Two Level System Noise (TLS) and RF Readouts

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Two Level System (TLS) and Superconducting Resonators

Have well known effects in superconducting resonator applications
• Energy dissipation – limits Q’s of devices (Q-bits, MKIDS, etc)
• Frequency shift – small shifts in resonant frequency
• Add Frequency Noise

No clear theoretical understanding of noise
• Temperature power power dependence well mapped
• Limited exploration of variation with resonator frequency
• Some TLS physics suggest lower noise as hf << kT
Possible use of LC resonators at Kinetic Inductance Thermometers (KITs)
- FIR radiation absorbed by suspended bolometer island
- Temperature read out via RF-KIT
- RF - Require large capacitors with amorphous dielectrics (TLS noise)

Quasiparticle density (therefore L) depends on temperature:

\[ n_{qp} \propto \sqrt{\frac{2\pi k_B T}{\Delta}} e^{-\Delta/k_B T} \]
Kinetic Inductance Thermometry And Radio-Frequency Readouts

TLS Noise - potentially limiting factor in this FIR detection scheme

Need TLS Noise < Photon Noise

\[ S_{TLS} < \frac{\beta^2}{4\frac{Q_i^2}{\sigma^2}} \frac{1+n}{n\Delta\nu} \]

\( \beta \) – ratio of frequency to dissipation response
\( n \) – optical efficiency ~ 1
\( \Delta\nu \) – optical bandwidth

\( \beta = \frac{\delta\sigma_2}{\delta\sigma_1} \sim 1 - 10 \)

Noise for a FIR spectrometer detector with typical values:
\( n = 1, \beta = 10, Q_i = 10^5, \Delta\nu=0.3 \text{ GHz}: \ S_{TLS} < 2 \times 10^{-17} / \text{ Hz} \)

Is this achievable with radio-frequency readouts?
Exploration of TLS effects at Radio-Frequency

Lumped LC resonators spanning wide frequency range

Inductance
• High $\alpha$ materials – TiN, NbTiN
• Vary frequency of resonators by adjusting length of meander inductors

Capacitance – goals:
• Interdigitated Capacitors – 250 MHz – 3 GHz
• Parallel Plate – 50 MHz – 1 GHz
• Multiple dielectrics – SiO2, SiN, Si, SOI

Fabricated our first device:
• 28 Resonators
• IDC, 250 MHz – 1 GHZ
Devices: Lumped LC resonators spanning wide frequency range

- Device design:
  - 31 Resonators

- Resonator + CPW center conductor:
  - NbTiN (Tc ~ 14 K)

- Ground Planes: Nb

- Dielectric coating: 200nm SiO2

- Frequency: 250 MHz – 1 GHz

- IDC:
  - Fingers 2μm wide, 2μm spacing
  - 32 Fingers total (~ 160 μm long)
  - Finger length: 1mm
  - Capacitance ~ 2 pF

- Inductor:
  - NbTiN ~ 6 pH / square
Probe devices by measuring forward transmission (S21)

-20 dB

V_{RF}

IQ Demodulator

LPF

ADC

I

Q

RT Amp

SiGe Amp

T = 4 mK

T_0 = 20 mK
Device response plots a circle in the IQ plane:

For the resonator with $f_{res} = 813$ MHz:

$$S_{21} = 1 - \frac{Q_r}{Q_c} \frac{1}{1 + 2i\delta x Q_r}$$

Fits yield:

$$Q_i = 1.0 \times 10^5$$
$$Q_c = 3.8 \times 10^6$$

Devices are undercoupled!
Shift in resonant frequency – Matches TLS predictions

\[ \frac{f_R - f_0}{f_0} = \frac{F \delta_{TLS}^0}{\pi} \left[ \text{Re} \left( \frac{1}{2} - \frac{\hbar \omega}{2 j \pi k_B T} \right) - \ln \left( \frac{\hbar \omega}{2 k_B T} \right) \right] \]

Lines are fits to:

- 335 MHz
- 813 MHz
- 1.10 GHz
Loss tangent fit over 28 resonators:

Very little change as frequency varies ~ 20%
Sonnet simulations indicate $F \sim 0.035$ for our geometry
$Q_{TLS} \sim 800$ for this amorphous SiO2
TLS saturates with increasing power – $T = 100$ mK
Observe decreasing Qi with temperatures.

Change in Qi with temperature
Internal Qi depends strongly on electric field and temperature

Weak Fields – TLS saturates as temperature increases

$$\delta_{TLS} = \delta_{TLS}^0 \tanh \left( \frac{\hbar \omega}{2kT} \right)$$

Under Bloch model TLS saturation condition

$$\Omega^2 T_1 T_2 \gg 1$$
$$\Omega = \vec{d} \cdot \vec{E} / \hbar$$

For SiO2 –

$$E_{critical} \approx 2.6 \left( \frac{f}{GHz} \right)^{3/2} \coth^{1/2} \left( \frac{hf}{2kT} \right) \left( \frac{T}{200 \text{ mK}} \right)^{0.75}$$

4 GHz, 200 mK: Ecrit \( \sim \) 30 V/m
500 MHz, 100mK: Ecrit \( \sim \) 1 V/m
Our fields \( \sim \) 10^3 V/m, well above critical field
Internal Qi depends strongly on electric field and temperature

Weak Fields – TLS saturates as temperature increases

\[ \delta_{TLS} = \delta_{TLS}^0 \tanh \left( \frac{\hbar \omega}{2kT} \right) \]

Under Bloch model TLS saturation condition

\[ \Omega^2 T_1 T_2 >> 1 \]
\[ \Omega = \vec{d} \cdot \vec{E} / \hbar \]

For SiO2 – \( E_{critical} \approx 2.6 \left( \frac{f}{GHz} \right)^{3/2} \coth^{1/2} \left( \frac{hf}{2kT} \right) \left( \frac{T}{200mK} \right)^{0.75} \)

4 GHz, 200 mK: \( \text{Ecrit} \sim 30 \text{ V/m} \)
500 MHz, 100mK: \( \text{Ecrit} \sim 1 \text{ V/m} \)
Our fields \( \sim 10^3 \text{ V/m} \), well above critical field
Measure noise as $S_{21}$ fluctuations

(I) Amplitude and Frequency ($Q$) components

- Decompose noise spectra ($S$) into parallel and perpendicular components
- Fractional Frequency Noise Spectrum

\[
\frac{S_{\delta f r}(v)}{f_r^2} = \frac{S_{||}}{16Q^2r^2}
\]

- Our devices – undercoupled ($Q_c/Q_r < 0.05$)
- TLS fluctuations not far above amplifier noise
- Phase noise $\sim 2-4x$ amplifier noise
- Measuring at internal powers not far below critical power in NbTiN
Fractional Frequency Noise Spectra - Power dependence

- Increasing power saturates TLS
- Observe near $P^{-1/2}$ dependence Indicative of TLS
- Observed from ~ 500 MHz – 1 GHz
Fractional Frequency Noise Spectra

- Increasing Temperature saturates TLS
- Observe $\sim T^{-2}$ dependence – characteristic of TLS
- Observed from $\sim 500$ MHz – 1 GHz
- Unusual slope is clear on temperature plot – usually $S_{\text{TLS}} \sim \nu^{-1/2}$

**Graphs:**

- $f_r = 537$ MHz, $P_{\text{read}} \sim -88$ dBm
- $f_r = 916$ MHz, $P_{\text{read}} \sim -84$ dBm

The graphs show the frequency spectra for different temperatures, with $S_{\delta f/r^2}$ plotted against frequency. The spectra are marked with different lines for $T = 20$ mK, $T = 100$ mK, and $T = 200$ mK.
Observed slope deviation from $\nu^{-1/2}$
- Operating about 10 dB below critical current – nonlinearities
- Severely undercoupled
  - Noise is large compared to radius of curvature
  - Phase noise is 2-4x amplifier noise
  - Mixing of I & Q components?

\[
\frac{S_{\delta f}}{f_r^2} (\text{rad/Hz}^2) = \frac{\epsilon_\parallel}{\epsilon_\perp} f = \frac{Q_r}{Q_c}
\]

$\nu = 916 \text{ MHz}$, $P_{\text{read}} \sim -84 \text{ dBm}$
FIR Applications:
• What is the TLS noise under conditions FIR detection?

\[ P_{opt} \sim P_{diss} \]
\[ P_{opt} = (\hbar \nu_{opt}) \Delta \nu \quad P_{diss} = \frac{\omega_{RF} E_{res}}{Q_i} \quad E = \frac{1}{2} CV^2 \]

Readout: \( Q_i \sim 10^5 \), \( \omega_{RF} \sim 100 \text{ MHz} \), \( C \sim 10 \text{ pF} \)
Spectroscopy: \( \nu = 300 \text{ GHz}, \Delta n = 0.3 \text{ GHz} - V \sim 1.3 \text{ mV} \)
Photometry: \( \nu = 300 \text{ GHz}, \Delta n = 100 \text{ GHz} - V \sim 25 \text{ mV} \)
$S_{TLS}$ versus applied voltage to IDC capacitor:

Fractional Frequency Noise

Calculated Capacitor Voltage $<V>$

$$S_{\delta f_r, TLS} < \frac{\beta^2}{4Q_i^2} \frac{(1+n)}{n\Delta \nu} \sim 10^{-17}$$
Conclusions

Measured TLS noise from 500 MHz – 1 GHz
• TLS noise may be suitable for FIR detection with RF readout schemes
• No clear readout frequency dependence noticed

Remaining goals:
• Measure over wider frequency range and lower powers
  • Improve coupling – measure at lower powers
  • Improve electronics – measure noise at lowest resonator frequencies
• More device geometries: Parallel plate, different size IDC, etc
Thanks

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Frequency dependence of response
Mattis-Bardeen: Surface impedance

\[
\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar \omega} \int_{\Delta} dE \frac{E^2 + \Delta^2 + \hbar \omega E}{\left(\sqrt{E^2 - \Delta^2}\right)\left(\left(E + \hbar \omega\right)^2 - \Delta^2\right)} \left[f(E) - f(E + \hbar \omega)\right]
\]

\[
\frac{\sigma_2}{\sigma_N} = \frac{1}{\hbar \omega} \int_{\Delta} dE \frac{E^2 + \Delta^2 - \hbar \omega E}{\left(\sqrt{E^2 - \Delta^2}\right)\left(\Delta^2 - \left(E + \hbar \omega\right)^2\right)} \left[1 - 2f(E)\right]
\]

High Qi’s and responses possible
Working at RF makes electronics simpler
Easily multiplex large number of detectors