Thin Film Fabrication of Quantum Upconverting Sensors for Dark Matter Detection

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Dark Matter is Out There!

- **Galaxy Rotation**
  - Observations from starlight
  - Expected from visible disk
  - From 21 cm hydrogen

- **Bullet Cluster**

- **CMB**
  - 4.9% Baryons (us!)
  - 26.8% Dark Matter
  - 68.3% Dark Energy
DM Radio tunes into dark matter waves

- DM Radio is optimized to search for wave-like dark matter: Axions and Hidden Photons
- Below 1 eV wavelengths are very long and the number density is big
  \[ \lambda_{\text{coherence}} \approx 100 \text{ km} \times (10^{-8} \text{ eV/m}) \]
- Lumped-Element resonators give us an advantage of an extremely wide tuning range from 1 kHz to 300MHz!
- Quantum Sensors will allow us to probe a swath of the QCD Axion band
Lumped-element approach can tune a huge range
DM Radio will detect or rule-out axions in big area
Building up the DM Radio for axion detection

Superconducting Shield
Building up the DM Radio for axion detection
Building up the DM Radio for axion detection
Building up the DM Radio for axion detection

Side View

Top Cutaway

Add a toroidal magnet inside for conversion of axions to photon fields
Building up the DM Radio for axion detection

Side View

B_0 toroid inside

Top Cutaway

B_0 dc circulating field
Building up the DM Radio for axion detection

A coupled axion will create an oscillating current parallel to $B_0$

$$\mathbf{J}_\alpha(t)$$

Side View

Top Cutaway
Building up the DM Radio for axion detection

$\vec{J}_a(t)$
DM Radio is a lumped-element dark matter detector
Now we have a harmonic oscillator driven by a dark matter signal.
Since this signal is small, we need to apply quantum techniques to sense it.
Let’s take a moment to look at LIGO for inspiration.
Laser Interferometer Gravitational-Wave Observatory

$\ell_y = 4 \text{ km}$

$\ell_x = 4 \text{ km}$

Gravity Wave
Two Sites for LIGO

LIGO
Hanford, WA

LIGO
Livingston, LA

3,000 km
Simplify LIGO to Get the Basic Physics

Detector

Laser

Gravity Wave
LIGO Exploits the Interplay Between Two Oscillators

Gravity Wave  Photons in Cavity

\[ \hat{H} = \hbar \omega_a (\hat{a}^\dagger \hat{a} + \frac{1}{2}) + \hbar \omega_b (\hat{b}^\dagger \hat{b} + \frac{1}{2}) + \hbar g \hat{a}^\dagger \hat{a} (\hat{b}^\dagger + \hat{b}) \]
We can borrow the lessons learned from LIGO and apply it to fabricated microwave circuits because the physics is the same!

Optical-Mechanical Resonator

Microwave Circuit Resonator

\[ \hat{H} = \hbar \omega_a (\hat{a}^{\dagger} \hat{a} + \frac{1}{2}) + \hbar \omega_b (\hat{b}^{\dagger} \hat{b} + \frac{1}{2}) + \hbar g \hat{a}^{\dagger} \hat{a} (\hat{b}^{\dagger} + \hat{b}) \]
Microwave Circuits Built with the Same Physics

- Dark matter excites a resonance (kHz – MHz) [red circuit]
- Couples to microwave resonator (GHz) [blue circuit]
- Up-conversion happens due to changes in flux through variable inductor (“moveable mirror”)

\[ \hat{H} = \hbar \omega_a (\hat{a}^\dagger \hat{a} + \frac{1}{2}) + \hbar \omega_b (\hat{b}^\dagger \hat{b} + \frac{1}{2}) + \hbar g \hat{a}^\dagger \hat{a} (\hat{b}^\dagger + \hat{b}) \]
LIGO as a Microwave Circuit Model for Dark Matter

“Laser Pump” — “Detector”

“Beam Splitter”

“Cavity”

“Moveable Mirror”

axion

DM Radio
Axion Detector
Initial Designs for RF Quantum Upconverter
Prototype Fabrication of RQUs

“Beam Splitter”

“Pump”

“Moveable Mirror”
Thin Film Fabrication for RQUs
Fabrication Layers for RQUs with Trilayer Oxidation

- High Resistivity Si Substrate
- High Purity Nb (200 nm)
- High Purity Nb (100 nm)
- High Purity Nb (200 nm)
- Insulator SiNx (350 nm)
- Top Wiring Nb (400 nm)
- Al-oxide
Conclusions

• RF Quantum Upconverters are based on the same physics from experiments like LIGO
• Low frequency oscillator (large occupation number state) coupled to a high frequency oscillator (small occupation number state)
• Thin film fabrication requires very clean environments, pure materials, and tight controls on the chemistry and energy of the deposition and etches.
• Stephen’s Talk will demonstrate the power of RQUs