Active Resonators for ADMX

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Idea

- Axion haloscopes experiments use high-Q microwave cavities.
- Expected signal power is proportional to Q:

$$P_{sig} \propto \min(Q_L, Q_a)$$

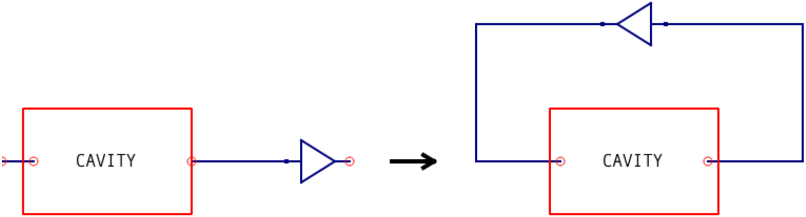
axion quality factor: $Q_a \simeq 10^6$

- Theoretical Q goes as

$$Q = \frac{L}{R+L}\frac{R}{\delta}$$

- anomalous skin depth (Cu): $\delta = 2.8 \times 10^{-5}\ \mathrm{cm}\left(\frac{\mathrm{GHz}}{f}\right)^{1/3}$
- $Q_L \approx 10^5$ for $f \approx 1$ GHz.
- Can we increase the loaded Q further?

Introduce Feedback



Improving Dark Matter Axion Searches with Active Resonators

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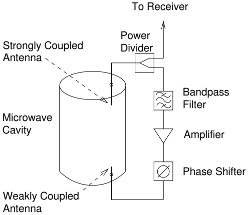
University of Washington
(Dated: March 27, 2014)

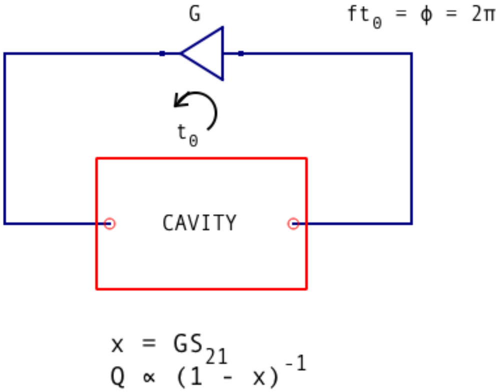
Axions are a well motivated candidate for dark matter. The most sensitive experiments searching for dark matter axions rely on the coupling of axions to the electromagnetic resonances of a microwave cavity immersed in a strong magnetic field. The sensitivity of the experiment is proportional to the Q of the resonance that is coupled to axions. To date, the resonators used in axion searches have all been passive, with Qs limited by power loss in the cavity walls. I propose the use of active feedback resonators to increase the Q of microwave cavity axion dark matter experiments by several orders of magnitude. This should allow experiments to significantly increase the rate at which they can test potential axion masses and couplings.



[0]arXiv:1403.6720

Active Feedback

$V_{out} = V_{in}S_{21}(1 + x + x^2 + \ldots) = V_{in}S_{21}(1 - x)^{-1}$



- Signal builds up through feedback
- Q increases by factor $(1 - x)^{-1}$
- Oscillation begins when $x = 1$

- This idea is old; patented in 1914 and used for making higher gain amplifiers and more selective radio circuits.[1]
- However, this amplifies noise and signal equally, so SNR should remain the same for constant amplitude signal:

$$\mathrm{SNR}_{\mathrm{cw}} \propto \text{const.}$$

- Since axion signal is proportional to Q, SNR increases

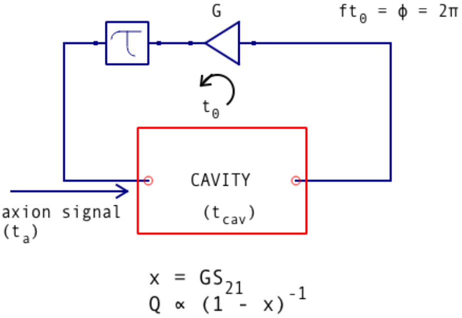
$$\mathrm{SNR}_{\mathrm{axion}} \propto (1-x)^{-1}$$

- We can utilize the different coherence times of signal and noise to get more improvement.

[1] Joe A. Rolf, "Q Multiplier Boosts Selectivity & Gain," Popular Electronics, April 1974

Time Delay

Introduce a time delay so t_0 greater than cavity coherence time



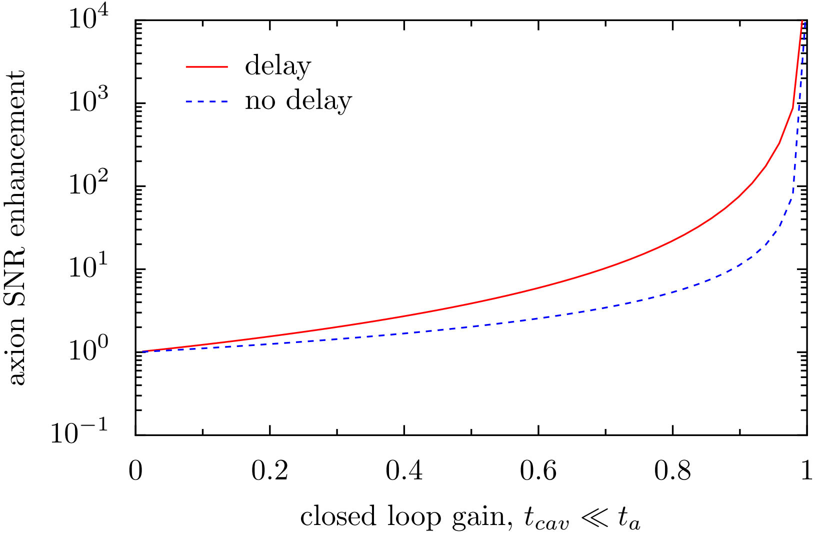
- Noise is only correlated over time t_{cav}
- Signal is coherent over longer time t_a
- If roundtrip time t_0 is greater than t_{cav}:

$$t_{cav} < t_0 < t_a$$

we expect noise to add incoherently and signal to add coherently

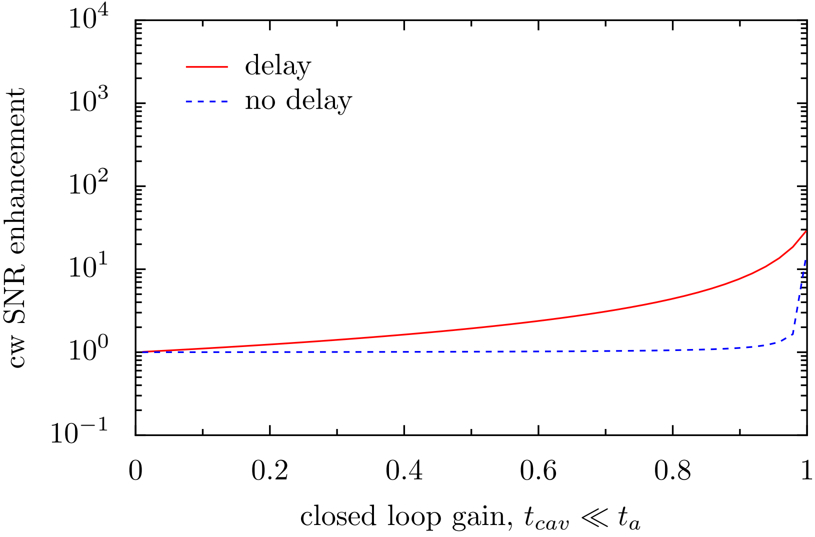
Expected Improvement in Axion SNR

axion snr improvement, SNR(x)/SNR($x = 0$), with and without delay line



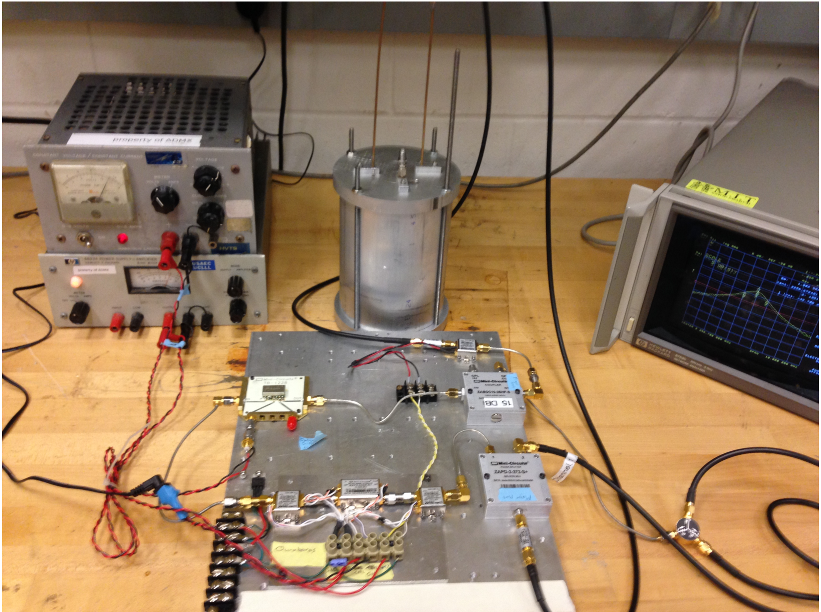
Expected Improvement in Constant Signal

cw snr improvement, $\mathrm{SNR}(x)/\mathrm{SNR}(x=0)$, with and without delay line



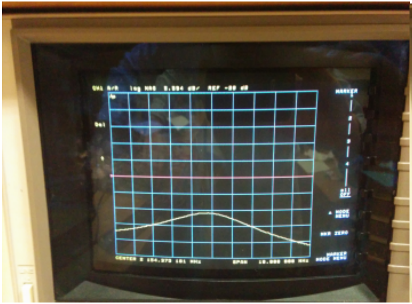
Initial Setup

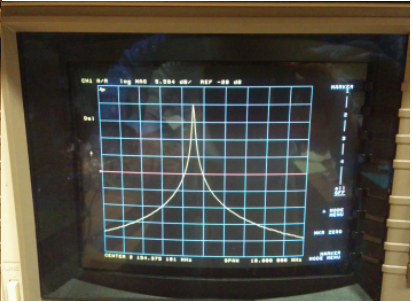
feedback using amplifiers, variable attenuator, and phase shifter



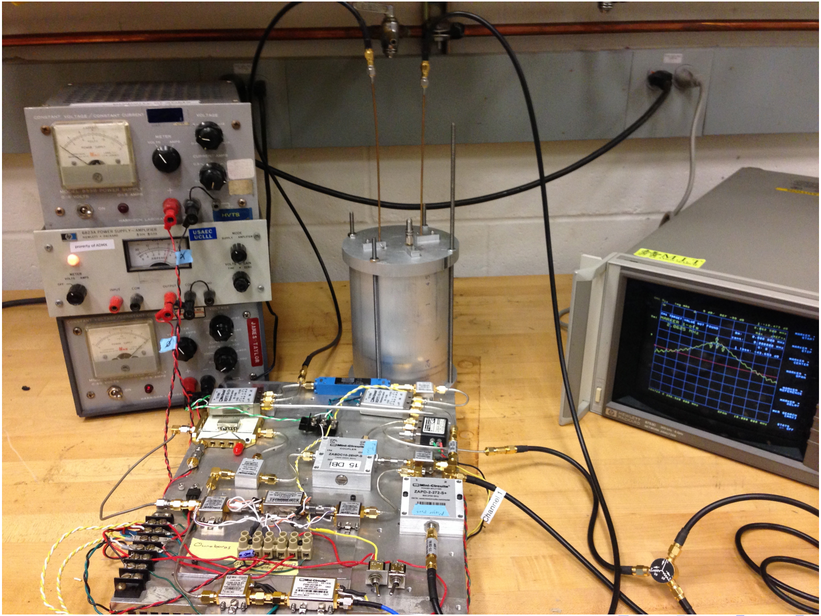
Q Enhancement

adjusting variable attenuator allows Q to range from 1000 to 9000 before oscillations begin

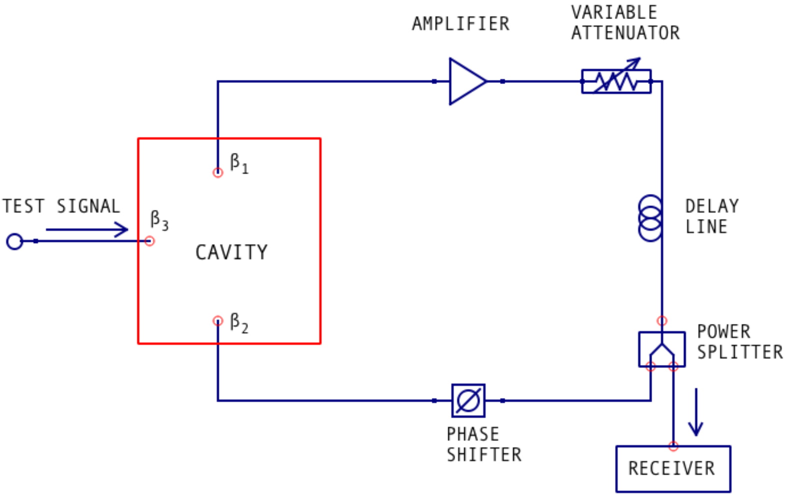




Setup



Schematic


AMPLIFIER
VARIABLE
ATTENUATOR
β_1
TEST SIGNAL
β_3
CAVITY
DELAY
LINE
β_2
POWER
SPLITTER
PHASE
SHIFTER
RECEIVER

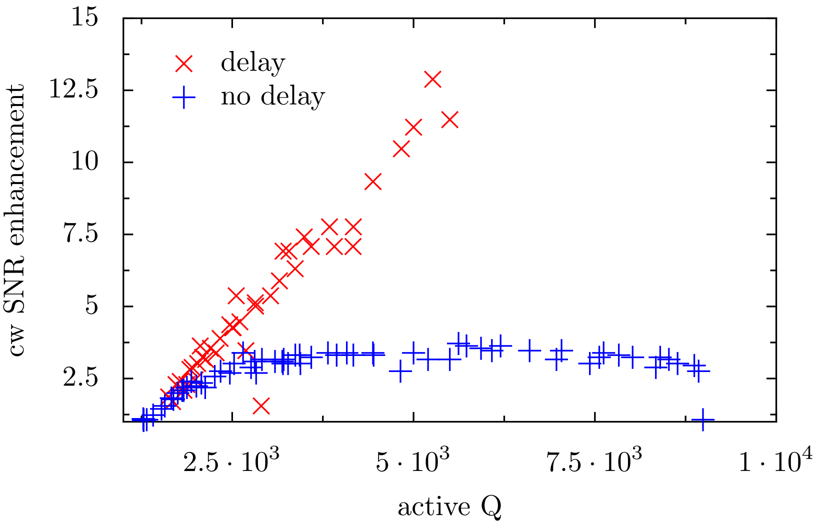
Parameters

Parameter	Values
f_{cav}	2.256 GHz
t_{delay}	2.4 μs
t_{cav}	170 ns
t_{axion}	141 μs

Experiment

- Set attenuation of variable attenuator
- Adjust phase so Q is maximal
- Measure Q, f_{cav}
- Inject constant amplitude signal at f_{cav}
- Measure height of signal relative to noise floor in detected spectrum

Results



delay
no delay
cw SNR enhancement
15
12.5
10
7.5
5
2.5
$2.5 \cdot 10^3$
$5 \cdot 10^3$
$7.5 \cdot 10^3$
$1 \cdot 10^4$
active Q

Considerations

- analog delay lines are narrowband frequency devices - move to digital delay lines.
- major design considerations would center around gain instability; to get 10x increase in Q, need $x \simeq 0.9$.
- amplifier saturation - our low noise SQUID saturates at 8K. If we have 100 mK system noise temperatures, but increase the Q by a factor of 10x, the noise power will increase by a factor of 100x.

Conclusions

- active feedback is a simple technique to increase Q
- delay line provides additional increase in SNR
- independent of other parts of the experiment
- does not need to be operated cryogenically

People

Lisa McBride, Kunal Patel, Gray Rybka

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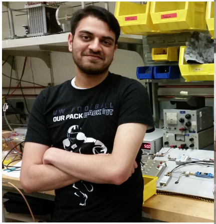
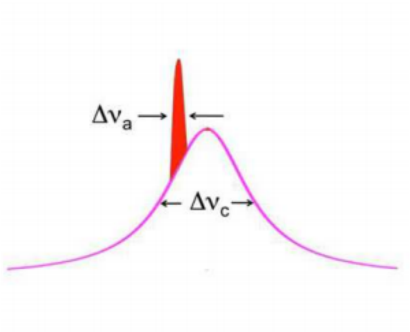


Backup

Backup Slides

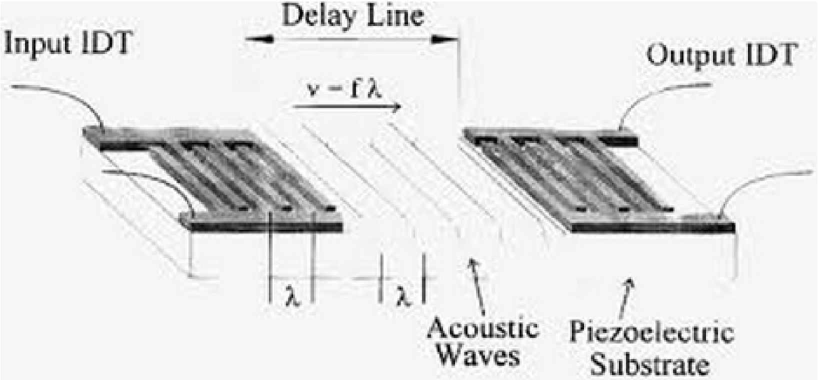
If $Q_L > Q_a$



If cavity Q is larger than axion Q (or $t_{cav} > t_a$), we no longer detect the full axion power within the cavity bandwidth.

Delay Lines

Surface Acoustic Wave (SAW) Resonator



Expected SNR Improvement

analysis of signal correlation

Scenario 1: $t_0 \ll t_{cav}$: .

$$\langle V_{in}(t)V_{in}(t-t_0)\rangle = \bar{V}_{in}^2$$
$$\langle |V_{out}|^2\rangle = |\bar{V}_{in}S_{21}|^2(1+x+x^2+\dots)^2 = \bar{V}_{in}^2|S_{21}|^2(1-x)^{-2}$$

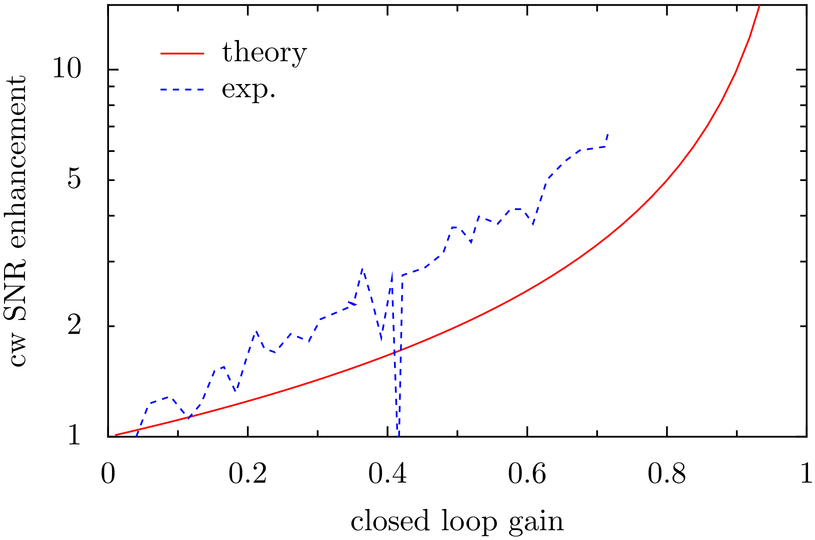
Scenario 2: $t_0 \sim \mathcal{O}(t_{cav})$:

$$\langle V_{in}(t)V_{in}(t-t_0)\rangle = \bar{V}_{in}^2 e^{-t_0/t_{cav}}$$
$$\langle |V_{out}|^2\rangle = |\bar{V}_{in}S_{21}|^2(1+xe^{-t_0/t_{cav}}+x^2e^{-2t_0/t_{cav}}+\dots)^2$$
$$= \bar{V}_{in}^2|S_{21}|^2(1-xe^{-t_0/t_{cav}})^{-2}$$

this analysis is not completely correct - it predicts a turnover at x=0.5. One needs to treat the nonlinearity properly to get the correct result:

$$\langle |V_{out}|^2\rangle = \frac{\bar{V}_{in}^2|S_{21}|^2}{(1-x)^2}\frac{1+xe^{-t_0/t_{cav}}}{1-xe^{-t_0/t_{cav}}}$$

Comparison (preliminary)



Interference Fringes

When $\Delta f t_0 > \pi$, one sees interference fringes, due to off resonant signals acquiring an extra phase shift of $\pi/2$ relative to the phase acquired by the resonant frequency.