Quantum noise limited microwave amplification using a graphene Josephson junction

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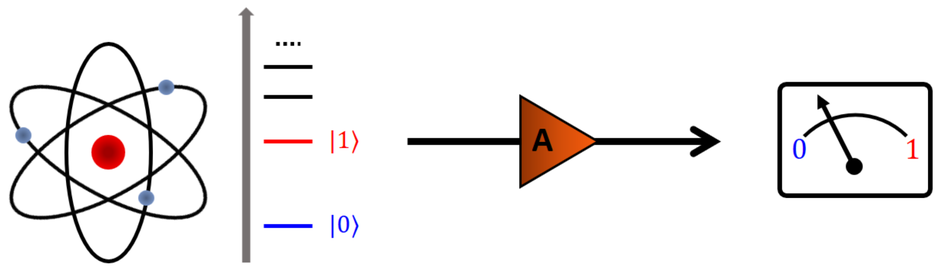
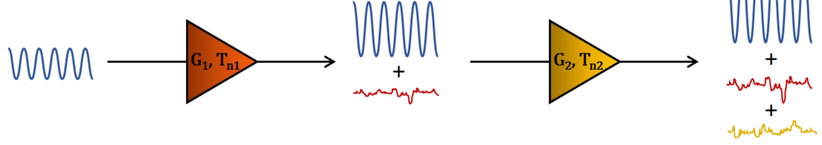
Quantum information processing: low-noise amplification

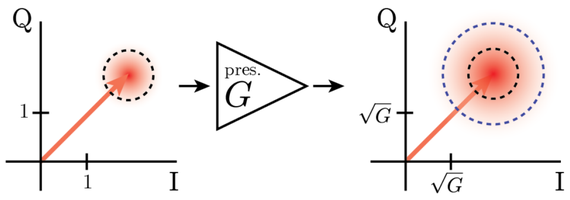


P ≈ -130 dBm ≈ 10^{-16} W
T ≈ 10 mK

P ≈ 10^{-3} W
T ≈ 300 K

Every amplification costs an added noise :(





- S.C. Macklin Ph.D. thesis, UC Berkeley (2015)

$$E(t) \propto \left(a_{\text{in}} e^{-i\omega t} + a_{\text{in}}^{*} e^{i\omega t}\right)$$

$$\frac{(\Delta \hat{a}_{\text{out}})^2}{G} \geq (\Delta \hat{a}_{\text{in}})^2 + \frac{1}{2}$$

Quantum uncertainty

$$T_{\text{eff}} = \frac{\hbar\omega}{2k_B}$$

SQL

A recap on parametric resonance and amplification

Driven damped harmonic oscillator:

$$\ddot{x} + b\omega_0\dot{x} + \omega_0^2 x = F\sin\omega_0 t$$

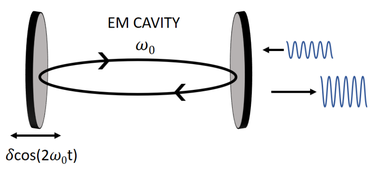
$$x_{sol} = \frac{F}{\omega_0^2 b}\sin(\omega_0 t + \phi)$$

Parametrically driven damped harmonic oscillator:

$$\ddot{x} + b\omega_0\dot{x} + \omega_0^2(1 + \delta\cos 2\omega_0 t)x = F\sin\omega_0 t$$

$$x_{sol} = \frac{F}{\omega_0^2(b - \frac{\delta}{2})}\sin(\omega_0 t + \phi)$$

reduction in damping



Non-linear driven damped oscillator:

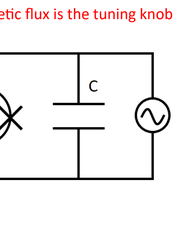
$$\ddot{x} + 2\Gamma\dot{x} + \omega_0^2(x - \alpha x^3) = F_p\cos\omega_p t$$

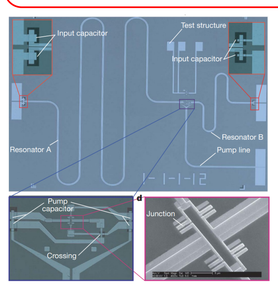
$$x_{sol}(t) = x_p\cos(\omega_p t + \phi)$$

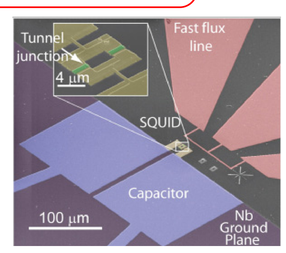
$$\ddot{x} + 2\Gamma\dot{x} + \omega_0^2(x - \alpha x^3) = F_p\cos\omega_p t + F_s\cos\omega_s t$$

$$x_{sol}(t) = x_p\cos(\omega_p t + \phi) + y(t) \qquad F_s \ll F_p,\ |y(t)| \ll x_p$$

$$\ddot{y} + 2\Gamma\dot{y} + \omega_{0,eff}^2(1 + k\cos 2\omega_p t)y = F_s\cos\omega_s t$$

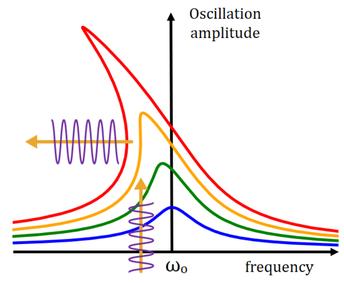






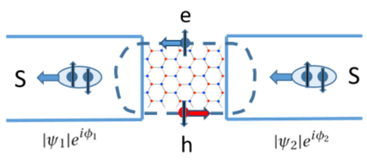
Hatridge et al., Phys. Rev. B 83, 134501 (2011)

- Magnetic flux is the tuning knob



Bergeal et al., Nature 465, 64–68 (2010)

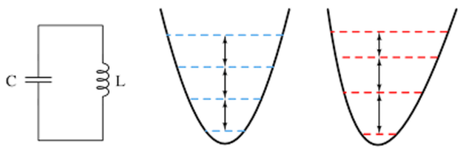
Graphene JJs: a platform of electrostatic control



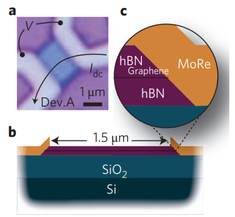
SNS JJ Current Phase Relation

$$I_s(\phi) = \frac{\pi\Delta_o}{2eR_n}\frac{\sin\phi}{\sqrt{1 - \tau\sin^2(\phi/2)}}$$

$$L_J(\phi) = \frac{\hbar}{2e}\left(\frac{\partial I_s}{\partial\phi}\right)^{-1}$$

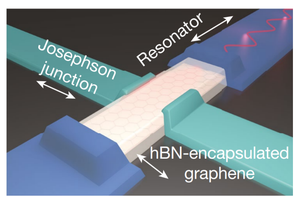


Gr-JJ



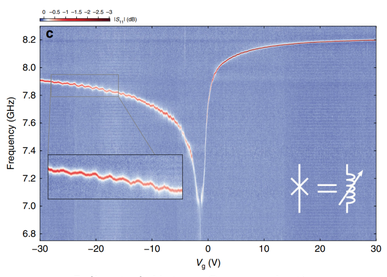
Calado et al. Nature Nanotechnology 10, 761–764 (2015)

Gr-JJ bolometers



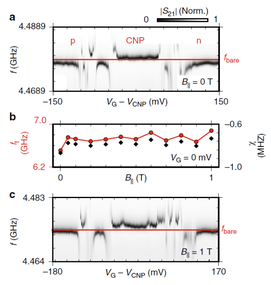
Lee et al., Nature 586, 42–46 (2020)
Kokkoniemi et al., Nature 586, 47–51 (2020)
Walsh et al., Science 372, 409–412 (2021)

Gr-JJ microwave resonator



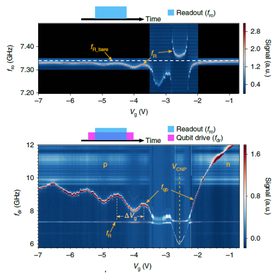
Felix et al. Nature Communications 9, 4069 (2018)

Field resilient Gr-JJ microwave resonator



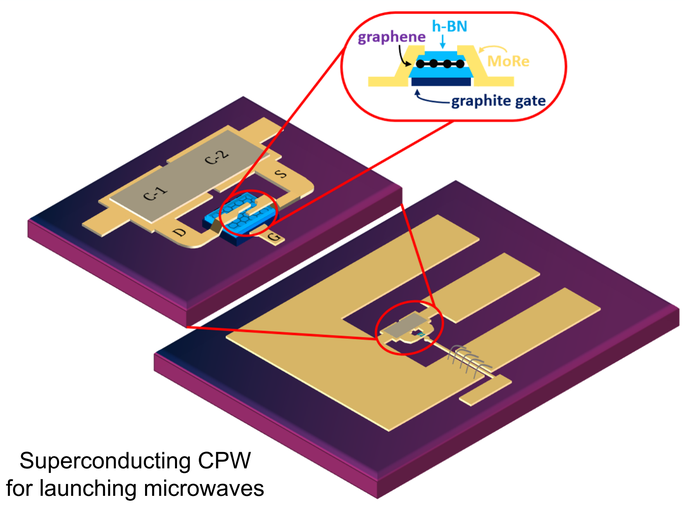
Kroll et al. Nature Communications 9, 4615 (2018)

Gr-transmon qubit

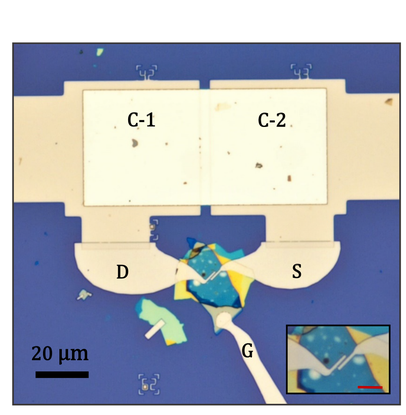


Wang et al. Nature Nanotechnology 14, 120-125 (2019)

Our implementation of the graphene based JPA

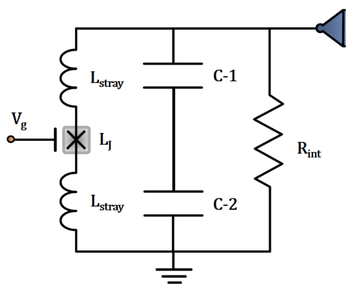


Superconducting CPW for launching microwaves

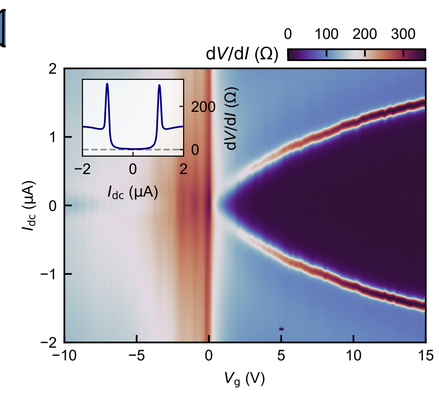


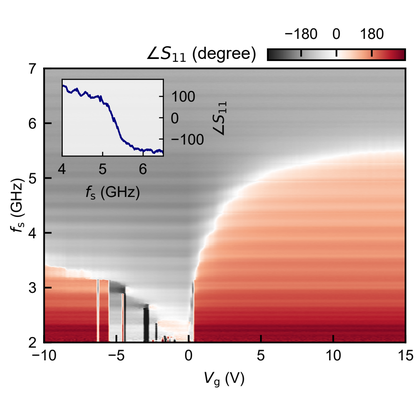
Lumped element LC resonator using Gr-JJ

Electrical characterization of the graphene JPA resonator



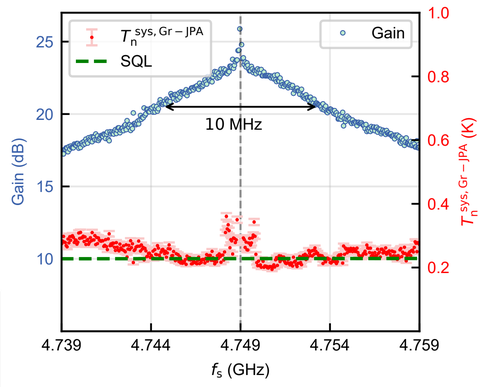
Tunable inductor, tuning via electrostatic gating

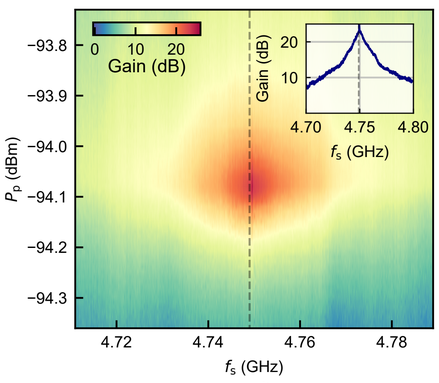


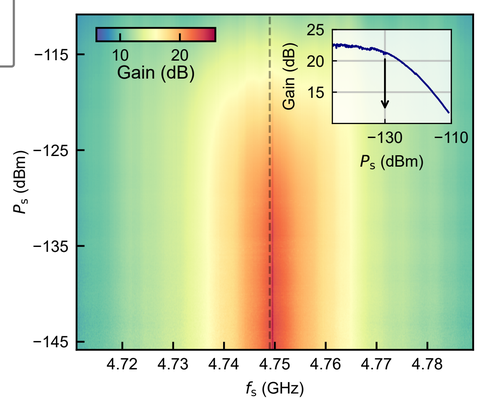


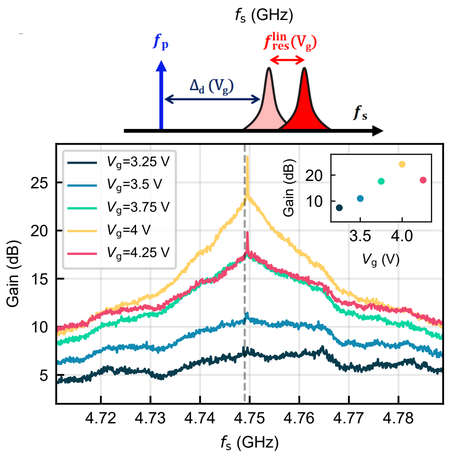
Quantum noise limited amplification from the graphene JPA

- 24 dB max gain
- 10 MHz BW
- 1-dB compression point ≈ - 130 dBm

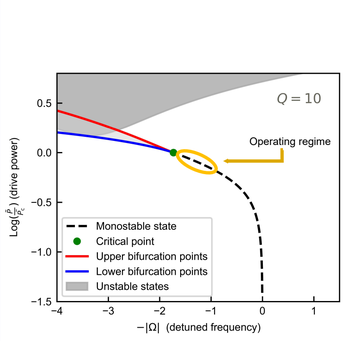




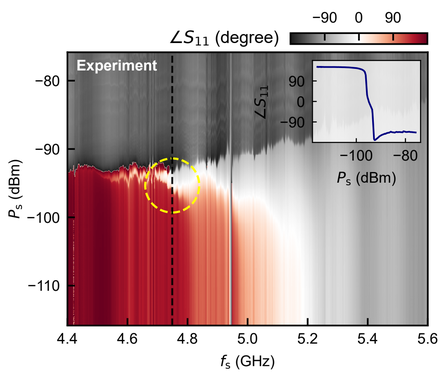


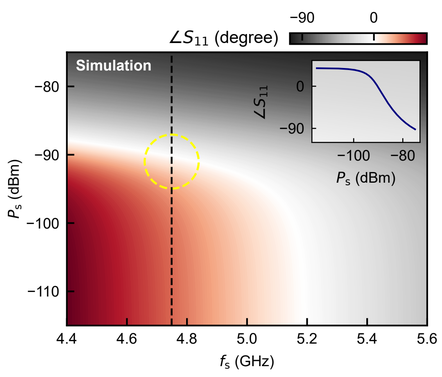


Non-linear action of the JPA resonator



Non-linear inductor, linear resonance is shifting with drive





Summary

- Graphene based quantum limited JPA, tunable via electrostatic gating.
- Furute explorations for highly sensitive quantum sensors for photons and magnons.
- Extending the pathway for searching 2D vdW material based quantum devices.
- For more details, kindly refer to our manuscript Sarkar et al., Arxiv: 2204.02103.