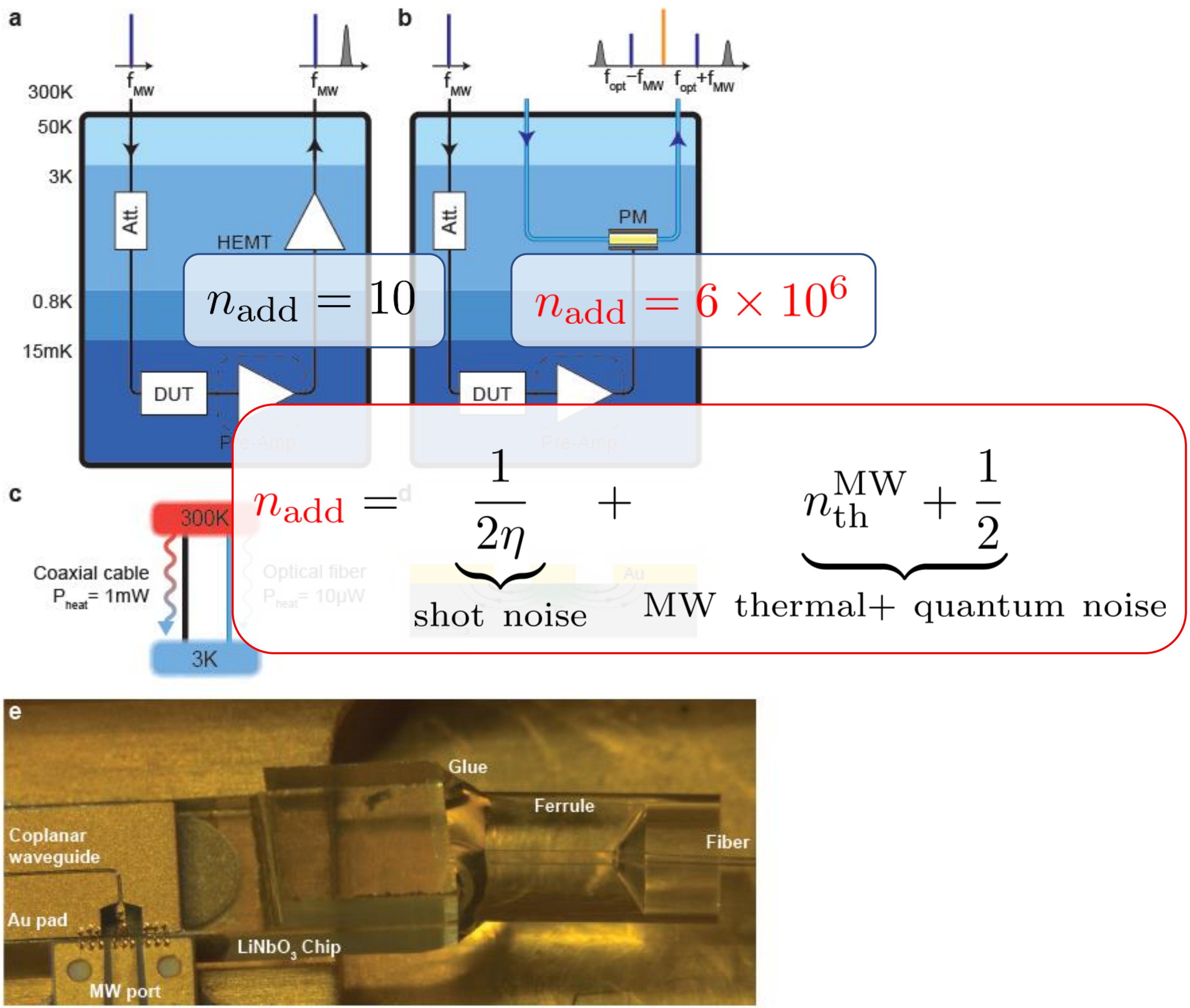
イントラフリッジ光リンク



A. Youssefi et al., Nature Electronics **4**, 326 (2021)

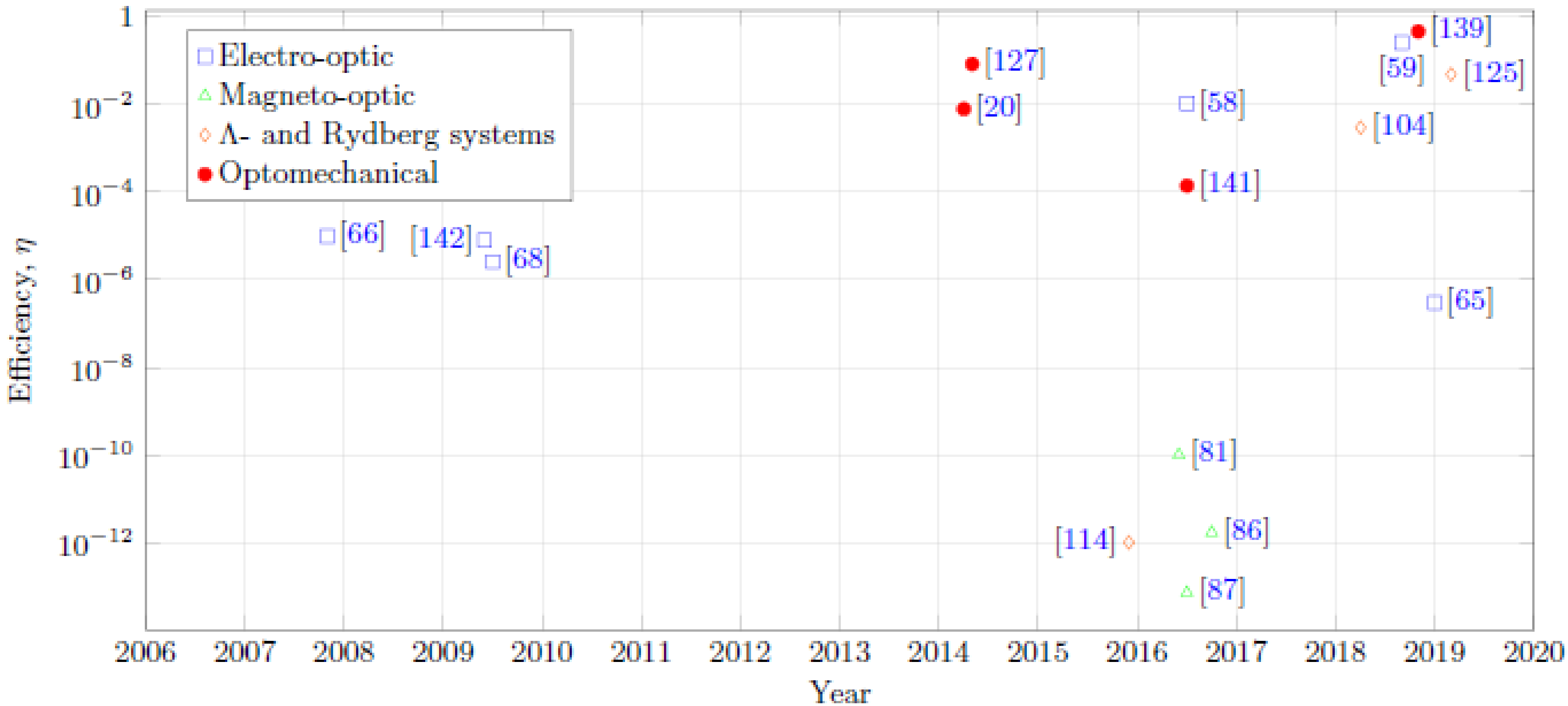
(News & Views: K. Usami and Y. Nakamura)

B



A. Youssefi et al., Nature Electronics **4**, 326 (2021)

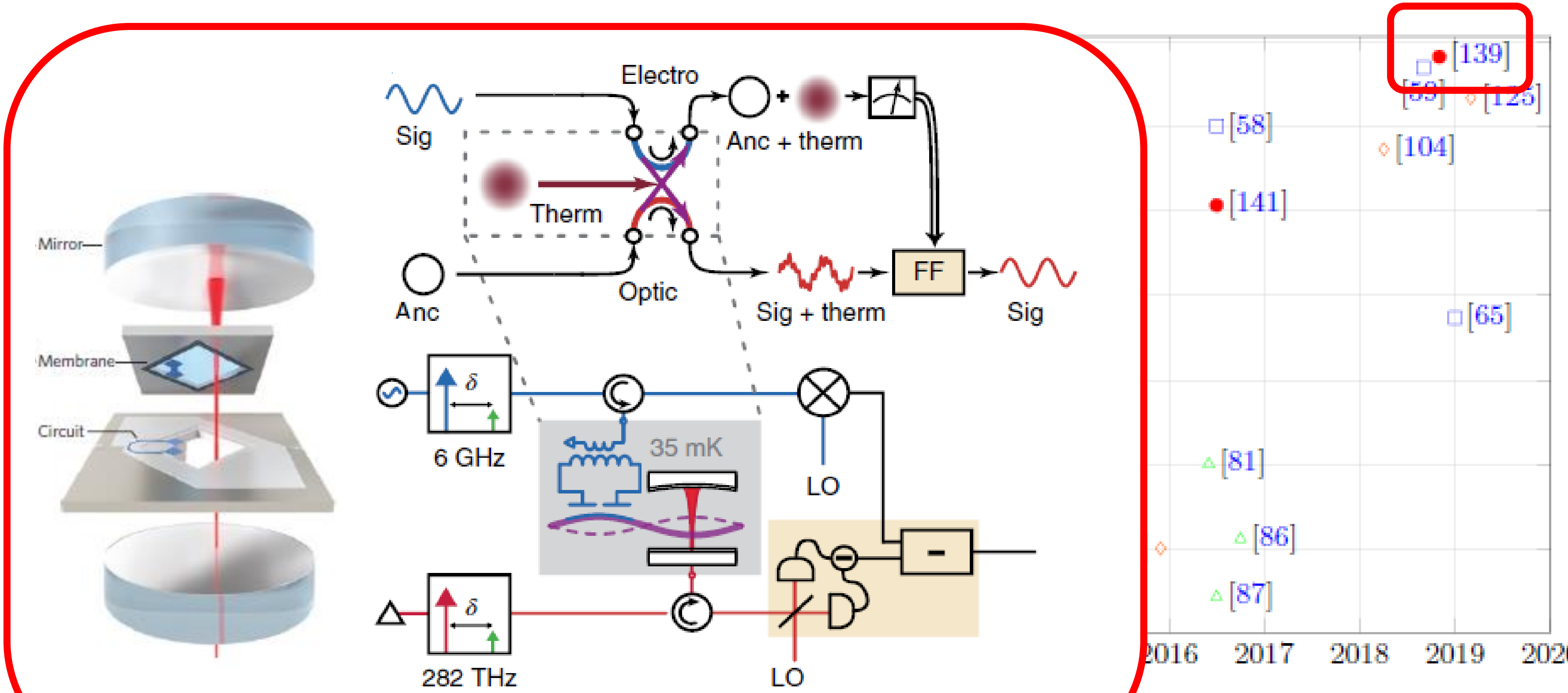
変換効率 η の変遷



Ref.	Type	Material system	Ω (GHz)	η	Bandwidth (MHz)
[58]	Electro-optic	$LiNbO_3$	8.9	0.0109	1.38
[143]	Λ-system	ER:YSO	5.18	1.2×10^{-5}	0.13
[59]	Electro-optic	AlN	8.31	0.259	0.59
[81]	Magneto-optic	YIG	10.5	10^{-10}	2.28
[125]	Λ-system	Rubidium atoms	84	5×10^{-2}	15
[139]	Optomechanical	Si_3N_4	6.16	0.47	1.2×10^{-2}

N. J. Lambert *et al.*, Adv. Quantum Technol. 3, 1900077 (2020).

変換効率 η の変遷

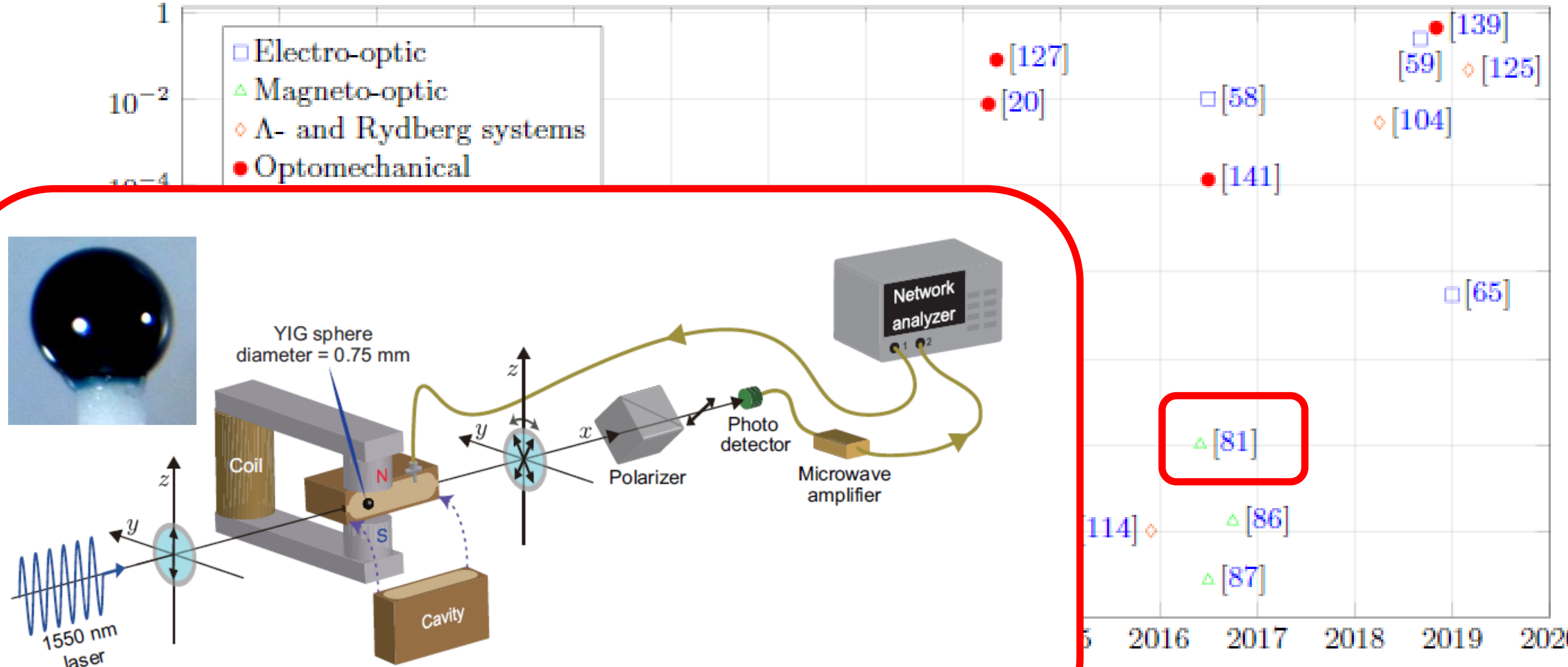


A. P. Higginbotham *et al.*, Nat. Phys. **14**, 1038 (2018)

				η	Bandwidth (MHz)
[58]	Electro-optic	$LiNbO_3$	8.9	0.0109	1.38
[143]	Λ-system	ER:YSO	5.18	1.2×10^{-5}	0.13
[59]	Electro-optic	AlN	8.31	0.259	0.59
[81]	Magneto-optic	YIG	10.5	10^{-10}	2.28
[125]	Λ-system	Rubidium atoms	84	5×10^{-2}	15
[139]	Optomechanical	Si_3N_4	6.16	0.47	1.2×10^{-2}

N. J. Lambert *et al.*, Adv. Quantum Technol. 3, 1900077 (2020).

変換効率 η の変遷



R. Hisatomi *et al.*, Phys. Rev. B **93**, 174427 (2016)

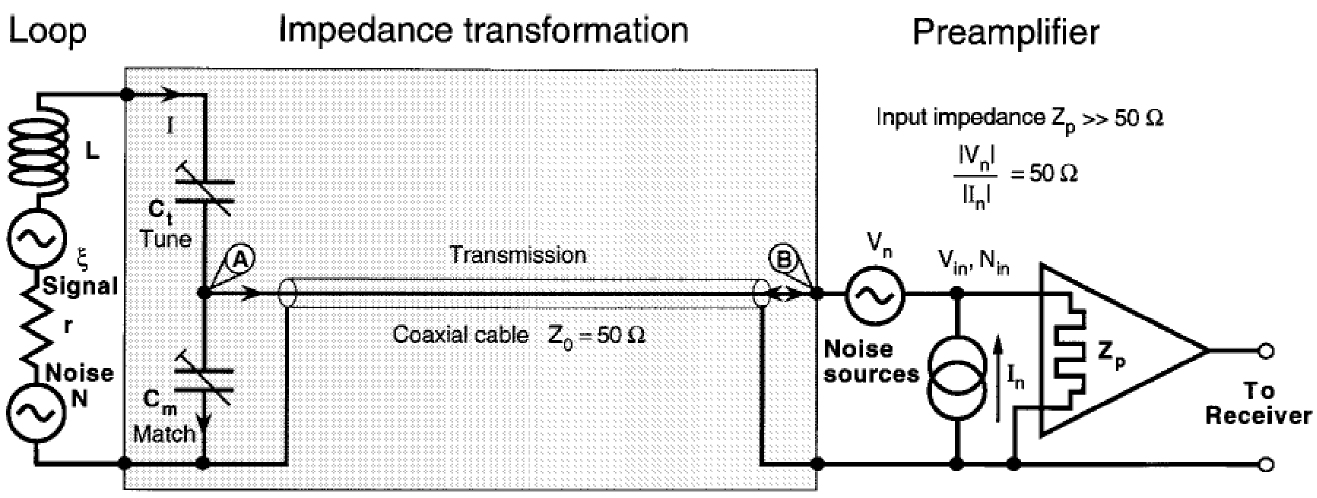
				η	Bandwidth (MHz)
[58]	Electro-optic	$LiNbO_3$	8.9	0.0109	1.38
[143]	Λ-system	ER:YSO	5.18	1.2×10^{-5}	0.13
[59]	Electro-optic	AlN	8.31	0.259	0.59
[81]	Magneto-optic	YIG	10.5	10^{-10}	2.28
[125]	Λ-system	Rubidium atoms	84	5×10^{-2}	15
[139]	Optomechanical	Si_3N_4	6.16	0.47	1.2×10^{-2}

N. J. Lambert *et al.*, Adv. Quantum Technol. 3, 1900077 (2020).

動機

- 量子ビットのネットワーク化
- 熱負荷の緩和
- 微弱ラジオ波信号の光検出

信号対雑音比



$$\Phi = \frac{\xi}{\sqrt{2rk_{\mathrm{B}}(T_c + T_n)\Delta\nu}}$$

電圧増幅器の雑音温度: $T_n = \sqrt{S_{VV}(\omega)S_{II}(\omega)} \sim 75\mathrm{K}$

D. I. Hoult and B. Bhakar, Concepts Magn Reson **9,** 277 (1997)

標準量子限界

電圧増幅:

$$\sqrt{S_{VV}(\omega)S_{II}(\omega)} \geq \frac{\hbar\omega}{2}$$

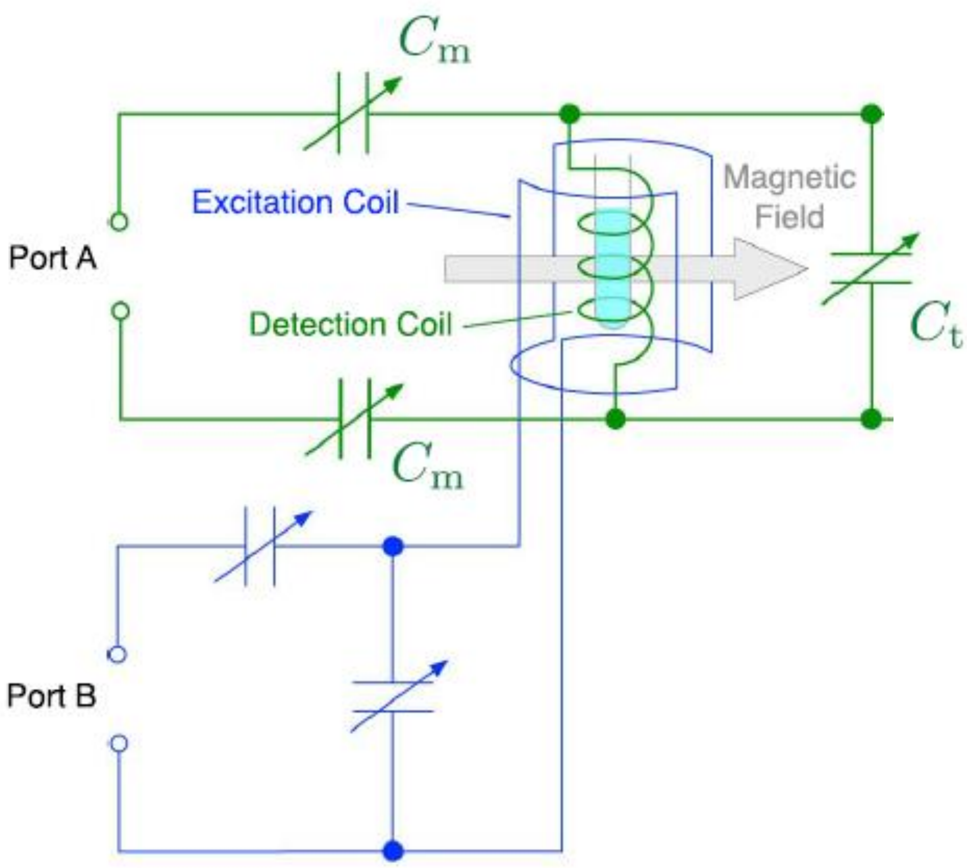
極低温では達成可

光学的位置測定:

$$\sqrt{S_{FF}(\omega)S_{xx}(\omega)} \geq \frac{\hbar}{2}$$

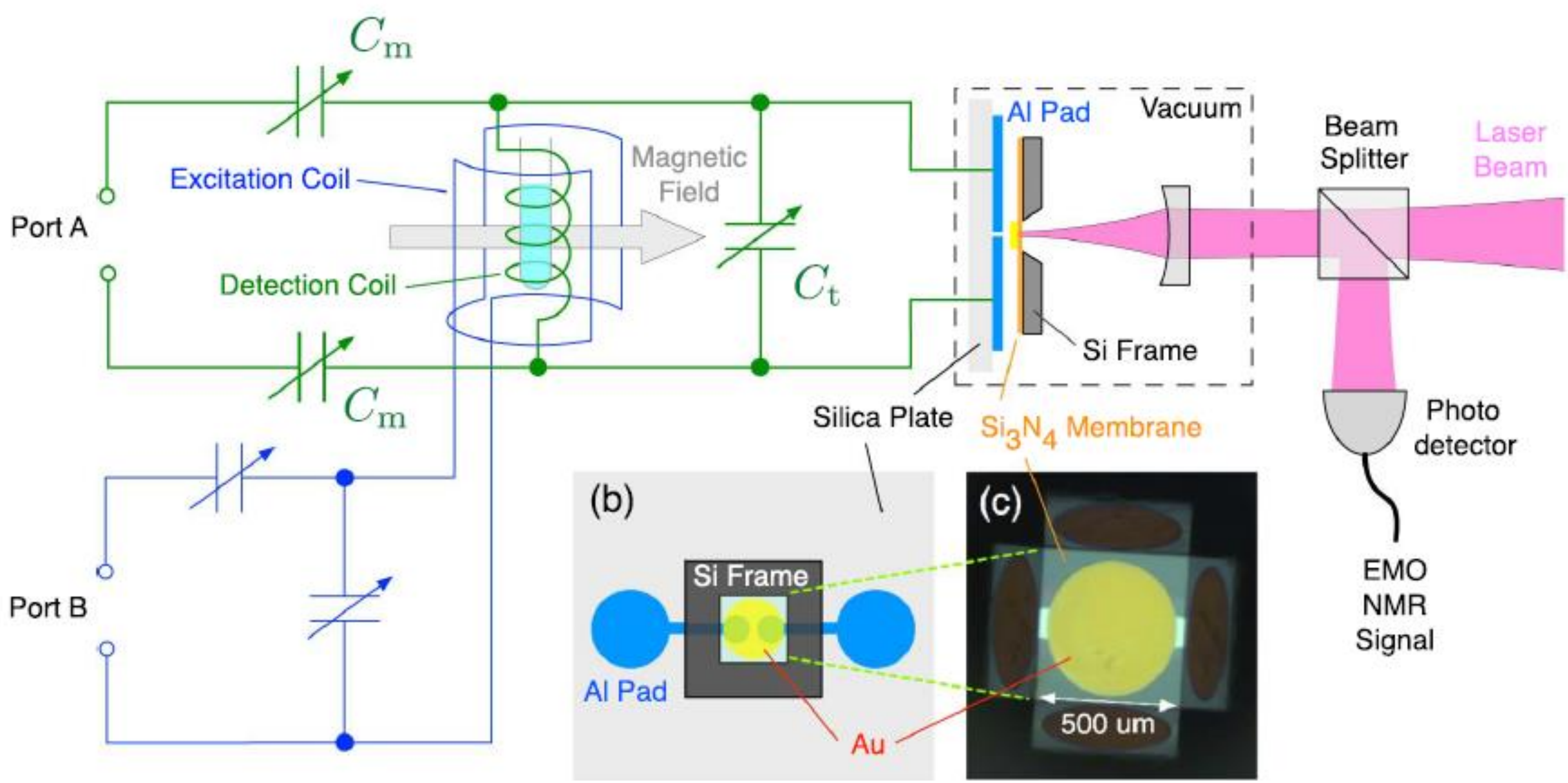
精密光学測定で達成可

NMR信号の光検出



C_m
Excitation Coil
Magnetic
Field
Port A
Detection Coil
C_t
C_m
Port B

NMR信号の光検出



K. Takade *et al.,* Optica **5**, 152 (2018)

Research Article

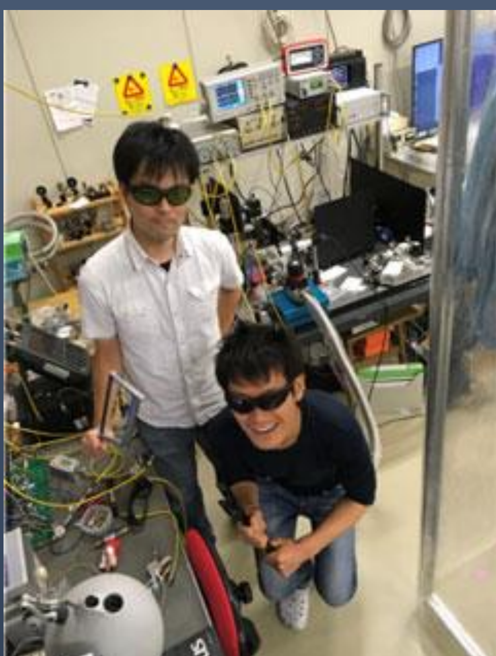
Vol. 5, No. 2 / February 2018 / *Optica* 152

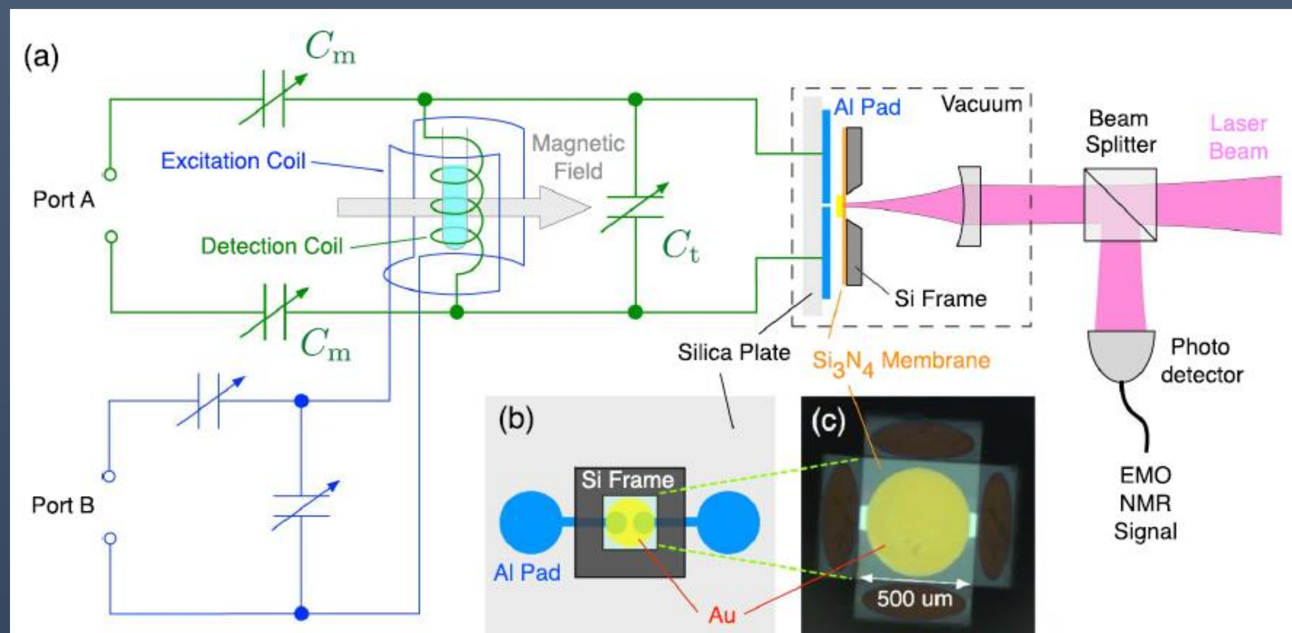
optica

Electro-mechano-optical detection of nuclear magnetic resonance

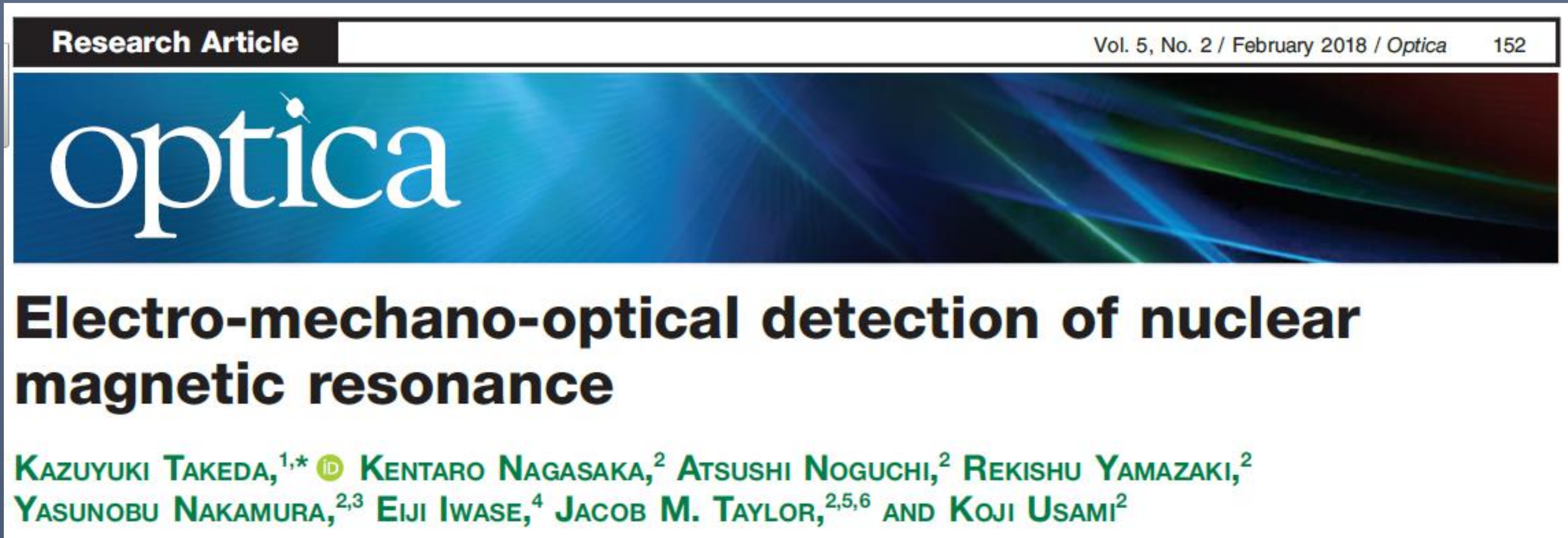
Kazuyuki Takeda,[1,*] Kentaro Nagasaka,[2] Atsushi Noguchi,[2] Rekishu Yamazaki,[2] Yasunobu Nakamura,[2,3] Eiji Iwase,[4] Jacob M. Taylor,[2,5,6] and Koji Usami[2]

京大・化学　武田和行さん



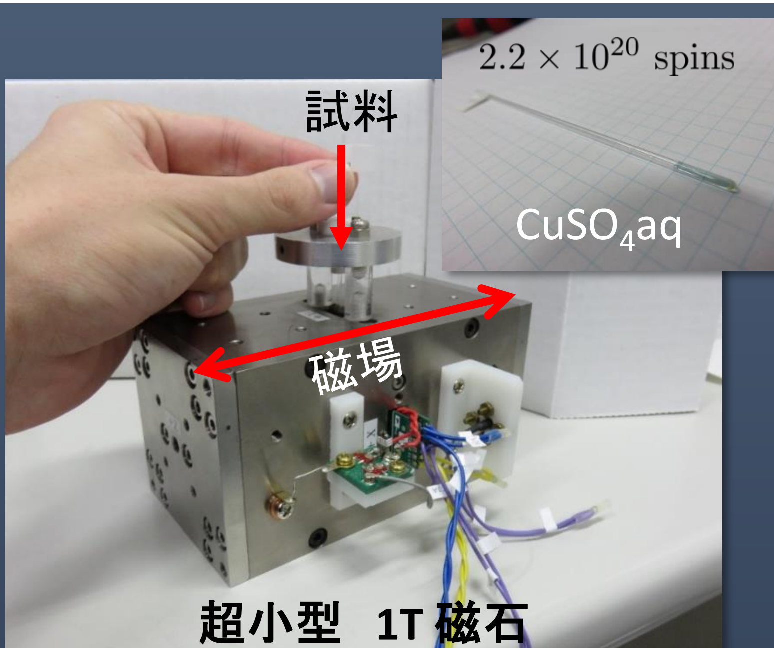


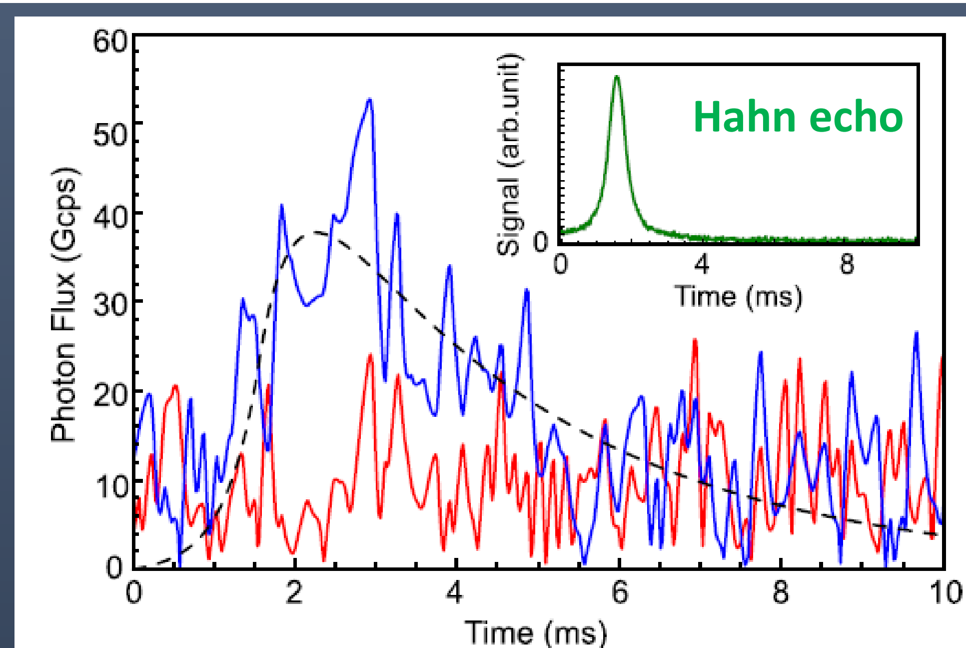
K. Takade *et al.*, Optica **5**, 152 (2018)


Research Article Vol. 5, No. 2 / February 2018 / *Optica* 152
optica

Electro-mechano-optical detection of nuclear magnetic resonance

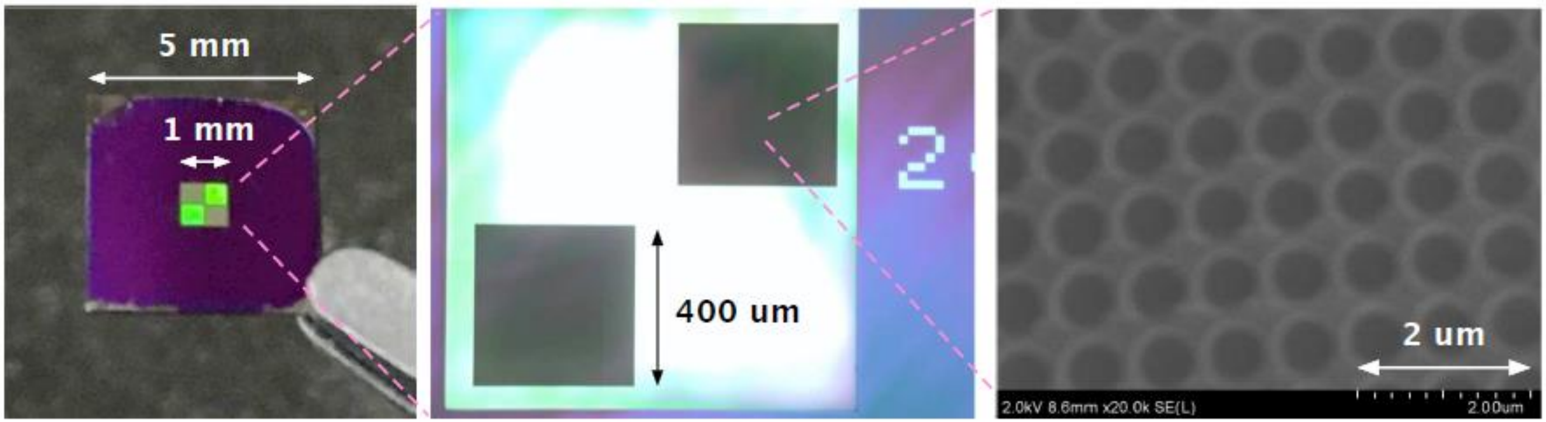
KAZUYUKI TAKEDA,[1,*] KENTARO NAGASAKA,[2] ATSUSHI NOGUCHI,[2] REKISHU YAMAZAKI,[2] YASUNOBU NAKAMURA,[2,3] EIJI IWASE,[4] JACOB M. TAYLOR,[2,5,6] AND KOJI USAMI[2]

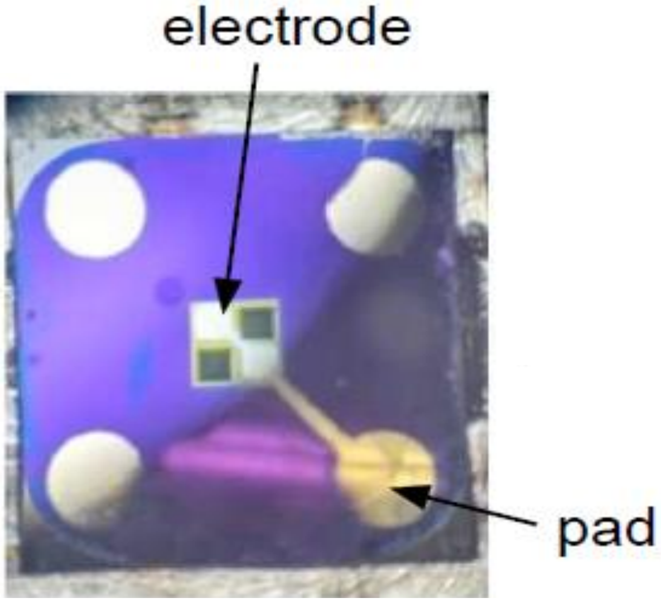




K. Takade *et al.*, Optica **5**, 152 (2018)

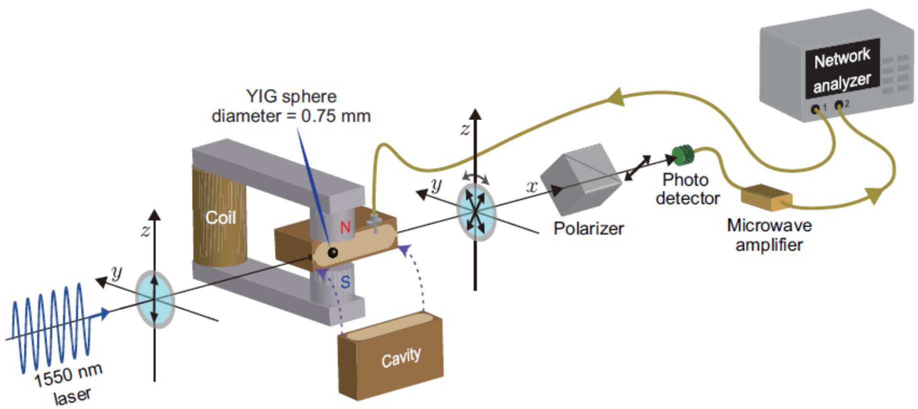
メタサーフェスミラーの採用





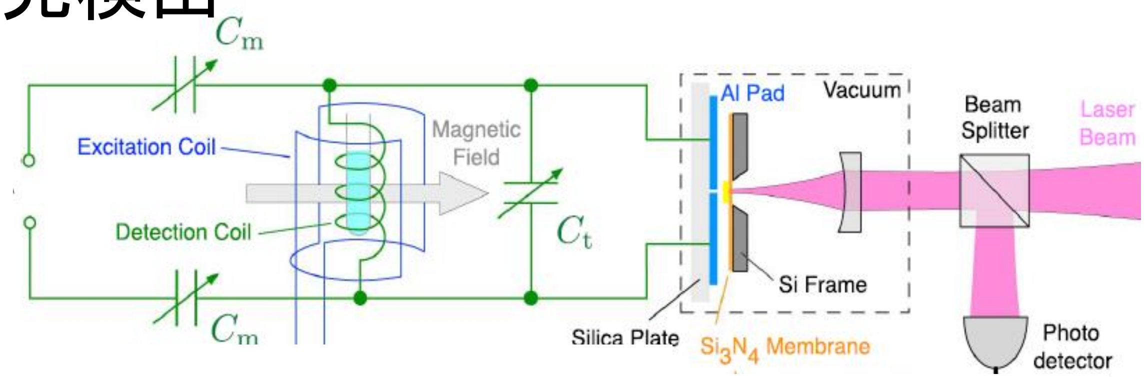
量子トランスデューサー

- 量子ビットのネットワーク化
- 熱負荷の緩和



R. Hisatomi *et al.,* Phys. Rev. B **93,** 174427 (2016)

- 微弱ラジオ波信号の光検出



K. Takade *et al.,* Optica **5**, 152 (2018)