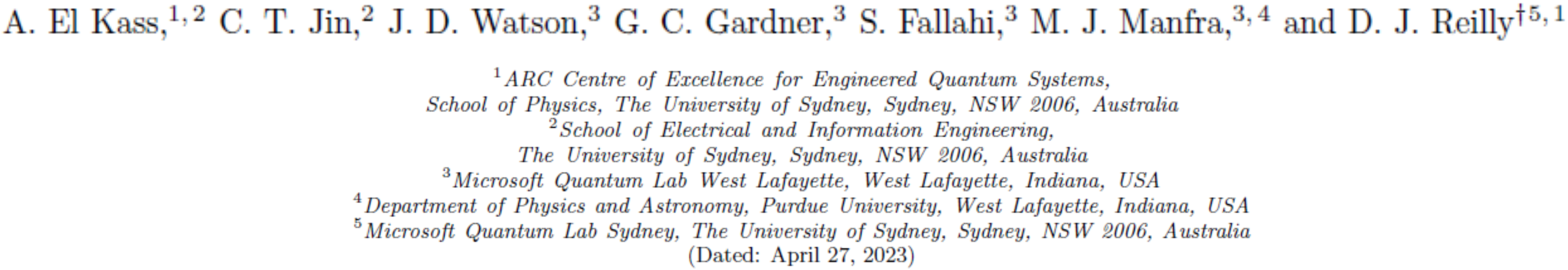
An RF Quantum Capacitance Parametric Amplifier



A. El Kass,[1,2] C. T. Jin,[2] J. D. Watson,[3] G. C. Gardner,[3] S. Fallahi,[3] M. J. Manfra,[3,4] and D. J. Reilly[†5,1]

[1] *ARC Centre of Excellence for Engineered Quantum Systems,*
School of Physics, The University of Sydney, Sydney, NSW 2006, Australia
[2] *School of Electrical and Information Engineering,*
The University of Sydney, Sydney, NSW 2006, Australia
[3] *Microsoft Quantum Lab West Lafayette, West Lafayette, Indiana, USA*
[4] *Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana, USA*
[5] *Microsoft Quantum Lab Sydney, The University of Sydney, Sydney, NSW 2006, Australia*
(Dated: April 27, 2023)

Group Meeting Talk, 24.01.2024

Rafael

Agenda

- Fundamentals of high-frequency signal detection
- Amplifiers, Noise & Quantum Limits
- Parametric Amplification

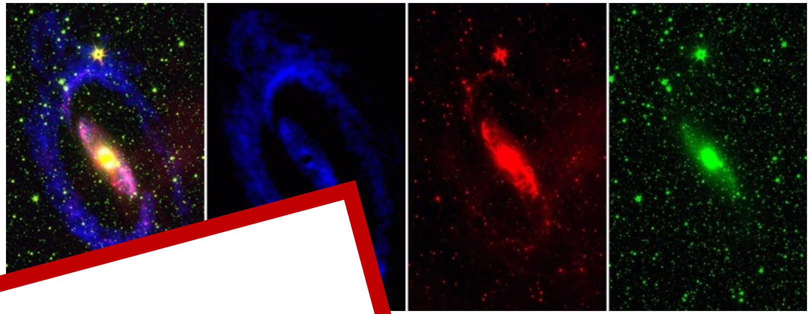
- Quantum Capacitance Parametric Amplifier
- Measurement Setup
- Performance: Degenerate Gain, Noise Temperature, Bandwidth, Compression Point etc.

- Quamplify: The STO Parametric Amplifier

Motivation: Radio-Frequency Amplifiers

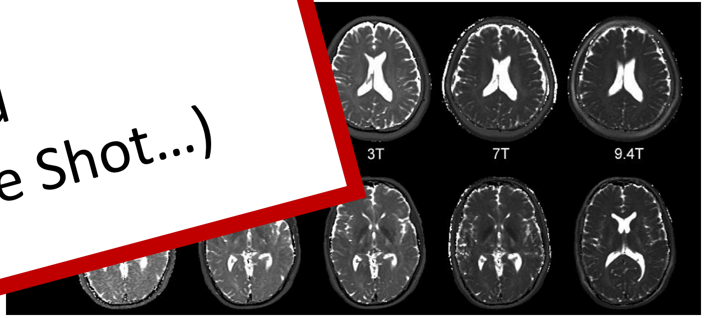
Radio Astronomy

$10\ MHz\ -$
$1\ THz$

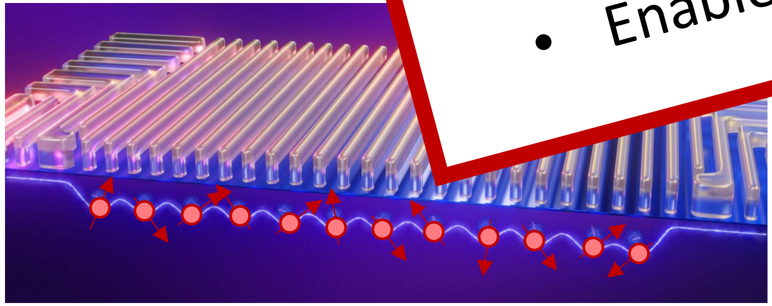


$10\ GHz$

Medical MRI, NM

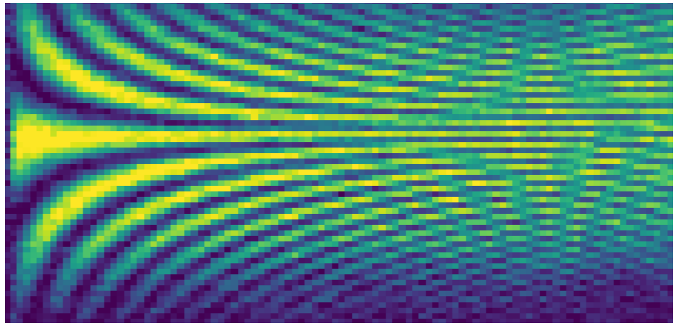


Narrow-band



(Spin) Qubits, Quantum Devices

$100\ MHz\ -$
$10\ GHz$

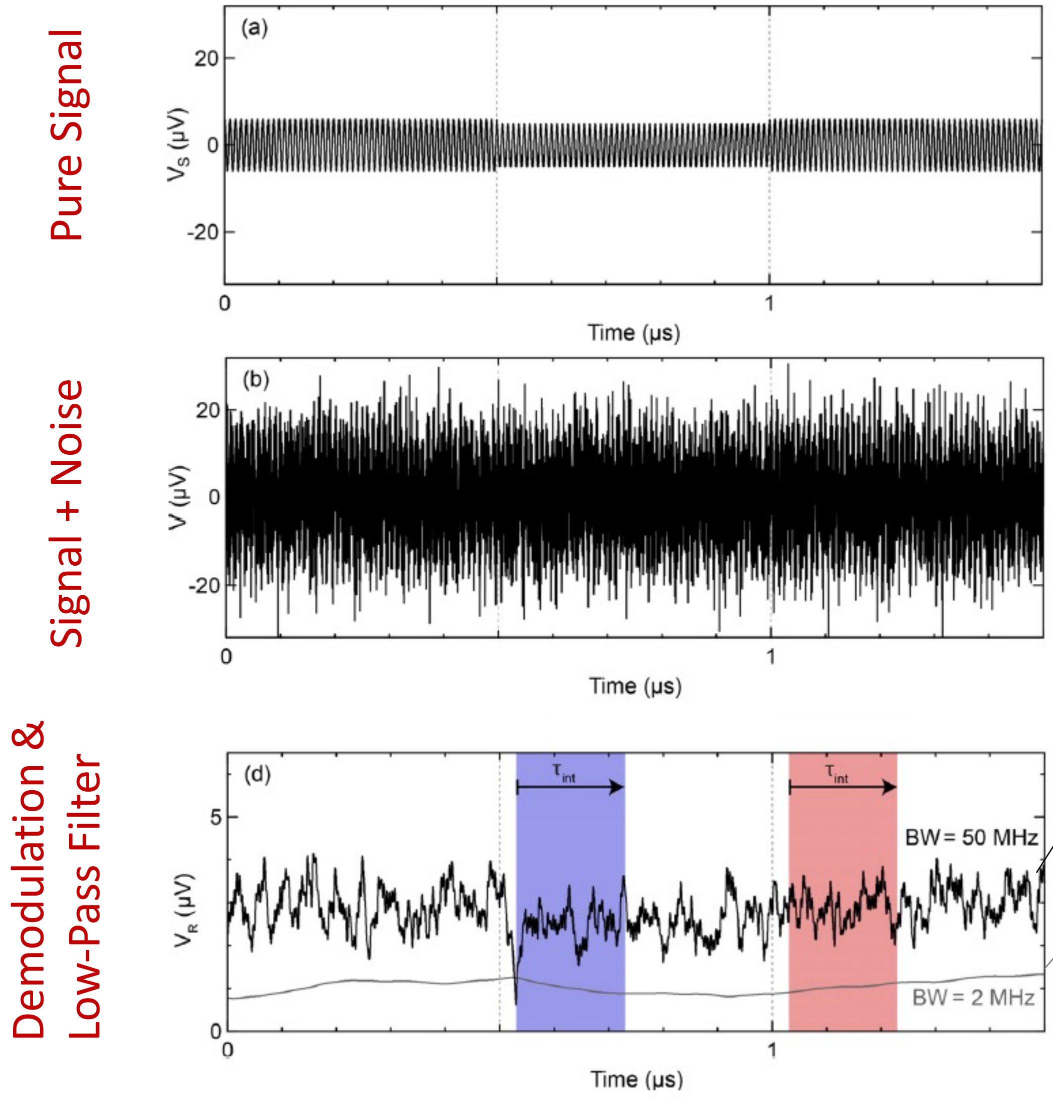


RF-SETs, Gate sensors $< 1\ GHz$

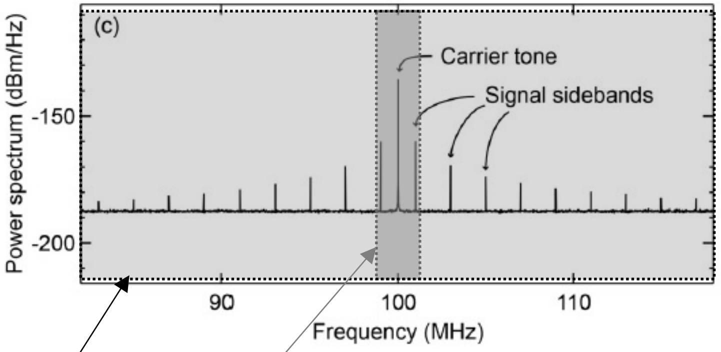
RF Amplifiers are important:

- Increase Signal-to-Noise Ratio
- Enhanced Measurement Speed
- Enable Specific Measurements (Single Shot…)

Fundamentals of High-Frequency Signal Detection



FFT



Voltage Spectral Density

Time-average of Filtered Signal Expectation Value

$$S_{VV}(f) = \lim_{B_f \to 0} \frac{\lceil \langle \mathbb{V}^2(t) \rangle \rceil}{B_f} = S^{\mathrm{S}}_{VV}(f) + S^{\mathrm{N}}_{VV}(f)$$

Filter Bandwidth around f

Signal

Noise

$$p_{\mathrm{N}}(f) \equiv \frac{S^{\mathrm{N}}_{VV}(f)}{Z_0}$$

Noise power

$$T_{\mathrm{N}}(f) \equiv \frac{p_{\mathrm{N}}(f)}{k_{\mathrm{B}}} = \frac{S^{\mathrm{N}}_{VV}(f)}{k_{\mathrm{B}} Z_0}$$

Noise temperature

$$N_{\mathrm{N}}(f) \equiv \frac{p_{\mathrm{N}}(f)}{hf} = \frac{k_{\mathrm{B}} T_{\mathrm{N}}}{hf}$$

Noise number

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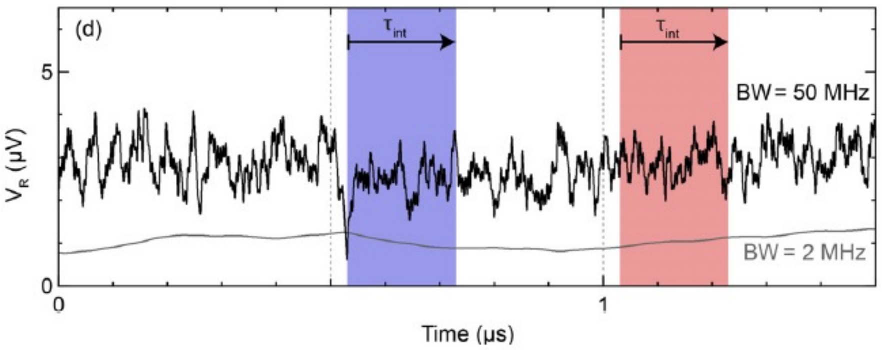
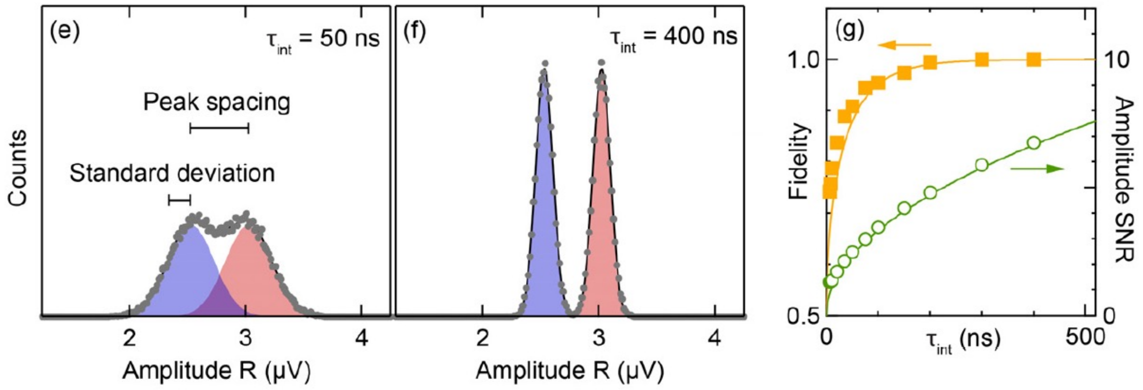
Fundamentals of High-Frequency Signal Detection

Demodulation & Low-Pass Filter



$$\frac{1}{t_{int}}\int_{t_0}^{t_1} V_R\,(t)$$



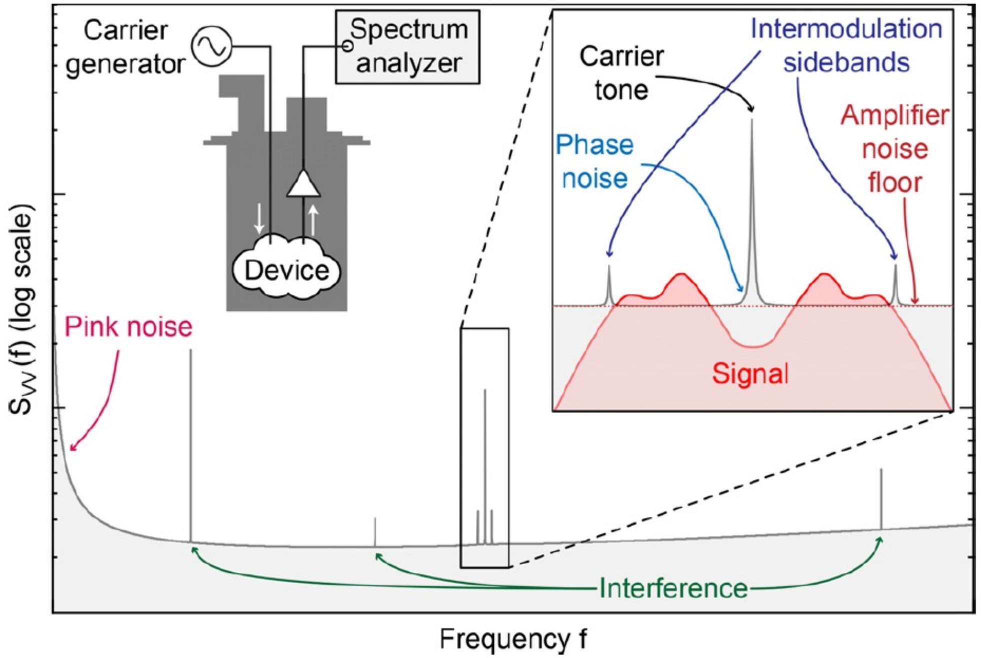
Components of the Voltage Spectral Density

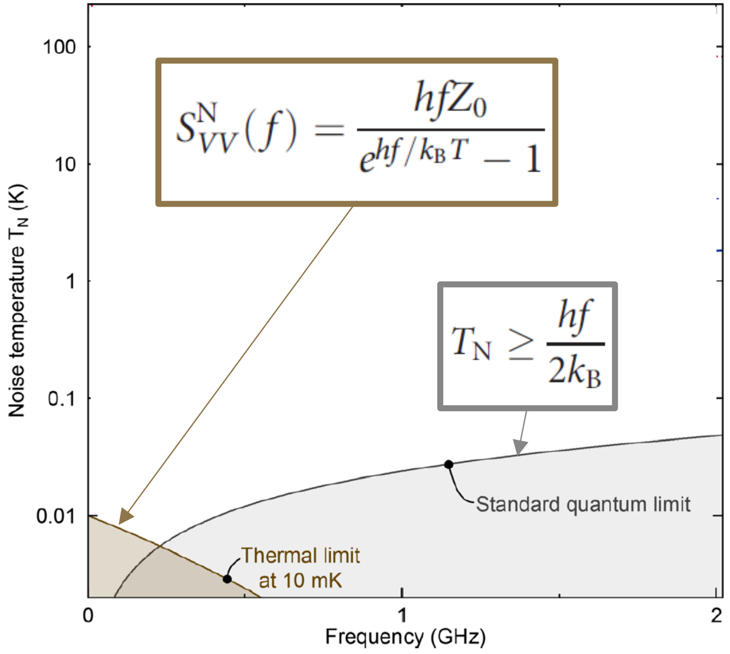
$$S_{VV}(f) = S^{S}_{VV}(f) + S^{N}_{VV}(f)$$

Pink Noise: $\boxed{S^{N}_{VV}(f) \propto 1/f}$

Amplifier Noise:

- Noise added by Amplifier
- Physical Temperature
- Fluctuation-Dissipation
- Technical Noise
- Relatively Smooth & Even





$$S^{N}_{VV}(f) = \frac{hfZ_0}{e^{hf/k_B T} - 1}$$

$$T_N \geq \frac{hf}{2k_B}$$

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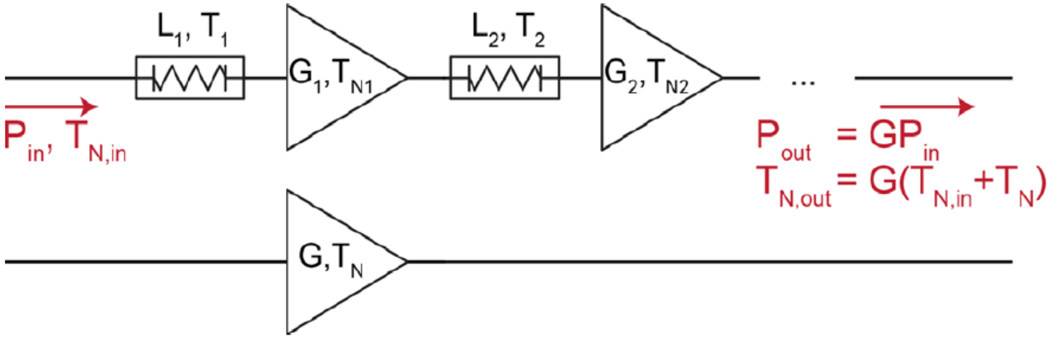
Amplifiers, Noise & Quantum Limits

Amplifier Chain:

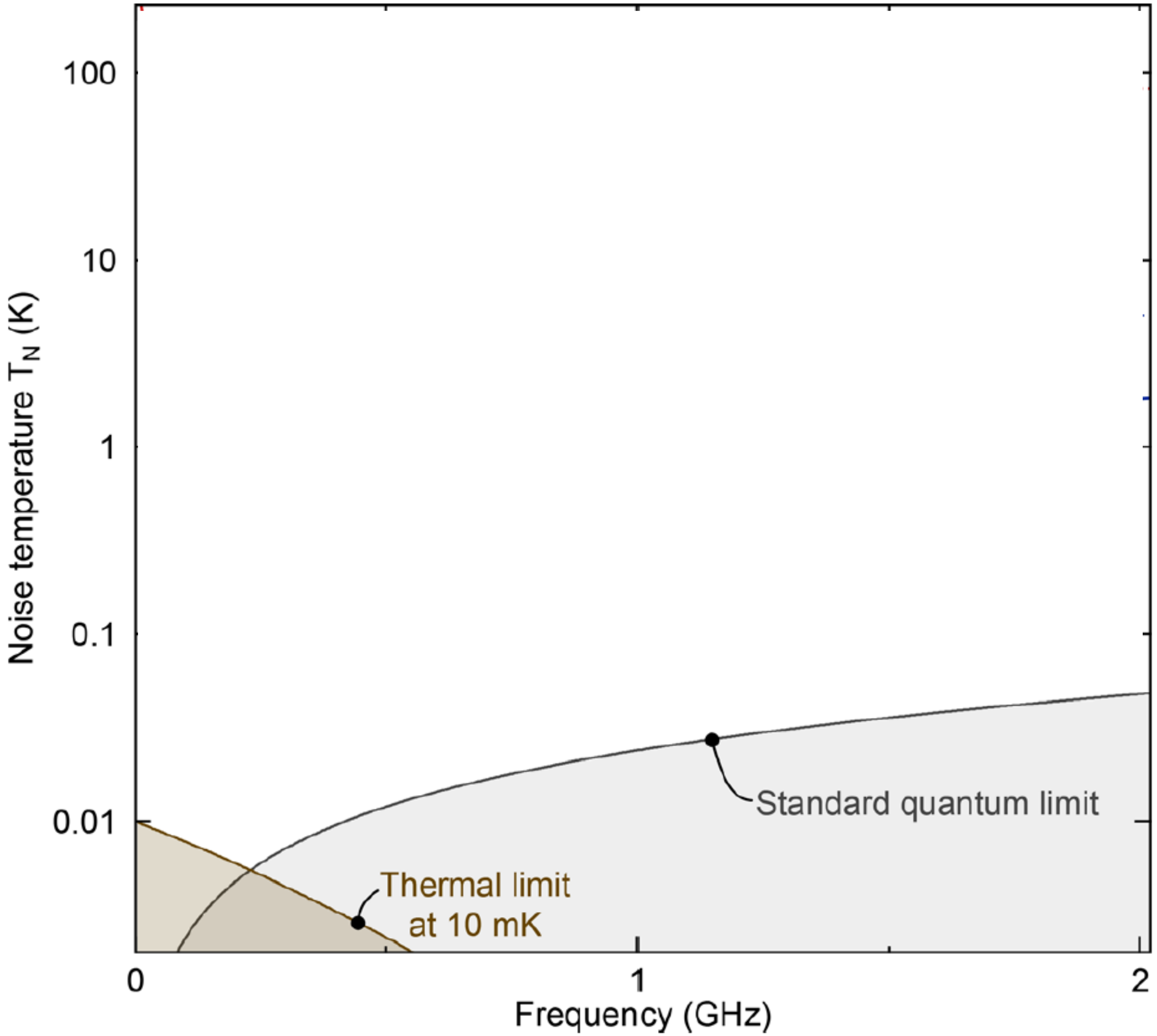


Cumulative Gain: $G = \frac{G_1 G_2 \dots}{L_1 L_2 \dots}$

$$T_\mathrm{N} = \boxed{L_1 T_{\mathrm{N}1}} + \frac{L_1 L_2}{\boxed{G_1}} T_{\mathrm{N}2} + \frac{L_1 L_2 L_3}{G_1 G_2} T_{\mathrm{N}3} + \cdots$$

First Amplifier in the Chain dominates T_N:

- Minimize T_{N1}
- Maximize G_1



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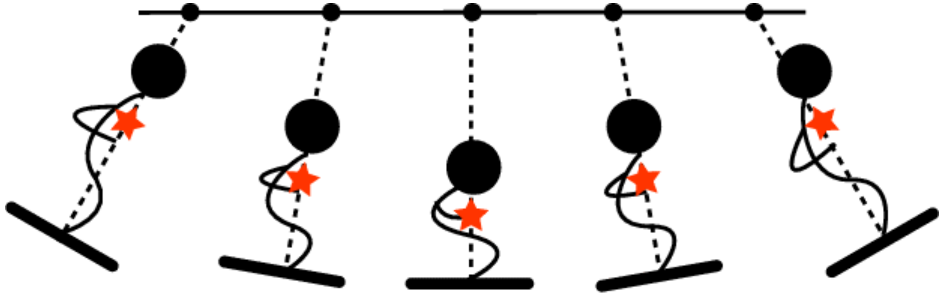
Parametric Amplifiers

New amplifier battles "noise"

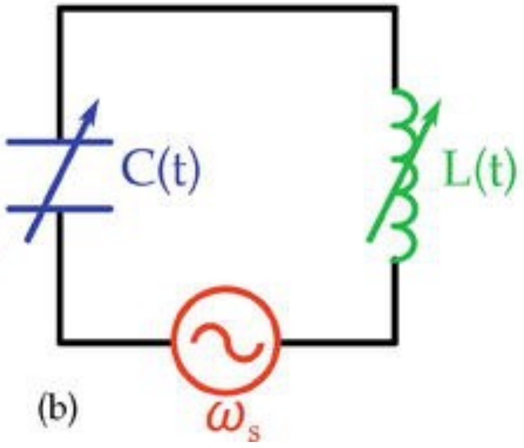
Four-stage junction diode amplifier was developed at Bell Telephone Laboratories by Rudolf Engelbrecht for military applications. Operates on the "varactor" principle, utilizing the variable capacitance of diodes. With 400-mc. signal, the gain is 10 db. over the 100-mc. band.

The tremendous possibilities of semiconductor science are again illustrated by a recent development from Bell Telephone Laboratories. The development began with research which Bell Laboratories scientists were conducting for the U. S. Army Signal Corps. The objective was to reduce the "noise" in UHF and microwave receivers and thus increase their ability to pick up weak signals.

Radio-Electronic Engineering **11,** (1958)



$$f_{swing}(t) = \frac{1}{2\pi}\sqrt{\frac{g}{L_{center\ of\ mass}(t)}}$$



$$f_{tank}(t) = \frac{1}{2\pi\sqrt{L(t)C(t)}}$$

Parametric Amplifiers

Superconducting PAs:
Josephson PA, Kinetic Inductance PA,
Travelling Wave PA …

Extremely low noise:
$T_N < 200\,mK$
Strong microwave squeezing
JPAs used for state-of the art spin RO

Disadvantages:
Highly susceptible to B-fields
Very low saturation/compression powers
Hard to operate below 1 GHz
Narrow bandwidths

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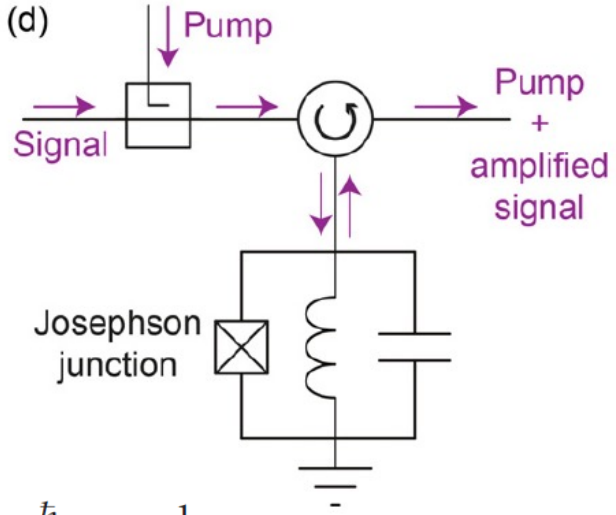
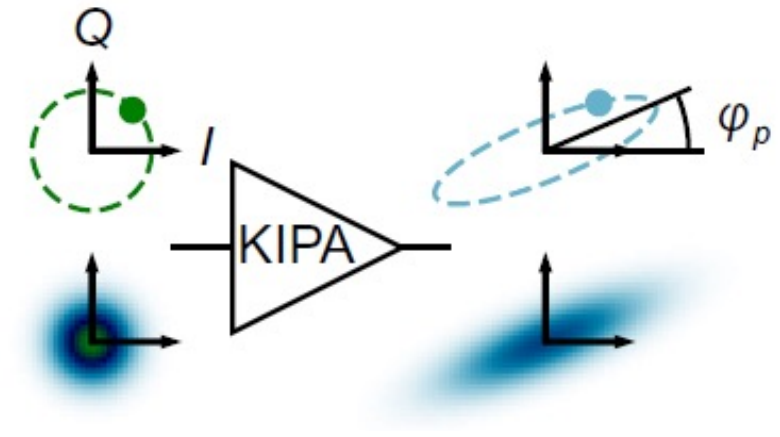
Superconducting Parametric Amplifiers:

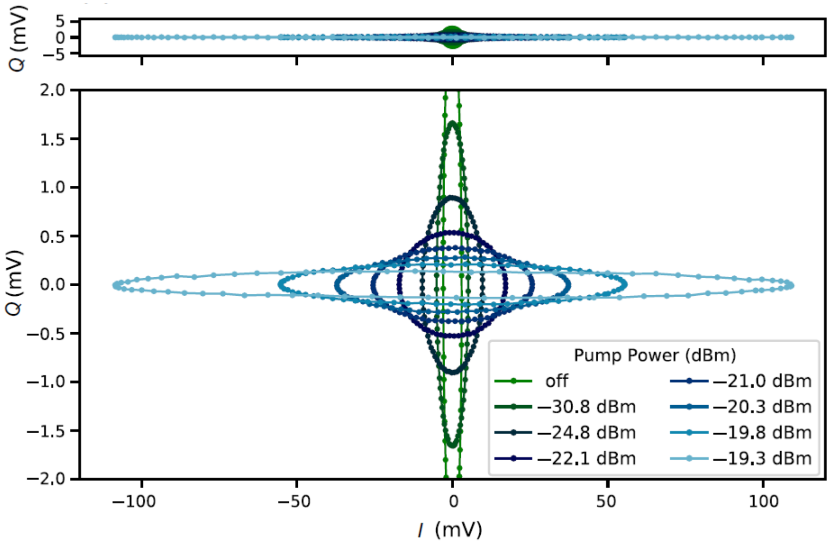


$$L_J(I) = \frac{\hbar}{2eI_0}\frac{1}{\sqrt{1 - I^2/I_0^2}}$$

Pump, Signal, Idler: Mixing & Squeezing

Kinetic Inductance PAs:

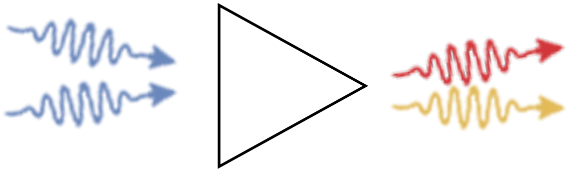




Four-Wave Mixing:

$$L_k(I) \approx L_0\left[1 + \left(\frac{I}{I_*}\right)^2\right]$$

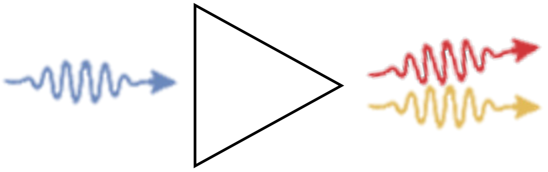
$$2\,\omega_{pump} = \omega_{signal} + \omega_{idler}$$

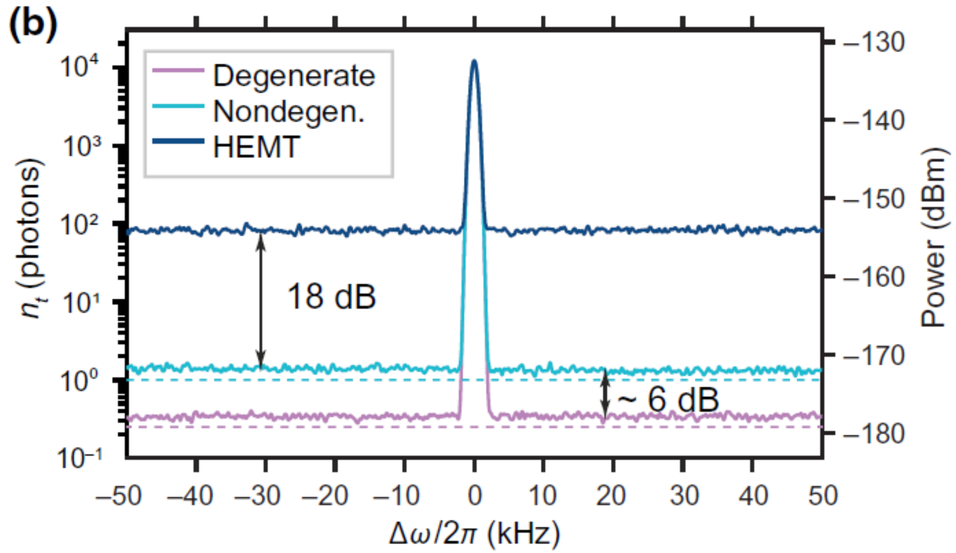


Three-Wave Mixing:

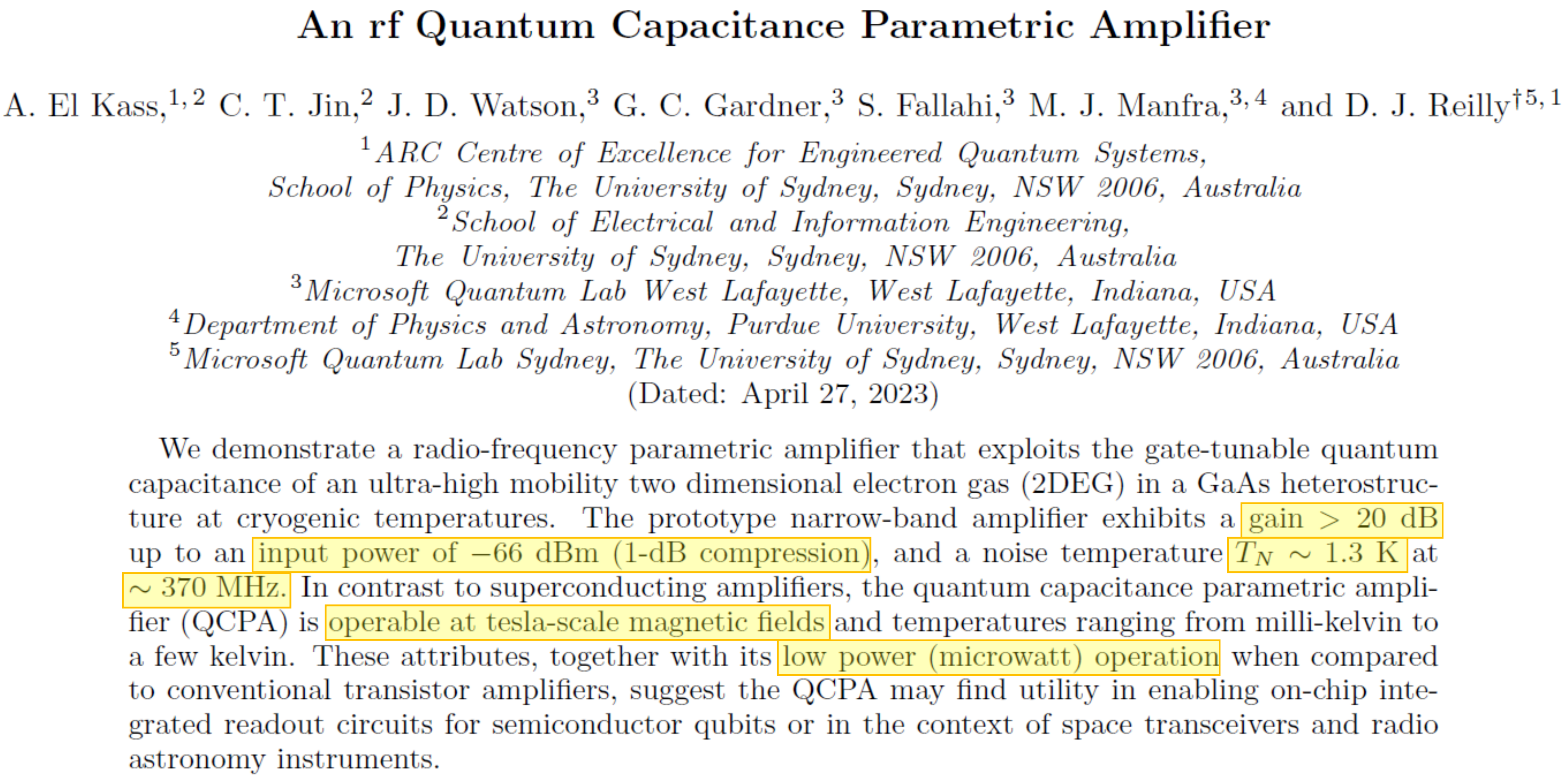
$$L_k(I) \approx L_0\left[1 + \left(\frac{I_{\rm dc}}{I_*}\right)^2 + 2\frac{I_{\rm dc}I_{\mu w}}{I_*^2} + \left(\frac{I_{\mu w}}{I_*}\right)^2\right]$$

$$\omega_{pump} = \omega_{signal} + \omega_{idler} = 2\,\omega_{signal}$$





D. J. Parker et al. Phys. Rev. Appl. **17** 034064 (2022)



An rf Quantum Capacitance Parametric Amplifier

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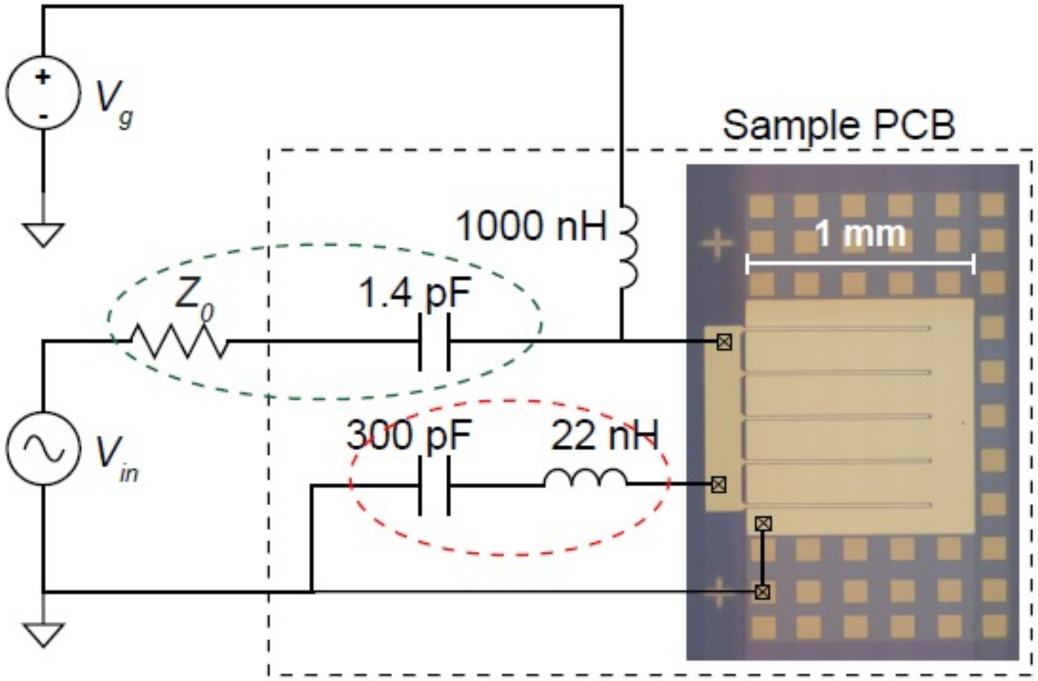
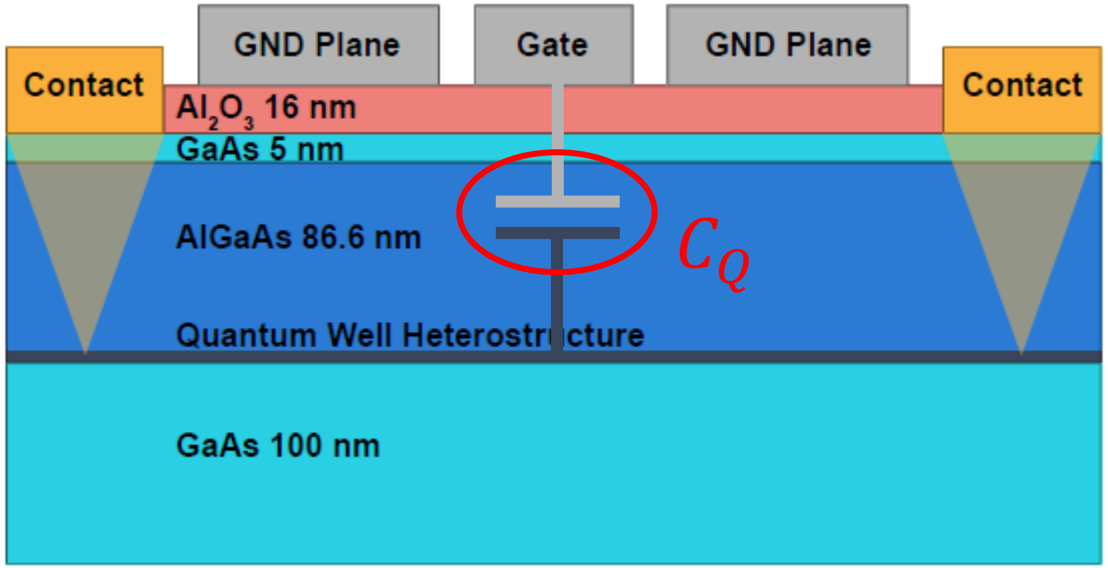
[4]*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana, USA*
[5]*Microsoft Quantum Lab Sydney, The University of Sydney, Sydney, NSW 2006, Australia*

(Dated: April 27, 2023)

We demonstrate a radio-frequency parametric amplifier that exploits the gate-tunable quantum capacitance of an ultra-high mobility two dimensional electron gas (2DEG) in a GaAs heterostructure at cryogenic temperatures. The prototype narrow-band amplifier exhibits a gain > 20 dB up to an input power of -66 dBm (1-dB compression), and a noise temperature $T_N \sim 1.3$ K at ~ 370 MHz. In contrast to superconducting amplifiers, the quantum capacitance parametric amplifier (QCPA) is operable at tesla-scale magnetic fields and temperatures ranging from milli-kelvin to a few kelvin. These attributes, together with its low power (microwatt) operation when compared to conventional transistor amplifiers, suggest the QCPA may find utility in enabling on-chip integrated readout circuits for semiconductor qubits or in the context of space transceivers and radio astronomy instruments.

The Quantum Capacitance Parametric Amplifier





Amplifier circuit:

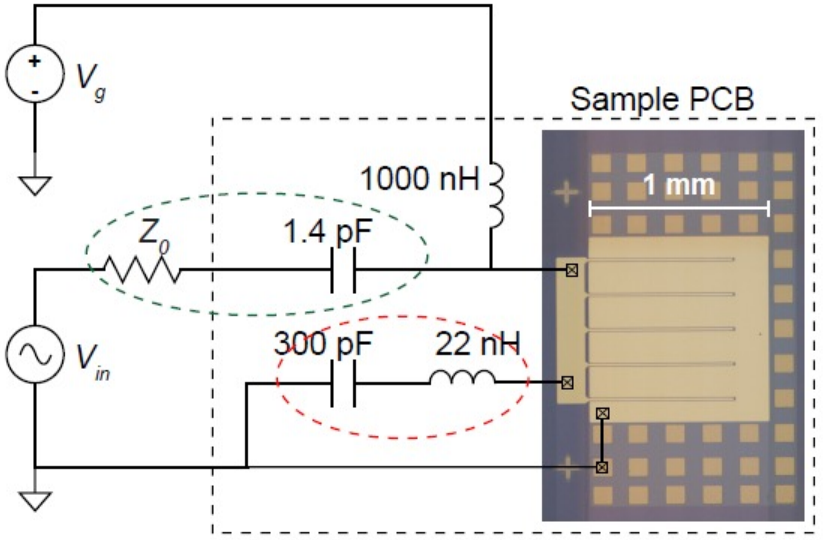
- Tunable quantum capacitance C_Q between 2DEG & Finger-gates
- Surface-mount Inductor in parallel forms LC
- Bias T for DC tuning of 2DEG
- Air-core copper spring SMD inductor

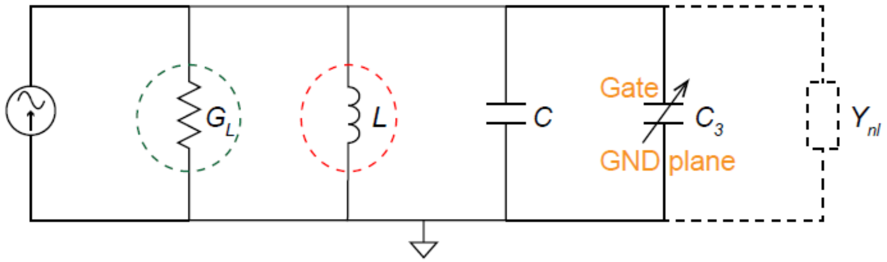
GaAs/AlGaAs 2DEG:

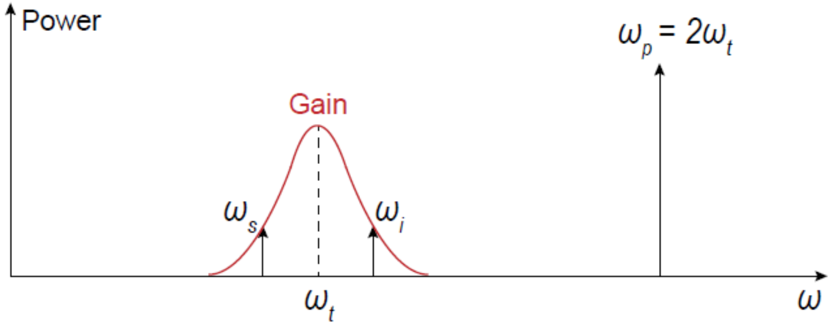
- Density: $1.8\times10^{11} cm^2$
- Mobility: $4.4\times10^{6} cm^2 V^{-1} s^{-1}$
- Depth: $91\ nm$

- “many” Au ohmics $\rightarrow R_{dc,single} \approx 100\ \Omega$
- Top Gates: NbTiN, $200\ nm$

The Quantum Capacitance Parametric Amplifier







Equivalent circuit:

- Parasitic, not-tunable C
- Loaded losses in the circuit G_L
- Loaded Quality Factor Q_t
- Detuning of source signal with respect to tank resonance $x = 2Q_t\, {}^{\omega_{source}}/_{\omega_{tank}}$

- Pumping results in **effective negative conductance** at the tank frequency G_{nl}

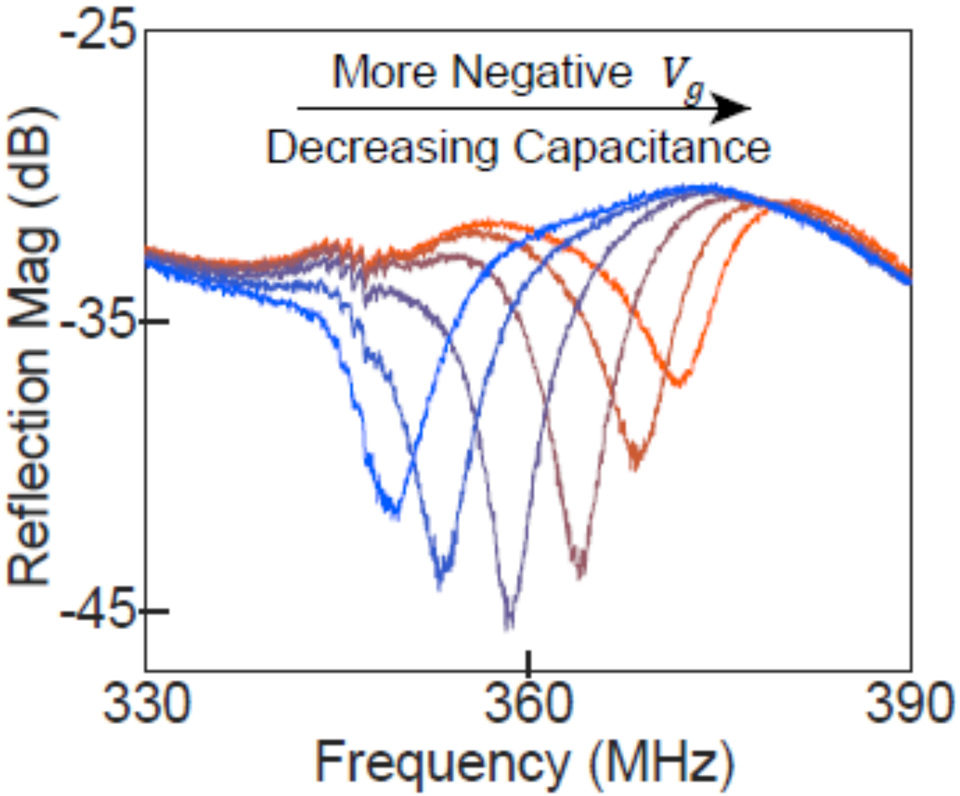
- Gain of amplifier:

$$G_p = \frac{G_{nl}^2 + x^2\left[G_{nl} + G_L(1+x^2)\right]^2}{\left[-G_{nl} + G_L(1+x^2)\right]^2 + x^2\left[G_{nl} + G_L(1+x^2)\right]^2}$$

- Gain-Bandwidth relationship linear (non-degenerate case):

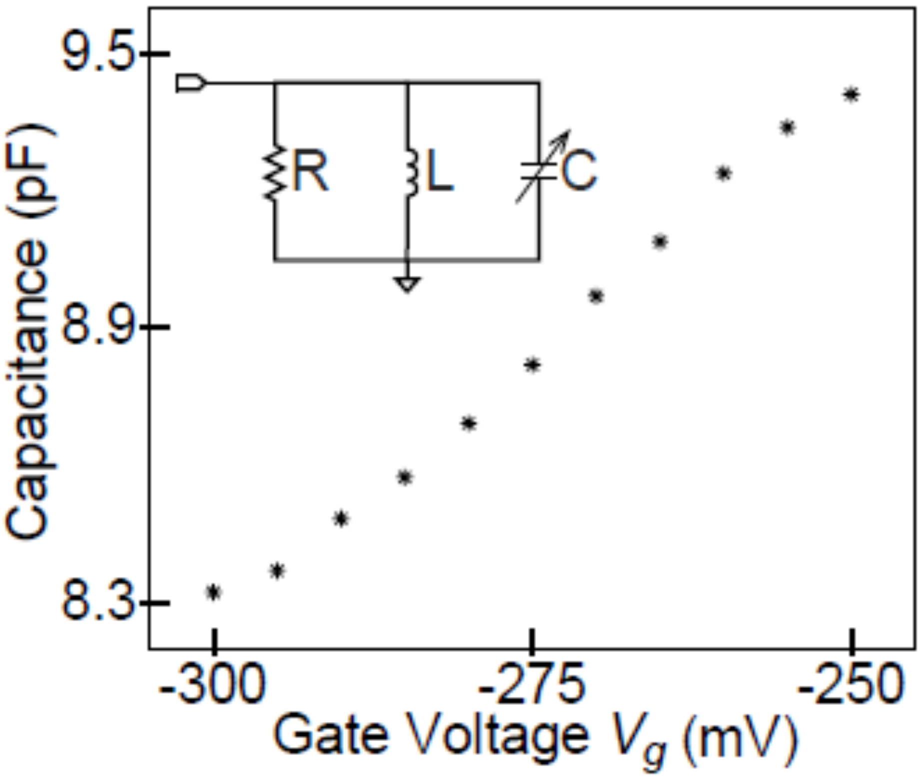
$$\sqrt{G} \times BW = \frac{f_t}{2Q_t}$$

DC Tunability of C_Q



Tank resonance frequency:

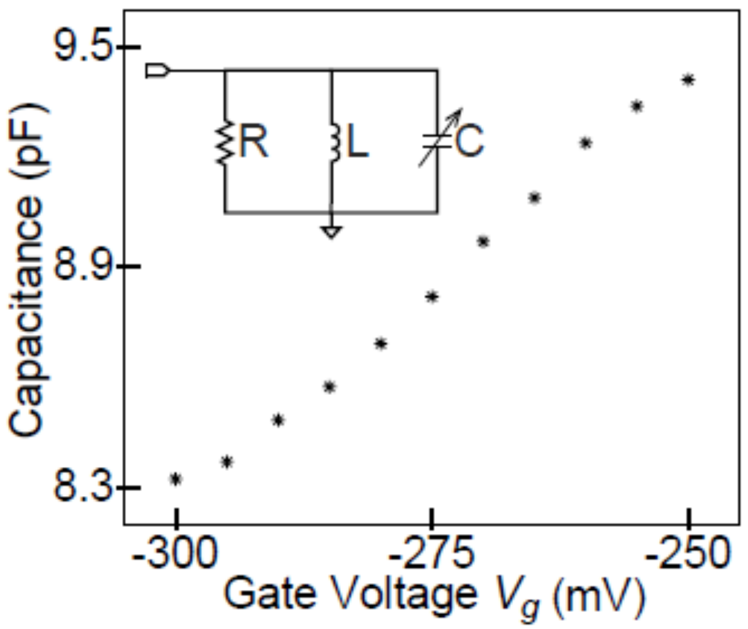
$$f_t = \frac{1}{2\pi\sqrt{LC}}$$

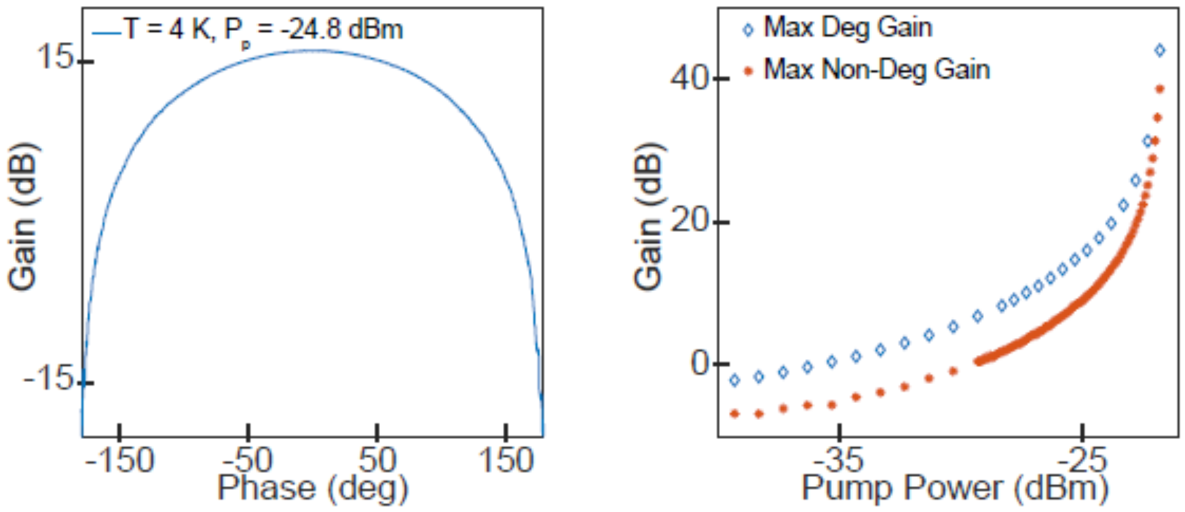


Very strong capacitance tunability (but only over 50mV):

$$\frac{dC}{dV} = 26.7\ {}^{pF}/_{V}$$

Measurement Setup, Gain & Compression point





Model yields:

$$Q_t = 14.3$$

$$C_{tunable} = 0.51 - 0.57\,pF$$

Note:

$$-25.3\,dBm \sim 34\,mV$$

Noise

Setup:

- Cryogenic Noise Source (Bluefors)
- Cryogenic RF switch:
  - QCPA
  - Open circuit

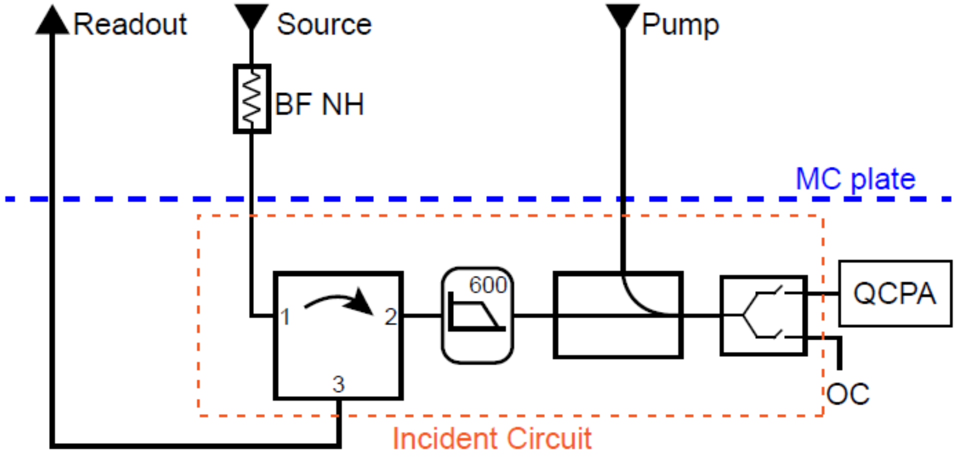
Y-factor method

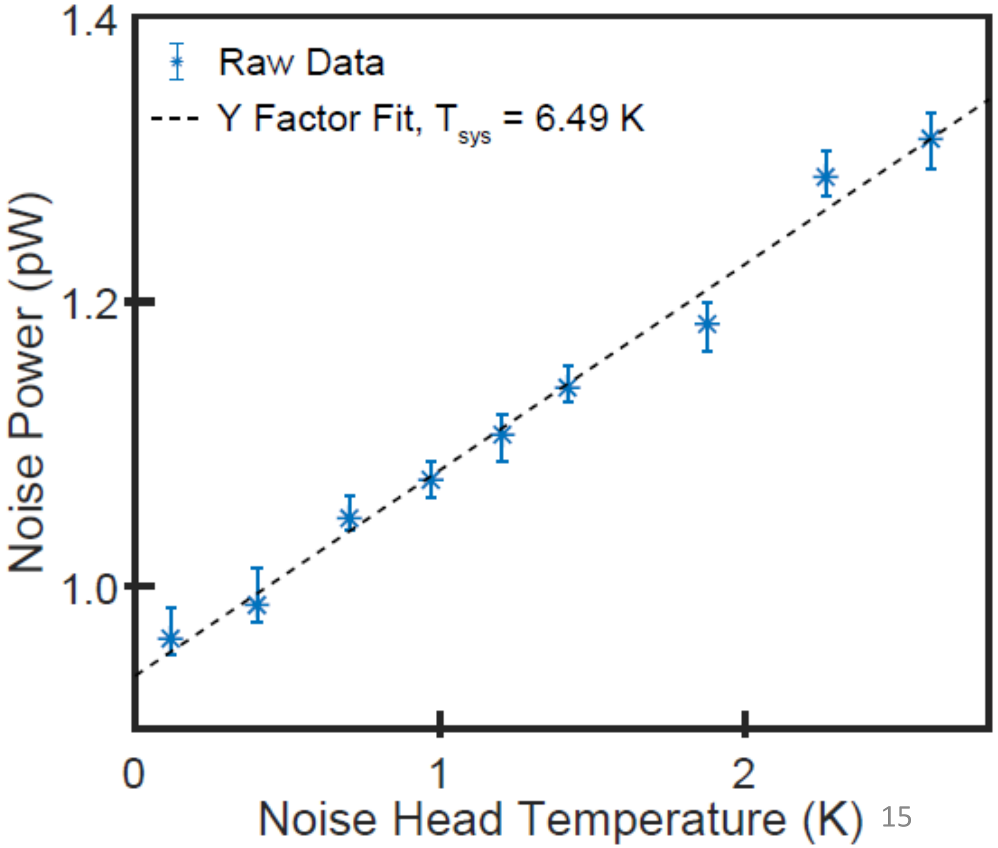
- Vary noise source temperature
- Integrate at amplifier output
- Total Noise of the system: $T_{sys} = 6.49\ K$
- With switch at OC: $T_{sys} = 20\ mK$
- -> $T_{sys} = 6.49\ K\ = T_{sys,idler} + T_{sys,source}$
- -> $T_{sys,source} = 3.25^{+0.53}_{-0.32}\ K$

System losses increase effective noise temperature:

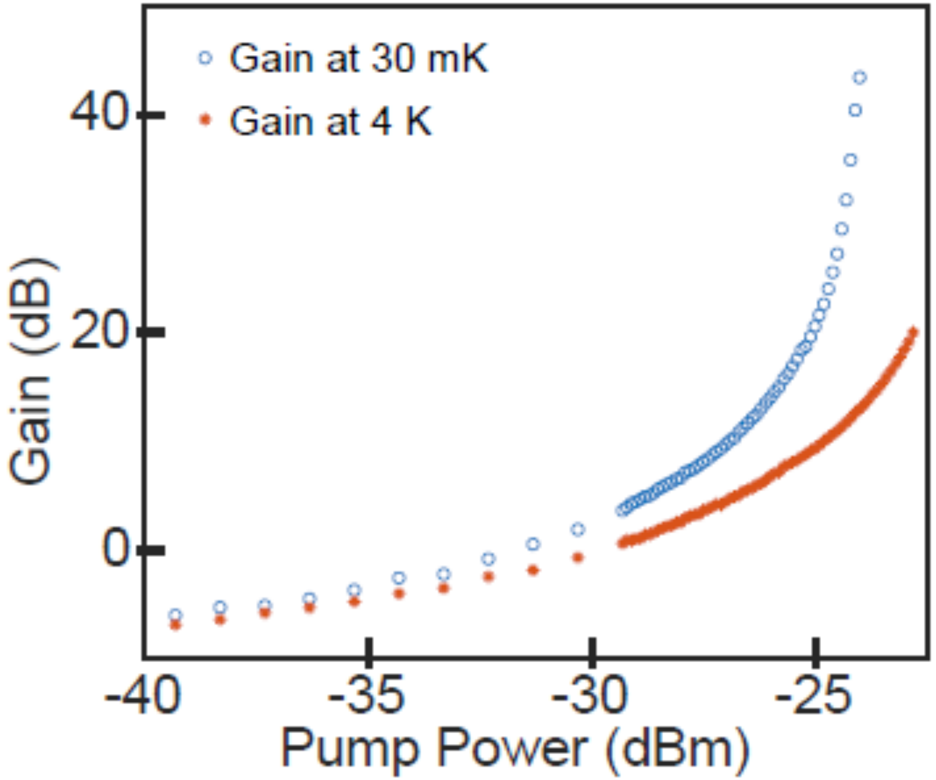
- Ferrite core of circulator $\sim 4.01\ dB$
- $T_{QCPA} = 1.29^{+0.21}_{-0.13}\ K$

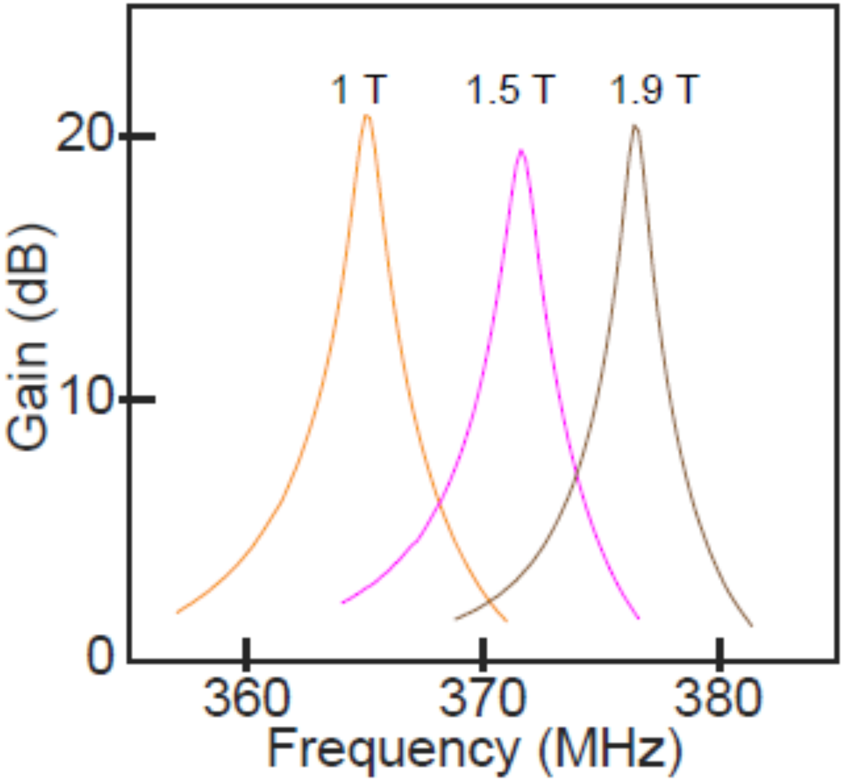
Heating the fridge: T_{QCPA} largely limited by physical temperature of the amplifier!





Temperature and Magnetic Field





Reduced gain at 4 K:

- Decreased transconductance
- Population of higher subbands

Shift in B (in-plane):

- Small decrease in C_Q
- Related to shift in 2d DOS
- Not clear what out-of-plane would do

Discussion & Conclusions

Lowering noise temperature:

- Reducing pump amplitude to decrease self-heating
- Increasing gate lever-arm, shallower 2DEQ
- Reducing losses:
  - Ohmic contacts
  - InAs for better Ohmics
  - Superconducing contacts

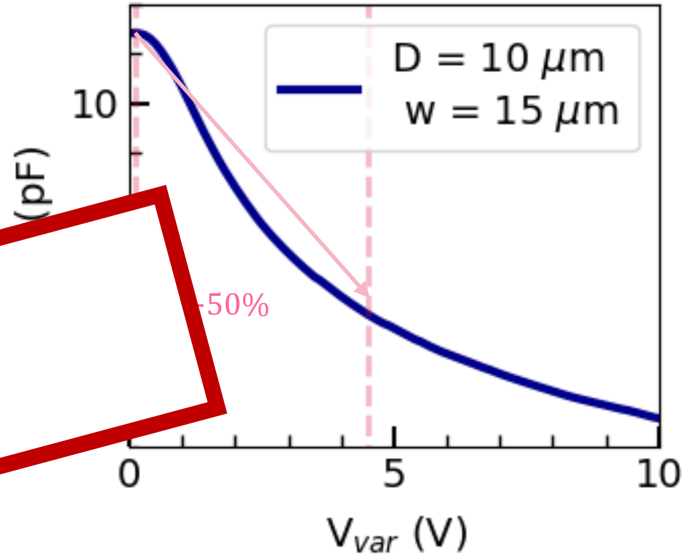
How useful is this device?

- Few 100 nW power dissipation
- mm size, but can be reduced further
- On-chip integration of 100s
- Travelling wave device: matched CPW for wideband operation

Implementation with other devices with large C_Q:

- VdW heterostructures
- Qubit readout circuits

Quamplify: The STO-PA



Thanks for your attention!