IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Invited presentation Wk2EOr3A-02 given at the virtual ASC 2020, November 3, 2020.

Novel Cryogenic Device Approaches for Superconducting Quantum Computing

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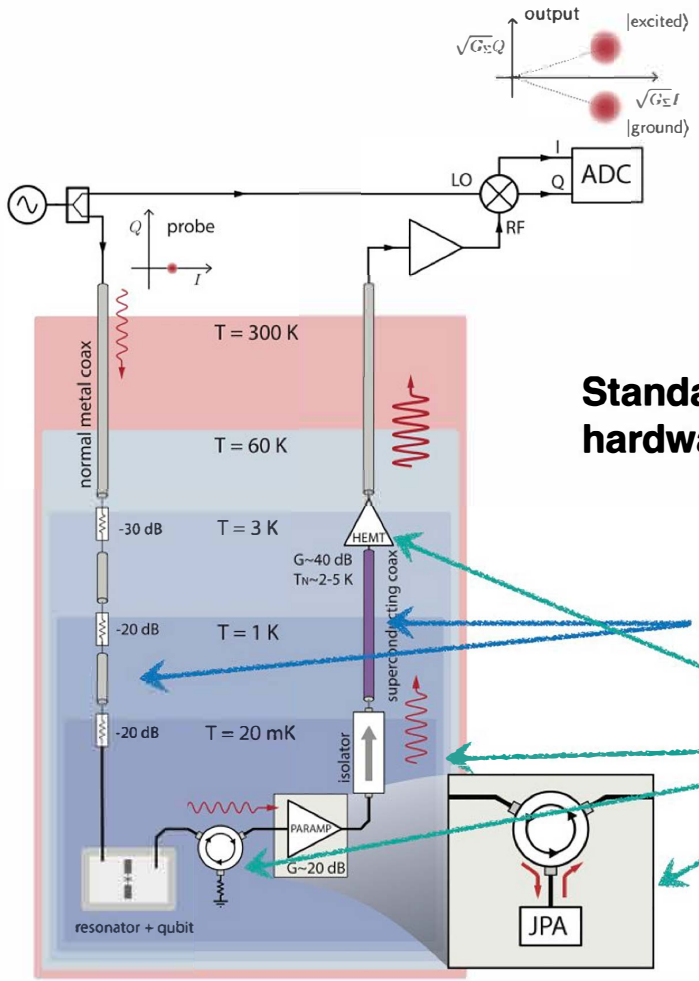
Students: Gabriel Peterson *(now at PsiQuantum)*, Benton Miller

ASC 2020: *Wk2EOr3A*

What are these “novel cryogenic devices” you’re talking about and why do we need them?



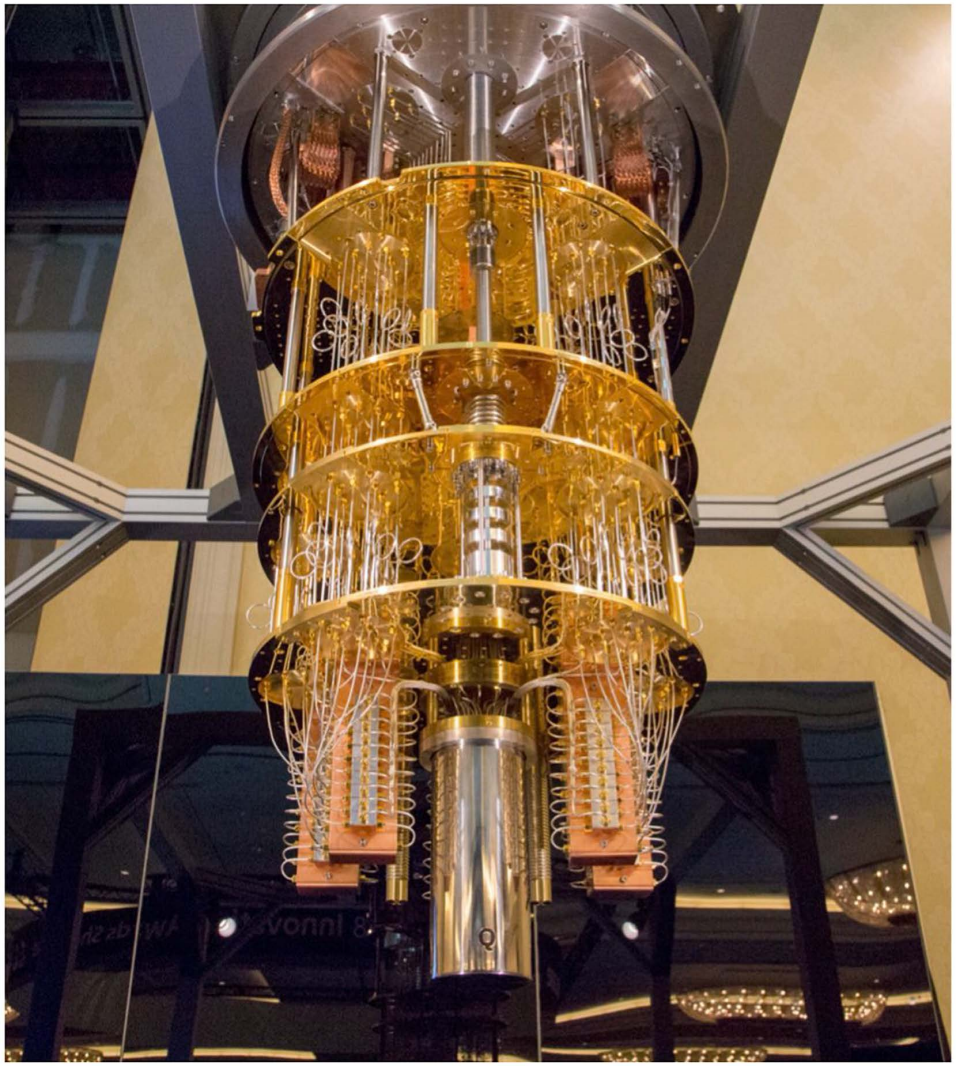
Standard control & dispersive measurement hardware resources

input/output *μwave cabling*

measurement *(active) parametric amplifiers*
(active) HEMT amplifier
(passive) circulators, isolators

Okay for a few qubits, what about more?

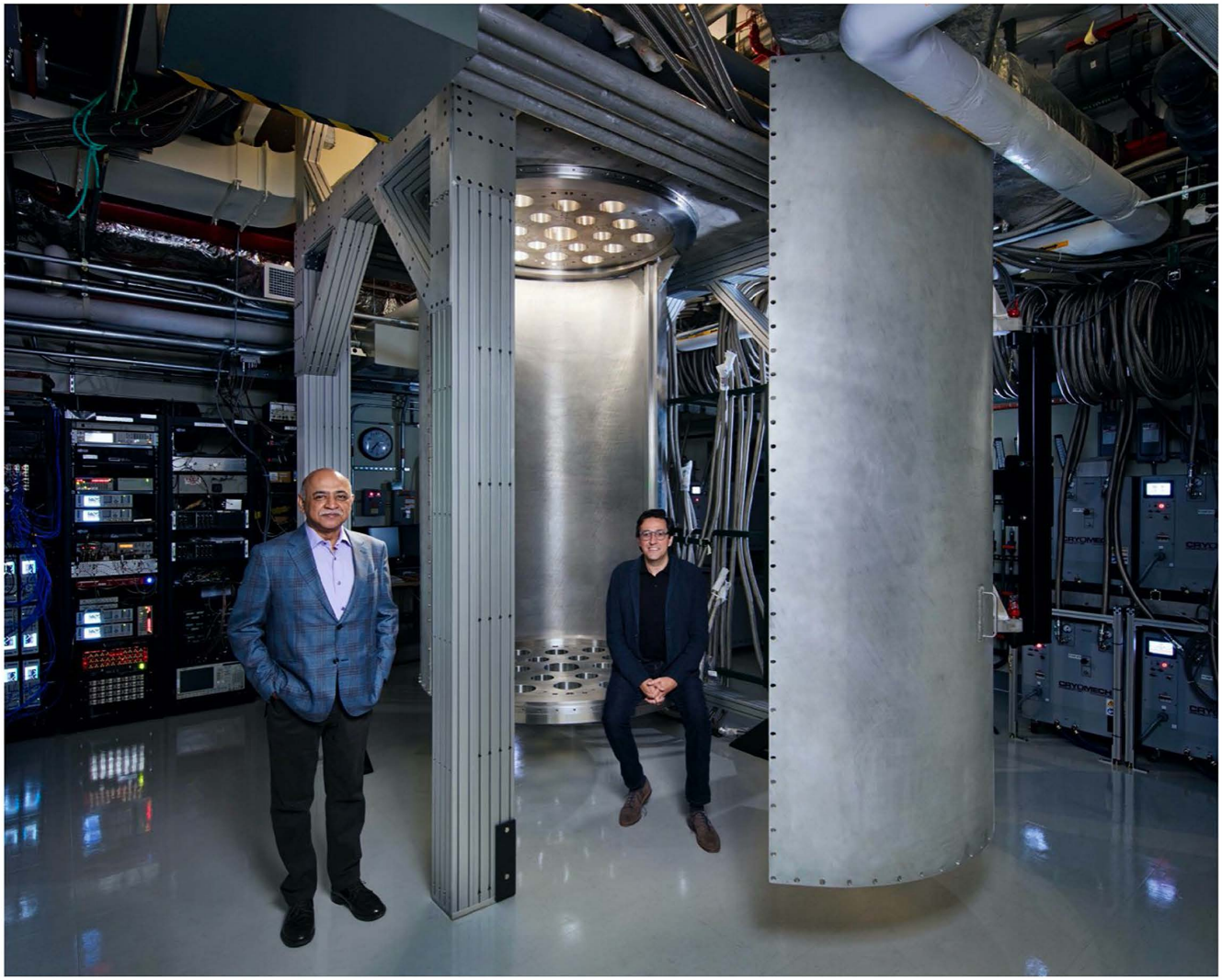
*JAA, IEEE Microwave Magazine **21**, 45-59 (2020)*



IBM

NEAR TERM
= brute force

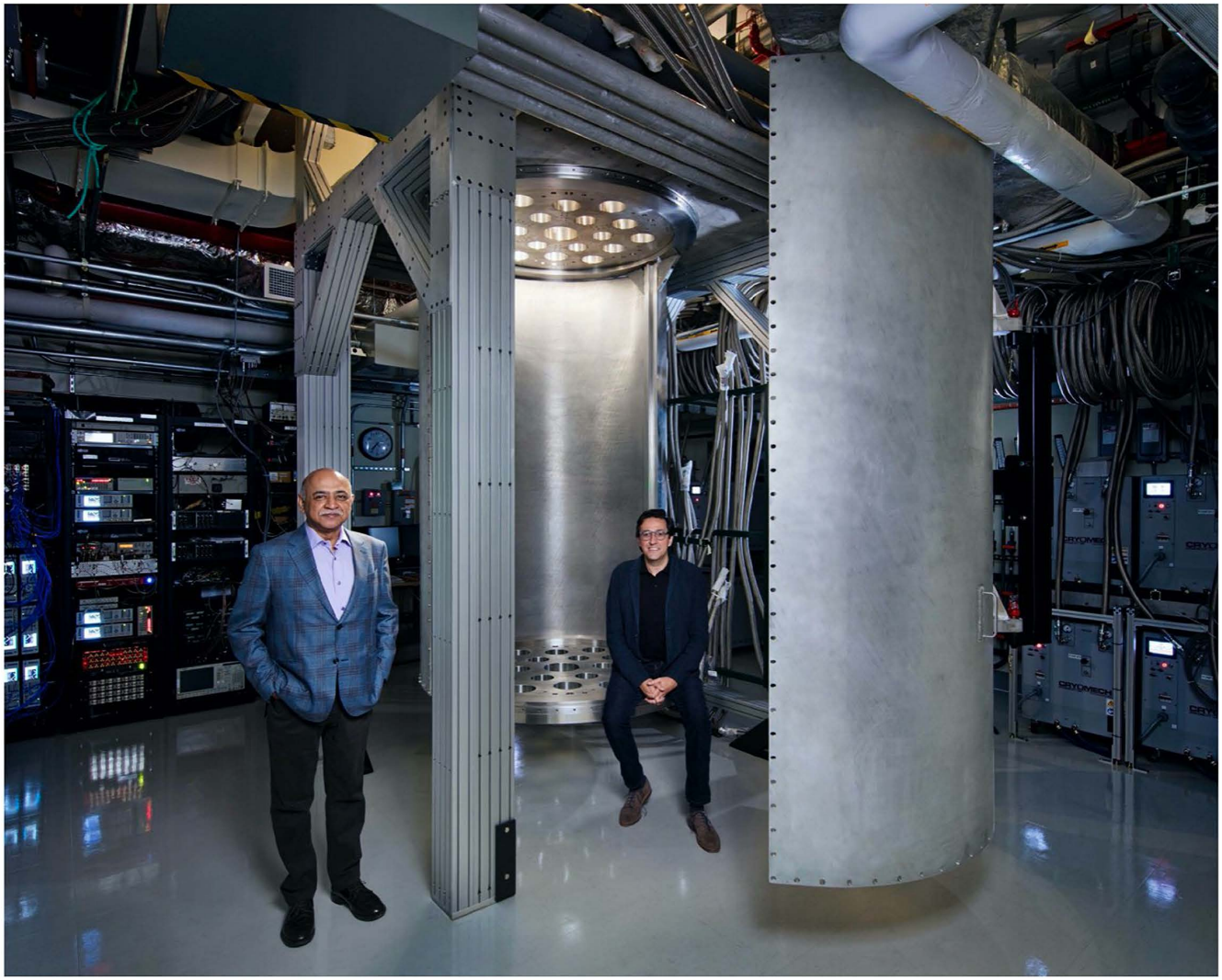
~50 qubits



IBM

NEAR TERM
= brute force

1000+ qubits!

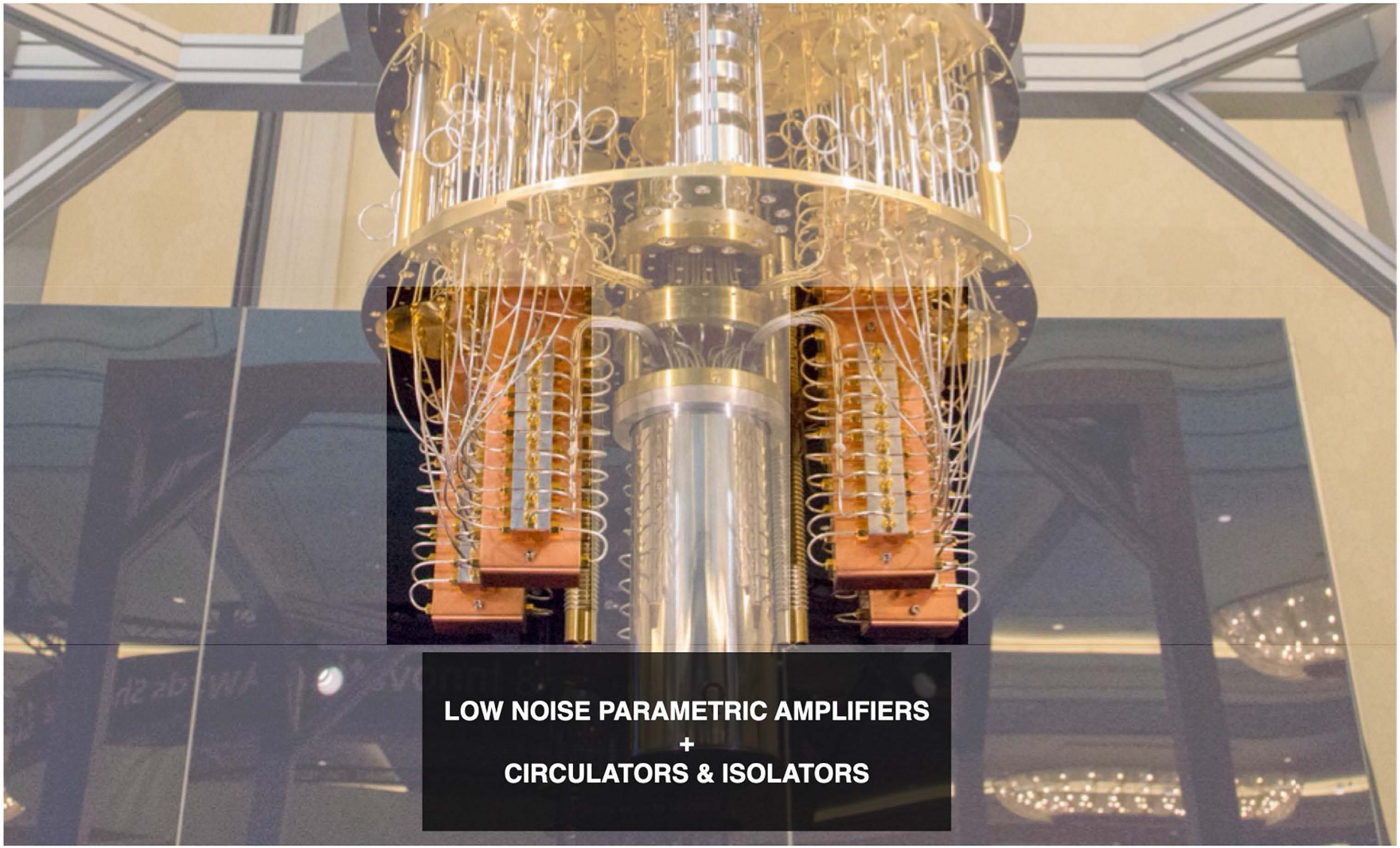


IBM

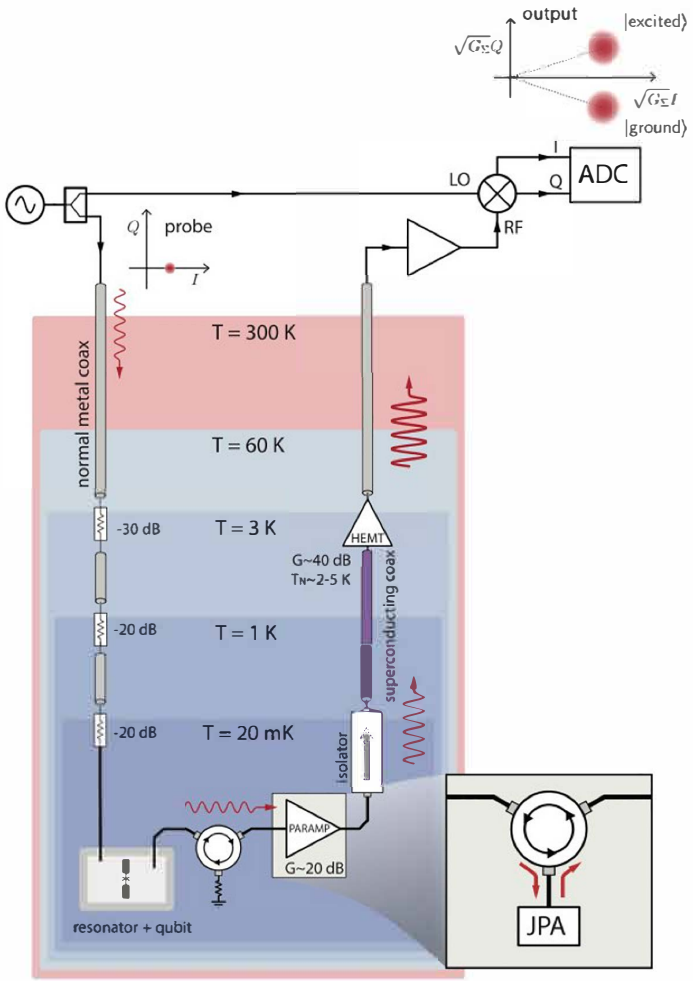
NEAR TERM
= brute force

1000+ qubits!

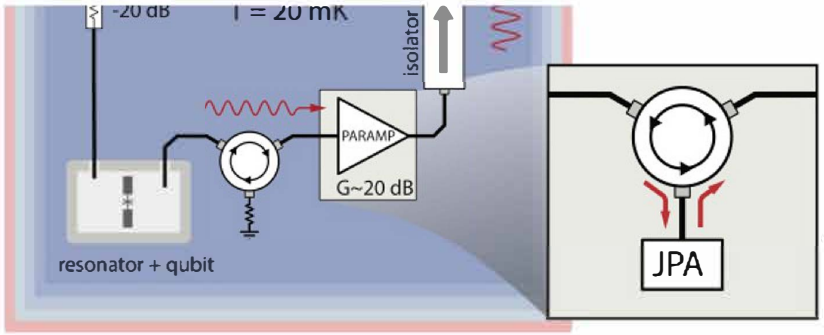
1e6 qubits?



IBM



*JAA, IEEE Microwave Magazine **21**, 45-59 (2020)*



Replace as much as we can with compact superconducting circuits

‘novel cryogenic device’ = *directional parametric circulators and amplifiers*

why parametric amplifiers?

LOW NOISE *relative to a cryogenic HEMT

intrinsic amplifier added noise is bounded by quantum mechanics
SQL = 'Standard Quantum Limit',

$$T_N^{\mathrm{SQL}}@6\mathrm{GHz} = 144\,\mathrm{mK} \quad \textit{vs} \quad T_{N,sys}^{HEMT} = 3-10\,\mathrm{K}$$

low power dissipation, can be operated close to qubits @ mixing chamber

allows qubit state measurement to happen in less than μs with high fidelity

Example:
Quantum jumps in a transmon qubit,
R Vijay, DH Slichter, & I Siddiqi
Phys. Rev. Lett. ***106****, 110502 (2011)*

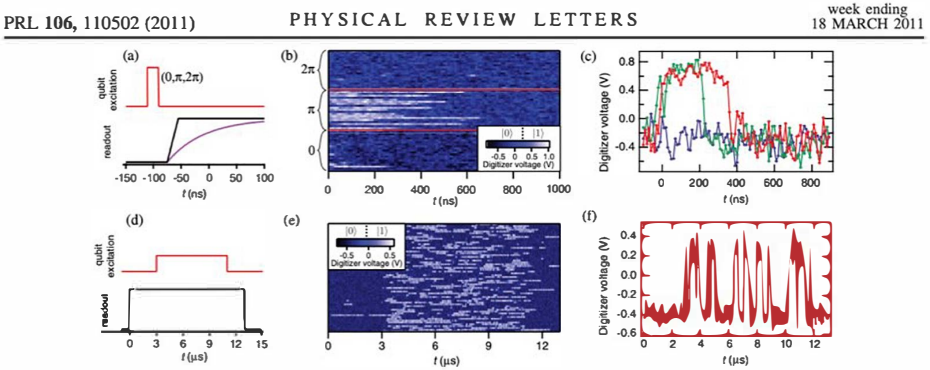


FIG. 3 (color online). Quantum jumps. (a) shows the pulse sequence used to generate (b) and (c). The qubit is excited with a pulse of

"Conventional" parametric amplification

reflection parametric amplifiers ('negative resistance') e.g., *JPAs, JPCs, FPJAs,…*

PROS: best (lowest) noise

CONS: limited dynamic range (-120 dBm) and bandwidth (10-100 MHz typical)

*See review, JAA, IEEE Microwave Magazine **21**, 45-59 (2020)*

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reflection parametric amplifiers ('negative resistance') e.g., *JPAs, JPCs, FPJAs,…*

PROS: best (lowest) noise

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traveling wave parametric amplifiers e.g., *J-TWPAs, KITs, …*

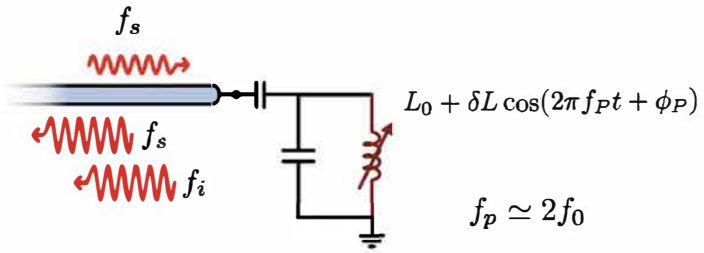
PROS: broadband (GHz BW), higher dynamic range

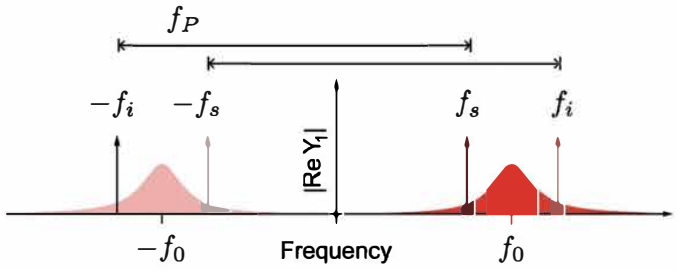
CONS: requires more power, isolation/filtering, bias tees, direction couplers,
noise 2-4x worse than JPAs

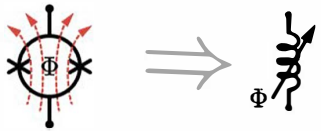
*See review, JAA, IEEE Microwave Magazine **21**, 45-59 (2020)*

"Conventional" parametric amplification

reflection parametric amplifiers ('negative resistance') e.g., *JPAs, JPCs, FPJAs,…*







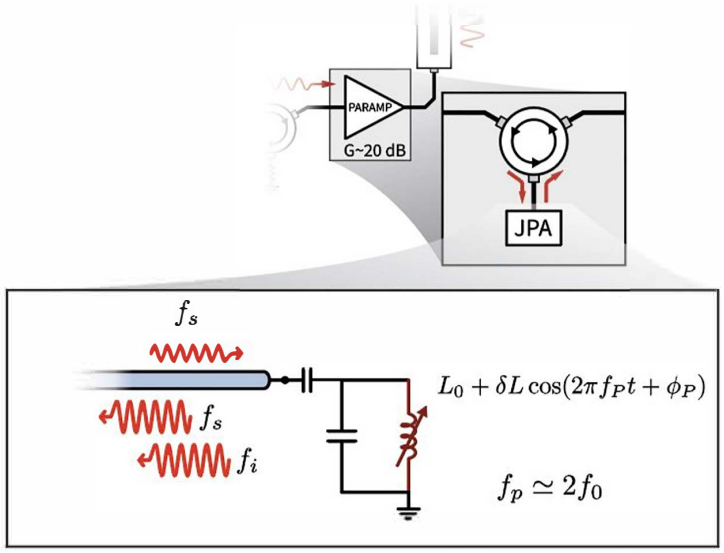
$I \ll I_0$

$$L_{SQ}(I,\Phi) = \frac{L_J(I)}{2\cos(\pi\Phi/\Phi_0)}$$

*see review, JAA, IEEE Microwave Magazine **21**, 45 (2020)*

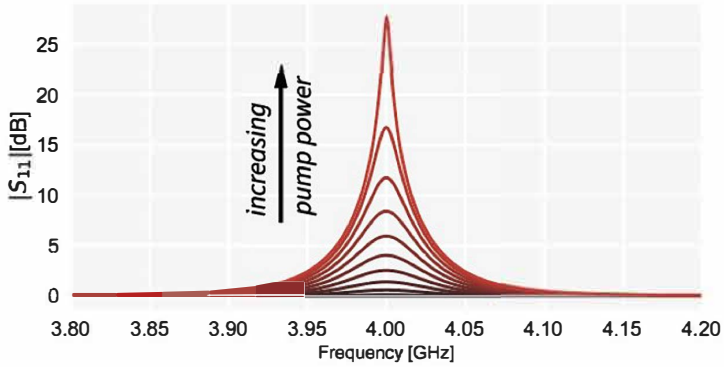
"Conventional" parametric amplification

reflection parametric amplifiers ('negative resistance') e.g., *JPAs, JPCs, FPJAs,…*



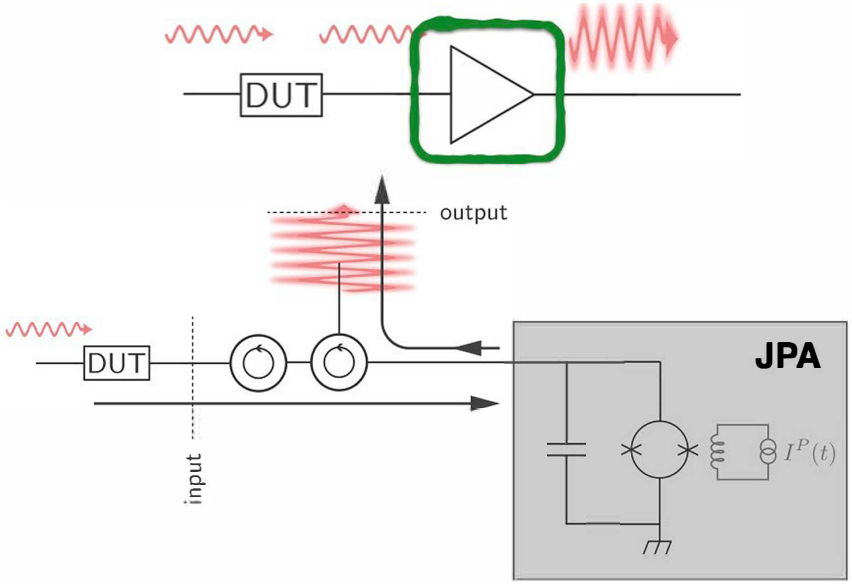
degenerate parametric amplifier
e.g., Josephson parametric amplifiers (JPAs)

single port device
requires circulators to isolate device-under-test

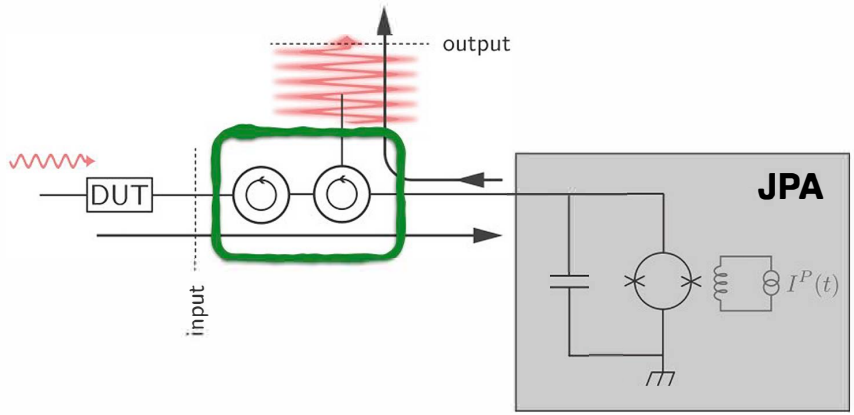


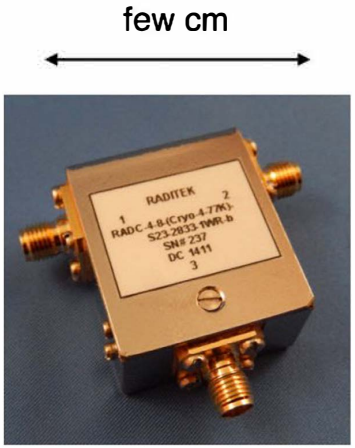
*See review, JAA, IEEE Microwave Magazine **21**, 45-59 (2020)*

Practical Issues Circulators



Practical Issues Circulators, size, & magnetic field

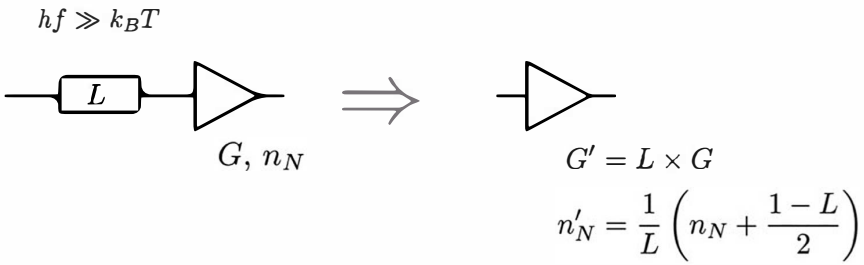


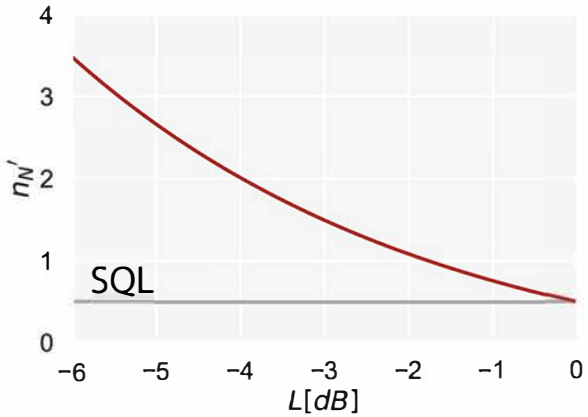


Practical cryogenic circulators are big and require big (kGauss) magnetic fields.

Hard to integrate closely with superconducting circuits.

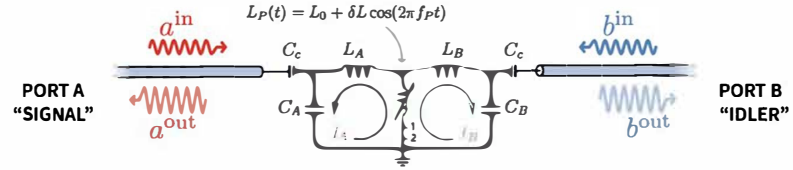
Practical Issues Circulators & Loss

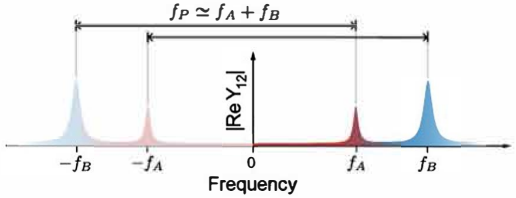




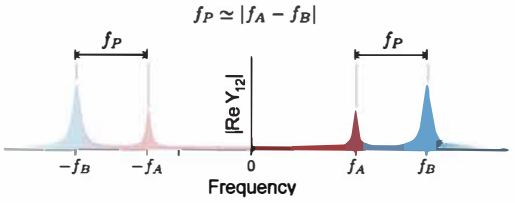
extra stuff [packaging, bias tees, connectors, couplers, circulators]
= loss = reduced noise performance/quantum efficiency

General 2-resonator/2-port parametric circuit

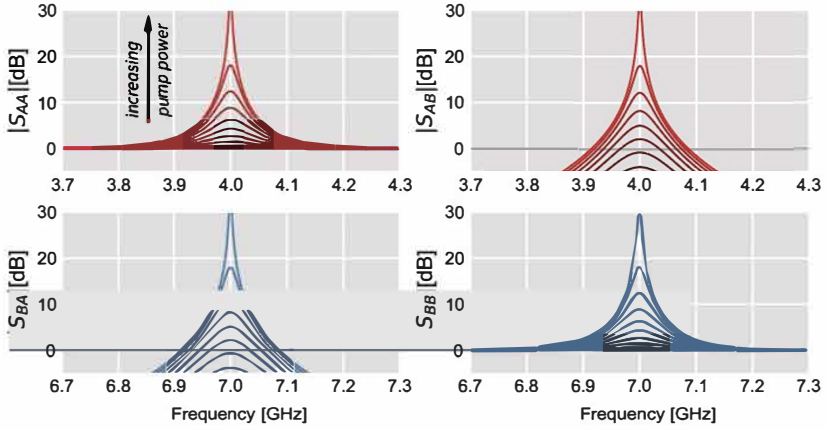




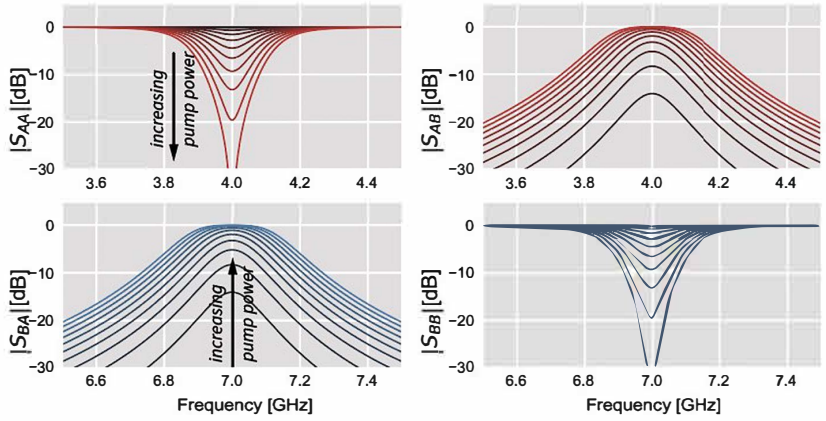
$$\begin{bmatrix} a^{\text{out}} \\ b^{\text{out}} \end{bmatrix} = \begin{bmatrix} S_{AA} & S_{AB} \\ S_{BA} & S_{BB} \end{bmatrix} \begin{bmatrix} a^{\text{in}} \\ b^{\text{in}} \end{bmatrix}$$



AMPLIFIER



FREQUENCY CONVERTER

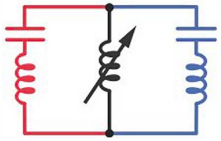


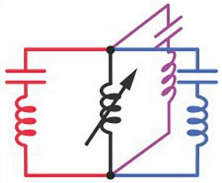
** See also: Josephson Parametric Converter (JPC), e.g., Bergeal, N., et al. Nature Physics **6**, 296 (2010)*

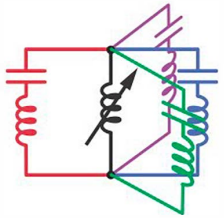
3+ modes?

2 modes: amplification & frequency conversion, but *not* directional

3+ modes: combine *multiple* amplification & freq. conversion processes for directionality

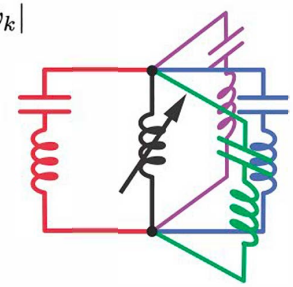




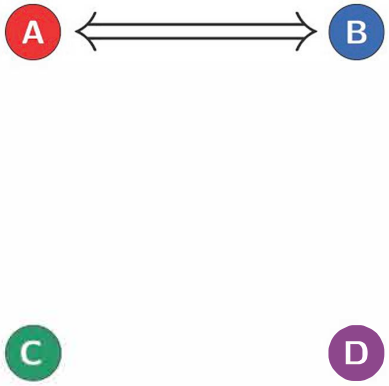


Graphs & Parametrically Coupled Modes

$$\omega_{jk}^{P} \equiv |\omega_j - \omega_k|$$



$$M(t) = M_0 + \delta M_{AB} \cos\left(\omega_{AB}^{P} t + \phi_{AB}\right)$$



Graphs & Parametrically Coupled Modes

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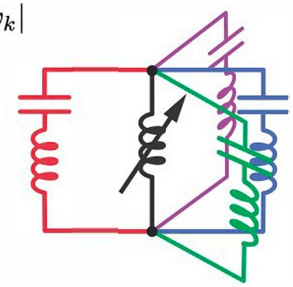
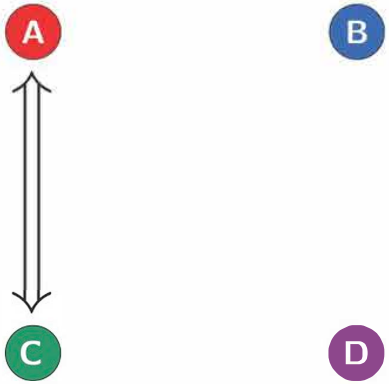
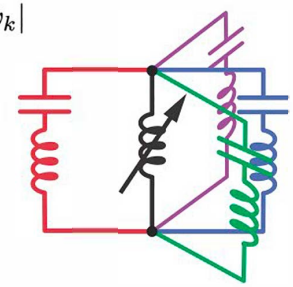


$$M(t) = M_0 + \delta M_{AC} \cos\left(\omega_{AC}^{P} t + \phi_{AC}\right)$$

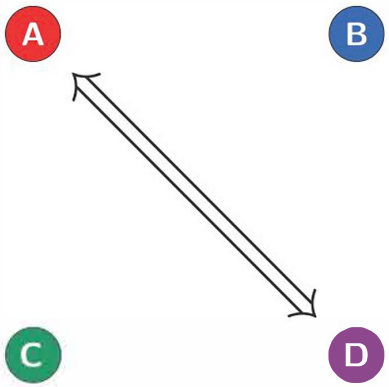


Graphs & Parametrically Coupled Modes

$$\omega_{jk}^{P} \equiv |\omega_j - \omega_k|$$

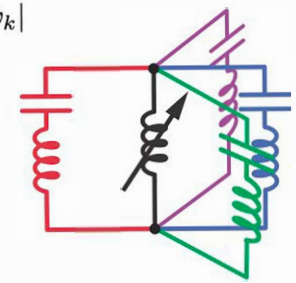


$$M(t) = M_0 + \delta M_{AD} \cos\left(\omega_{AD}^{P} t + \phi_{AD}\right)$$

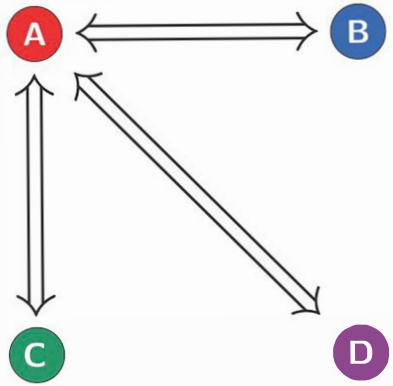


Graphs & Parametrically Coupled Modes

$$\omega_{jk}^{P} \equiv |\omega_j - \omega_k|$$

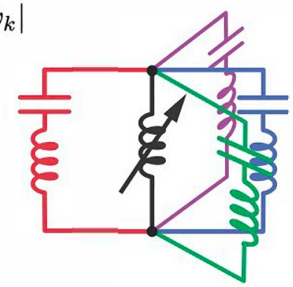


$$\begin{aligned} M(t) = & M_0 + \\ & \delta M_{AB} \cos(\omega_{AB}^{P} t + \phi_{AB}) \\ & \delta M_{AC} \cos(\omega_{AC}^{P} t + \phi_{AC}) \\ & \delta M_{AD} \cos(\omega_{AD}^{P} t + \phi_{AD}) \end{aligned}$$

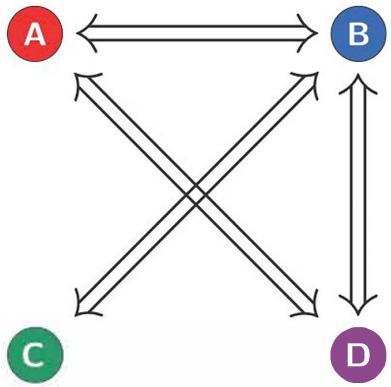


Graphs & Parametrically Coupled Modes

$$\omega_{jk}^{P} \equiv |\omega_j - \omega_k|$$

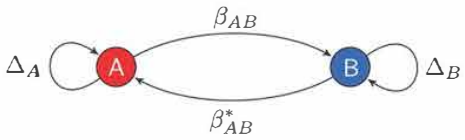


$$\begin{aligned} M(t) = & M_0 + \\ & \delta M_{AB} \cos\left(\omega_{AB}^{P} t + \phi_{AB}\right) \\ & \delta M_{BC} \cos\left(\omega_{BC}^{P} t + \phi_{BC}\right) \\ & \delta M_{BD} \cos\left(\omega_{AD}^{P} t + \phi_{BD}\right) \\ & \delta M_{AD} \cos\left(\omega_{AD}^{P} t + \phi_{AD}\right) \end{aligned}$$



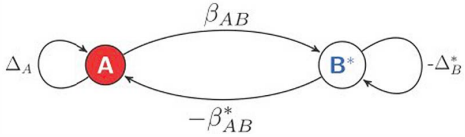
Multi-mode Graphs

FREQUENCY CONVERSION

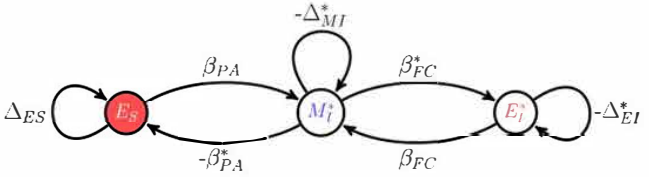


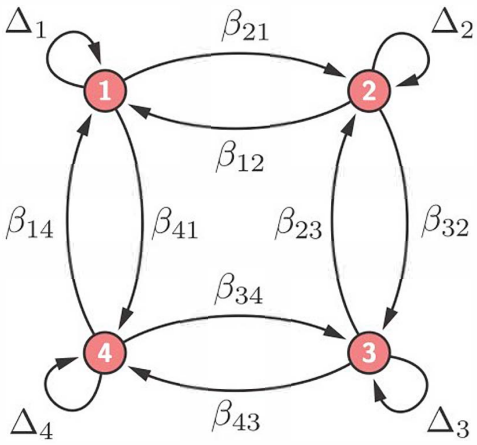
$$\omega^P_{AB} = |\omega_A - \omega_B|$$

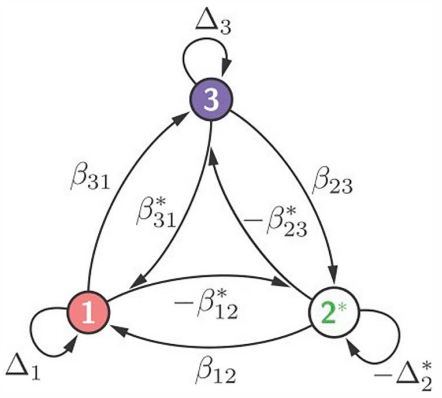
AMPLIFICATION



$$\omega^P_{AB} = \omega_A + \omega_B$$

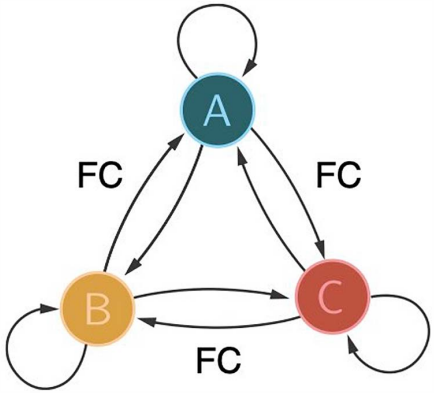




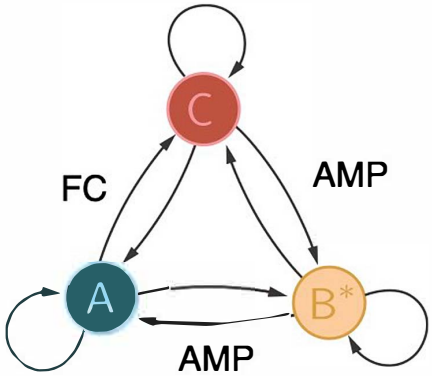


see Ranzani & JA, New J. Phys. ***17****, 023024 (2015)*

Graphs + Scattering + Directionality



"Delta Circulator"



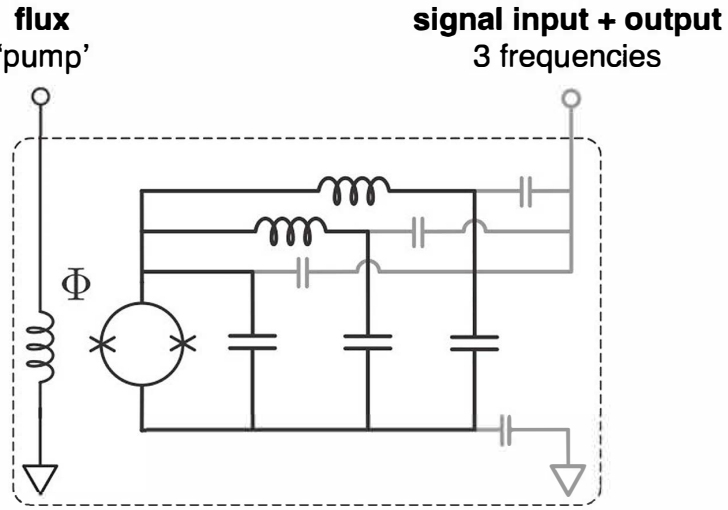
"Delta Amplifier"

realize by building a 3-resonator circuit

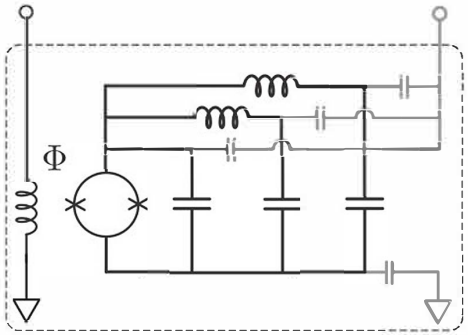
*see Ranzani & JA, New J. Phys. **17**, 023024 (2015)*

Build Circuit Schematic

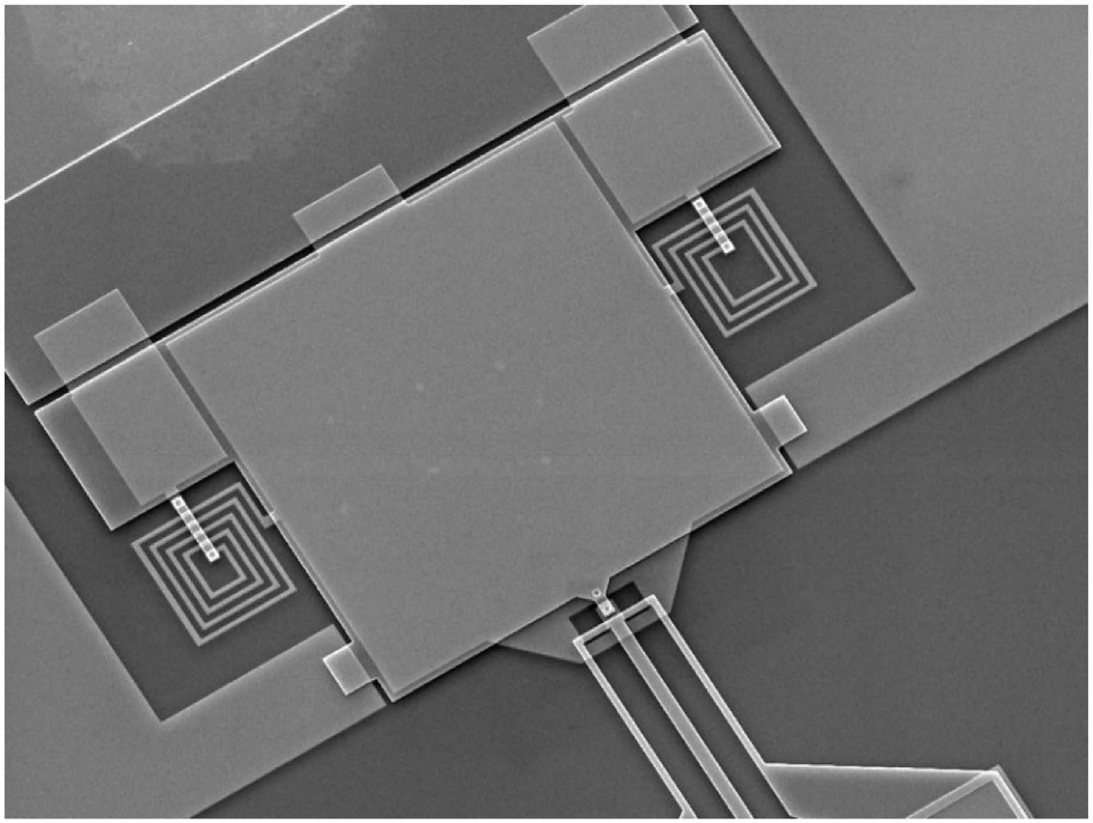
$$L_{SQ}(t) = \frac{L_{J0}}{|\cos(2\pi\Phi(t)/\Phi_0)|}$$



Build fabricated circuit

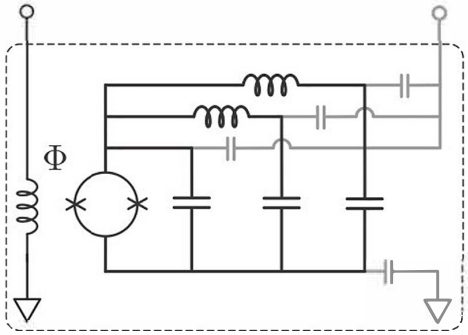


- **NIST Nb tri-layer junctions**
- **Nb wiring**
- **α-Si, *tan δ* ~10^{-4}**
- **SQUID I_c~10 μA**

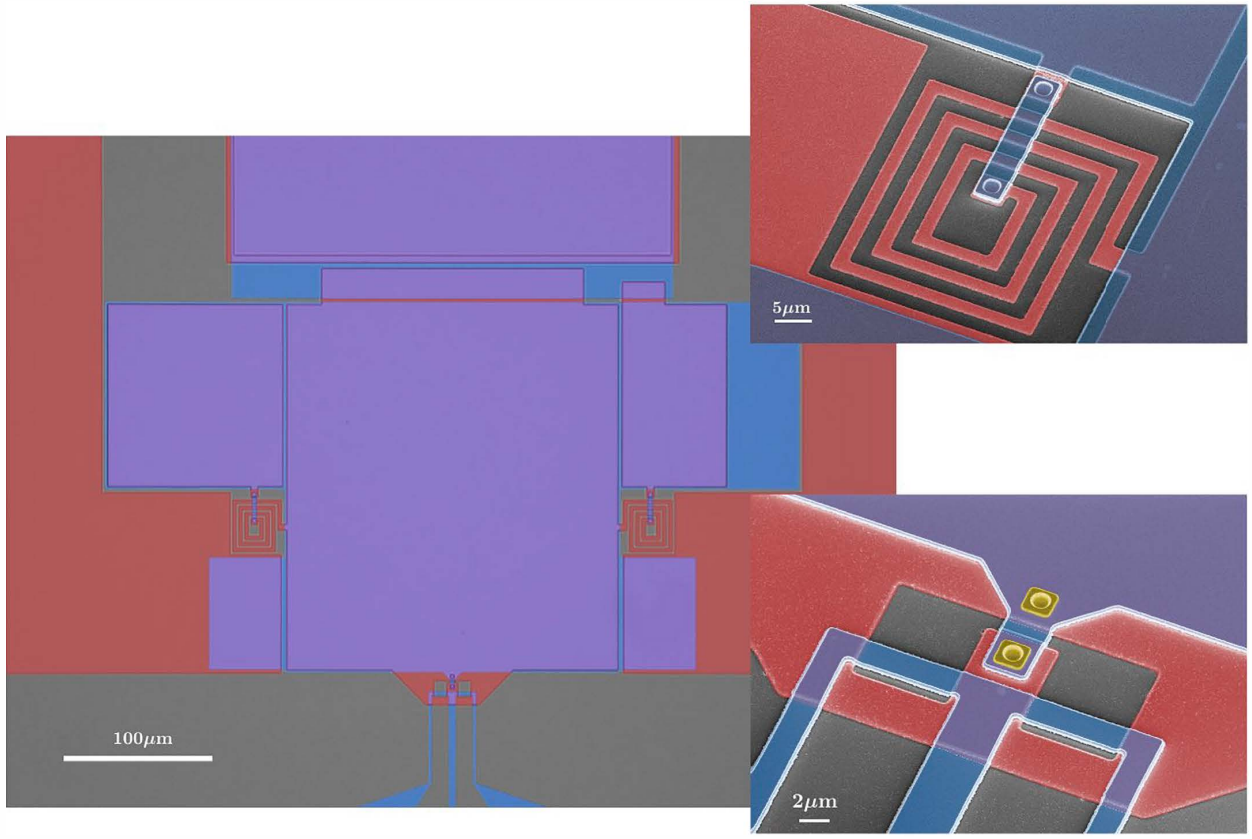


*see F. Lecocq, …, JAA, Phys. Rev. Applied **7**, 024028*

Build Fabricated Circuit

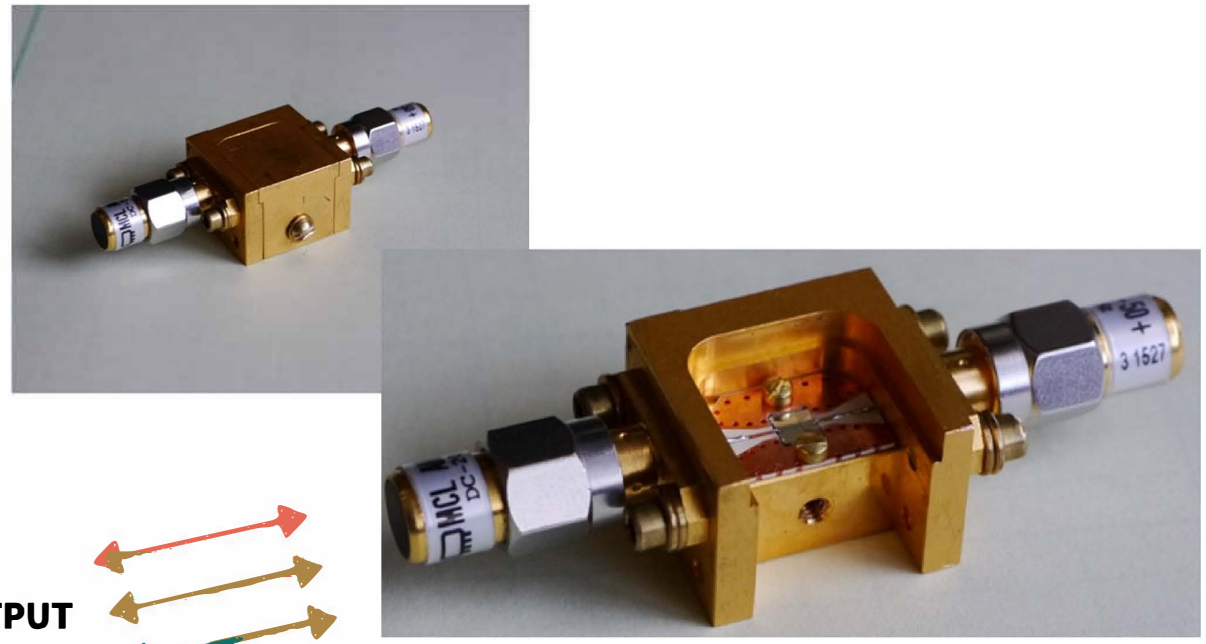


- **NIST Nb tri-layer junctions**
- **Nb wiring**
- **α-Si, *tan δ* ~10^{-4}**
- **SQUID I_c~10 μA**

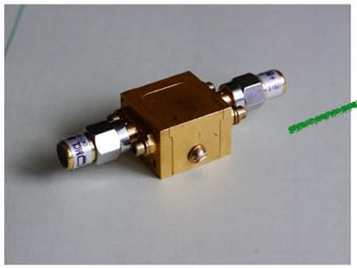


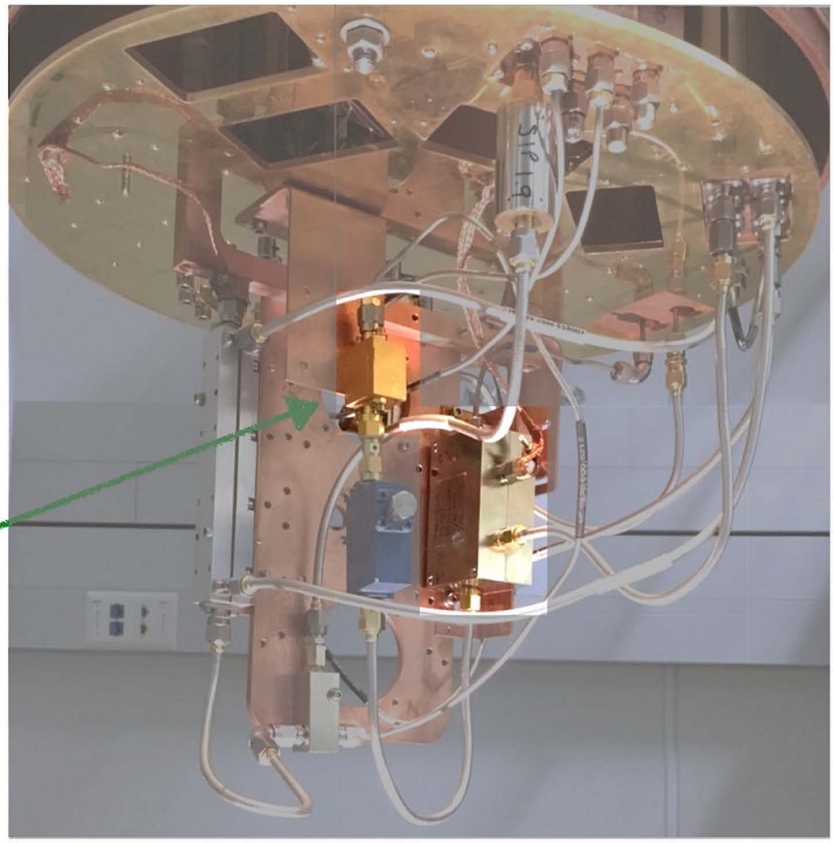
*see F. Lecocq, …, JAA, Phys. Rev. Applied **7**, 024028*

Build Packaging

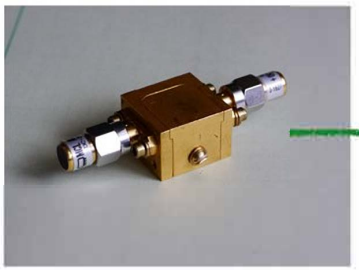


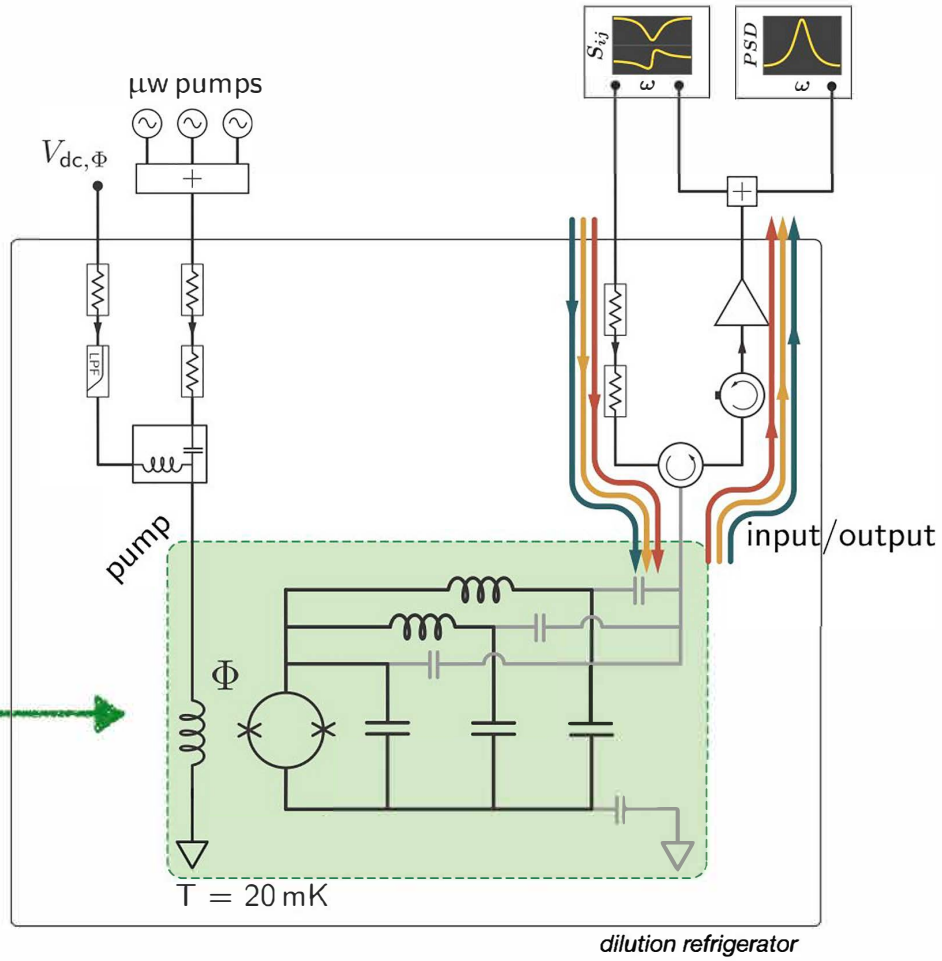
Setup



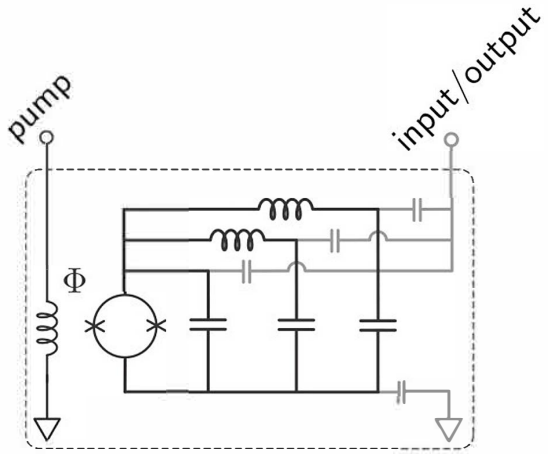


Setup



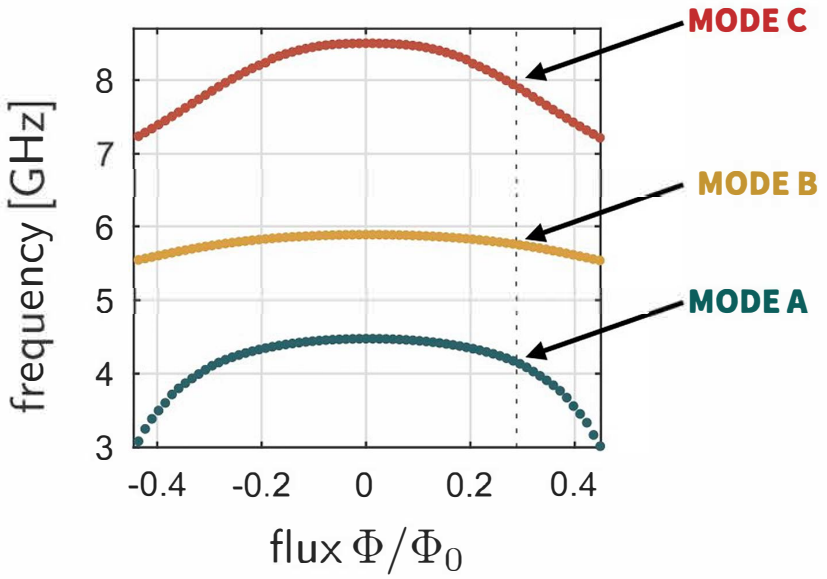

μw pumps
$V_{dc,\Phi}$
LPF
pump
S_{ij}
PSD
ω
ω
input/output
Φ
T = 20 mK
dilution refrigerator

Data Flux Modulation

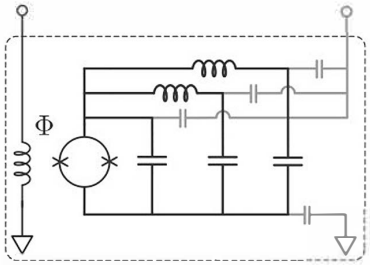


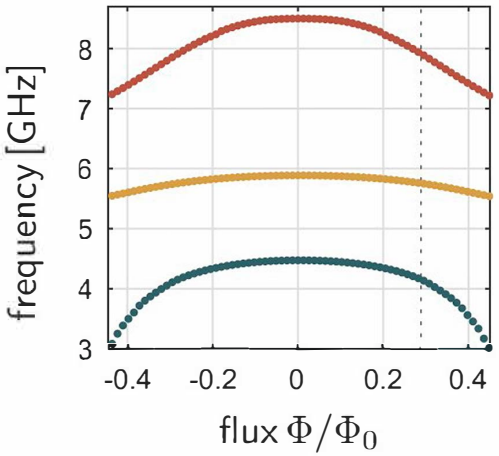
Mode k	$\omega_k/2\pi$[GHz]	$\gamma_k/2\pi$[MHz]	$\gamma_k^{in}/2\pi$[MHz]
A	4.155	29.8	1.4
B	5.756	29.5	1.2
C	7.915	59.3	2.4

$$g_{jk} \propto \sqrt{\frac{\partial \omega_j}{\partial \Phi}\frac{\partial \omega_k}{\partial \Phi}}$$

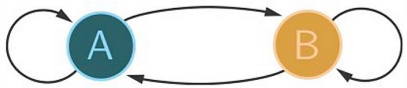


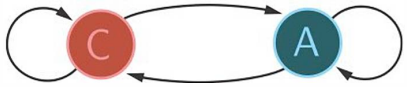
Data 2-mode Frequency Conversion



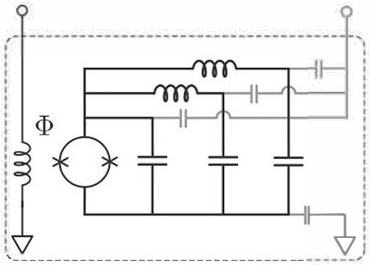


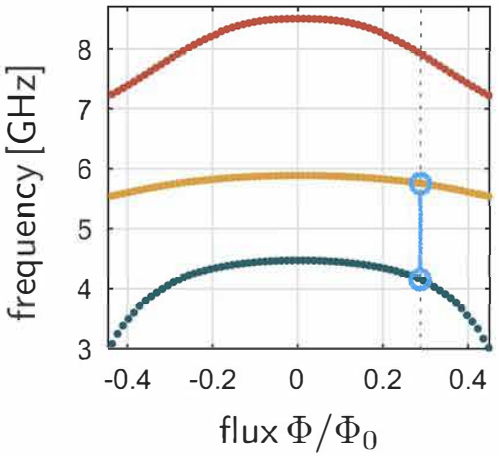
$$\omega_P \simeq |\omega_j - \omega_k|$$

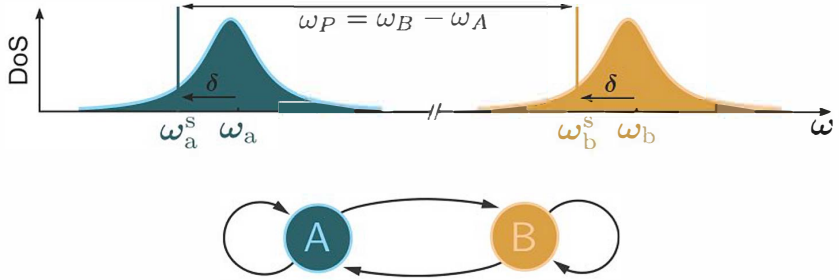


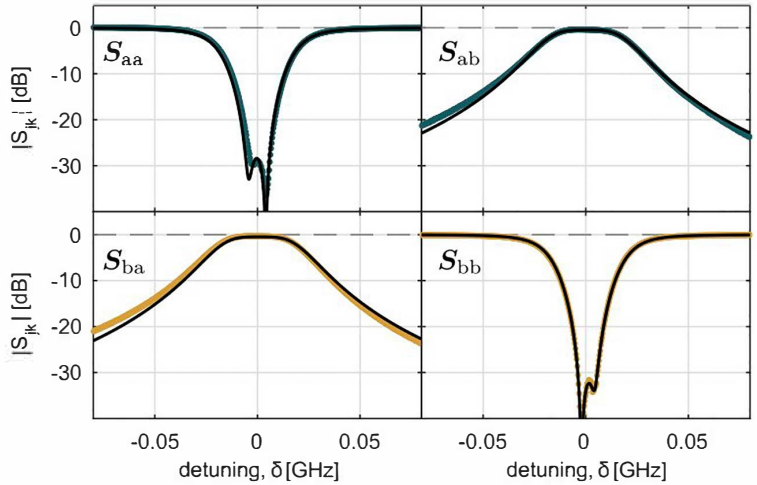


Data 2-mode Frequency Conversion

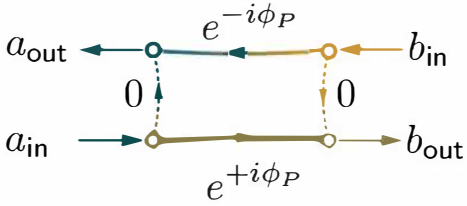




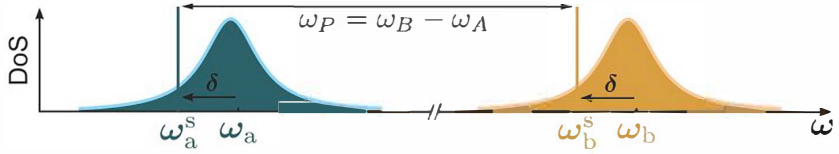


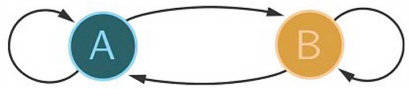


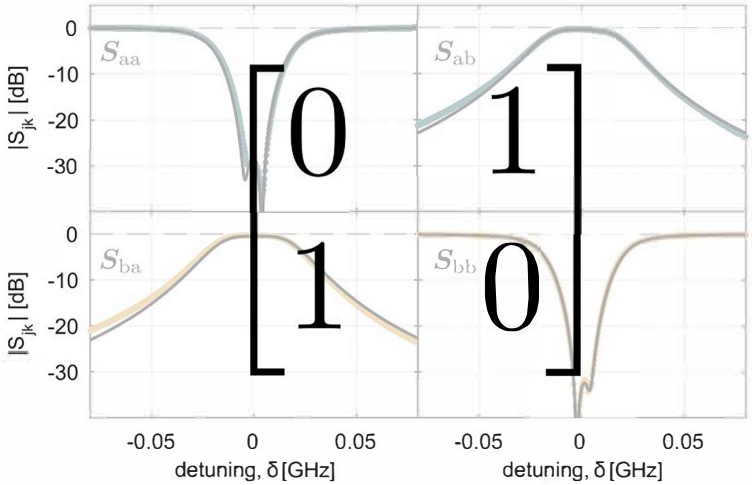
Data 2-mode Frequency Conversion



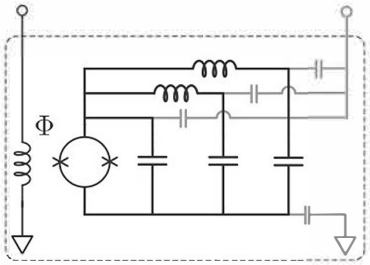
$$|S_{BA}| \simeq -0.5\,\text{dB}$$
$$|S_{AA}|, |S_{BB}| < -30\,\text{dB}$$

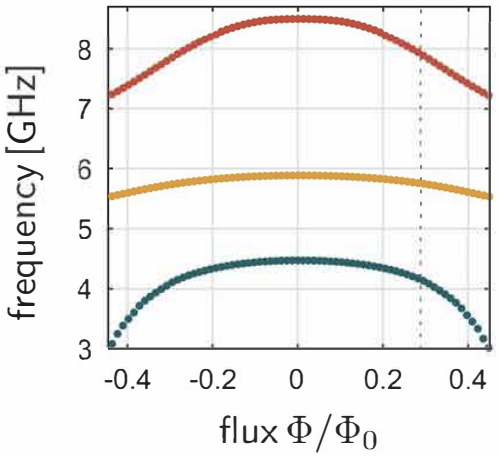


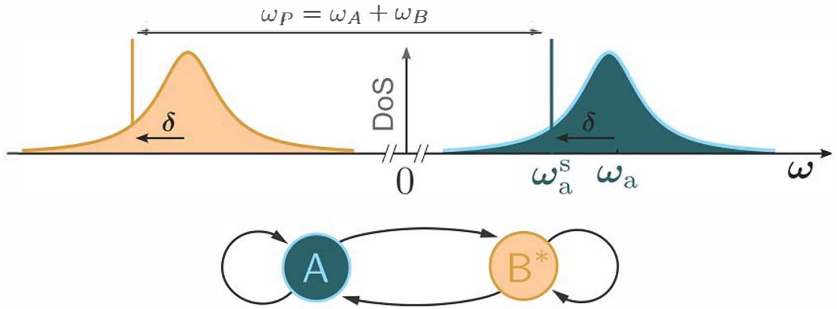


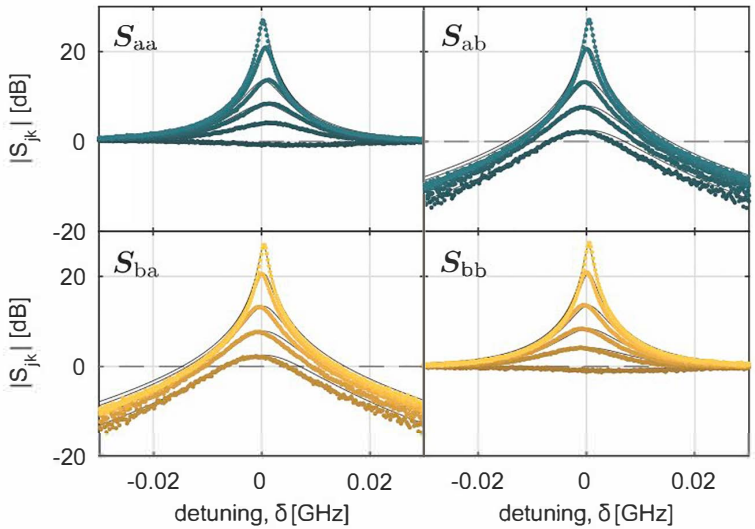


Data 2-mode amplification [“non-degenerate”]

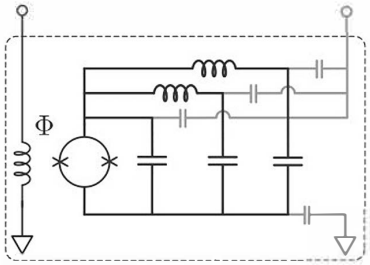


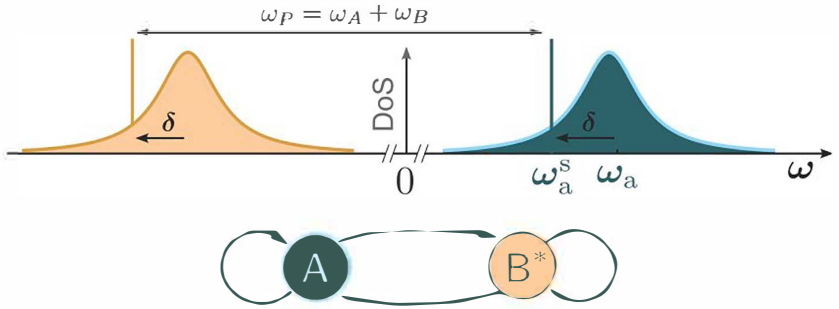


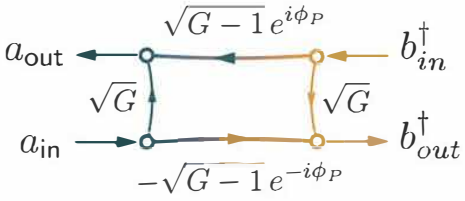


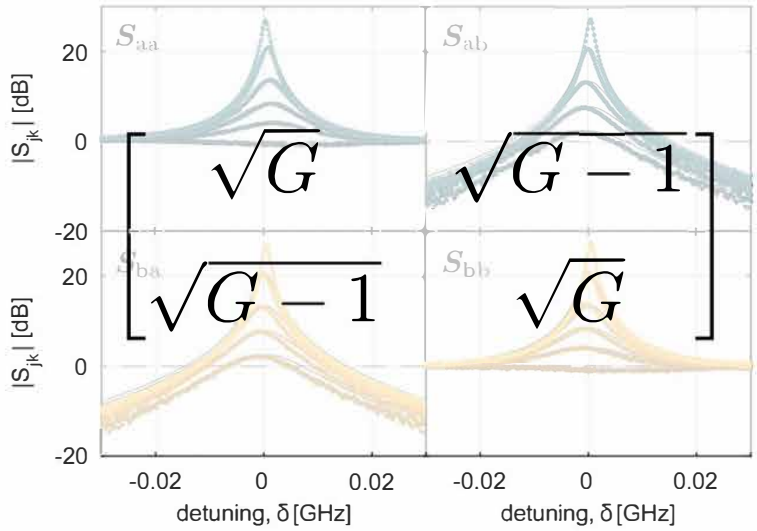


Data 2-mode amplification [“non-degenerate”]

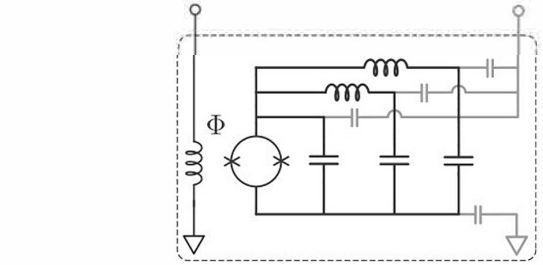




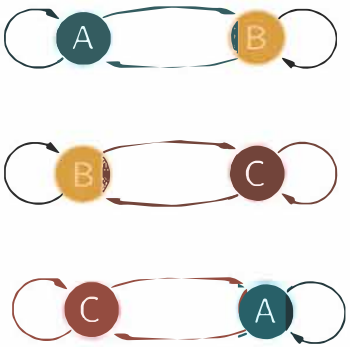


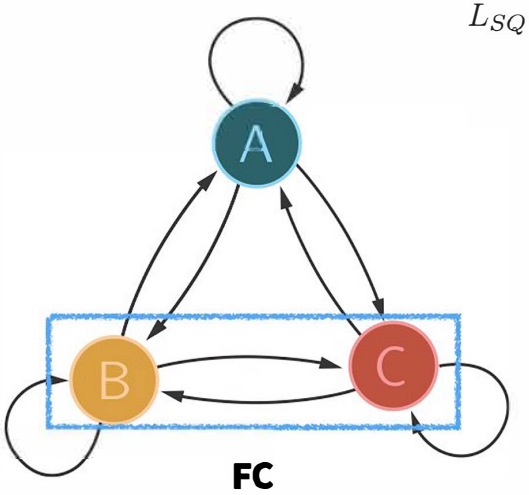


Data 3-mode Frequency Circulation



$$\omega_P = |\omega_j - \omega_k|$$



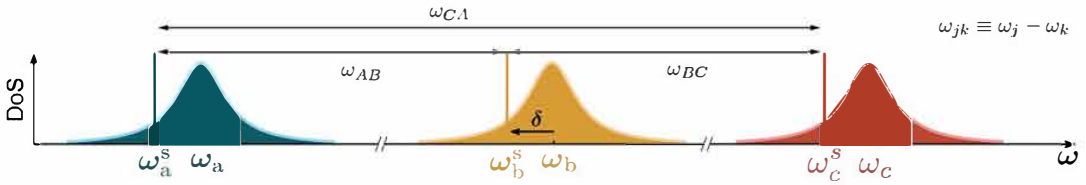


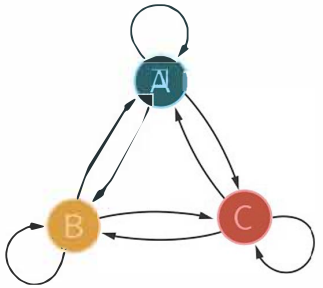
FC

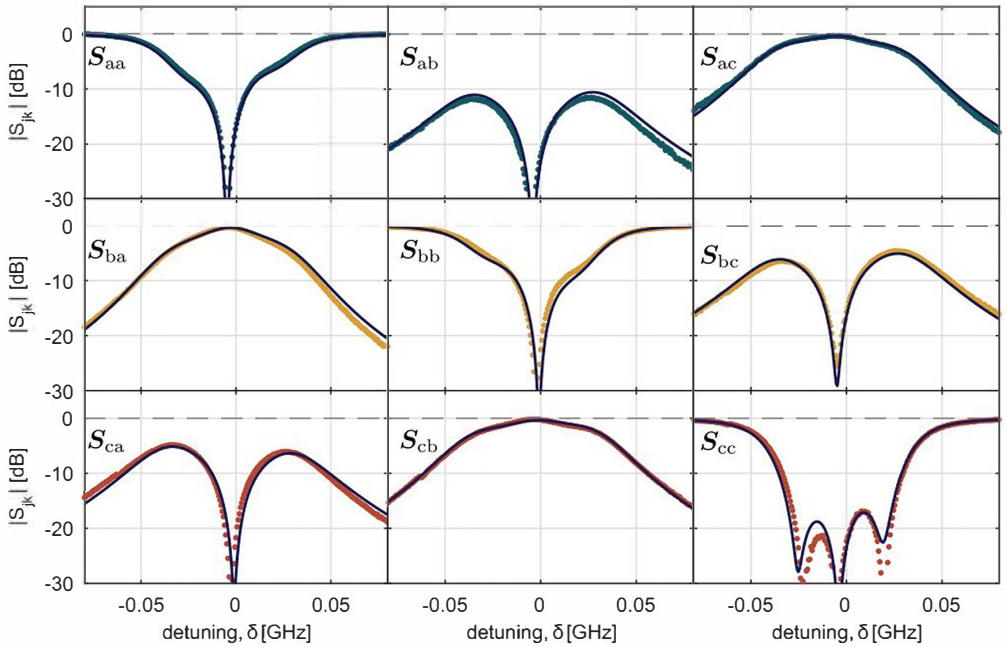
$$\begin{aligned} L_{SQ} = L_{SQ,0} &+ \delta L_{AB}\cos(|\omega_A - \omega_B|t + \phi_{AB}) \\ &+ \delta L_{AC}\cos(|\omega_A - \omega_C|t + \phi_{AC}) \\ &+ \delta L_{BC}\cos(|\omega_B - \omega_C|t + \phi_{BC}) \end{aligned}$$

*see F Lecocq, et al., Phys. Rev. Applied **7**, 024028 (2017)*
*see also KM Sliwa, et al., Phys. Rev. X **5**, 041020 (2015)*

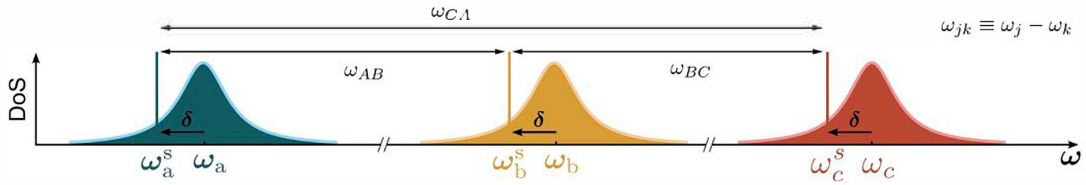
Data 3-mode Frequency Circulation

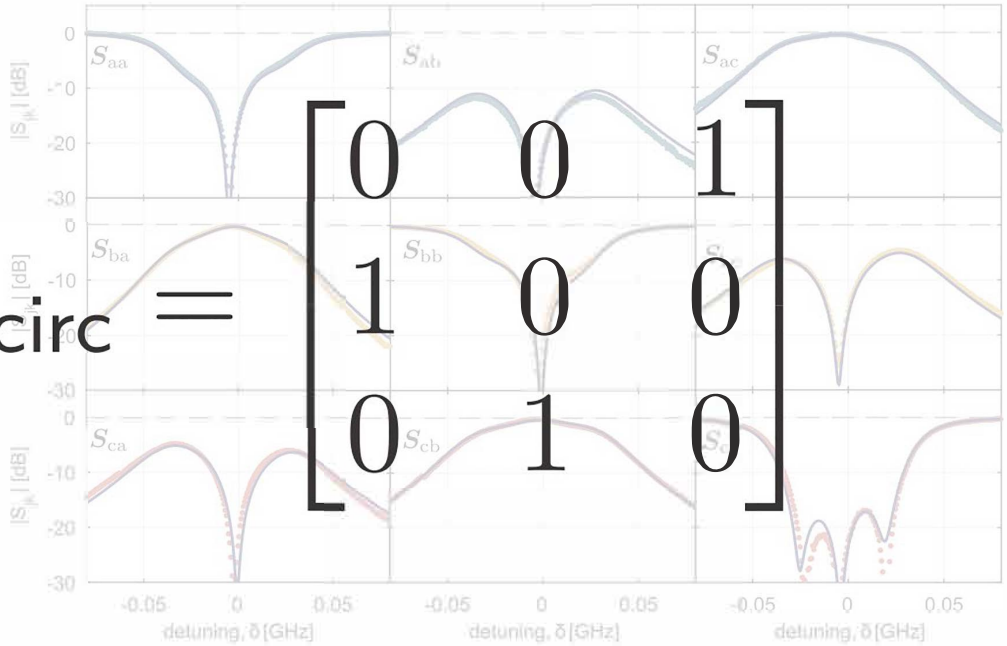




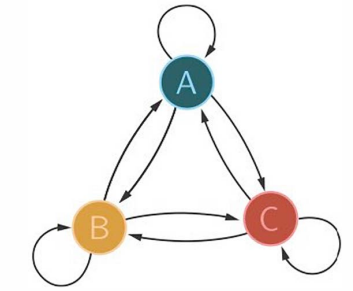


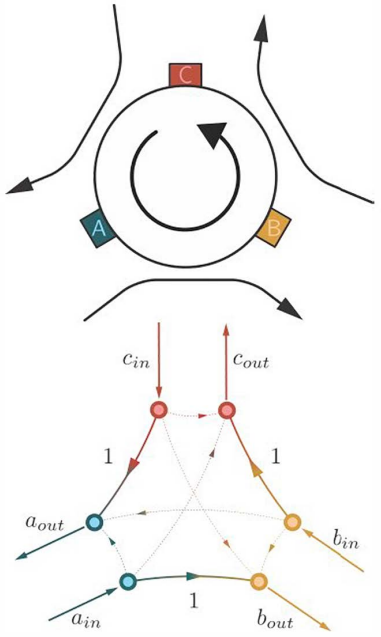
Data 3-mode Frequency Circulation





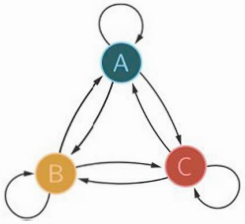
$$S_{\text{circ}} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$





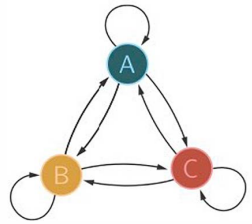
Data 3-mode Frequency Circulation

Loop phase dependence $\phi_\Sigma \equiv \phi_{AB} + \phi_{AC} + \phi_{BC}$

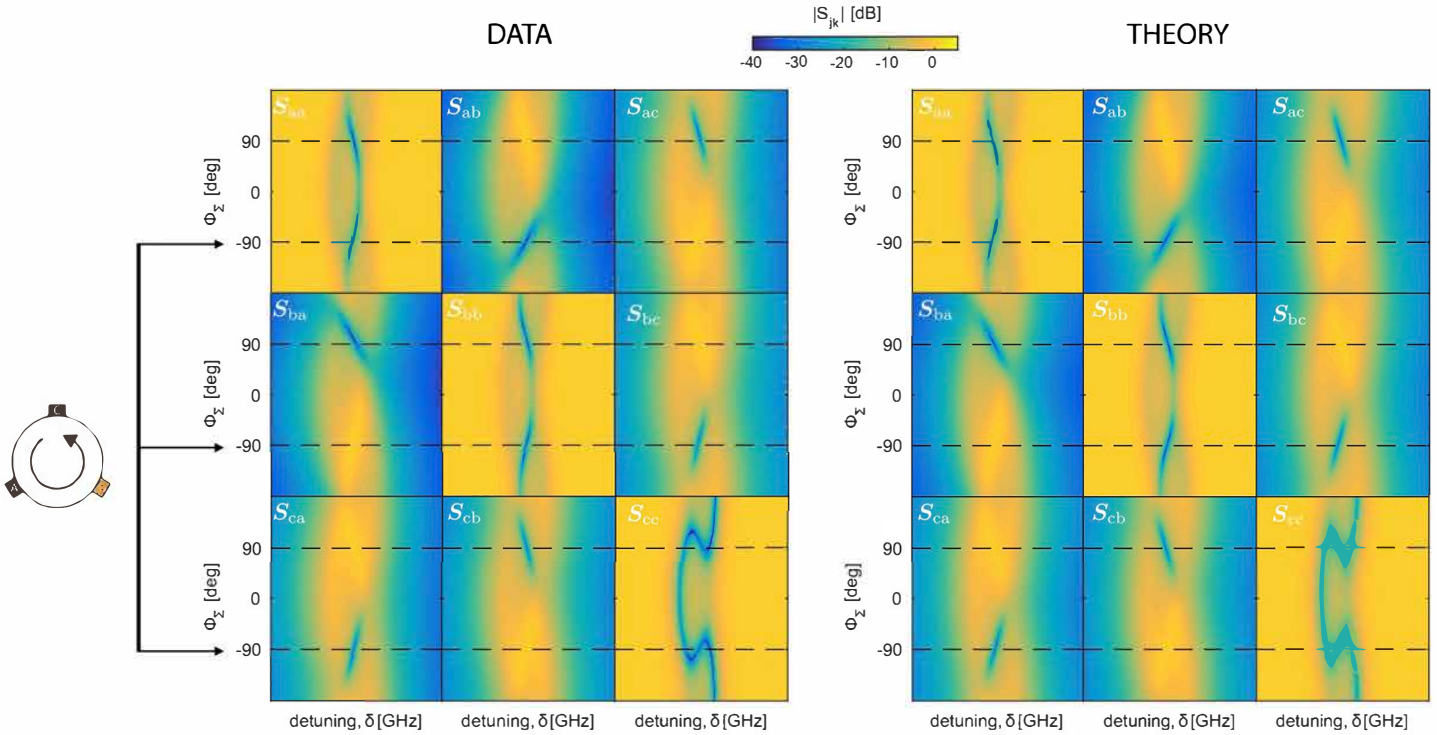


$$\begin{aligned} L_{SQ} = L_{SQ,0} &+ \delta L_{AB} \cos(|\omega_A - \omega_B|t + \phi_{AB}) \\ &+ \delta L_{AC} \cos(|\omega_A - \omega_C|t + \phi_{AC}) \\ &+ \delta L_{BC} \cos(|\omega_B - \omega_C|t + \phi_{BC}) \end{aligned}$$

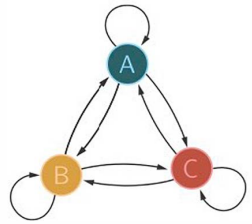
Data 3-mode Frequency Circulation



Loop phase dependence $\phi_\Sigma \equiv \phi_{AB} + \phi_{AC} + \phi_{BC}$



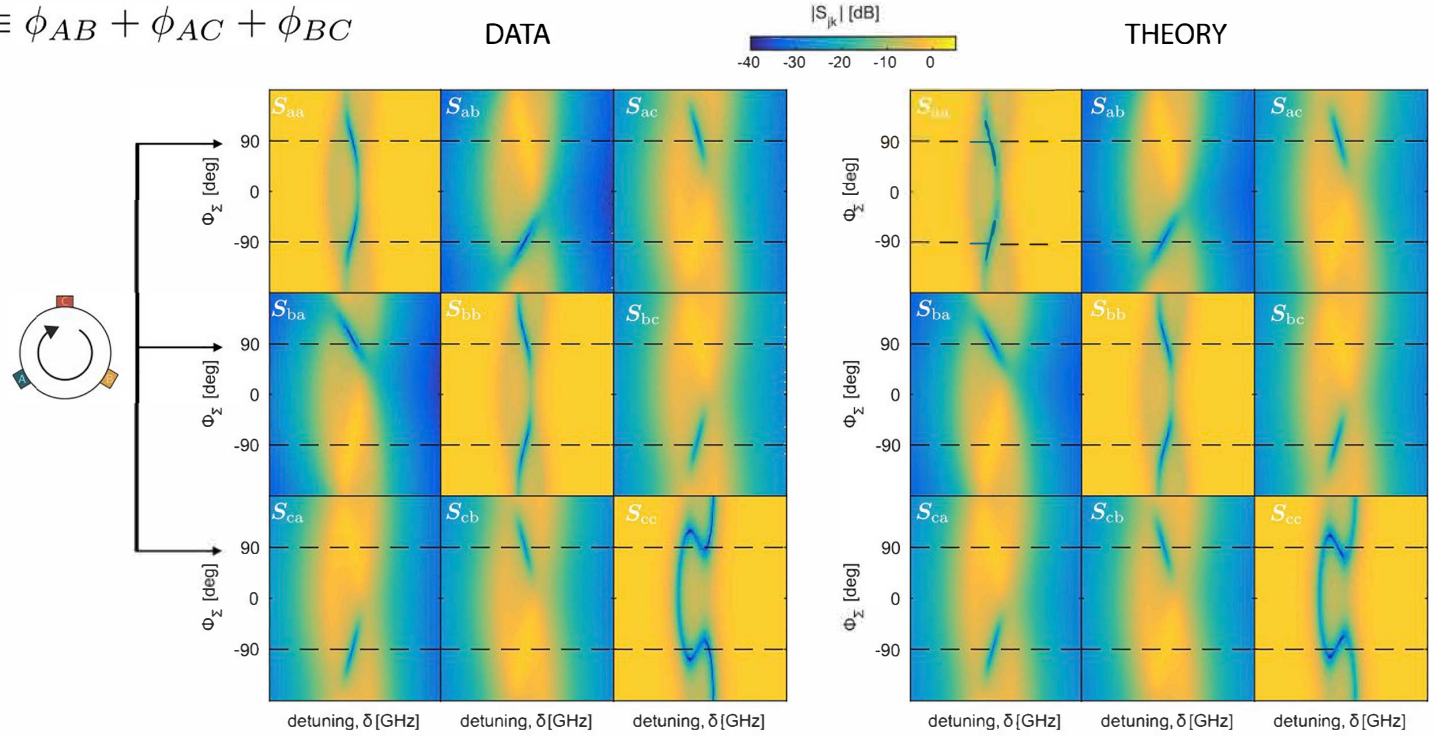
Data 3-mode Frequency Circulation



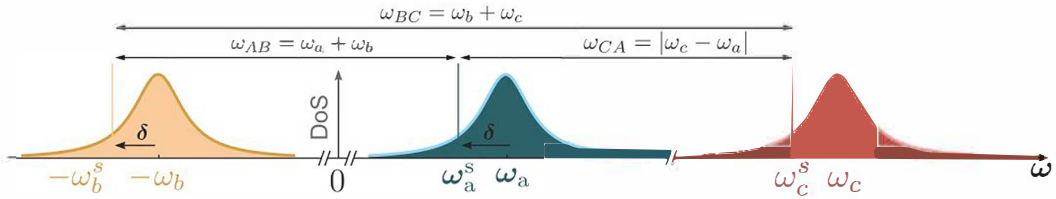
Loop/pump phase changes circulation sense

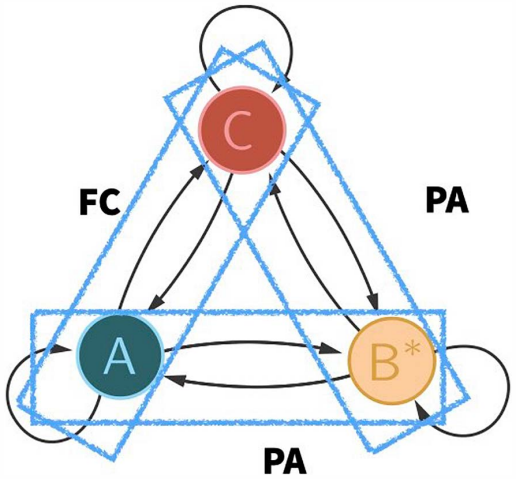
$$\phi_\Sigma \equiv \phi_{AB} + \phi_{AC} + \phi_{BC}$$

DATA



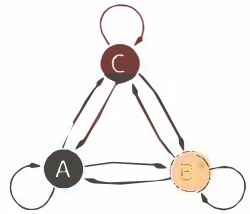
Data 3-mode Frequency Amplification

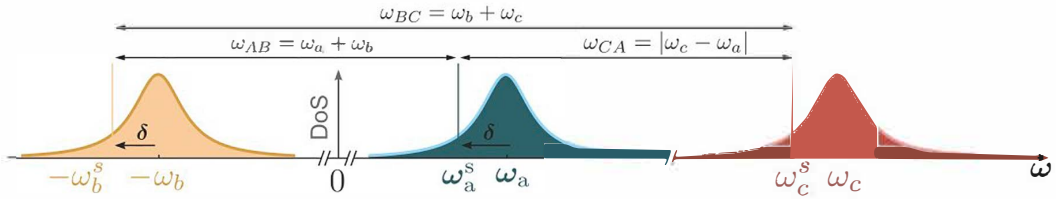


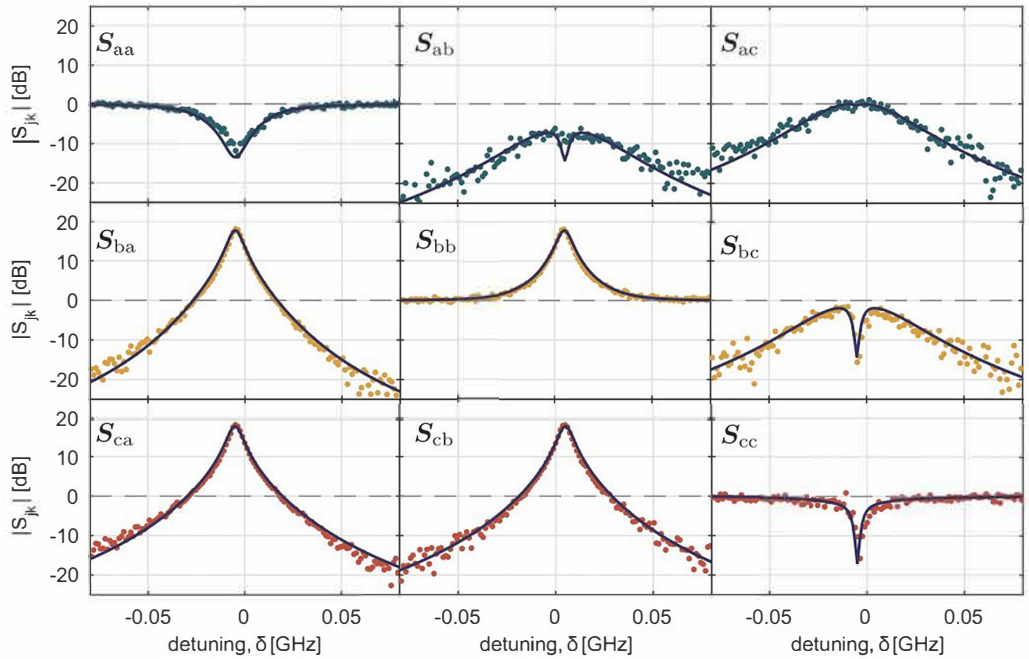


*see F Lecocq, et al., Phys. Rev. Applied **7**, 024028 (2017)*
*see also KM Sliwa, et al., Phys. Rev. X **5**, 041020 (2015)*

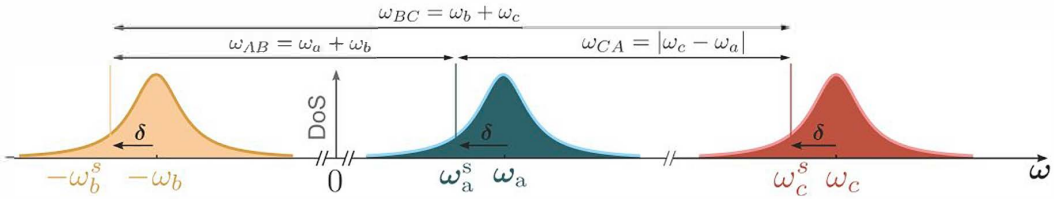
Data 3-mode Frequency Amplification

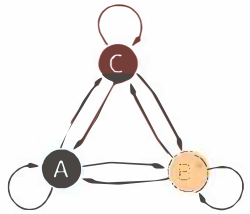




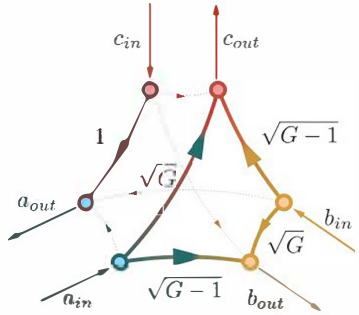


Data 3-mode Frequency Amplification

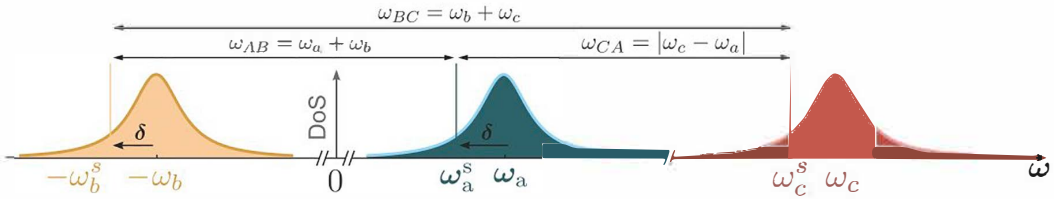


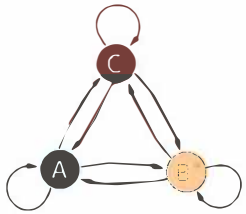


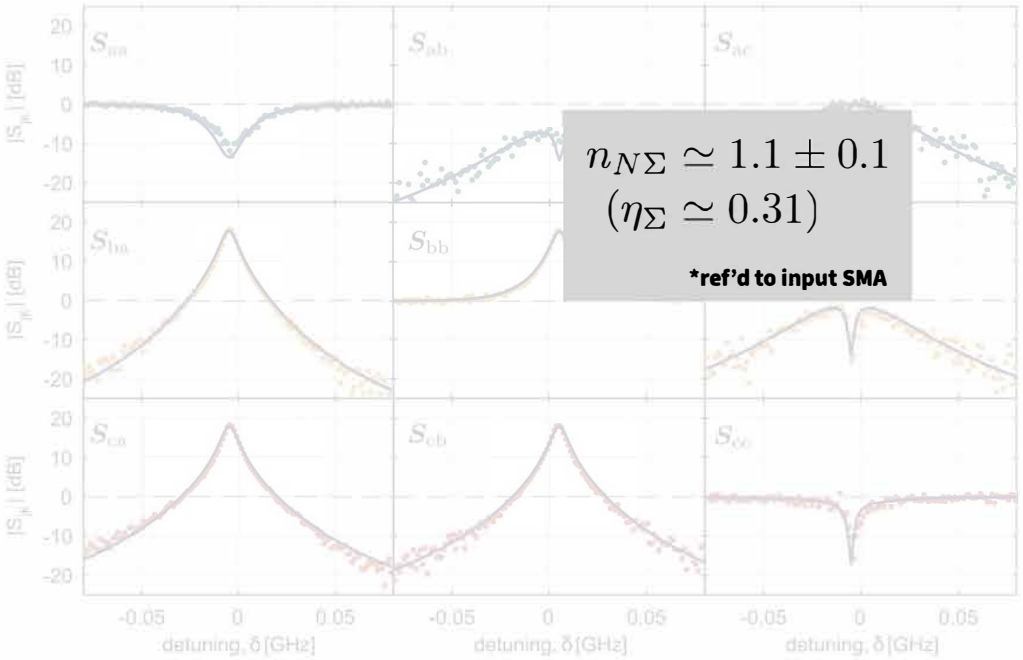
$$S_\Delta = \begin{bmatrix} 0 & 0 & 1 \\ \sqrt{G-1} & \sqrt{G} & 0 \\ \sqrt{G} & \sqrt{G-1} & 0 \end{bmatrix}$$



Data 3-mode Frequency Amplification

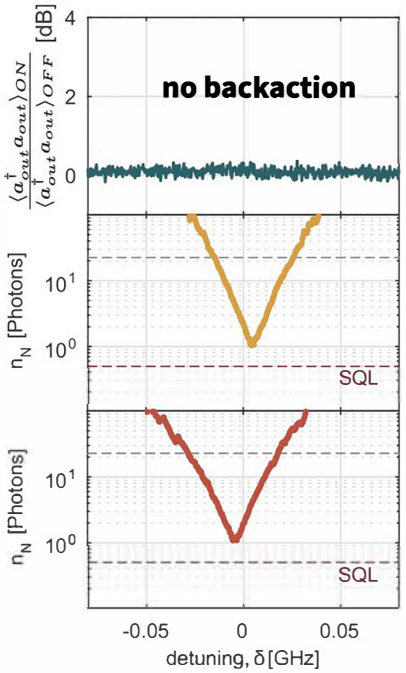




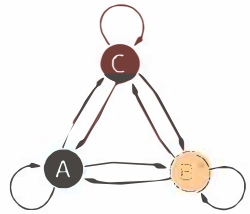


$$n_{N\Sigma} \simeq 1.1 \pm 0.1$$
$$(\eta_\Sigma \simeq 0.31)$$

***ref'd to input SMA**

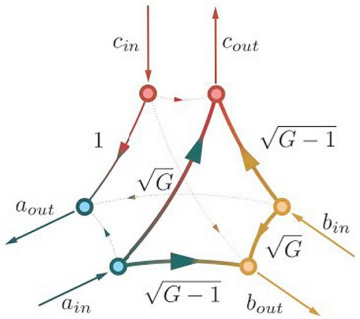


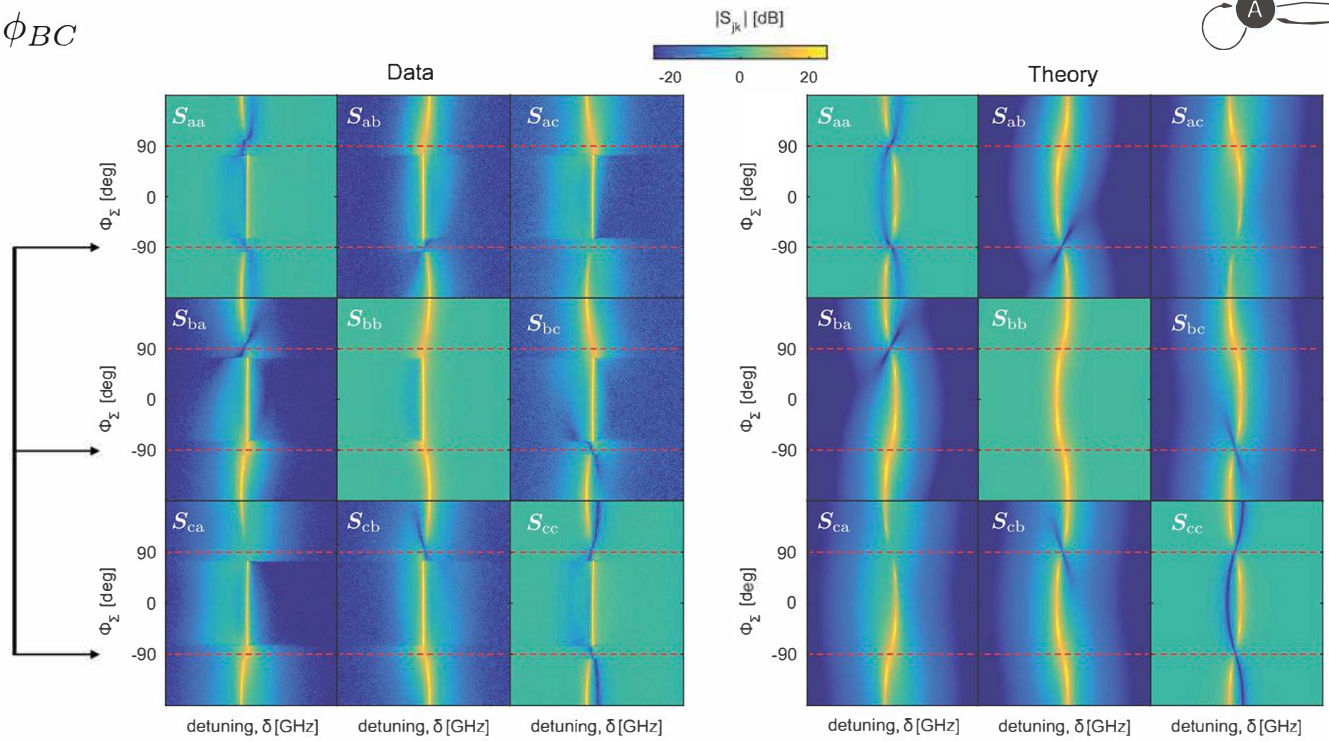
[Data] 3-mode frequency amplification



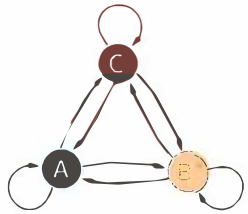
Loop phase dependence

$$\phi_\Sigma \equiv \phi_{AB} + \phi_{AC} + \phi_{BC}$$





Data 3-mode Frequency Amplification



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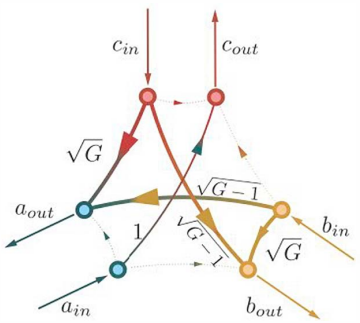
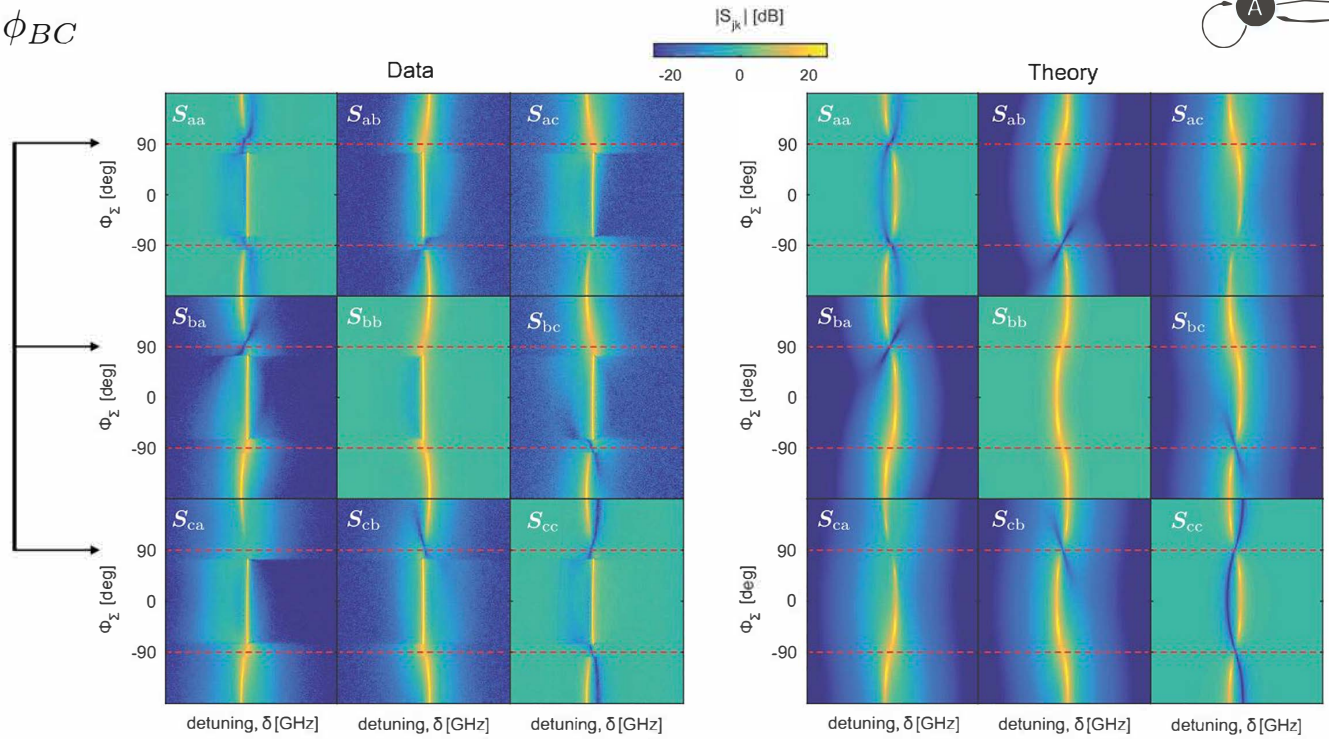
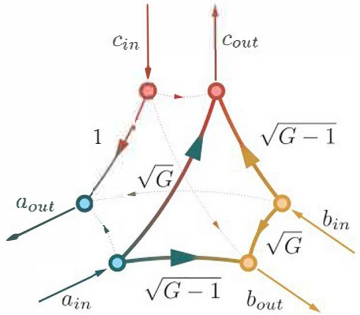
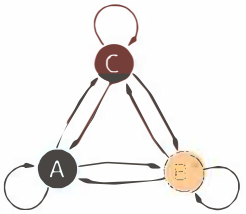




Data 3-mode Frequency Amplification

$$S_\Delta = \begin{bmatrix} 0 & 0 & 1 \\ \sqrt{G-1} & \sqrt{G} & 0 \\ \sqrt{G} & \sqrt{G-1} & 0 \end{bmatrix}$$





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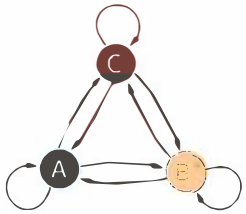

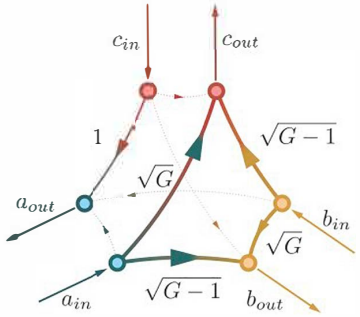

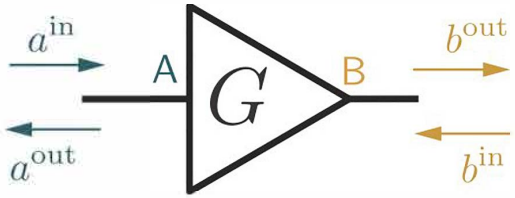

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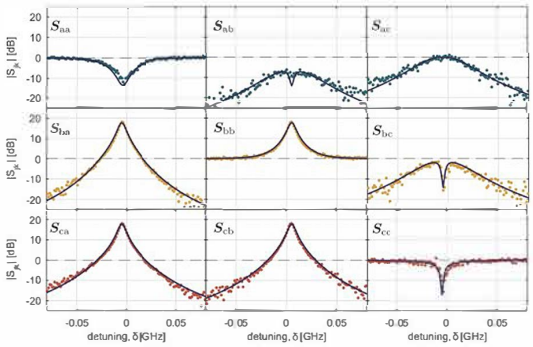

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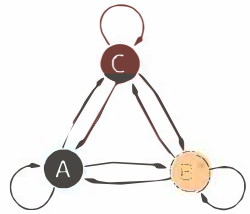

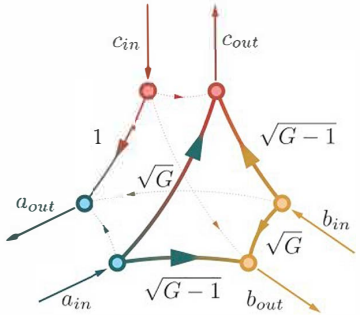

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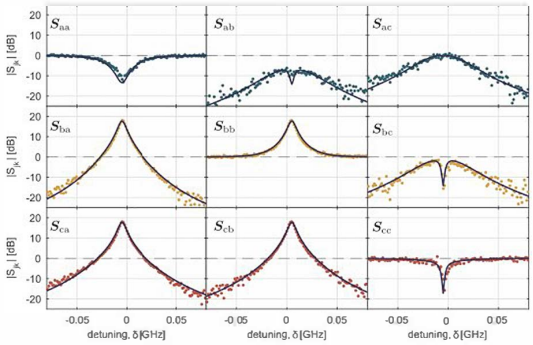

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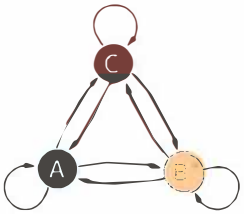
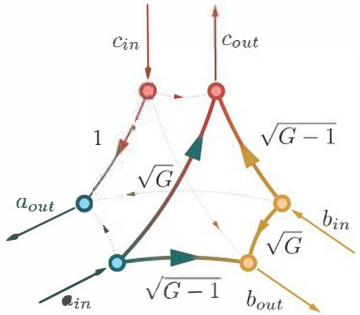
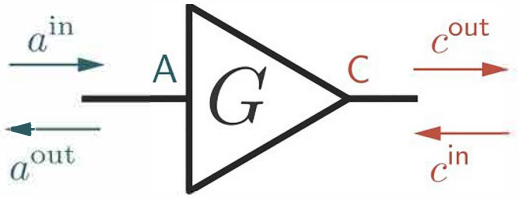
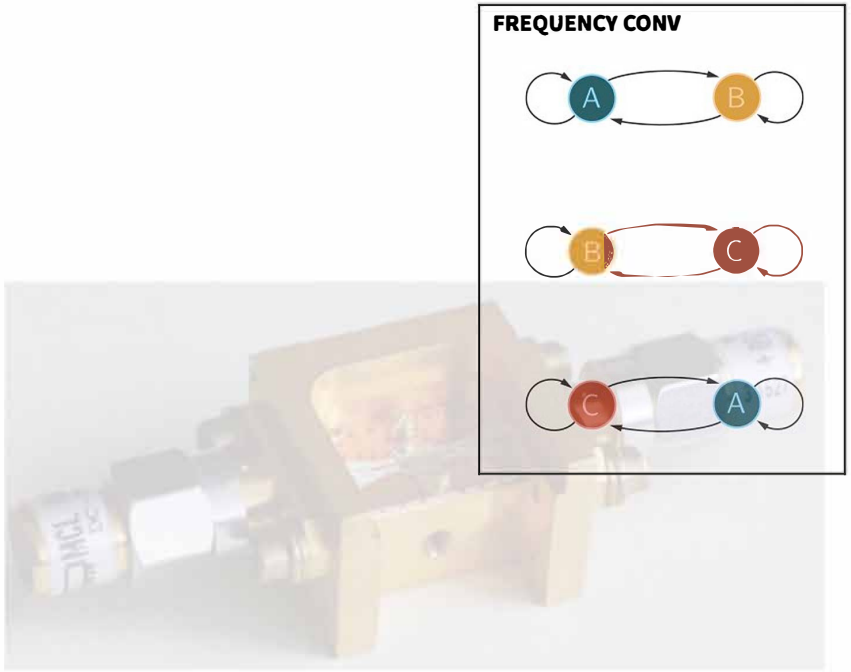






Programmability = Field Programmable Josephson Amplifier (FPJA)



*see F Lecocq, et al., Phys. Rev. Applied **7**, 024028 (2017)*

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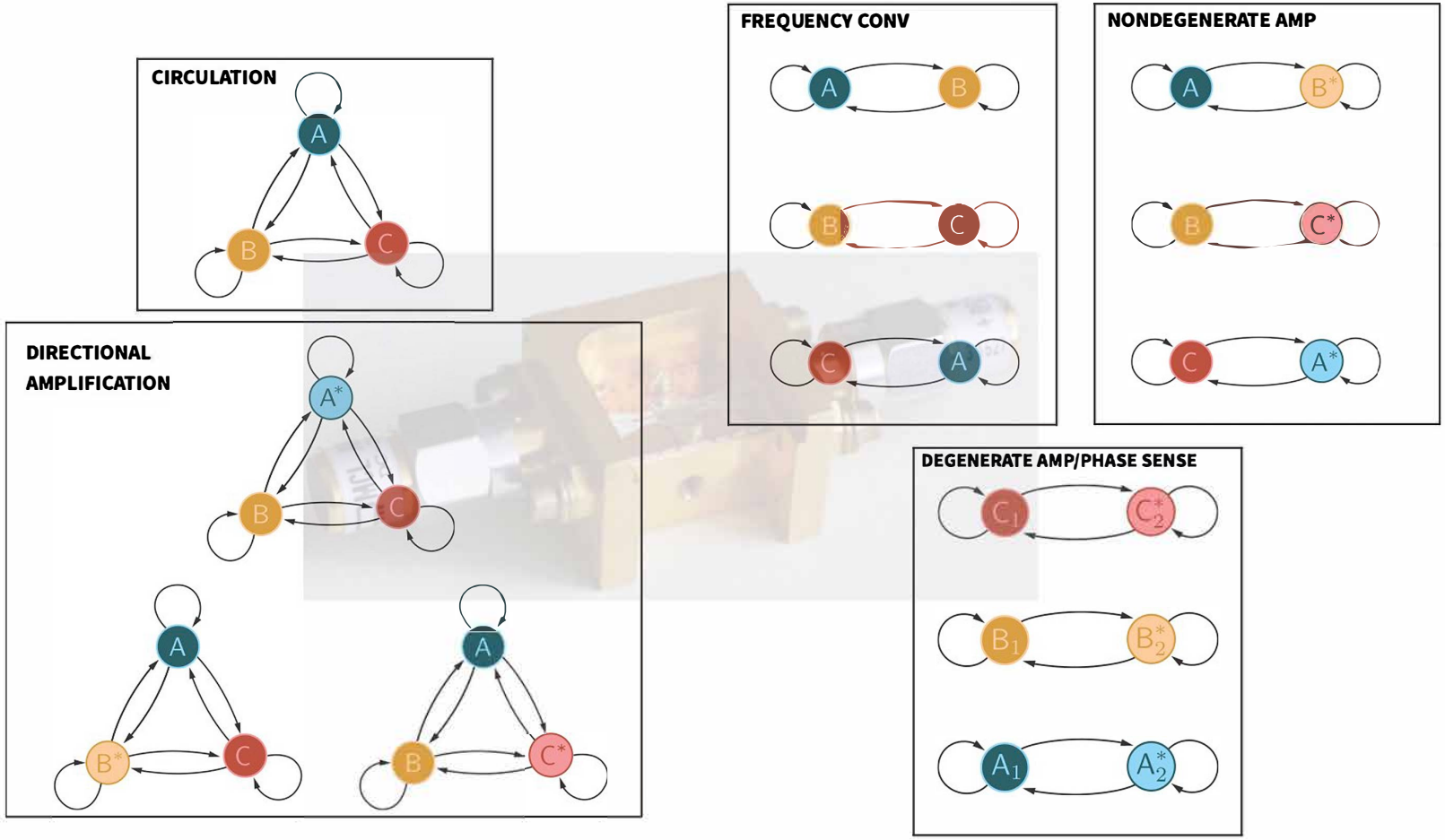

*see F Lecocq, et al., Phys. Rev. Applied **7**, 024028 (2017)*

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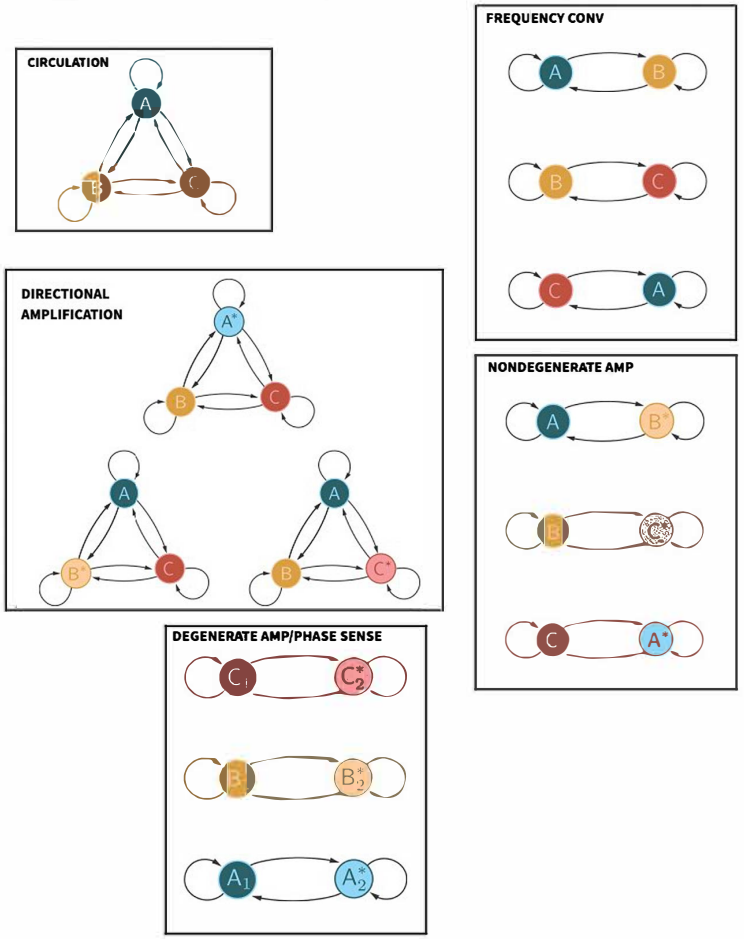
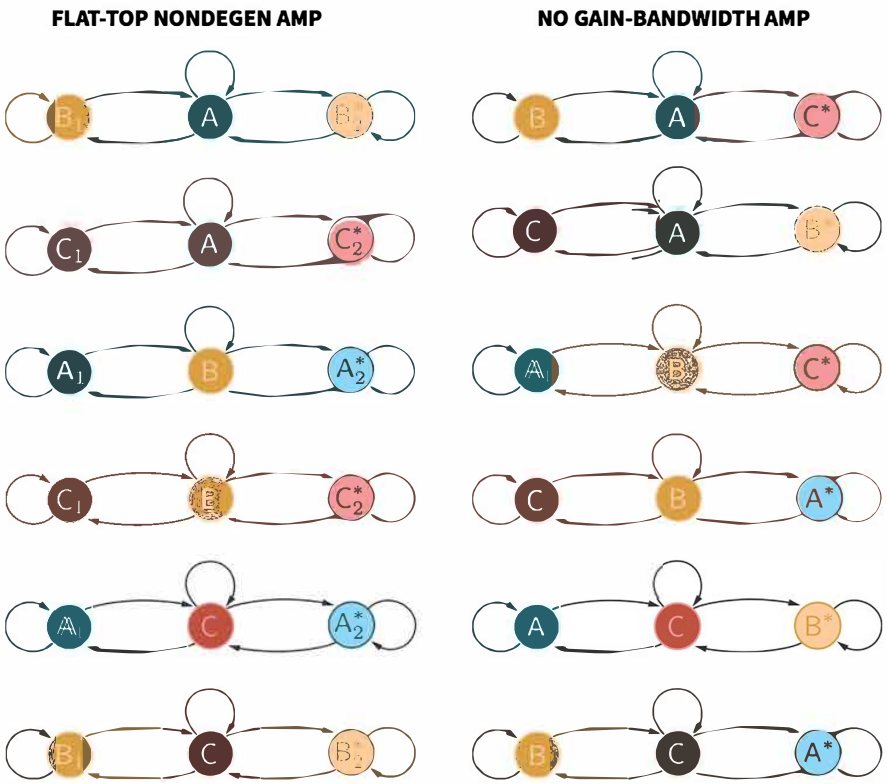




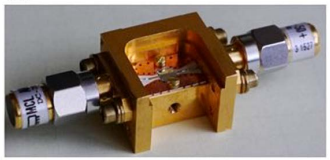
*see F Lecocq, et al., Phys. Rev. Applied **7**, 024028 (2017)*

OUTLOOK

discrete devices

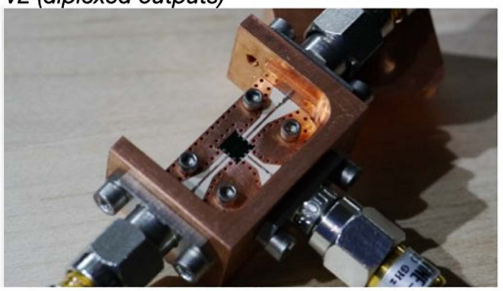
2+ port devices

v1



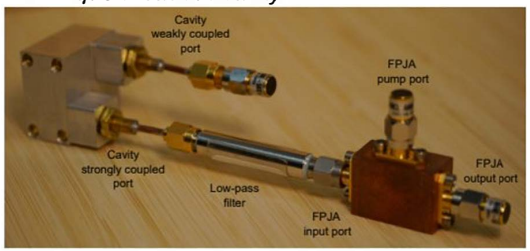
*Phys. Rev. Applied **7**, 024028 (2017)*

v2 (diplexed outputs)



*Phys. Rev. Applied **13**, 044005 (2020)*

v2 + qubit readout cavity



F. Lecocq, et al. arXiv:2009.08863 (2020)

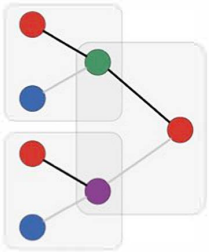
on-chip integration

- *flip chip couple FPJA-type circuits to qubit+resonator circuits*
- *use resources already on chip (resonators, SQUIDs, JJ nonlinearity) to build nonlinearity into*

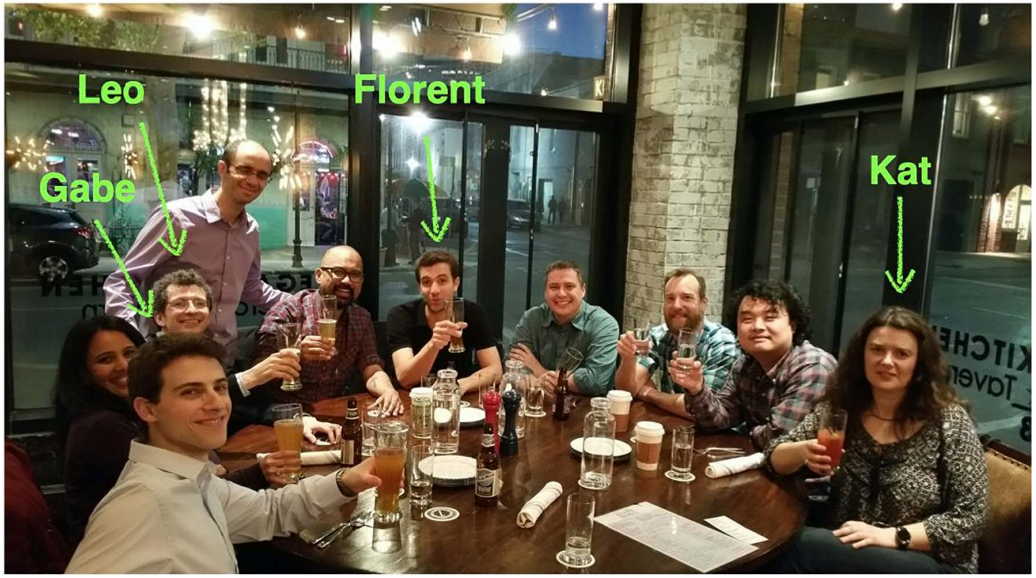
other applications

sequenced coupling ⇨

- *tunable isolation & switch networks*
- *hyper-local amplification and routing on chip*



Thanks!



Boulder Advanced Microwave Photonics Group 686.05

https://www.nist.gov/programs-projects/advanced-microwave-photonics

PIs: **J. Aumentado**
Ray Simmonds
John Teufel

PDs: **Kat Cicak**
Bastien Dassonneville
Bradley Hauer
Xiaoyue Jin
Shlomi Kotler (now at Hebrew U.)
Florent Lecocq
Taewan Noh
Leonardo Ranzani (now at Raytheon/BBN)

Students: Benton Miller
Gabriel Peterson (now at PsiQuantum)

Relevant Publications

Graph-based analysis of nonreciprocity in coupled-mode systems
L Ranzani & J Aumentado
New Journal of Physics **17**, 23024, (2015)

Nonreciprocal microwave signal processing with a field-programmable josephson amplifier
F Lecocq, L Ranzani, GA Peterson, K Cicak, RW Simmonds, JD Teufel, & J Aumentado
Physical Review Applied **7**, 024028 (2017)

Microwave measurement beyond the quantum limit with a nonreciprocal amplifier
F Lecocq, L Ranzani, GA Peterson, K Cicak, A Metelmann, S Kotler, RW Simmonds, JD Teufel, & J Aumentado
Physical Review Applied **13**, 044005 (2020)

Efficient qubit measurement with a nonreciprocal microwave amplifier
F Lecocq, L Ranzani, GA Peterson, K Cicak, XY Jin, RW Simmonds, JD Teufel, & J Aumentado
arXiv:2009.08863 (2020)

REVIEWS
Circulators at the quantum limit: recent realizations of quantum-limited superconducting circulators and related approaches
L Ranzani, J Aumentado
IEEE Microwave Magazine **20**, 112 (2019)

Superconducting Parametric Amplifiers: The State of the Art in Josephson Parametric Amplifiers
J Aumentado
IEEE Microwave Magazine **21**, 45 (2020)