Modeling Superconducting Microwave Resonators for Astronomical Photon Detection

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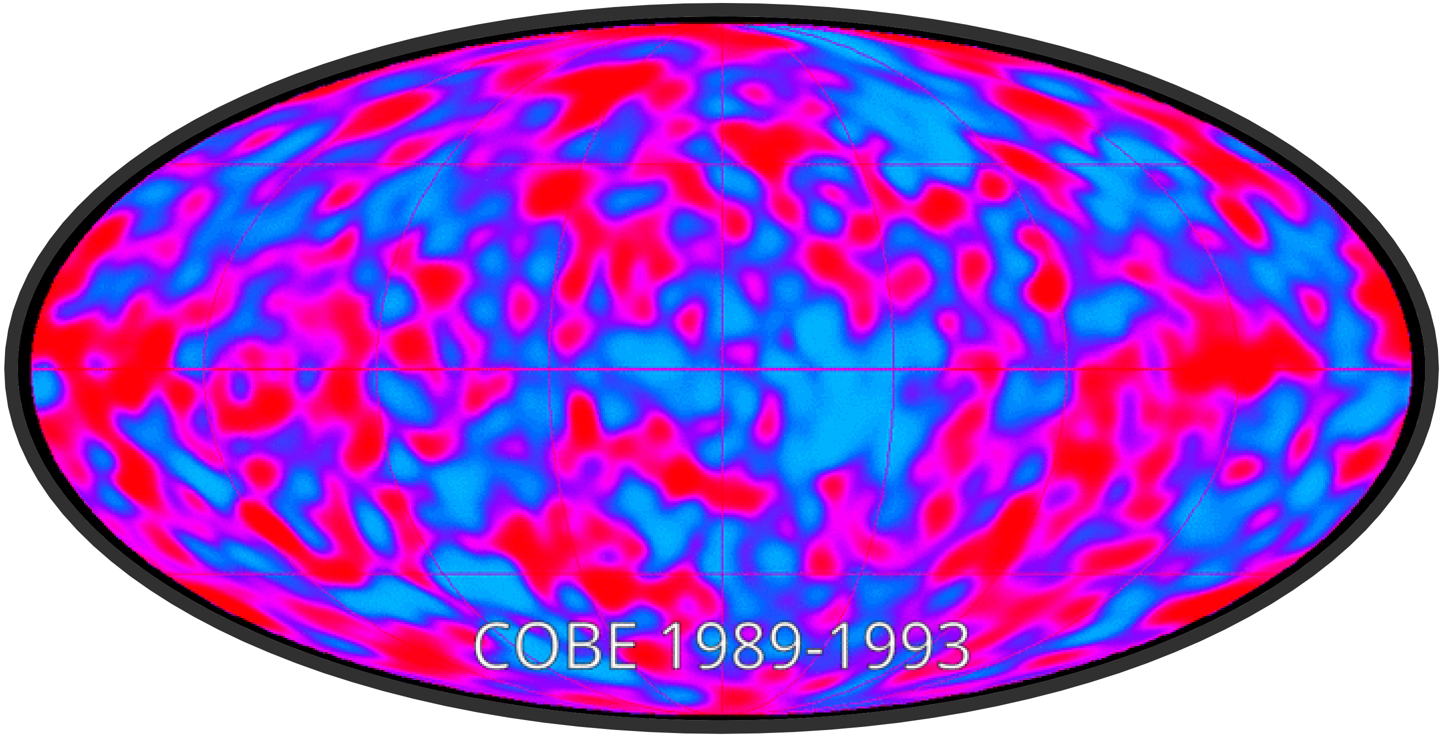
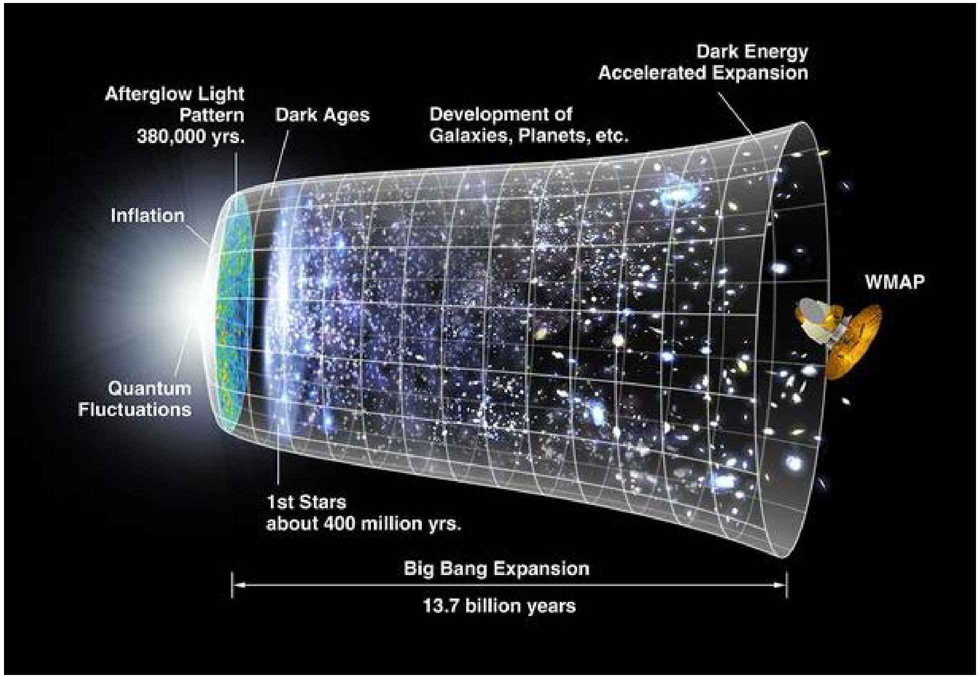
Cosmic Microwave Background (CMB)

Origins of the Universe



Cosmic Microwave Background (CMB)

Big Bang Model



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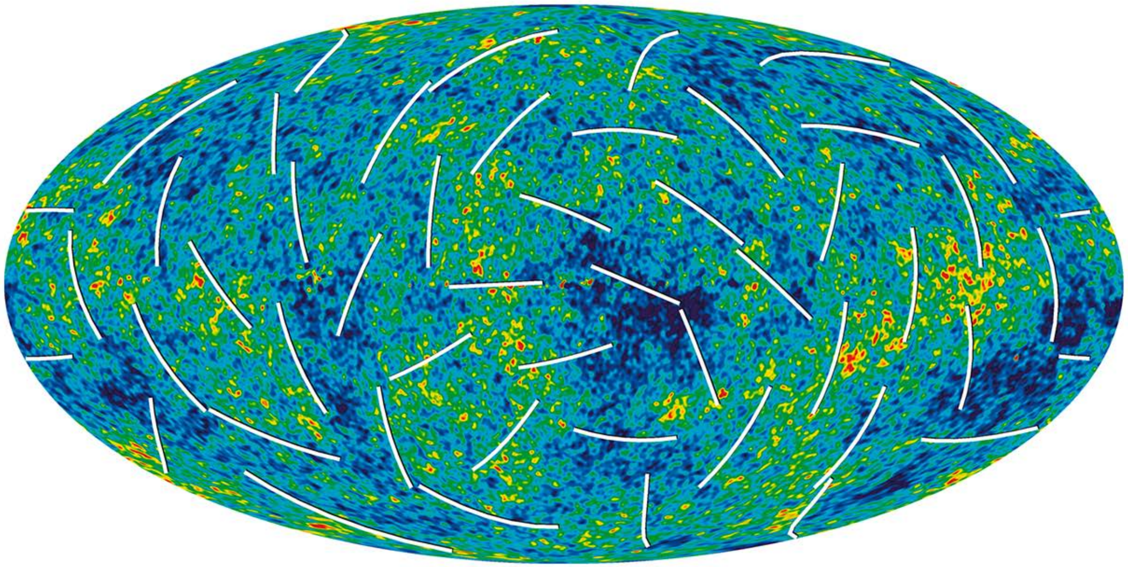
"The predominant theory of the origin of the universe is the Big Bang." - John Mather

Cosmic Microwave Background (CMB)

Polarimetry



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Detectors Used for Polarimetry

Requirements

- Must operate at sub-Kelvin (approximately 0.1K) temperatures
- Must have ability to be multiplexed into large arrays of similar detectors
  - Common feedline
- High sensitivity for photon detection

Microwave Kinetic Inductance Detectors (MKID)

Theory

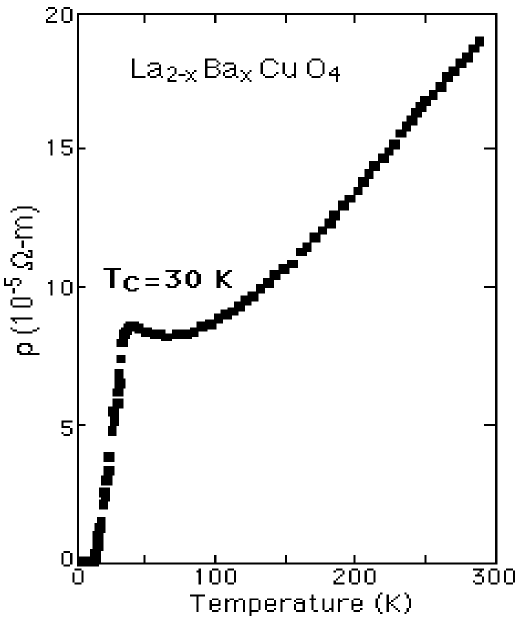
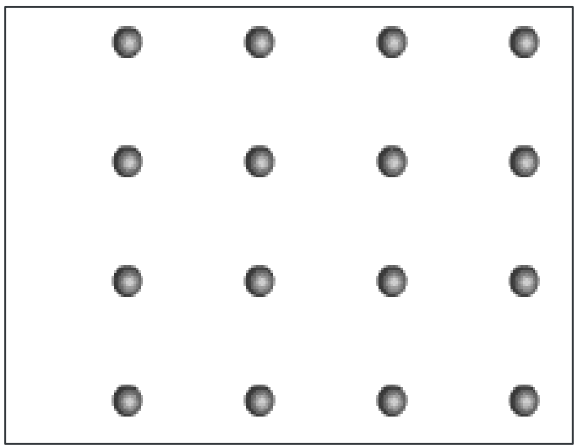


Figure 1. Plot of resistivity (ρ) against temperature (K)

H.K. Onnes 1911, http://ummalqura-phy.com/HYPER1/scex.html



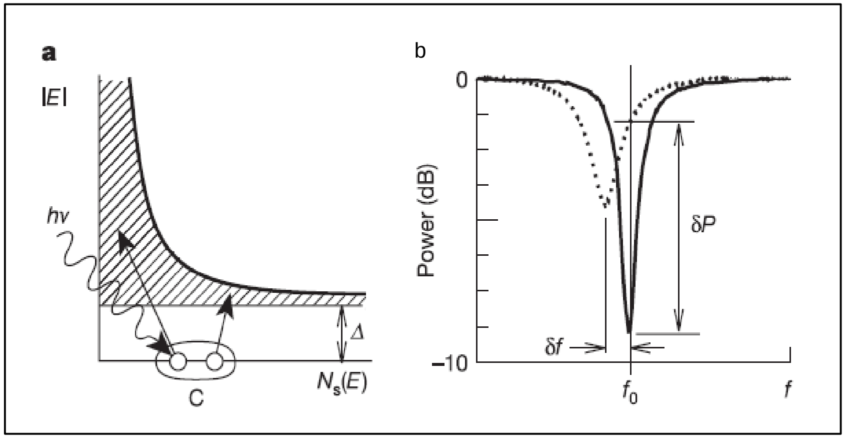
Microwave Kinetic Inductance Detectors (MKID)

Theory

Figure 4.

a) Energy level diagram of photon-Cooper pair interaction in a superconductor

b) Shift in resonant frequency (δ*f*) caused by breaking Cooper pairs



S. McHugh, et al., "A readout for large arrays of microwave kinetic inductance detectors", Review of Scientific Instruments, 83:4, 2012

Microwave Kinetic Inductance Detectors (MKID)

Design

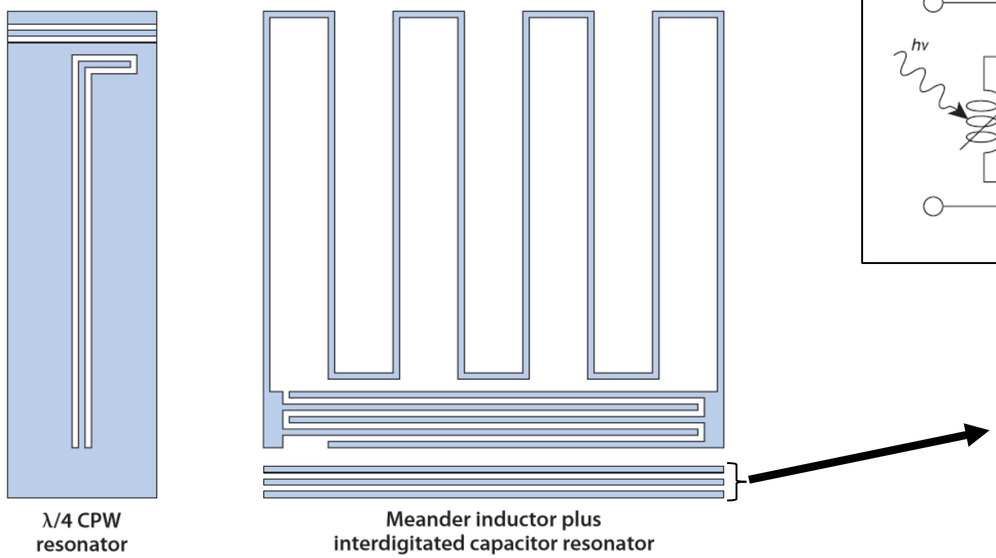


Figure 1. MKID Model Geometries: Distributed & Lumped Element

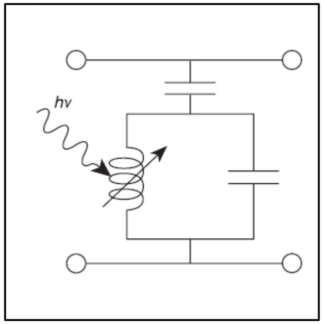


Figure 2. MKID realized as an LC circuit

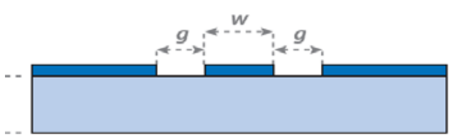


Figure 3. Cross-Sectional Diagram of a Coplanar Waveguide (CPW)[4] : The superconductor (dark blue) is on a dielectric substrate (light blue)

J. Zmuidzinas, "Superconducting Microresonators: Physics and Applications", Annu. Rev. Condens. Matter Phys. 3:169-212, 2012

Microwave Kinetic Inductance Detectors (MKID)

My Project Goals

- Use COMSOL Multiphysics ® to model superconducting MKID geometries
  - ➢ Compare results to other finite-element solver software (*HFSS*, *Sonnet*, *Designer*)
- Predict parameters of models in COMSOL Multiphysics ®
  - ➢ *Phase velocity, characteristic impedance, effective dielectric function*
- Determine if COMSOL is capable of properly modeling MKIDs for future CMB Polarization detection purposes

Microwave Kinetic Inductance Detectors (MKID)

COMSOL Microstrip Line Geometry

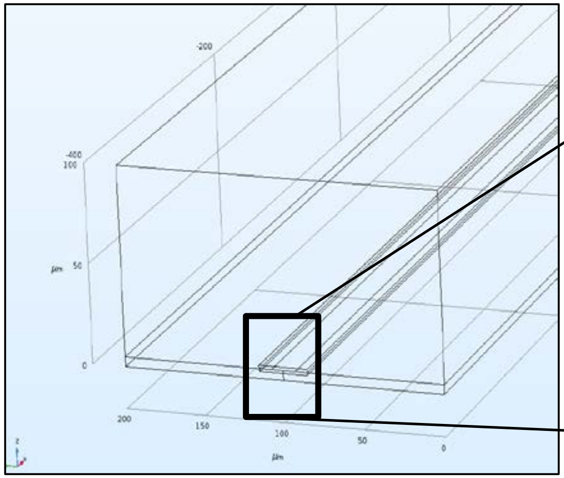


Figure 4. Microstrip line modeled in COMSOL

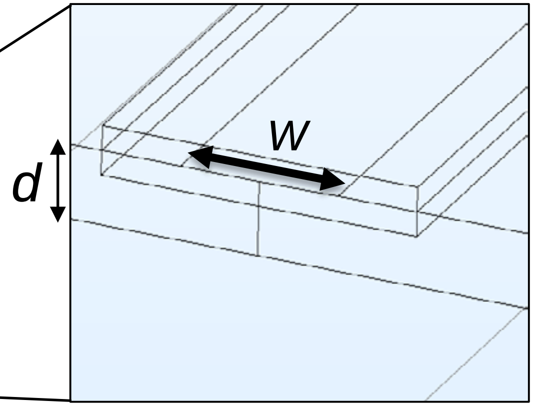


Fig. 4a. Close-up view of microstrip line geometry modeled in COMSOL, where *W* is the width of the microstrip line and *d* is the thickness of the dielectric substrate (silicon)

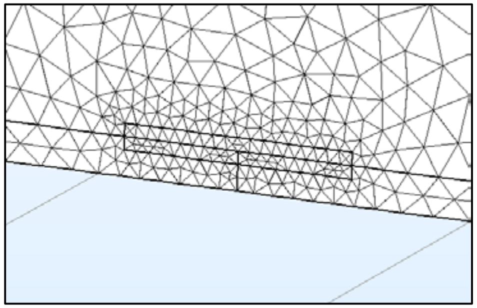


Figure 6. Mesh created in COMSOL

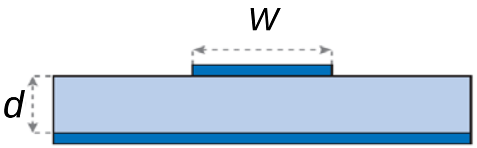


Figure 5. Cross-Sectional Diagram of a Microstrip Line : The superconductor (dark blue) is on a dielectric substrate (light blue)

Predicting Parameters of My Models

Microstrip: Characteristic Impedance

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_{r,e}}} \ln\left(\dfrac{8d}{W} + \dfrac{W}{4d}\right) & \dfrac{W}{d} \le 1 \\ \dfrac{120\pi}{\sqrt{\varepsilon_{r,e}}\left[\dfrac{W}{d} + 1.393 + 0.667 \ln\left(\dfrac{W}{d} + 1.444\right)\right]} & \dfrac{W}{d} > 1 \end{cases}$$

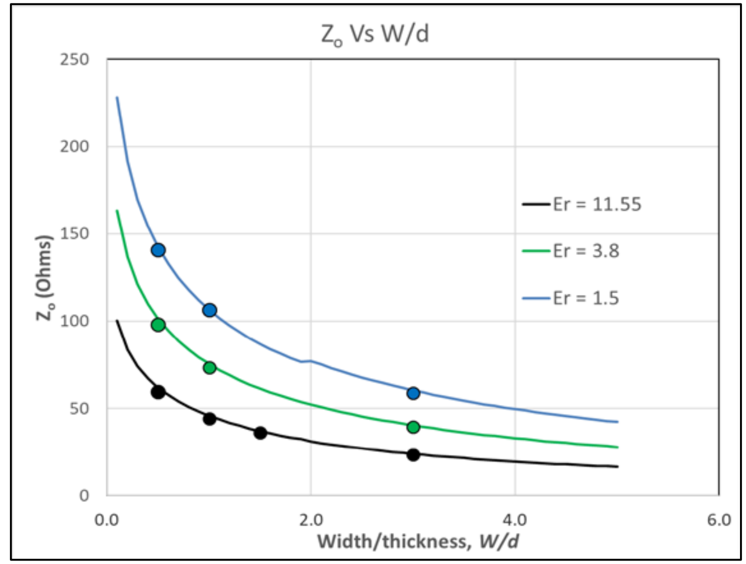


Figure 7. Characteristic Impedance, Z_o , is plotted as a function of microstrip line width to dielectric thickness ratio.

Predicting Parameters of My Models

Microstrip: Effective Dielectric Function

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + \frac{12d}{W}}} \right)$$

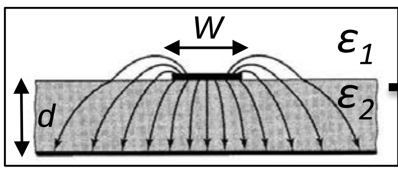


Figure 8. Field lines from a microstrip line with two heterogeneous dielectric substrates.

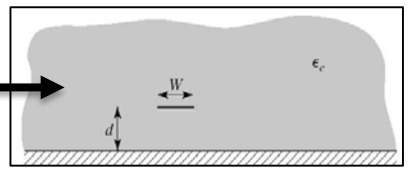


Figure 9. Homogenizing the two substrates into one effective dielectric function for static fields.

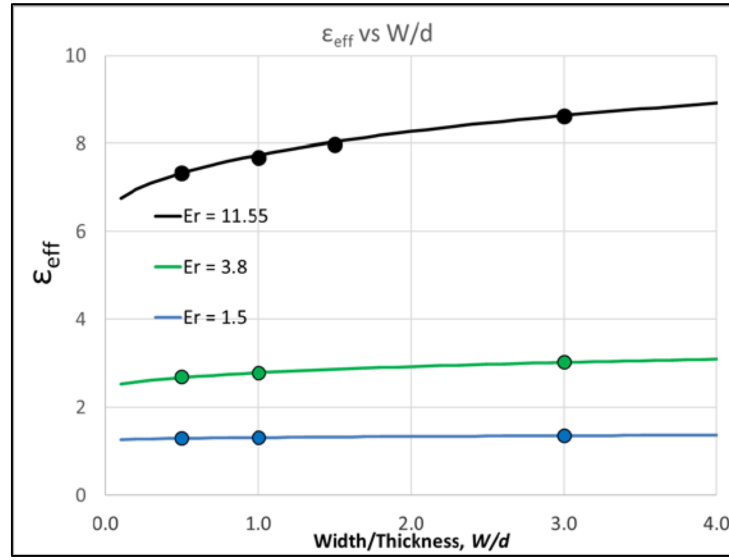


Figure 10. Effective permittivity, $\varepsilon_{eff,}$ is plotted as a function of microstrip line width to dielectric thickness ratio.

Microwave Kinetic Inductance Detectors

COMSOL Split-Ring Resonator: S-Parameters

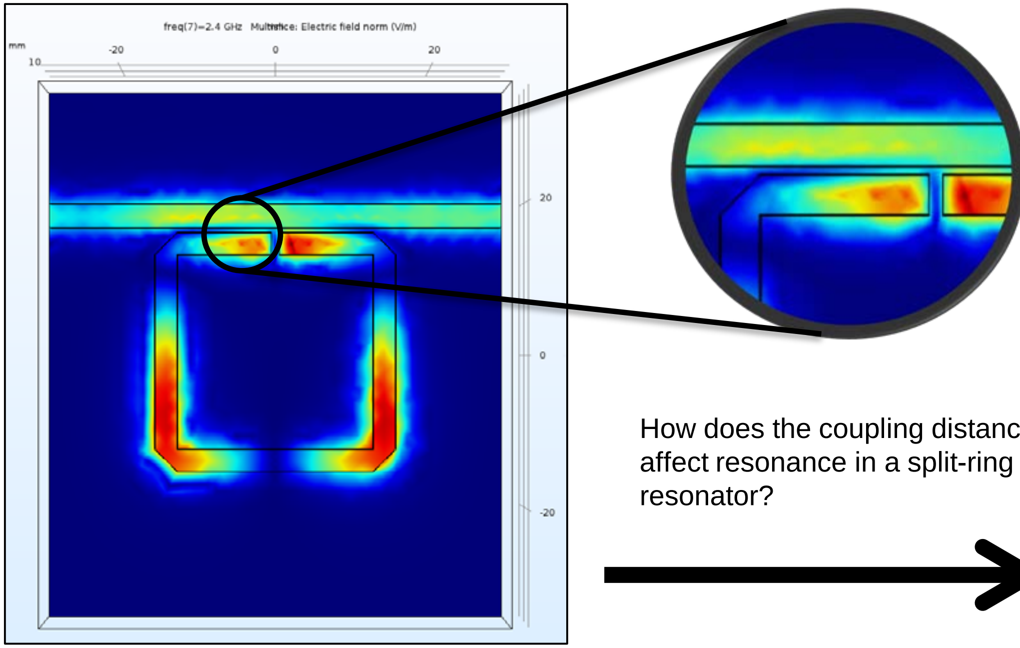


Figure 11. COMSOL Microstrip Split-Ring Resonator Model

How does the coupling distance affect resonance in a split-ring resonator?

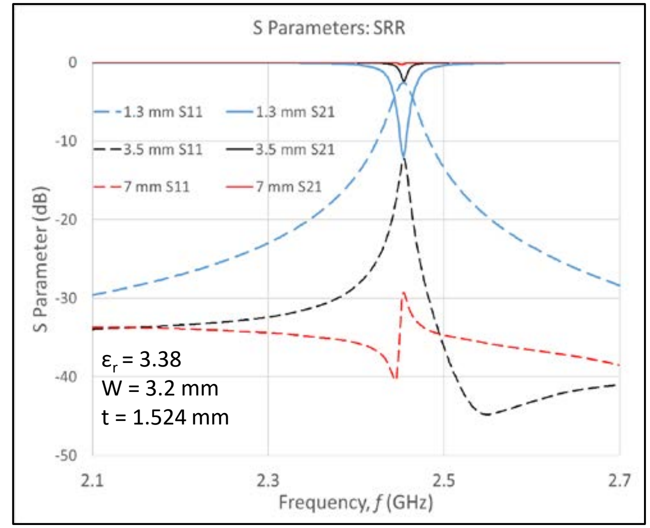


Figure 11a. S_{11} & S_{21} Parameters for a Microstrip Transmission Line Split-Ring Resonator

Conclusions

- Perfectly conducting microstrip lines and split-ring resonators were evaluated with COMSOL and compared to analytical expressions from the literature. Relative errors of few percent were observed.
- **Incorporation of superconductors** was identified as **an issue** in the current COMSOL RF module release and conveyed to the vendor. A new software release is planned for the fall of 2018 which would allow the correct boundary conditions to be applied for a superconducting model.
- Completion of the software evaluation for superconducting designs is anticipated before the new year

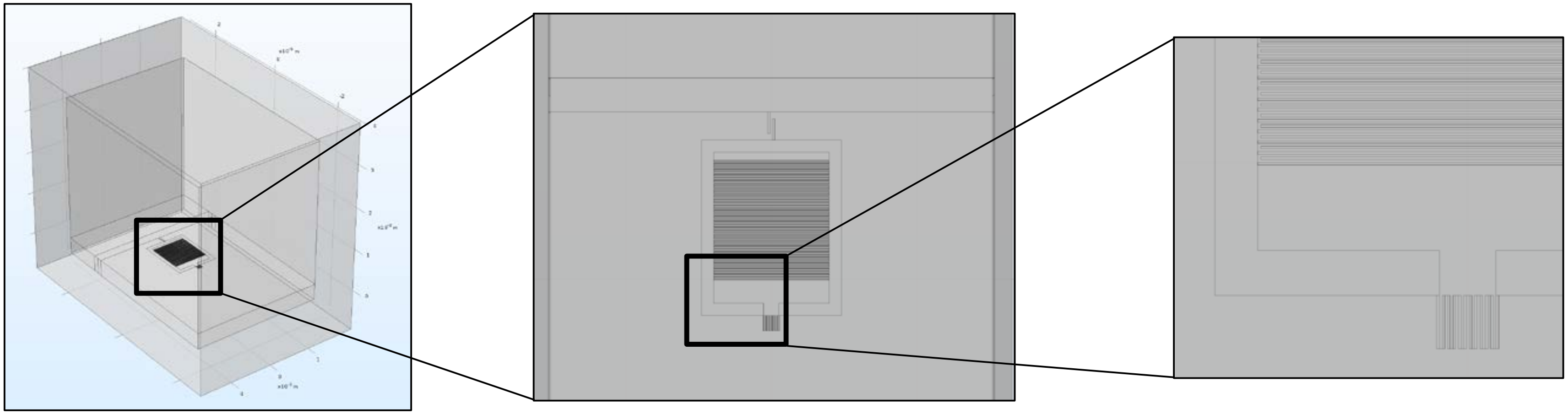
Thank You

Acknowledgements

- Society of Physics Students Summer Internship Program
- NASA GSFC
  - *Dr. Edward J. Wollack, Dr. Karwan Rostem, Dr. Kyle Helson, Marco Sagliocca, and Sophia Singh*
- Fellow SPS Interns

Extras

These wait until Fall 2018…

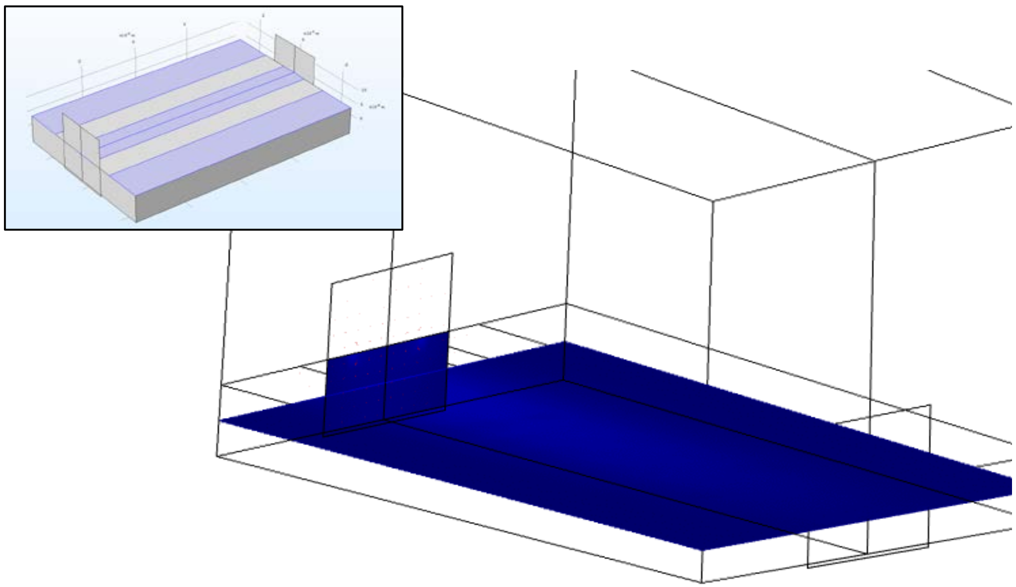


LC Circuit, Q = 20K, f_0 = *5.25 GHz*

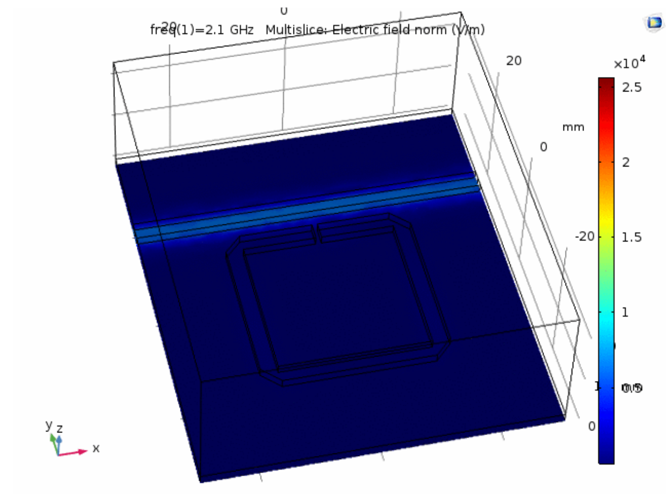
Extras

These wait until Fall 2018…

CPW, f_0 = *TBD*



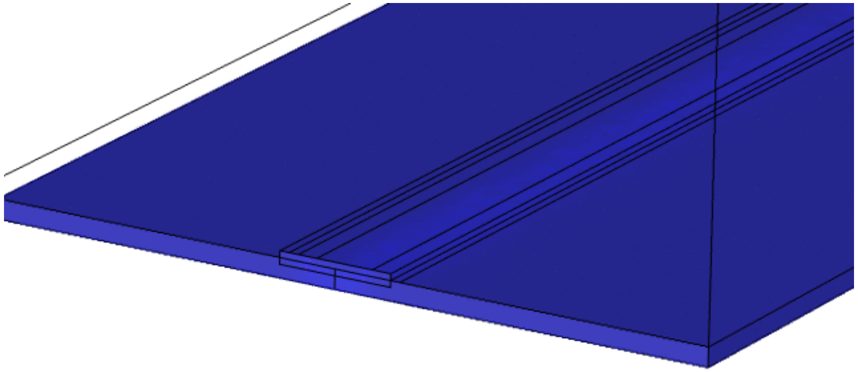
SRR's "breathing" E fields into them



Extras

These wait until Fall 2018…

Microstrip



Extras

J.I.C.

Polarization