Optimizing the Josephson Parametric Amplifier

for Fast High-Fidelity Microwave Frequency Qubit Readout

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Introduction

Low noise microwave frequency amplifiers in demand:

- High fidelity readout for superconducting quantum bits
- Quantum optics at microwave frequencies
- Astrophysics: Axion detection

Motivation: Successful demonstration of high fidelity qubit readout and observation of quantum jumps using a Josephson parametric amplifier

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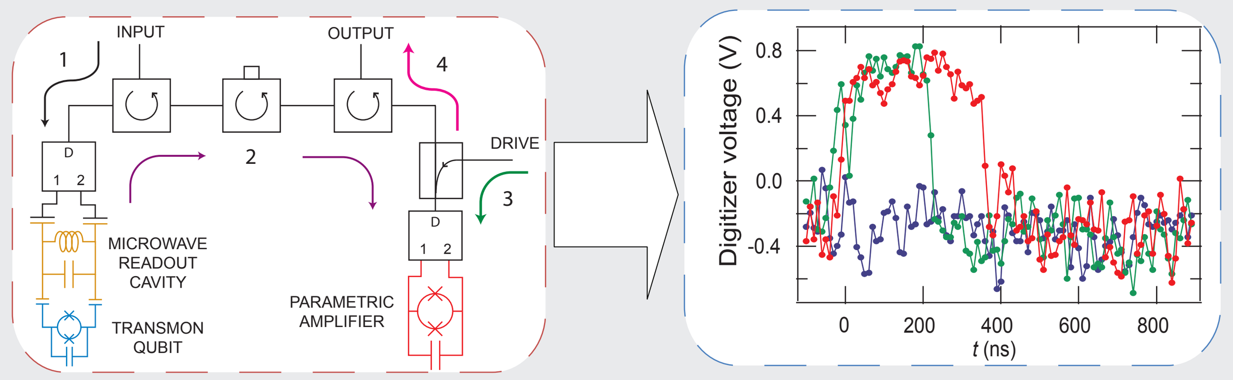
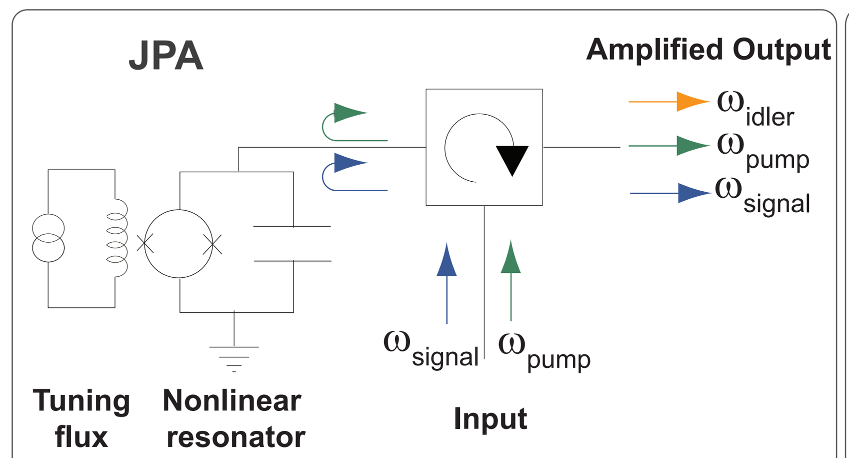
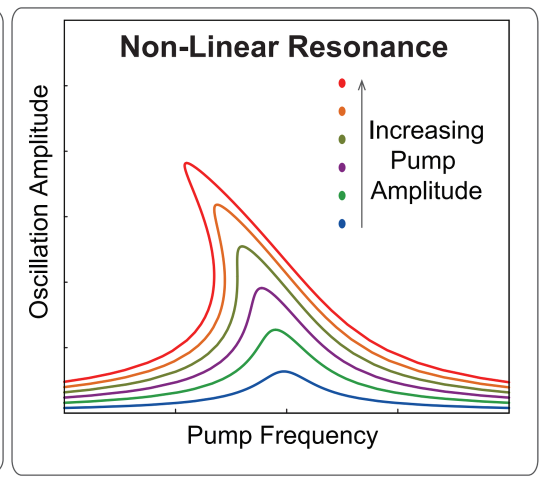


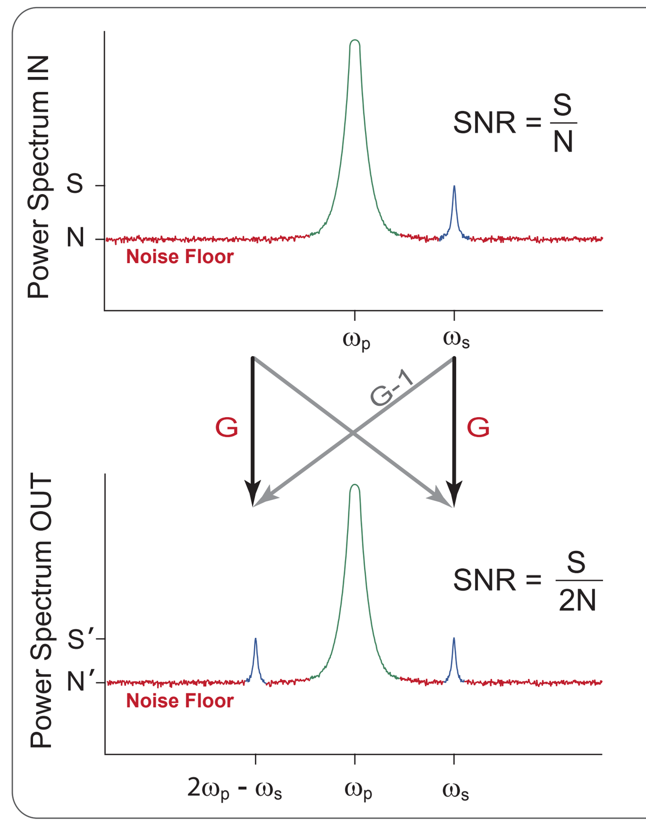
Limitations: Amplifier saturation and narrow bandwidth

Goal: Explore device parameters to optimize parametric amplifier performance for bandwidth and dynamic range while maintaining high gain and low noise.

Josephson Parametric Amplifier





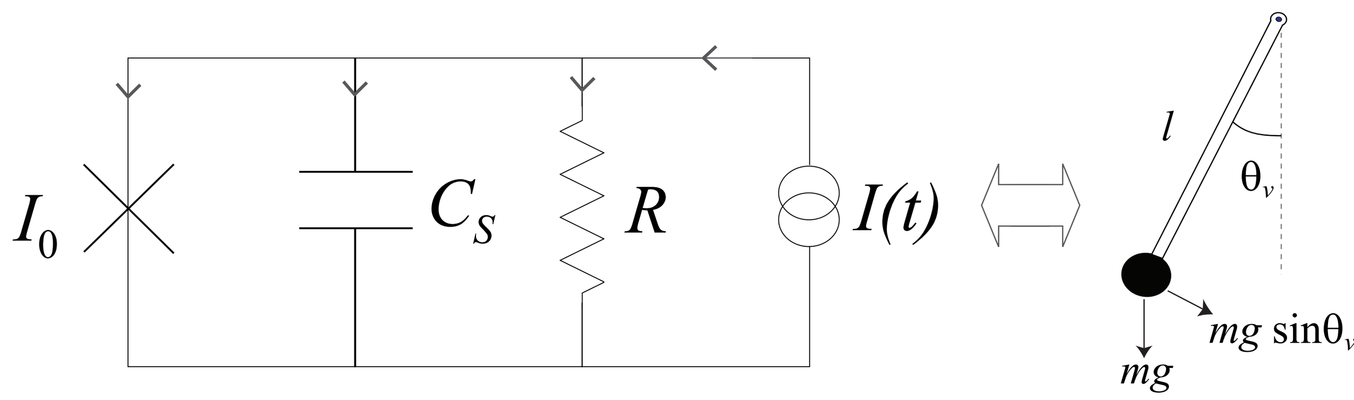


How it works?

- Strong pump (ω_{pump}) biases nonlinear oscillator
- Weak input signal (ω_{signal}) combined with pump
- Input signal amplified with power gain G
- Idler signal generated with power gain G-1
- Noise from idler band mixed into signal band
- Ideal paramp degrades SNR by 2
- Quantum limit achieved when $k_B T \ll \hbar\omega_{signal}$

Simulation Model

Numerically solve the differential equation for a driven, damped, nonlinear Josephson oscillator.



Differential equation

$$I_{C} + I_{R} + I_{J} = I_{source}$$

$$C_S\varphi_0\frac{d^2\delta(t)}{dt^2} + \frac{\varphi_0}{R}\frac{d\delta(t)}{dt} + I_0\sin(\delta(t)) = I(t)$$

Inertia Term — Damping Term — Restoring Force — Driving Term

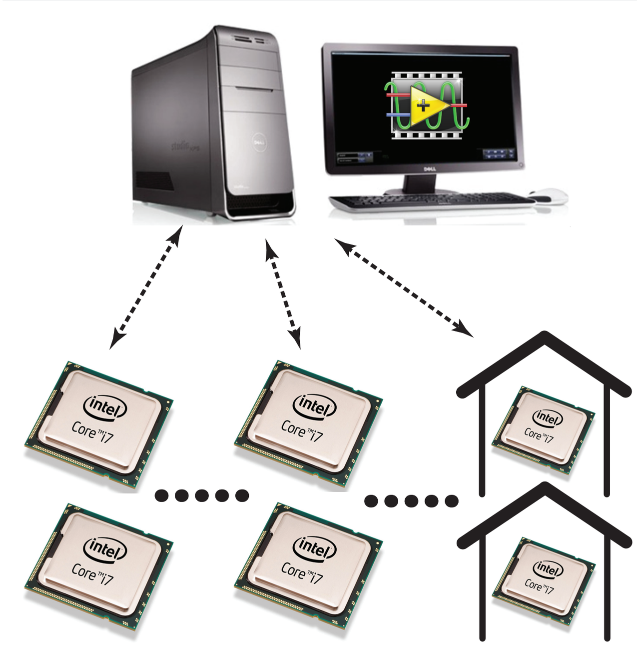
$I(t) = I_{pump}\cos(\omega_{pump}t) + I_{noise}(t)$ — Harmonic drive + noise

$\omega_{res} = \sqrt{\frac{I_0}{C_S\varphi_0}}$ — Linear resonant frequency

$Q = RC_S\omega_{res}$ — Quality factor

$\Omega = 2Q\frac{\omega_{res} - \omega_{pump}}{\omega_{res}}$ — Reduced drive detuning

Simulation architecture

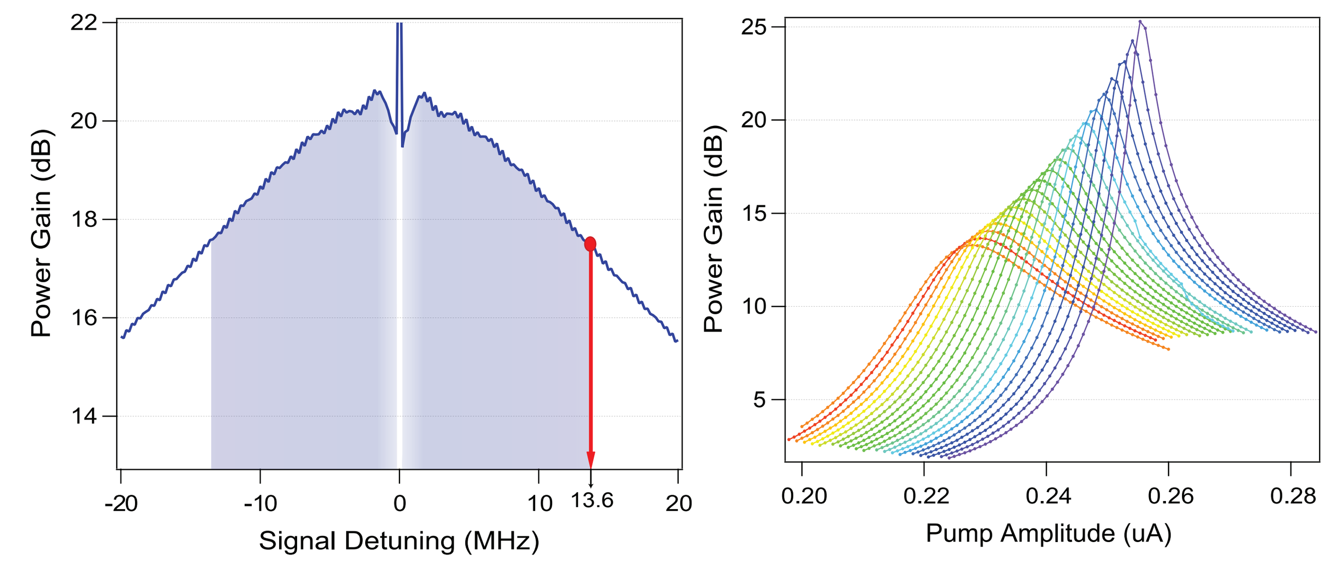


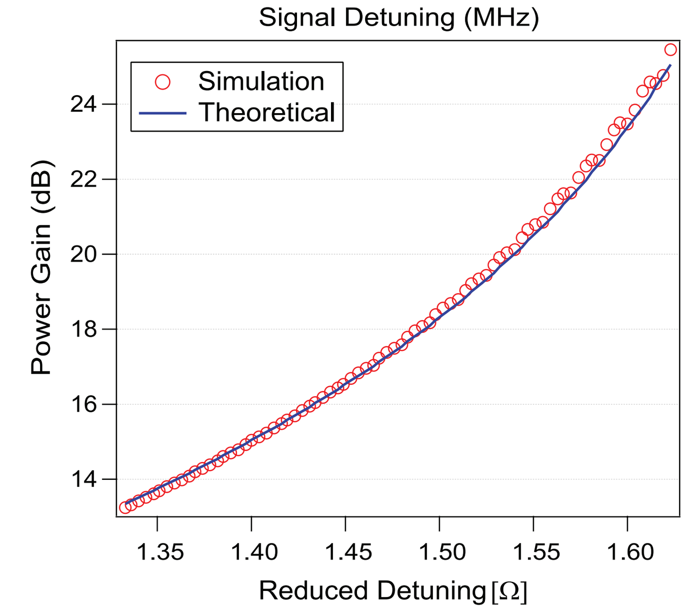
Numerical technique

- 4th order Runge-Kutta algorithm
- Finite temperature effects included using gaussian noise
- Solver written in C++ and compiled as DLL
- Labview front end for user friendly interface
- Labview program controls solver across multiple cores on multiple computers
- Ability to extend to any number of computers over a network

Numerical Simulation Results

Noise-free simulation & theory





Simulation parameters

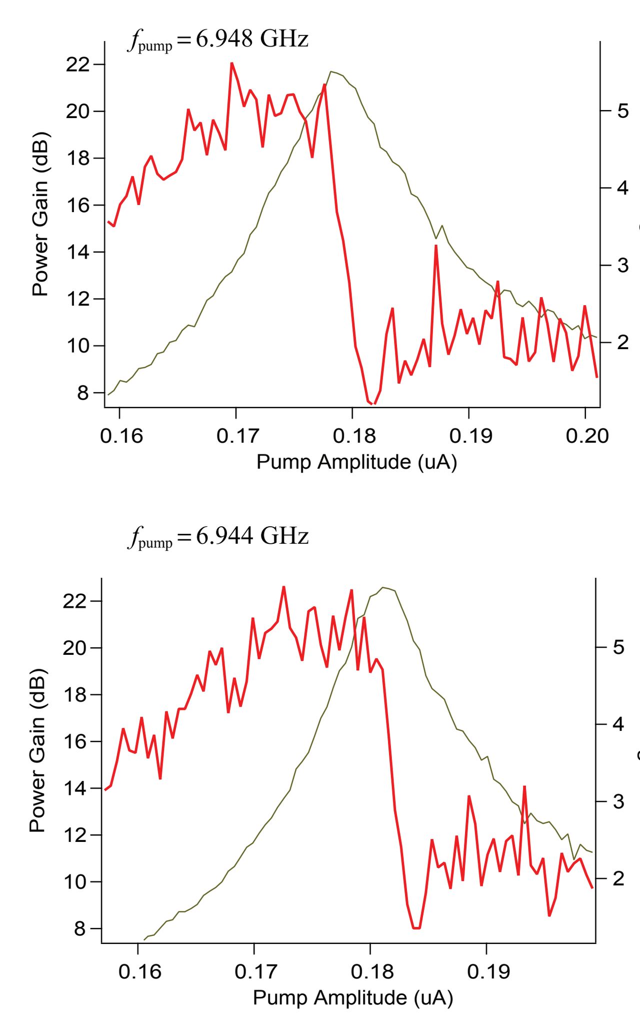
$I_0 = 4\,\mu A$ $C_s = 6\,pF$ $R = 50\,\Omega$
$f_{pump} = 6.750\,GHz$ $f_{signal} = 6.751\,GHz$

Universal gain curve

$$G_{max} = 1 + \frac{1}{3 + 7\Omega^2 - 4\sqrt{3}\,\Omega\sqrt{1+\Omega^2}}$$

Simulation agrees with ideal noise-free analytical theory

Noise performance



Simulation parameters

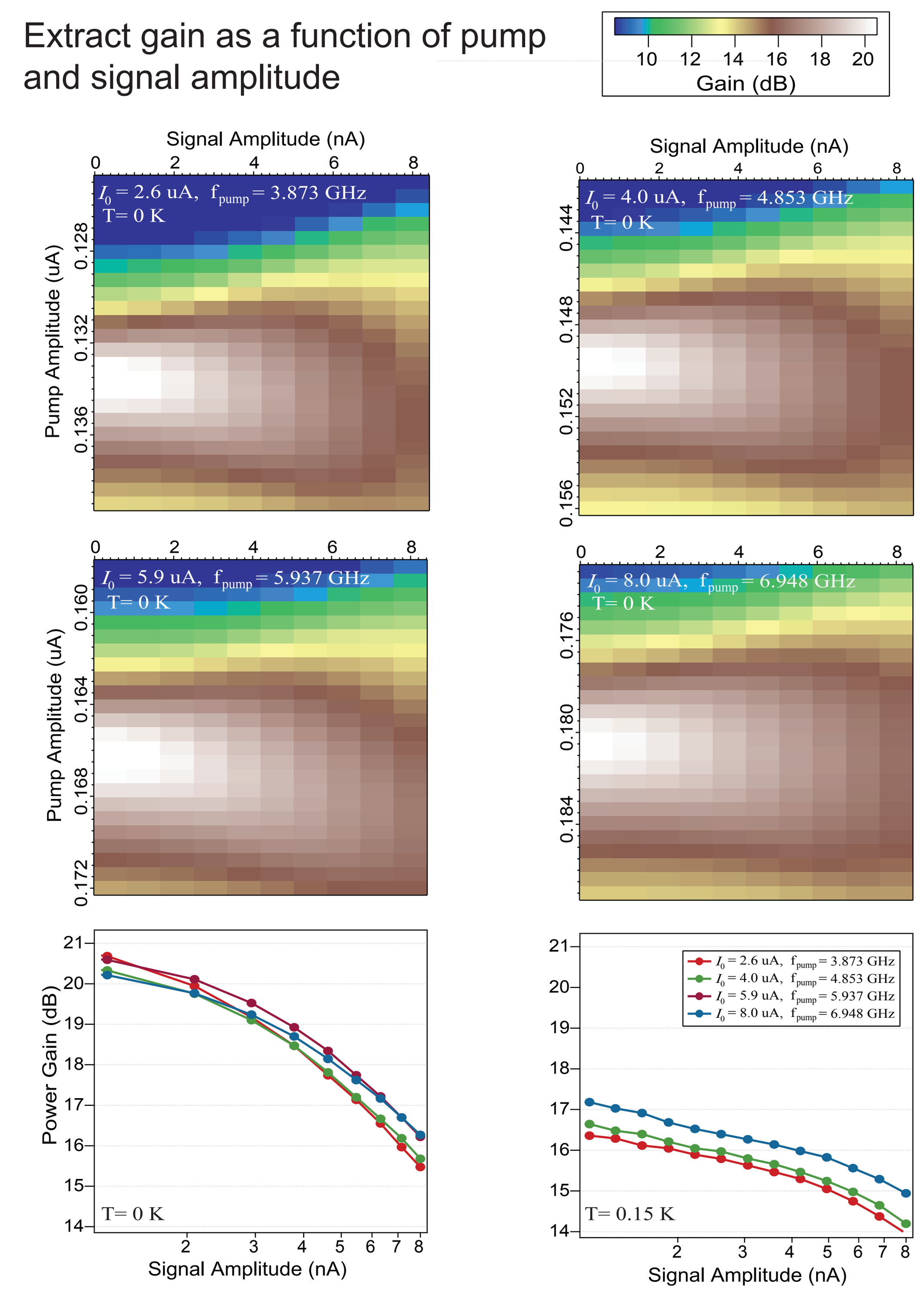
$I_0 = 8\,\mu A$ $C_s = 12\,pF$ $R = 50\,\Omega$
$f_{signal} = f_{pump} + 1\,MHz$ $T = 0.15\,K$

Noise Results

- Simulate with and without noise to compute SNR degradation
- SNR degradation shows asymmetry around maximum gain point
- Ideal SNR degradation of 2 observed

Dynamic range

Extract gain as a function of pump and signal amplitude



- Amplifier frequency band tunable with critical current
- No significant change in 1 dB compression point across 4 - 7 GHz band
- Noise suppresses maximum gain for given drive detuning (Ω)

Conclusions & Future Directions

- Implemented numerical solver for studying parametric amplifier performance
- Noise free simulations agree with predictions of analytical theory
- Simulations with noise show gain suppression and asymmetry in SNR degradation
- Explore maximum achievable bandwidth by varying quality factor (Q)
- Study the effects of stray parameters on amplifier performance
- Simulate multiple junction paramp for improved dynamic range

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