Broadband parametric amplifiers

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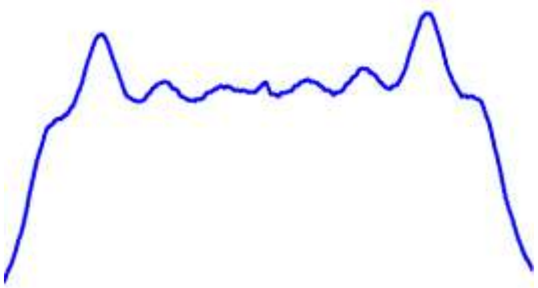

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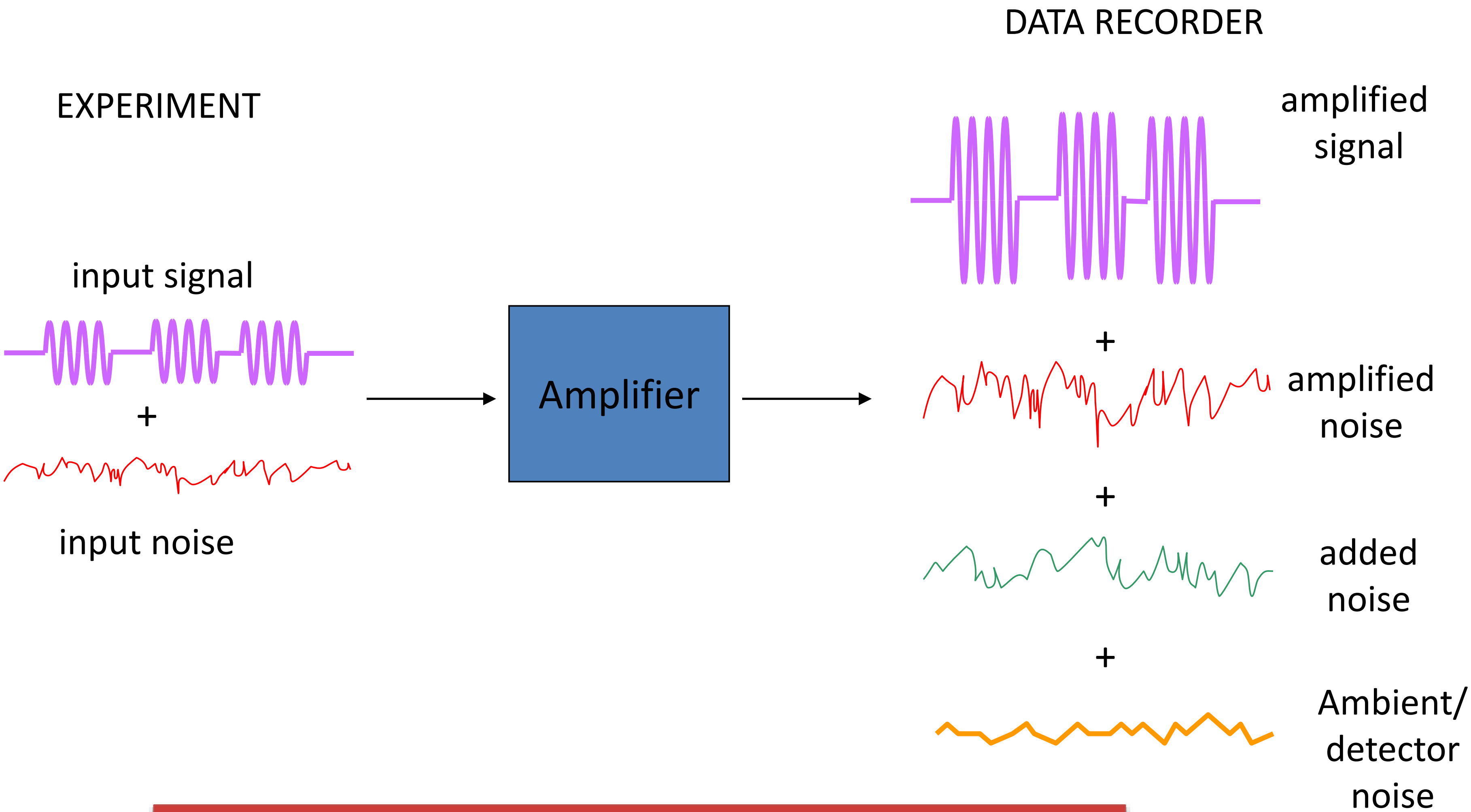
1. Quantum error correction
2. Weak measurements
3. Novel qubit designs
4. Ultra-low noise amplifiers
5. High speed digital/analog signal processing with FPGA
6. Opto-mechanical systems
7. Quantum simulations

Outline

- Parametric amplification
  - Superconducting parametric amplifiers
- Enhancing amplifier bandwidth
- Future directions

Amplification process



An amplifier in general degrades signal to noise ratio

BUT IT MAKES THE AMBIENT/DETECTOR NOISE INCONSEQUENTIAL

Added Noise

- What is the origin of the added noise ?
- Can we make added noise zero ?

QM: HEISENBERG'S UNCERTAINTY PRINCIPLE

Position and Momentum: $\Delta p \, \Delta x > h/4\pi$

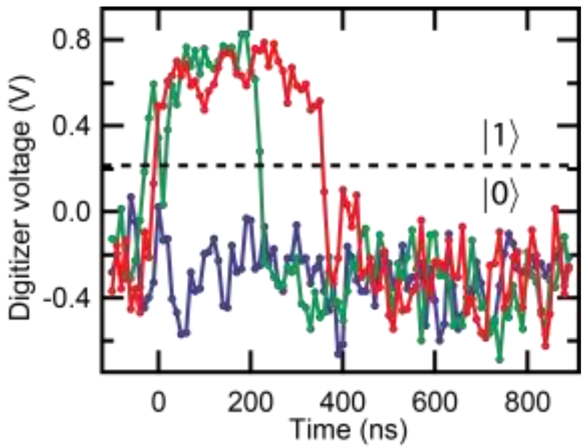
Quanta and phase of oscillations: $\Delta n \, \Delta \phi > 1/2$

Minimum added noise for phase preserving amplification

Clerk at al., Rev. Mod. Phys. **82**, 1155 (2010)

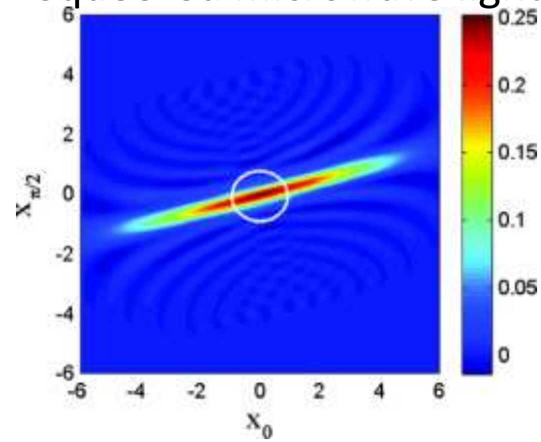
The power of good SNR

Quantum jumps



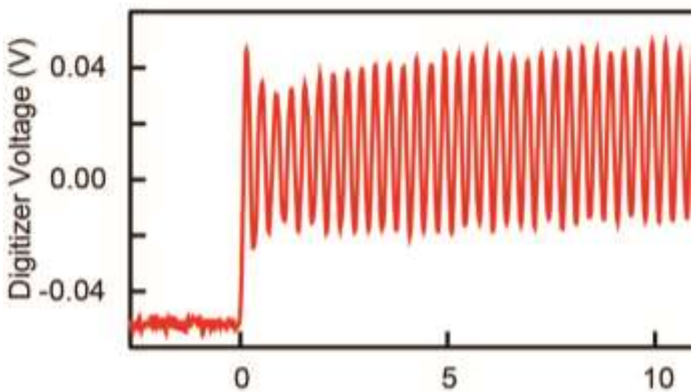
PRL **106**, 110502 (2011))

Squeezed microwave light



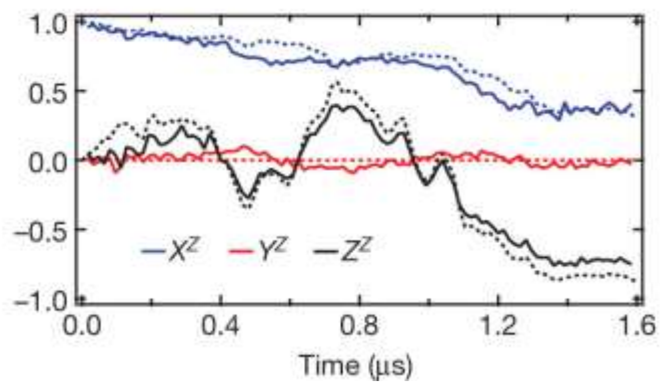
PRL **106**, 220502 (2011)

Quantum feedback



Nature **490**, 77-80 (2012)

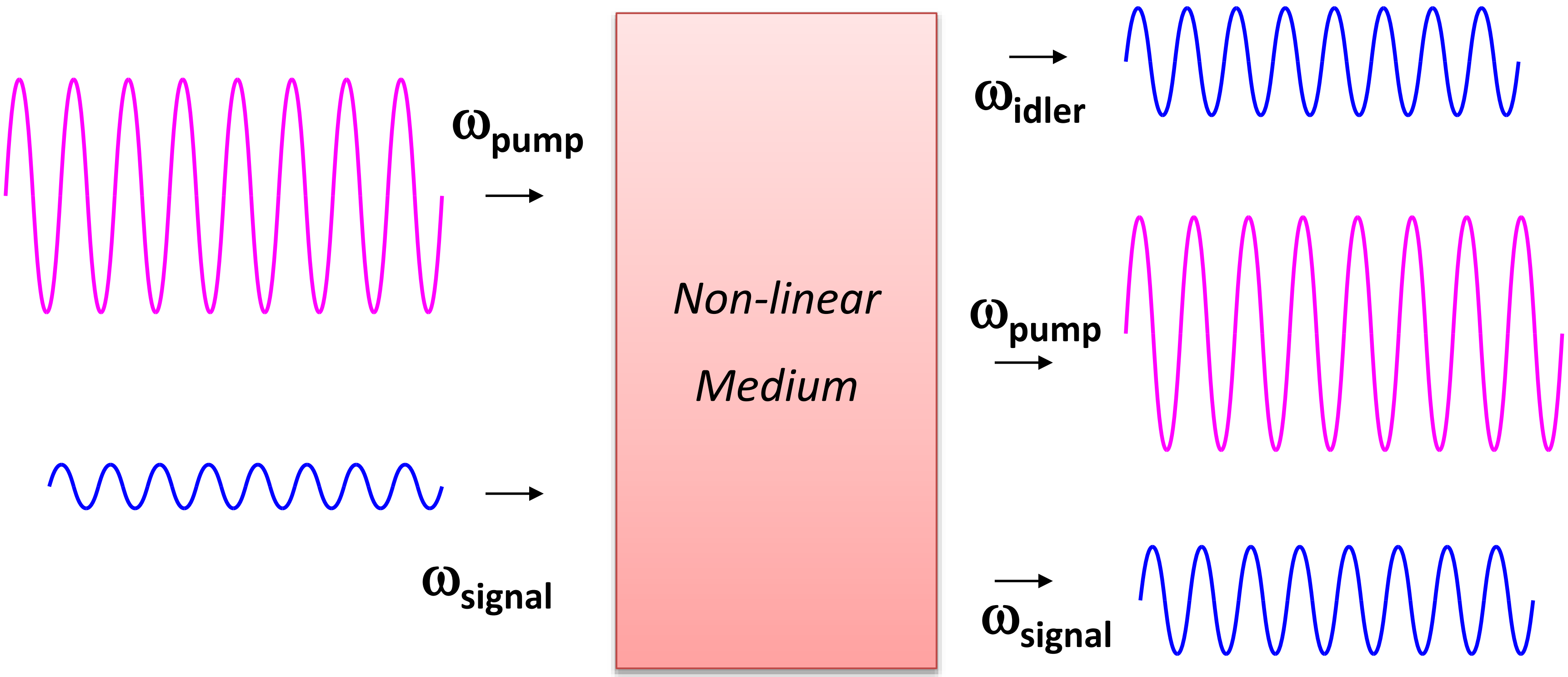
Single quantum trajectories



Nature **502**, 211-214 (2013)

And much much more…..

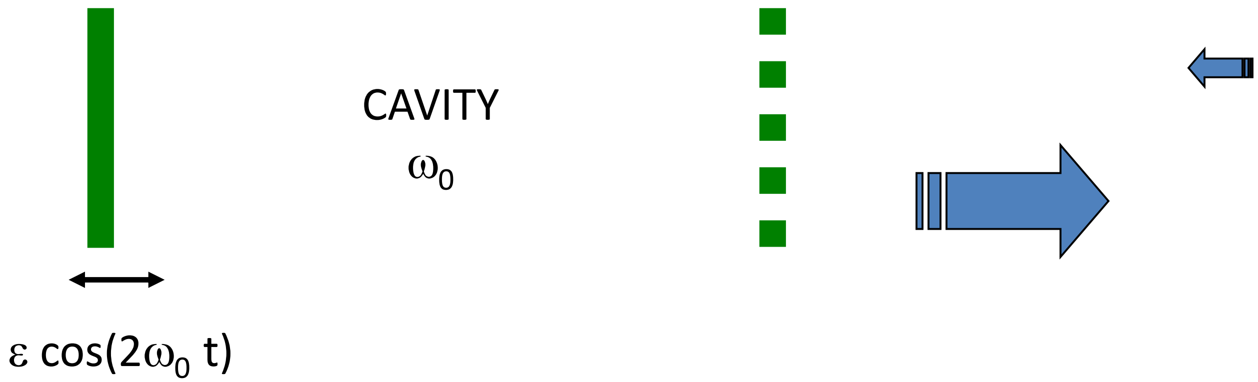
Parametric Amplification

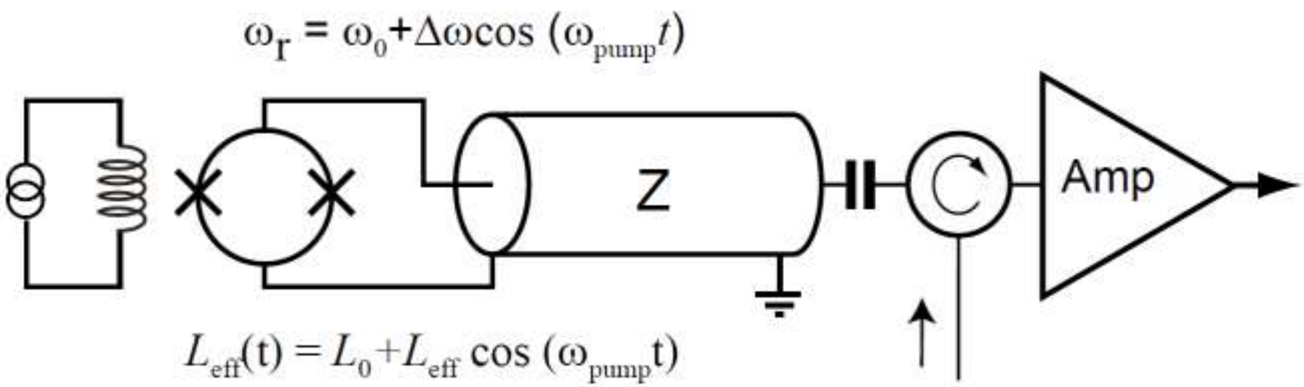


$$\omega_{pump} = \omega_{signal} + \omega_{idler}$$

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

Parametric amplification in resonators





UCSB: APL **103**, 122602 (2013)

Saclay : Phys. Rev. B 89, 214517 (2014)

Parametric Amplification

- Harmonically varying system parameter ω_0

$$\ddot{x} + 2\Gamma\dot{x} + {\omega_0}^2[1 + \underbrace{\alpha\cos 2\omega_0 t}_{\text{Pump}}]x = \mathrm{F}\cos\omega_s t$$

$$\omega_s \sim \omega_0$$

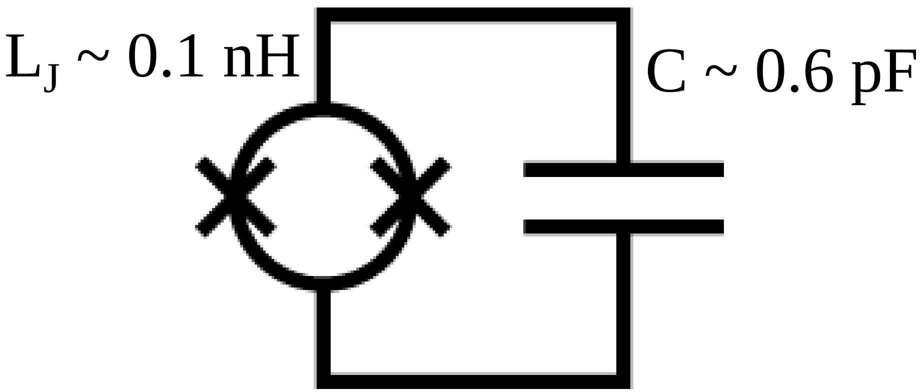
Pump $\omega_p = 2\omega_0$

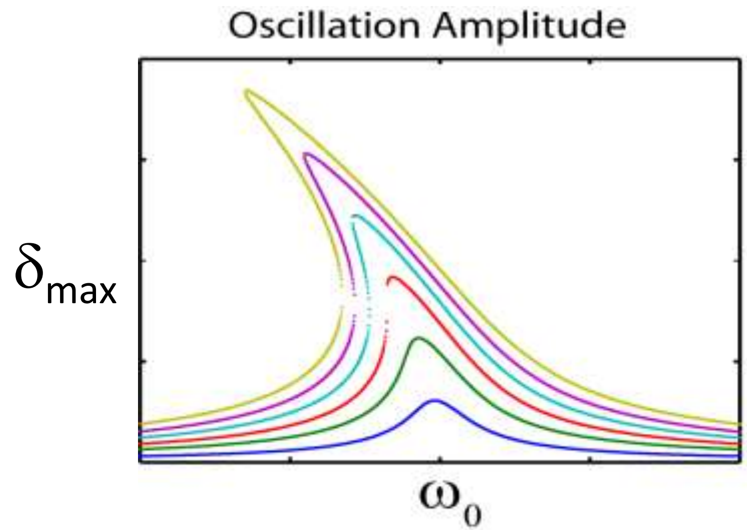
Response $\omega_s\ ,\omega_p - \omega_s$

$$x(t) = \mathrm{A}\cos(\omega_s t + \varphi_1) + \underbrace{\mathrm{B}\cos((2\omega_0 - \omega_s)\,t + \varphi_2)}_{\text{Idler}(\omega_I)}$$

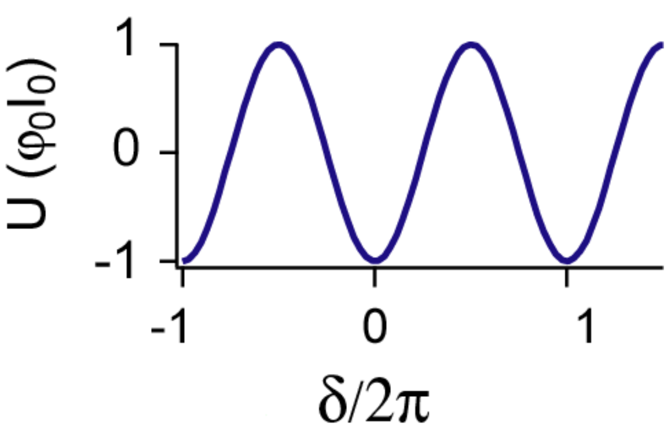
Energy for amplification is drawn from the pump

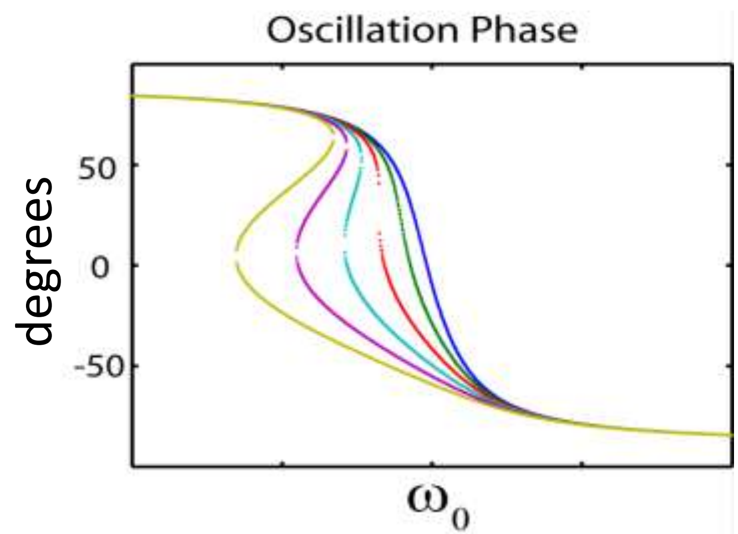
Nonlinear classical oscillator





Classical oscillator





Driven non-linear oscillator

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

$$x(t) = x_p \cos(\omega_p t + \phi_p)$$

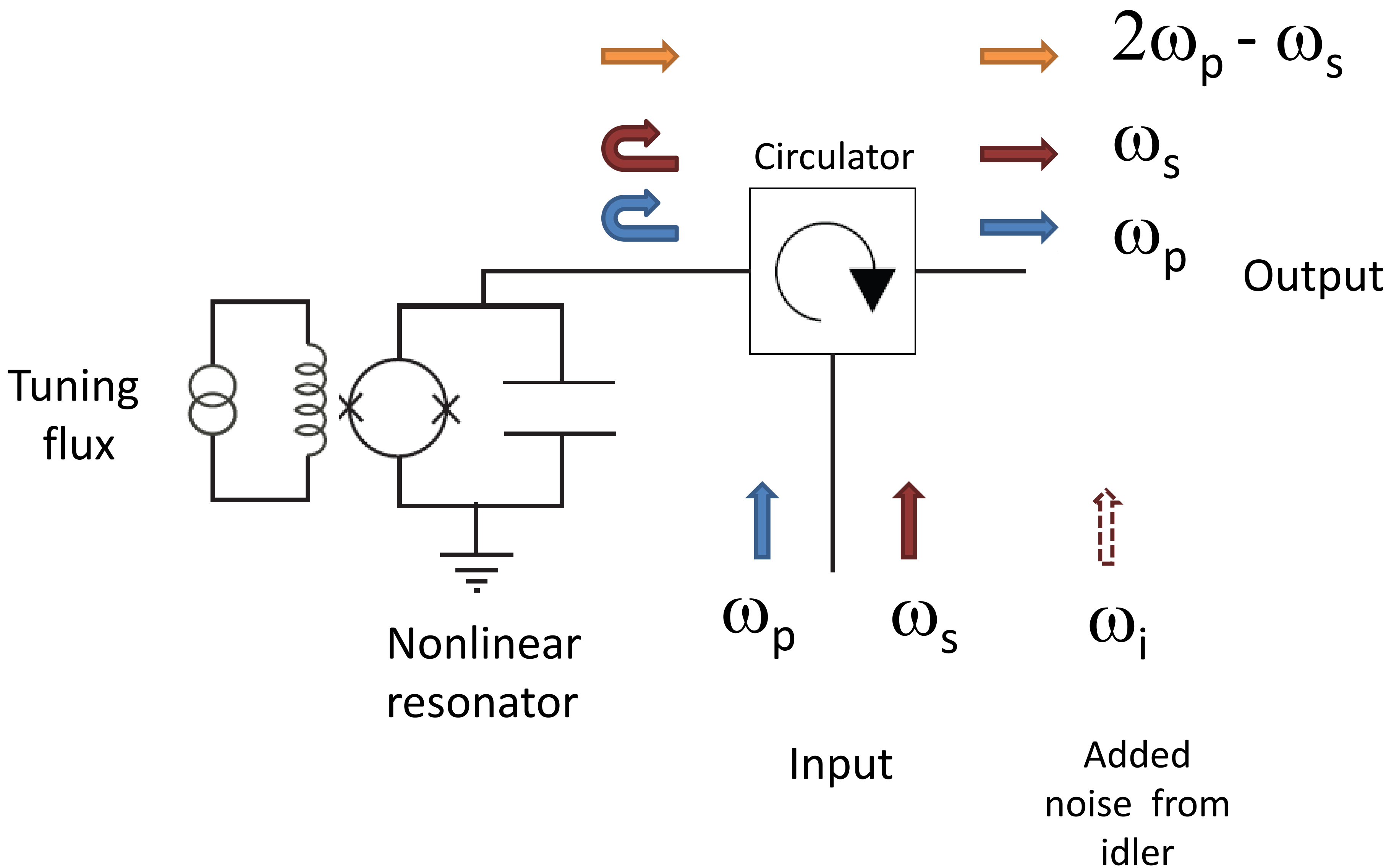
$$\ddot{x} + 2\Gamma\dot{x} + {\omega_0}^2[x \ - \alpha x^3] = F_p \cos \omega_p t + F_s \cos \omega_s t$$

$$x(t) = x_p \cos\left(\omega_p t + \phi_p\right) + y(t) \qquad F_s \ll F_p \,, |y(t)| \ll x_p$$

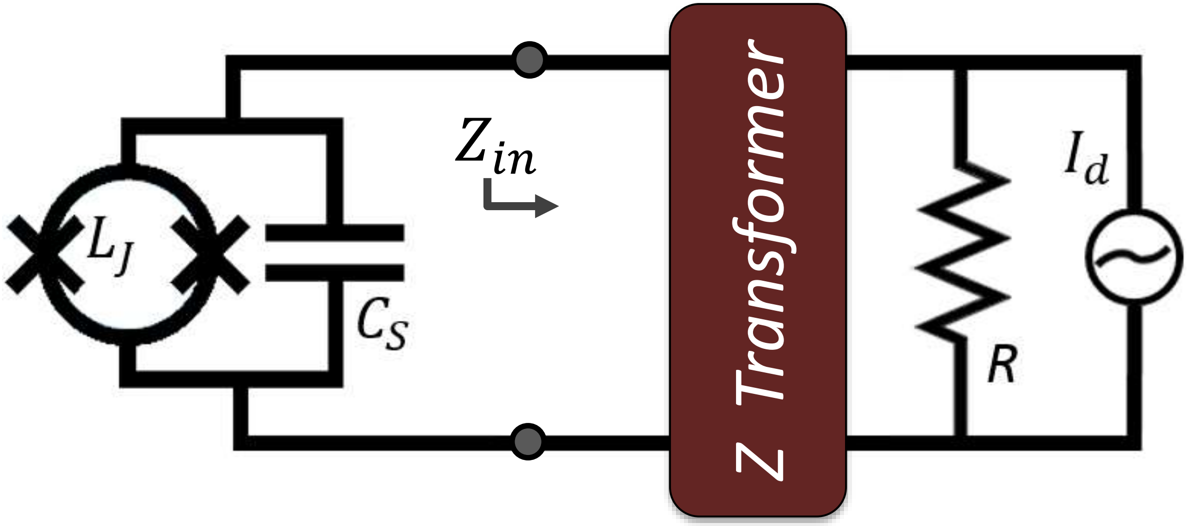
$$\ddot{y} + 2\Gamma\dot{y} + {\omega_{0,eff}}^2\left[1 + k \cos 2\omega_p t\right] y = F_s \cos \omega_s t$$

Detuned pump: $\omega_p \neq \omega_{0,eff}$

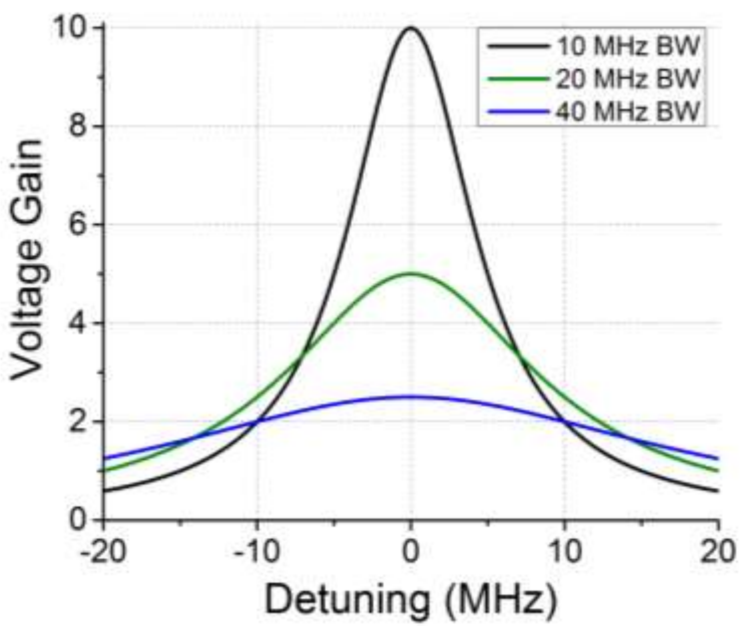
Non-linear oscillator as a paramp



Beyond Gain Bandwidth Product



$$\kappa = \frac{1}{2RC_s}$$



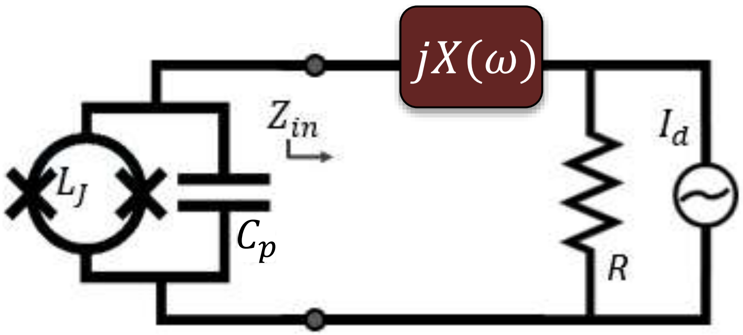
Gain × Bandwidth (BW) = const.

Increase κ to increase BW

⇒ Drive harder : Instability?

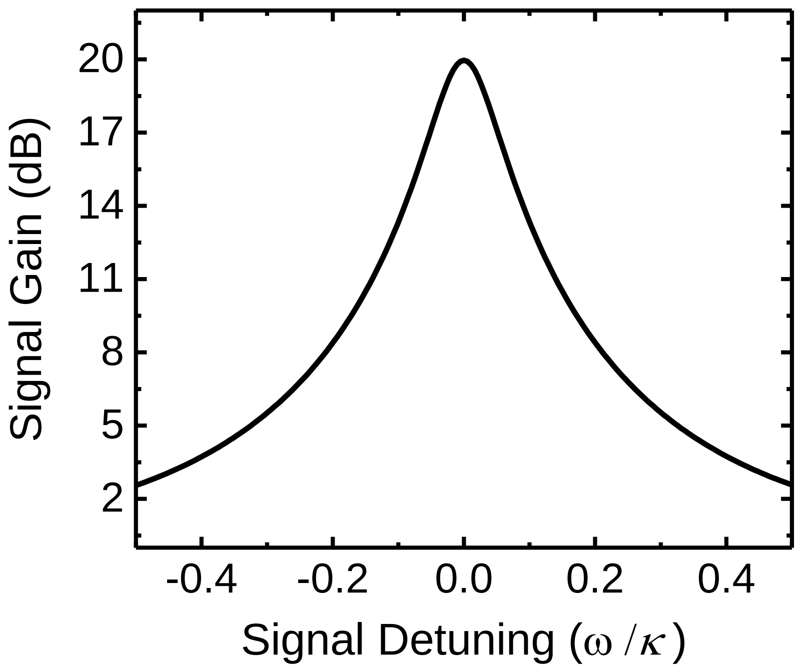
More BW without changing κ?

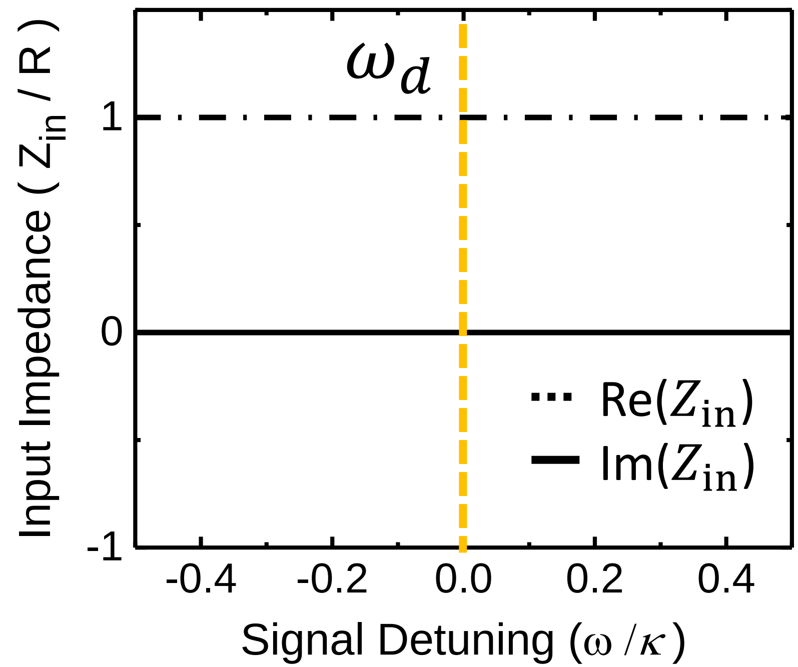
Transformer Design



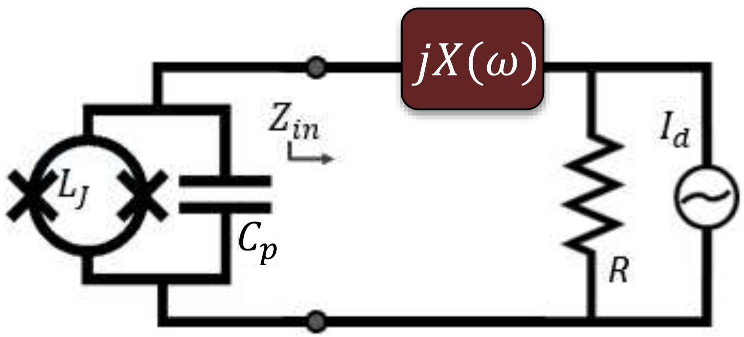
$$X(\omega_d) = 0$$

Biasing unmodified





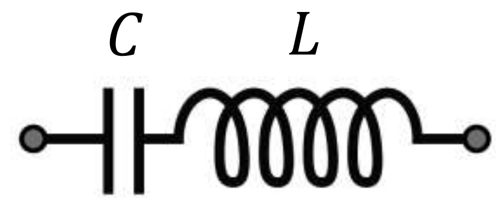
Transformer Design



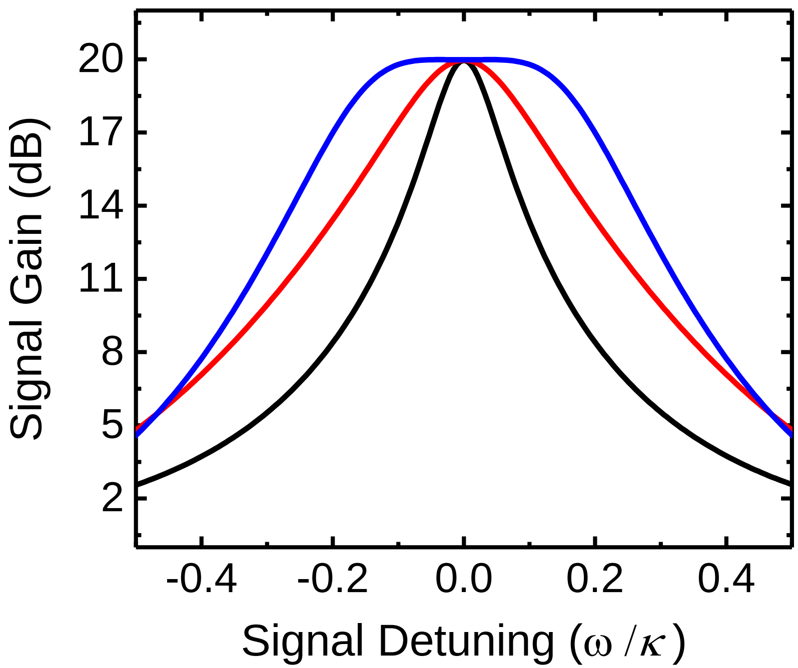
$X(\omega_d) = 0$

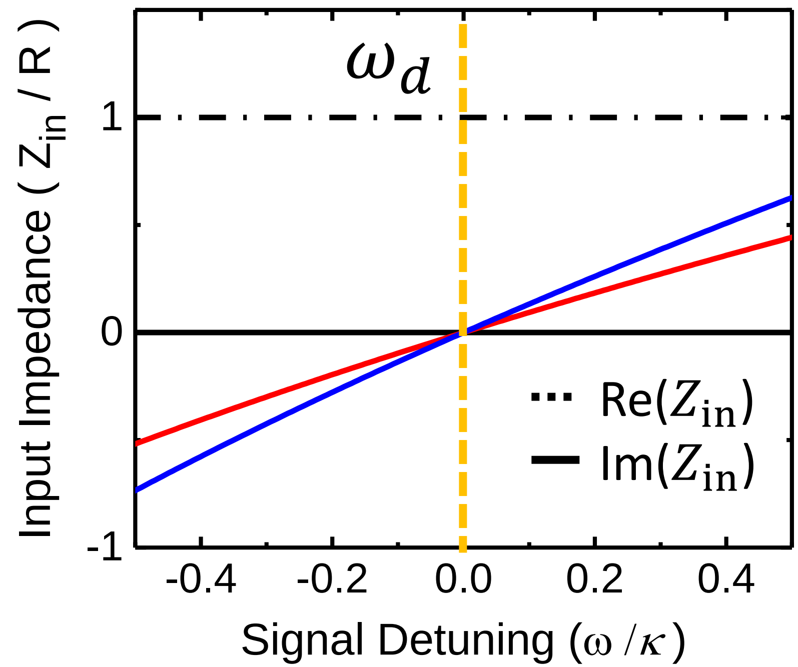
⇓

Biasing unmodified



$Z_0 = \sqrt{L/C}$





BW enhancement ~ $\sqrt{\text{Gain}}$

Theory: The Hamiltonian

System: detuned non-degenerate parametric amplifier

$$\hat{H}_A = \underbrace{\omega'_d}_{\text{Effective detuning}} \left(\hat{a}_1^\dagger \hat{a}_1 + \hat{a}_2^\dagger \hat{a}_2\right) - i \underbrace{\lambda}_{\text{Pump strength}} \left(\hat{a}_1^\dagger \hat{a}_2^\dagger - \hat{a}_1 \hat{a}_2\right)$$

$$\vec{a}[\omega] = \chi[\omega]\ \vec{a}_{\mathrm{in}}[\omega] \qquad \vec{a}[\omega] = \begin{pmatrix} \hat{a}_1 \\ \hat{a}_2^\dagger \end{pmatrix}$$

$$\boxed{(\chi[\omega])^{-1} = -i \begin{pmatrix} \omega - \omega'_d - \Sigma_1[\omega] & i\lambda \\ i\lambda & \omega + \omega'_d - \Sigma_2[\omega] \end{pmatrix}}$$

$$\Sigma_1[\omega] = -\frac{i}{2C_p} Y_{\mathrm{in}}^*[\omega]; \quad \Sigma_2[\omega] = -\frac{i}{2C_p} Y_{\mathrm{in}}[-\omega];$$

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With Aash Clerk

Theory: Signal and Idler Gain

$$\boxed{(\chi[\omega])^{-1} = -i\begin{pmatrix} \boxed{\omega} - \omega_d' - \boxed{\Sigma_1[\omega]} & i\lambda \\ i\lambda & \omega + \omega_d' - \Sigma_2[\omega] \end{pmatrix}}$$

$$\Sigma_1[\omega] = -\frac{i}{2C_p} Y_{\text{in}}^*[\omega]; \quad \Sigma_2[\omega] = -\frac{i}{2C_p} Y_{\text{in}}[-\omega];$$

Signal gain:

$$G_s = |r_s|^2 = |1 - \kappa\chi_{11}|^2$$

Idler gain:

$$G_i = |r_i|^2 = |\kappa\chi_{12}|^2$$

$$\kappa = \frac{\text{Re}[Y_{\text{in}}]}{C_p}$$

Frequency Independence $\Longrightarrow \begin{cases} \text{Re}\big[Y_{\text{in}}[\omega]\big] = 1/R \\ \text{Im}\big[Y_{\text{in}}[\omega]\big] = -2C_p\omega \end{cases}$

$$Z_{\text{in}} = \frac{1}{Y_{\text{in}}}$$

$$\boxed{\text{Re}\big[Z_{\text{in}}[\omega]\big] = R}$$

$$\boxed{\text{Im}\big[Z_{\text{in}}[\omega]\big] = 2R^2C_p\omega}$$

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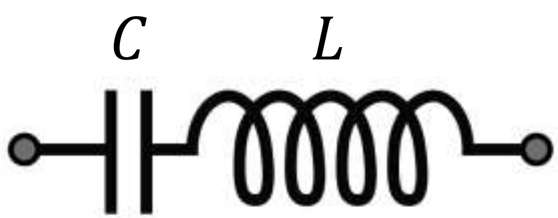
Optimization

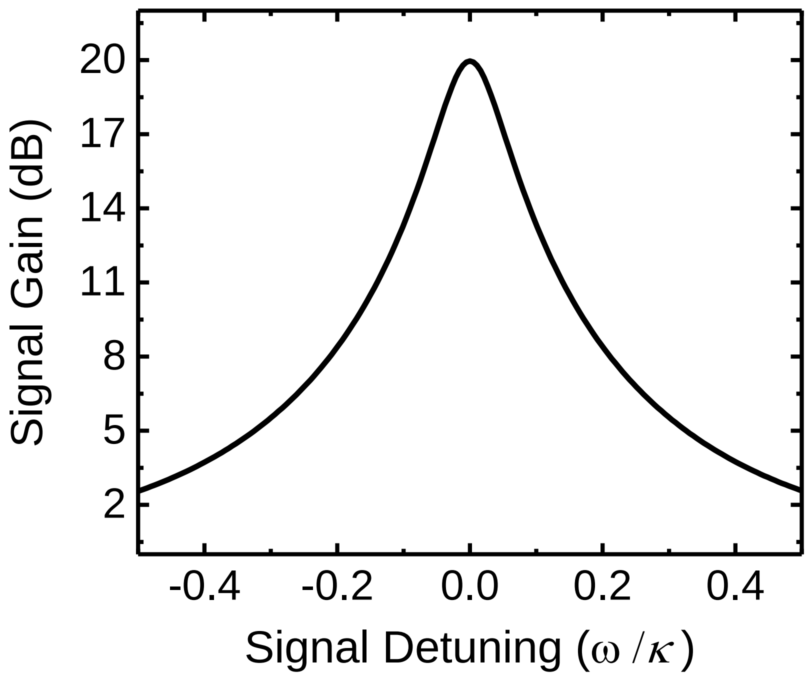
Signal gain:

$$G_s = |r_s|^2 = |1 - \kappa\chi_{11}|^2$$

$$= 1 + a_0 + \boxed{a_2\omega^2} + a_4\omega^4 + \cdots$$



$$Z_0 = \sqrt{L/C}$$



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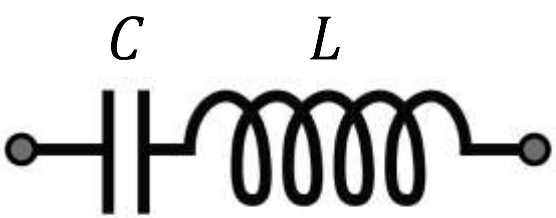
Optimization

Signal gain:

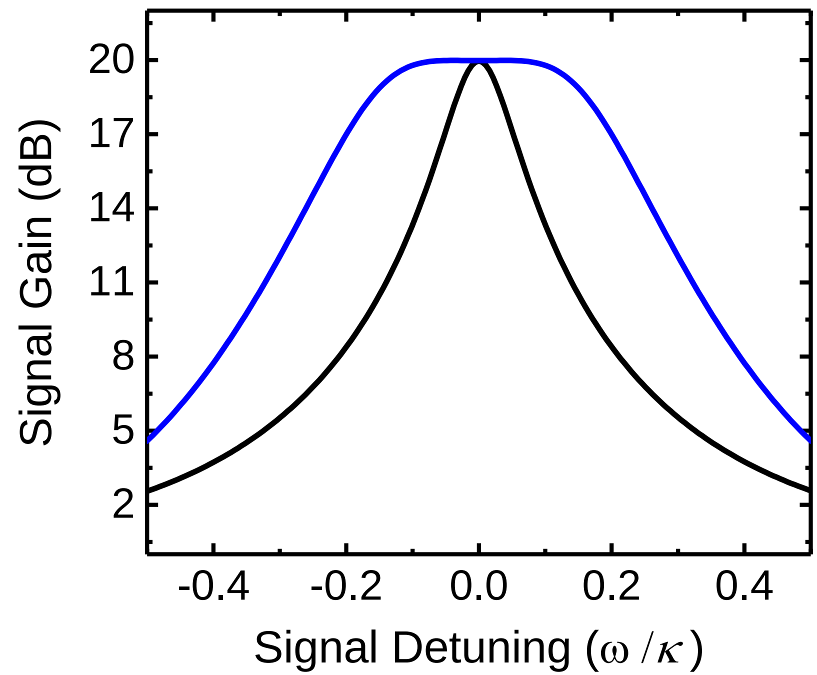
$$G_s = |r_s|^2 = |1 - \kappa\chi_{11}|^2$$

$$= 1 + a_0 + \cancel{a_2\omega^2} + a_4\omega^4 + \cdots$$



$$Z_0 = \sqrt{L/C}$$

At optimal slope: Z_{opt}



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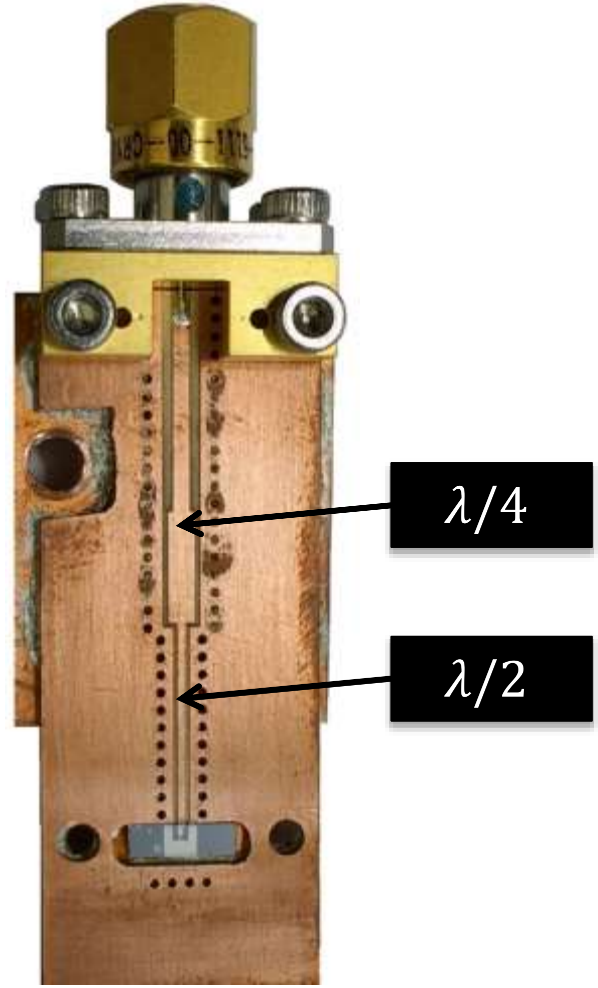
Implementation

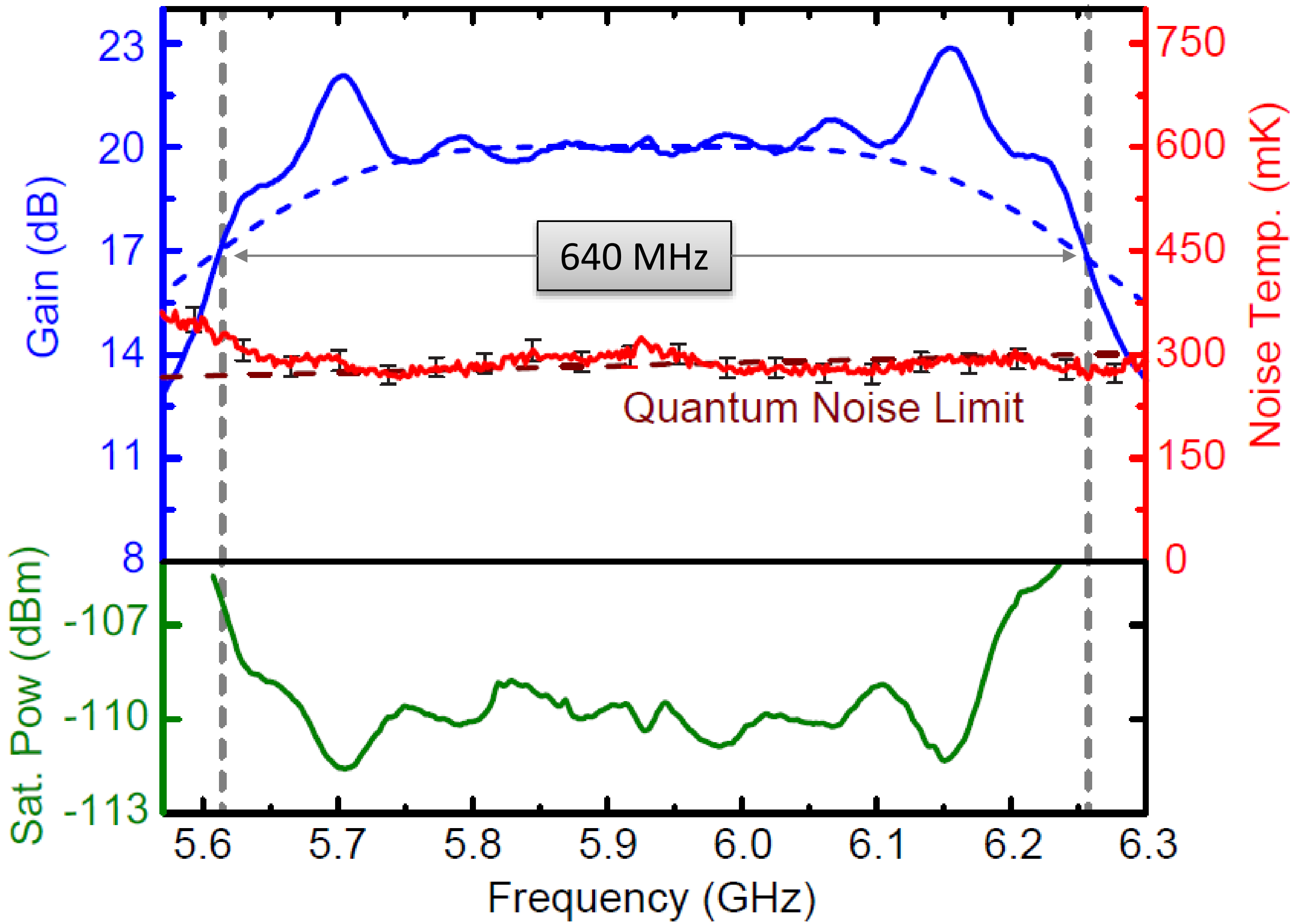
Standard
180^o hybrid

Modified
180^o hybrid



New impedance
transformer

Experimental Result



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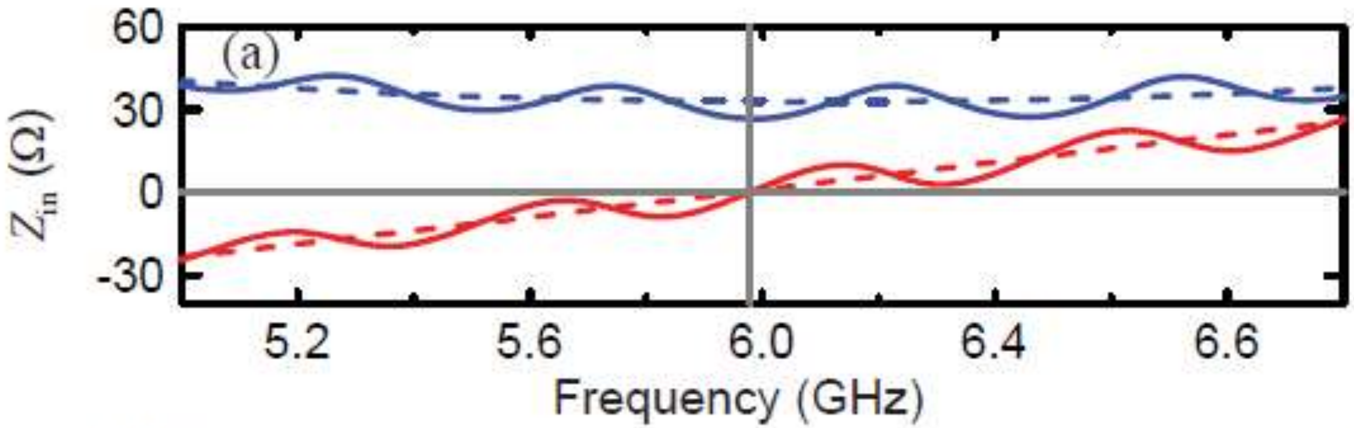
Non ideal environment



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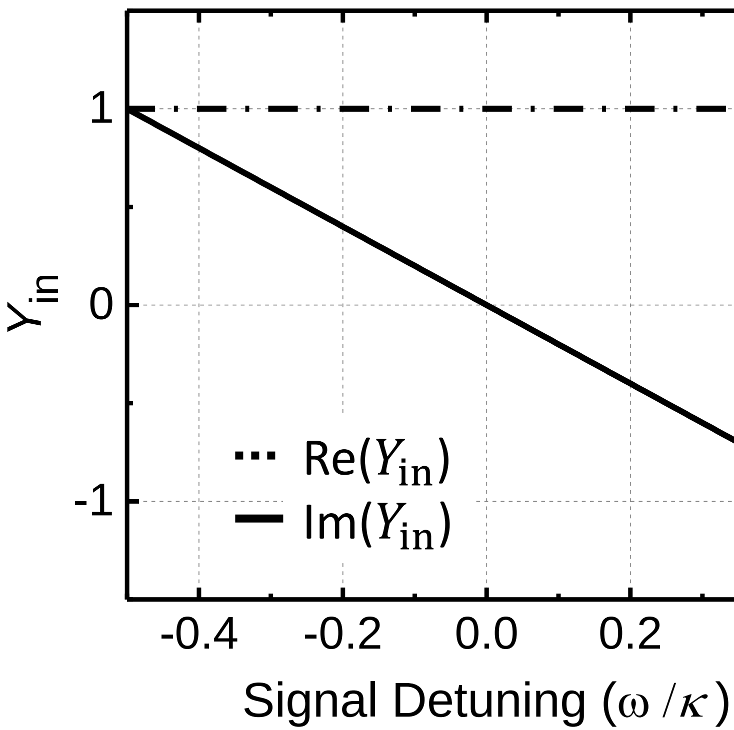
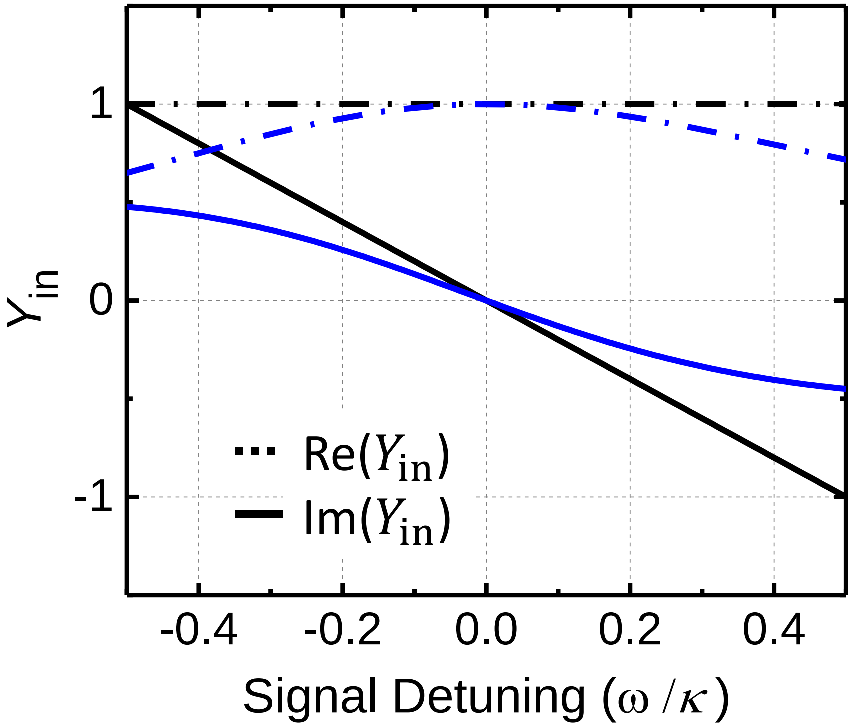
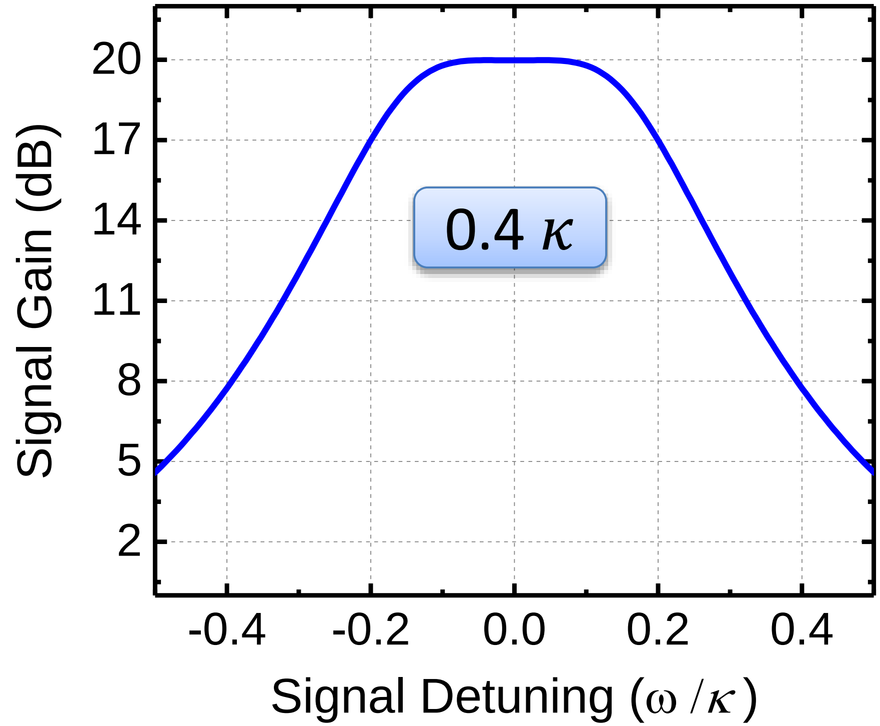
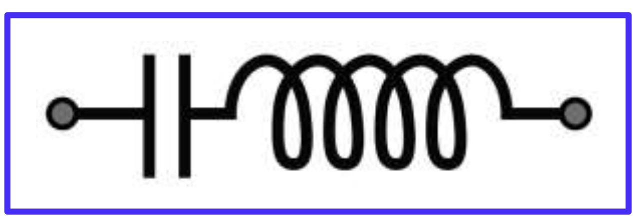
Optimizing Input Admittance (Y_{in})



Optimizing Input Admittance (Y_{in})







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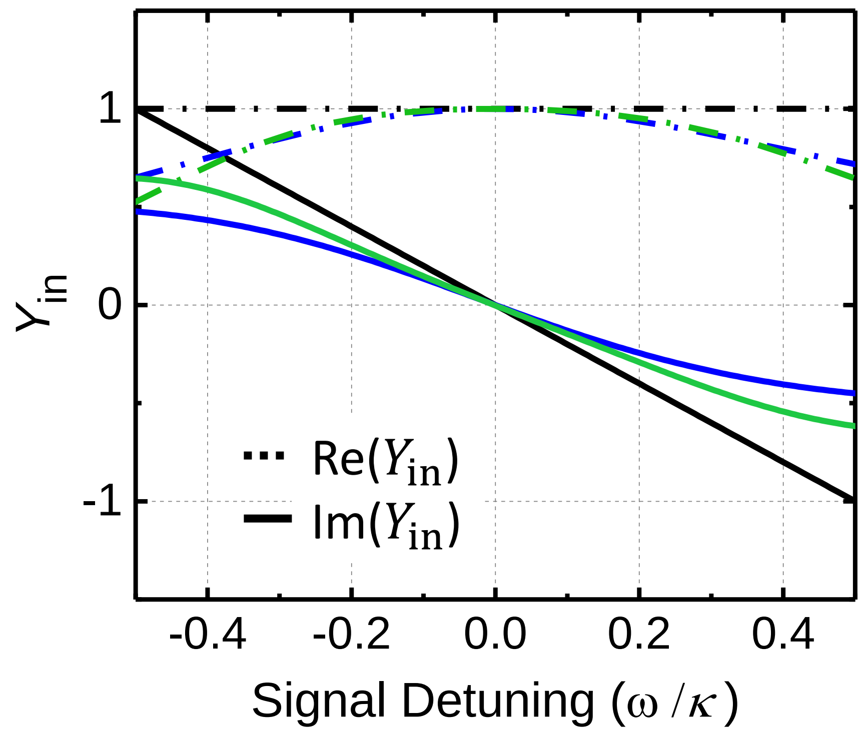

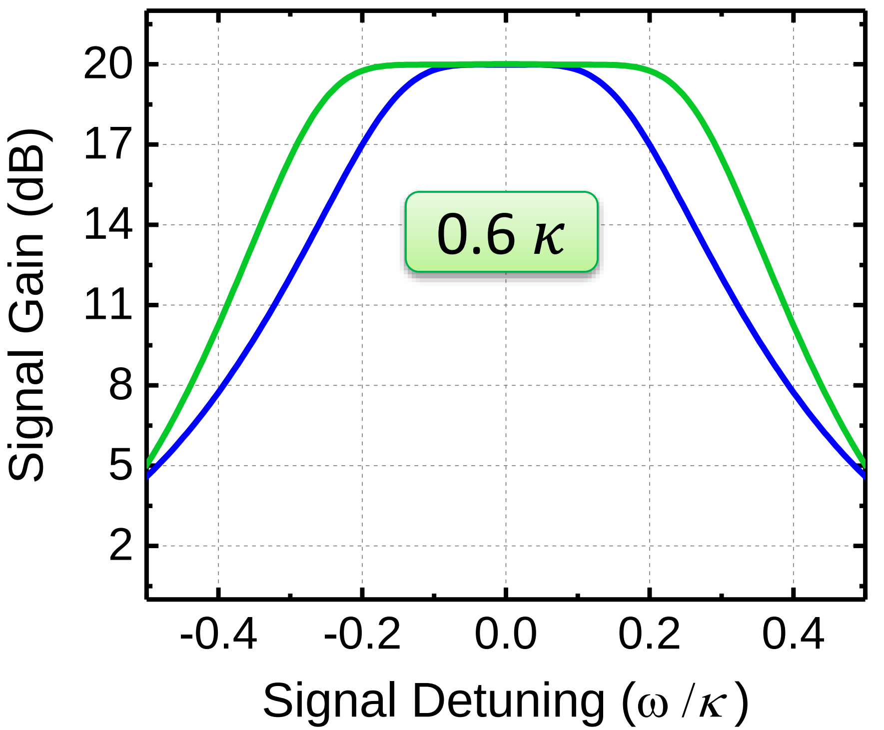

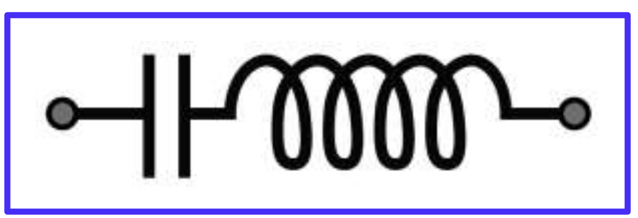

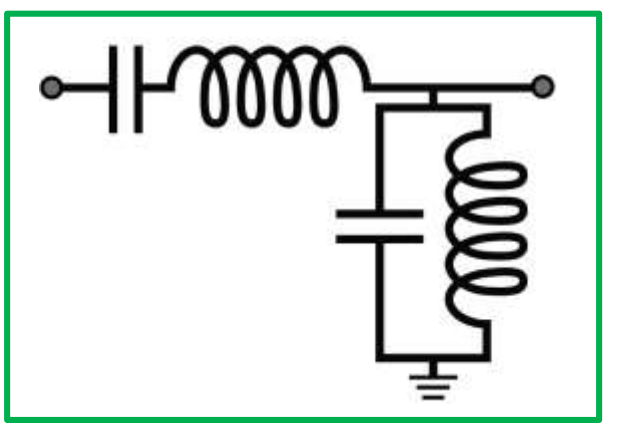

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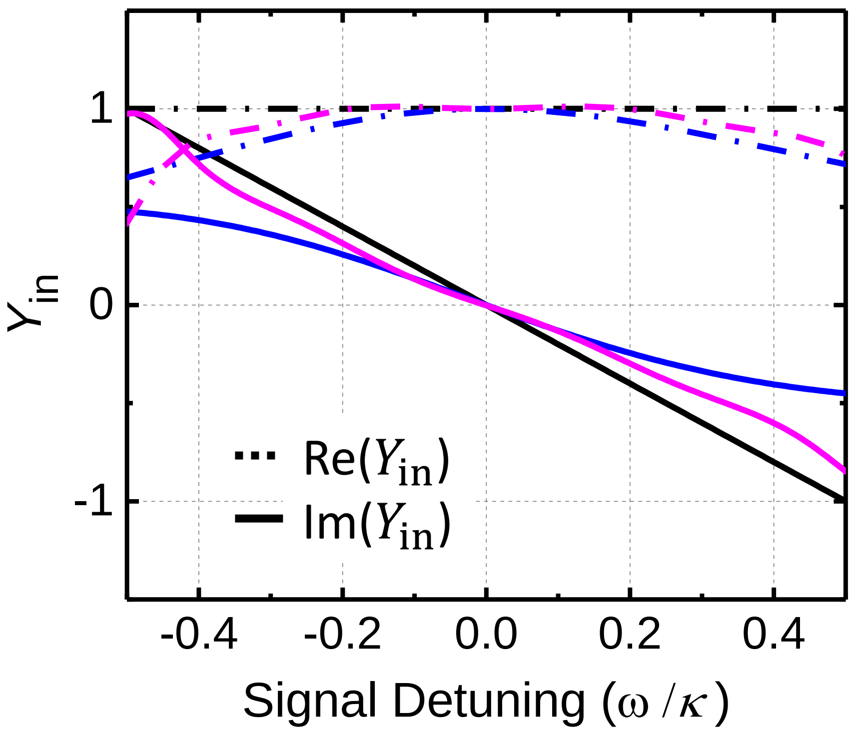
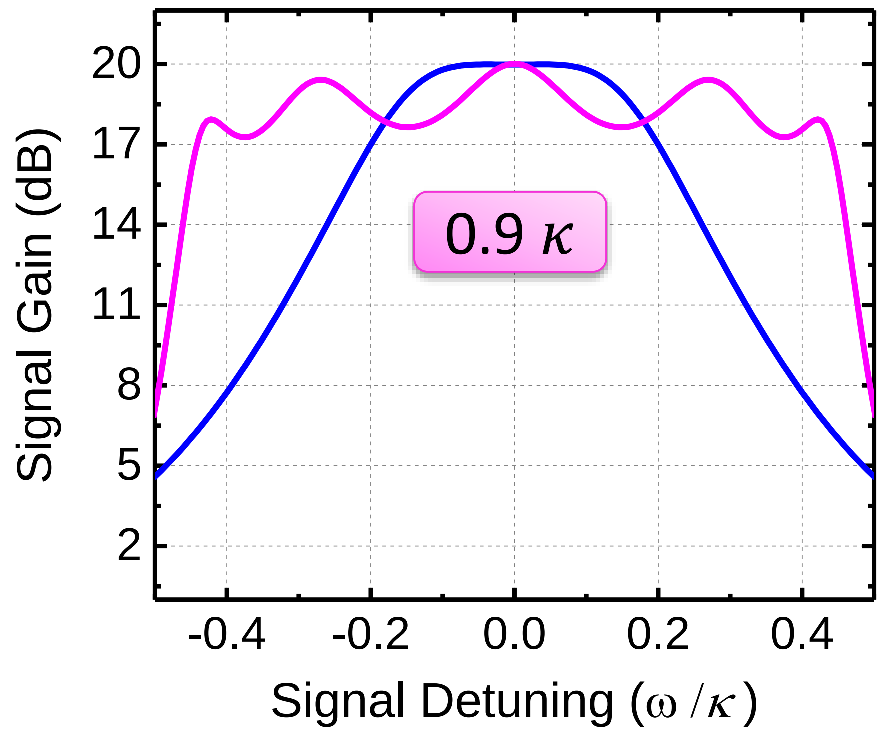
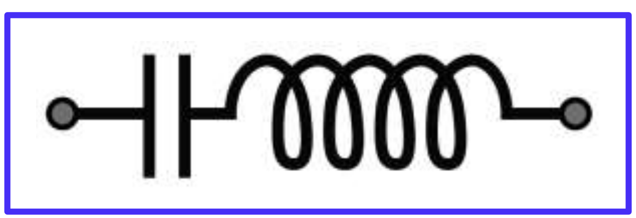
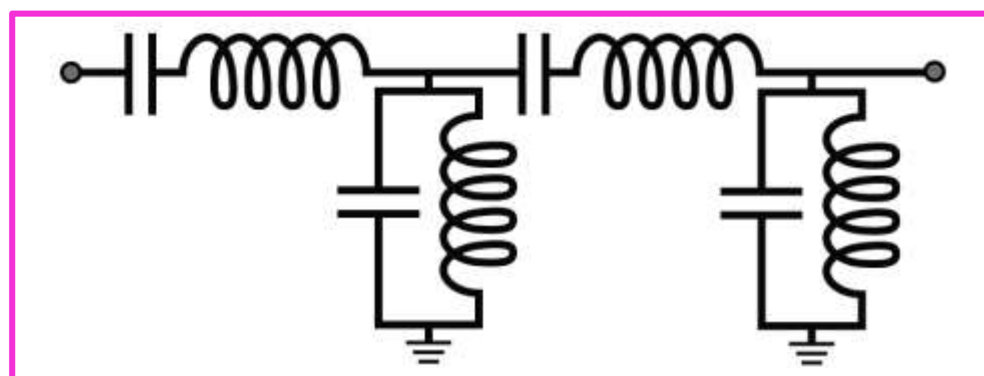








Other paramp designs

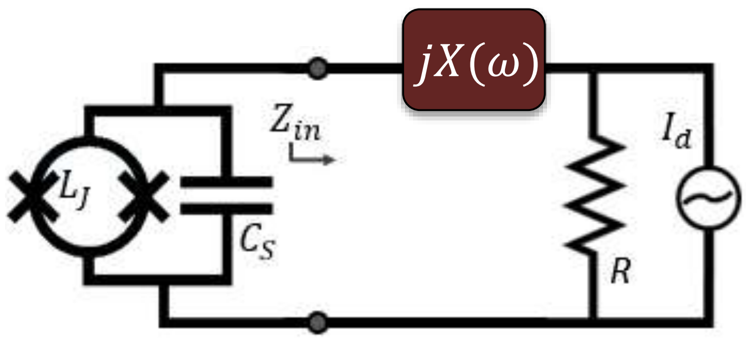
Direct pumping

Parallel LC paramp

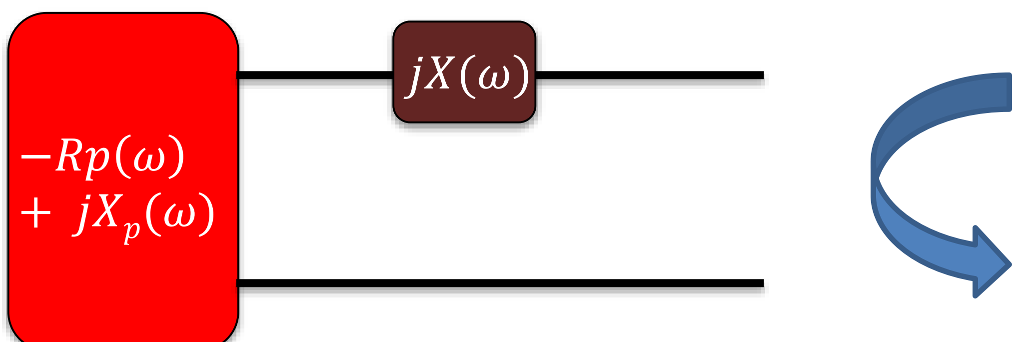
Flux pumping

Series array LC paramp

With Nicolas Roch

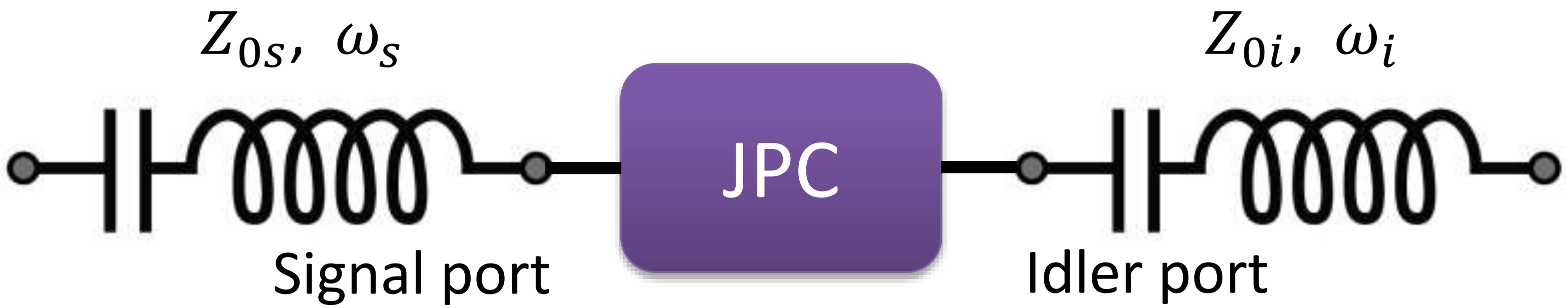


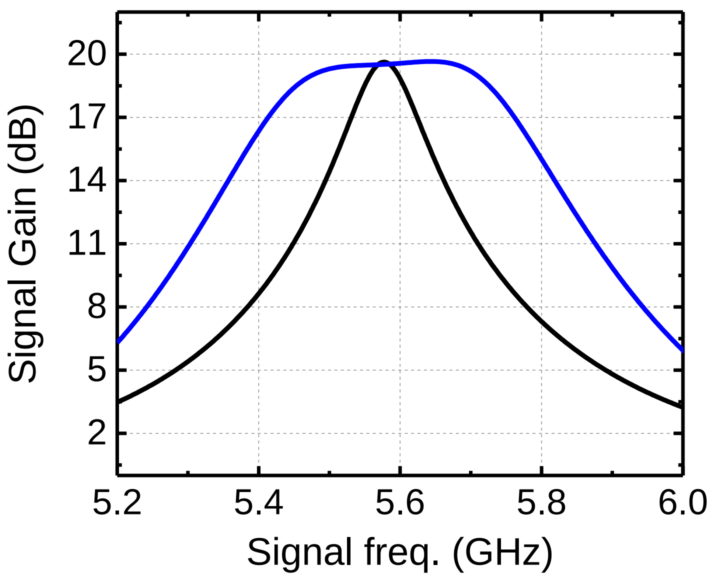
Negative resistance amplifier

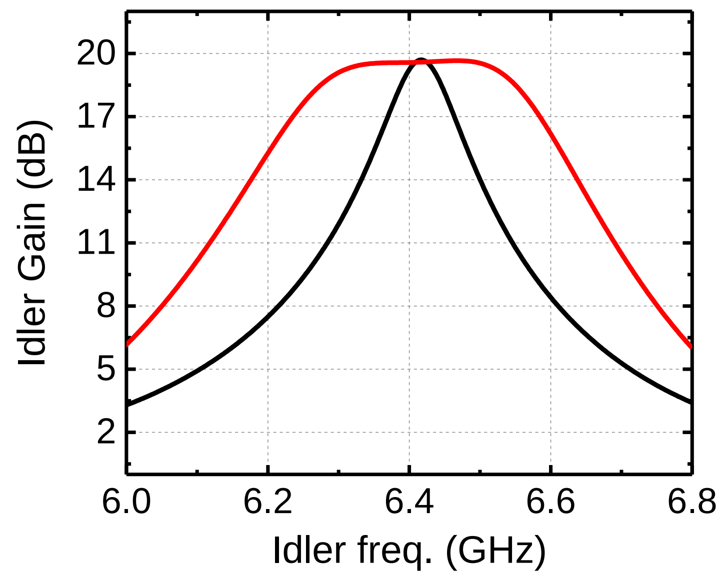


$$\Gamma = \frac{Z - Z_0}{Z + Z_0}$$

Two port amplifiers: JPC?

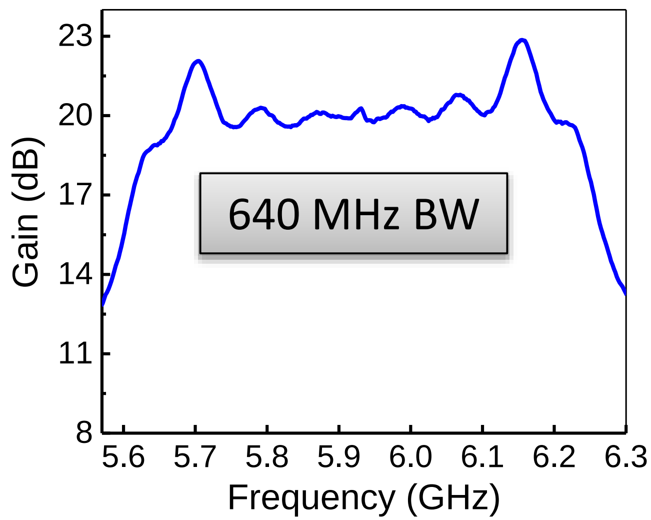


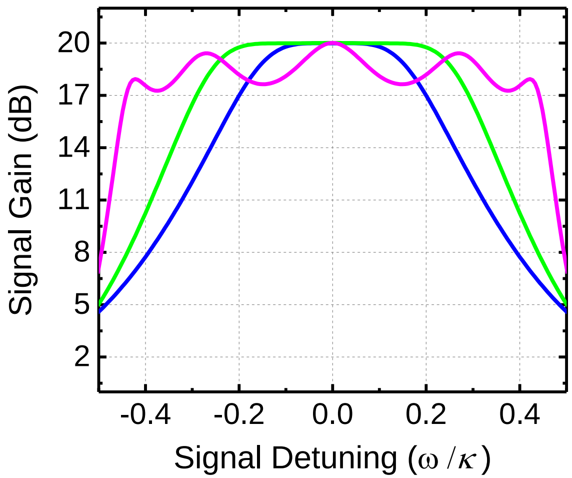




In progress….

Conclusion





Future Directions

- Implement and test multi-pole designs
- Improve saturation power
- Combine the two techniques
- Experimental tests of other paramp designs
- Multiplexed multi-qubit readout
- Photon correlation measurements
- Fast high fidelity readout