Cryogenic Testing of Superconducting Resonators (SCR)

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Goal

The goal of this project was to construct a crogenic system that reaches sub 4K on the second stage, sub 300mK on the final stage and have a final stage that can mount a six inch detector wafer. Furthermore, we set out to test an MKID resonator given to us from Stanford in order to develop the code for determining the quality factors and resonant frequencies for the resonators within the detector. The purpose of the data is to determine the intrinsic quality factor of the Niobium detector sent by Stanford to determine its quality and performance. Lastly, the plan was to design and implement a circuit setup for characterizing the noise within MKIDs.

Applications of SCRs

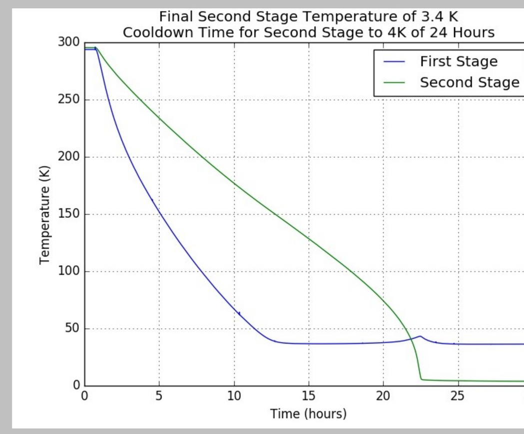
[1]Optics:
A growing technique in astronomical observations is the use of Microwave Kinetic Inductance Detectors (MKIDs) to detect radiation from various sources. As demonstrated in the power and temperature shift sections, an MKIDs response varies with temperature due to its superconducting properties. When a photon comes into contact with an MKID it locally heats up the location of impact and breaks local cooper pairs, and the same shifting of resonance and quality factor occurs. Some research groups are exploiting this phenomena to observe electromagnetic radiation. MKIDs can be created to be very small and then research groups can use large arrays of MKIDs, multiplex their output and analyze the data, essentially creating a highly sensitive camera for microwave radiation.

[2]Parametric Amplification:
The kinetic inductance is nonlinear for current through the device (quadratic in form as shown in the equation in the power shift section) and thus can be used as a parametric amplifier. Furthermore, the resonant frequency changes not only with temperature, but also with magnetic field through the device, and thus the resonant frequency of the parametric amplifier can be tuned via an input magnetic field.

[3]Quantum Computing:
Superconducting resonators have also been used as circuit examples of quantum systems in testing and investigating quantum computing. There is interest and hope in using superconducting resonators for quantum computing experiments.

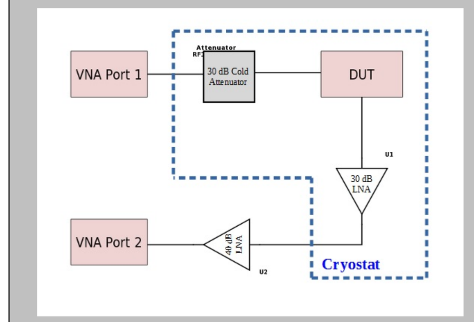
Cryostat and SCR Testing Setup

Cryostat Assembly with 4K Plate and Shell with 40K Plate

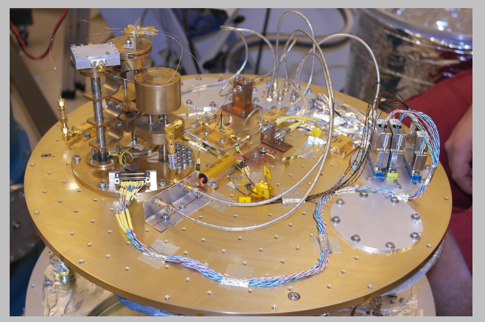


Cooldown Curve for Cryostat with Sorption Installed

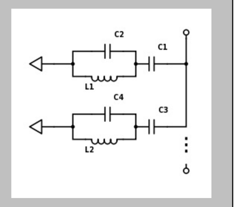
In order to reach our goal temperature of sub 4K on the second stage of the cryostat a lot of tweaking was needed. Multi-Layer Insulation was added to the outside of each part of the first and second stages (10 layers to first stage and 6 to second stage). The eight stainless steel struts for supports for the stages had to be thinned down from 2mm thick to 10 mil thick to decrease conductive heat loading. The 4K stage was gold plated to increase heat conductivity with the coldheads of the pulse tube and to decrease the emissivity of the second stage. Final results with everything installed, wired, and devices attached for testing on the second stage was a cooldown time of 30 hours and a final temperature of 2.25K on the 4K stage.



Circuit Schematic for Testing of Stanford MKID



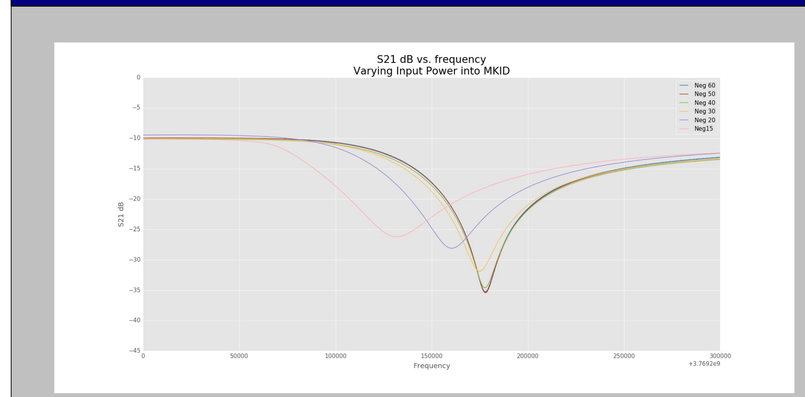
Setup of Stanford MKID on 250mK stage



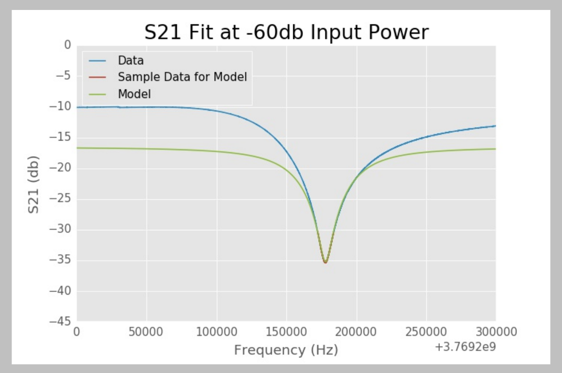
Circuit of Stanford MKID

Once the sorption fridge was reaching sub 300mK on its coldhead, an MKID resonator provided by Stanford was tested in the cryostat. The device is in the small, square, grey package attached directly to the coldhead in the upper left of the figure above. Data was collected for the resonance and quality factor shift due to changing temperature. The MKID was made of Niobium, which has a critical temperature for superconductivity of about 9K.

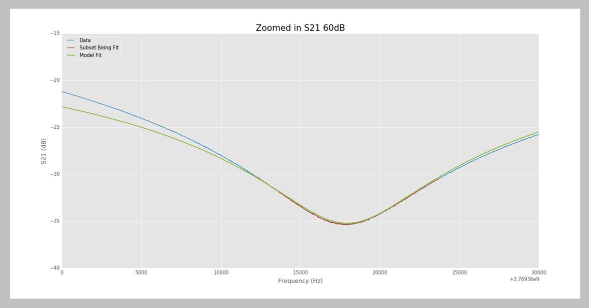
Power Shift



Graph of S_{21} vs. Frequency at Various Input Power



Curve Fit for S_{21} at -60 dB Input Power



Zoomed In On Curve Fit for S_{21} at -60 dB Input Power

$$L_k = L_{k0}\left(1+\frac{I^2}{I_o^2}\right) \qquad L_{K0}=\frac{ml}{ne^2A} \qquad w=\sqrt{\frac{1}{LC}}$$

L_k is the kinetic inductance of the material, and n is the number density of cooper pairs. As the temperature of the material is increased, the number density of cooper pairs decreases, therefore the kinetic inductance increases and subsequently the resonant frequency decreases.

$$S_{21}=1-\frac{Q_r/Q_c}{1+2iQ_r\dfrac{f-f_o}{f_o}}$$

Equation for S_{21} used in curve fits by varying f_o (resonant frequency), Q_r (resonant quality factor) and Q_c (coupling quality factor)

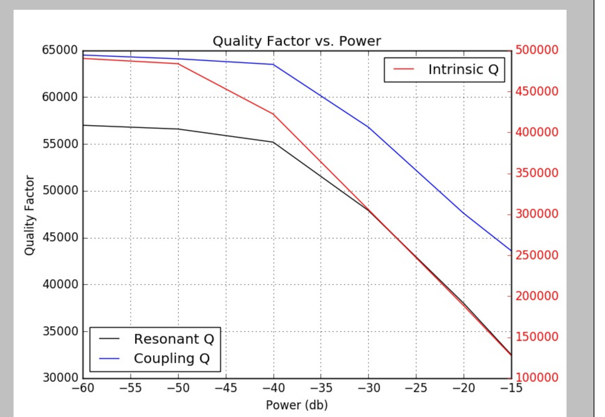
$$\frac{1}{Q_i}=\frac{1}{Q_r}-\frac{1}{Q_c}$$

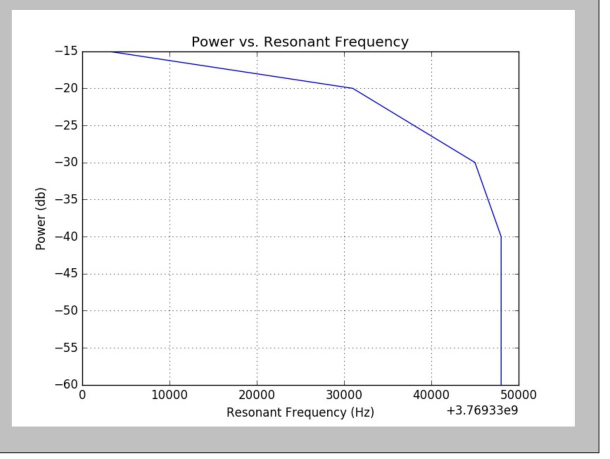
Equation to calculate Q_i (intrinsic quality factor) of resonator

[4]All equations from Dr. Phil Mauskopf's Paper

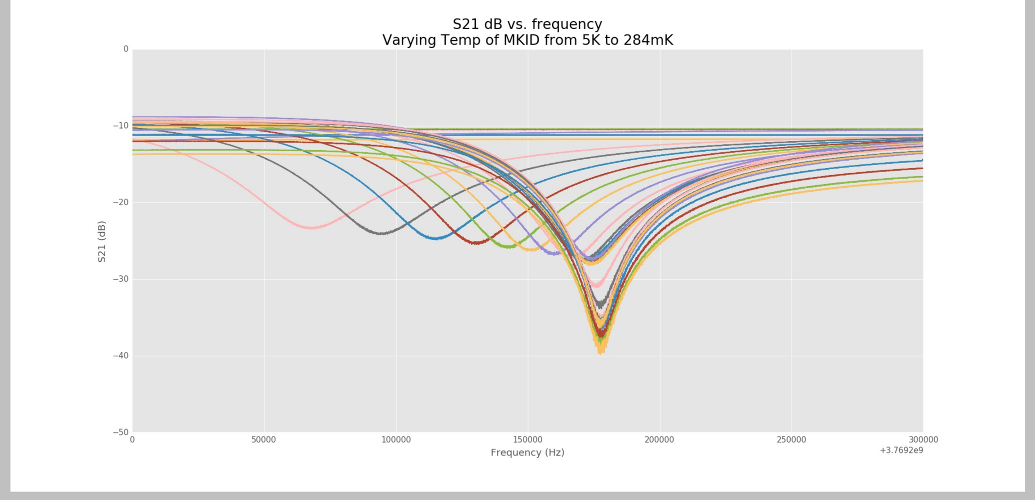
Power (dB)	Q_r (e4)	Q_c (e4)	Q_i (e4)	f_o (GHz)
-15	3.25	4.36	12.8	3.769332
-20	3.80	4.76	18.8	3.769360
-30	4.79	5.68	30.6	3.769375
-40	5.53	6.35	42.3	3.769378
-50	5.66	6.41	48.4	3.769378
-60	5.70	6.45	49.0	3.769378

Quality Factor and Resonant Frequency at Various Power

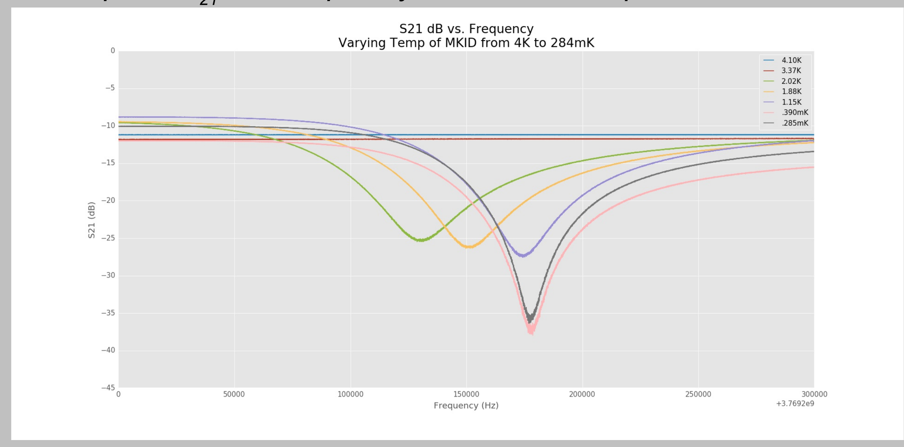




Temperature Shift



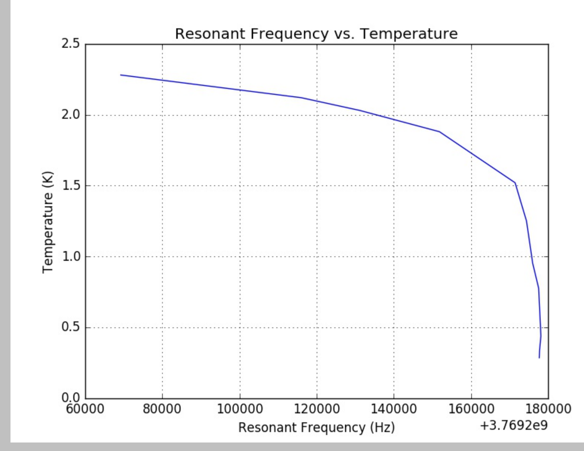
Graph of S_{21} vs. Frequency at Various Temperatures

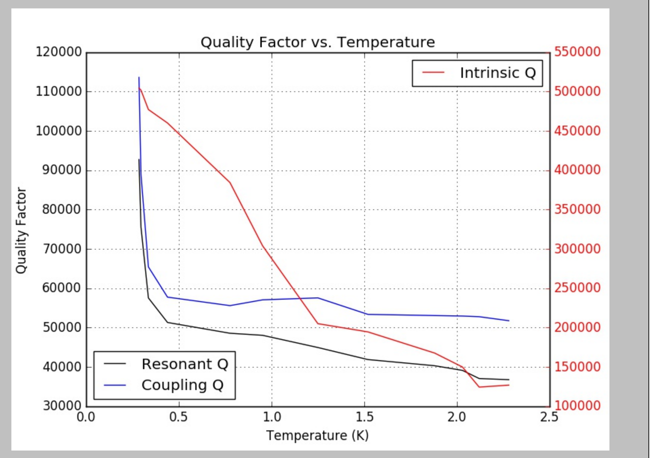


Graph of S_{21} vs. Frequency at Various Temperatures

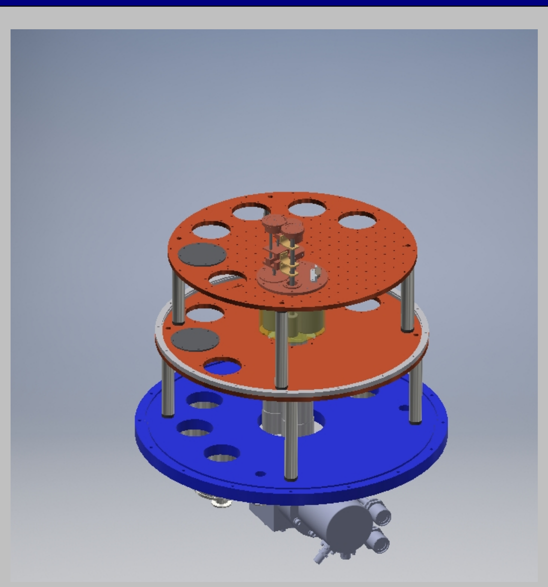
Temp. (K)	Q_r (e4)	Q_c (e4)	Q_i (e4)	f_o (GHz)
2.28	3.68	5.18	12.7	3.769269
2.12	3.71	5.28	12.4	3.769316
2.03	3.91	5.29	14.9	3.769331
1.88	4.03	5.31	16.8	3.769352
1.52	4.19	5.34	19.5	3.769372
1.25	4.49	5.76	20.5	3.769374
0.952	4.80	5.71	30.4	3.769376
0.775	4.86	5.56	38.4	3.769376
0.439	5.13	5.78	46.0	3.769378
0.336	5.74	6.55	47.7	3.769378
0.296	7.56	8.89	50.2	3.769378
0.285	9.27	11.4	50.5	3.769378

Quality Factor and Resonant Frequency at Various Temp.

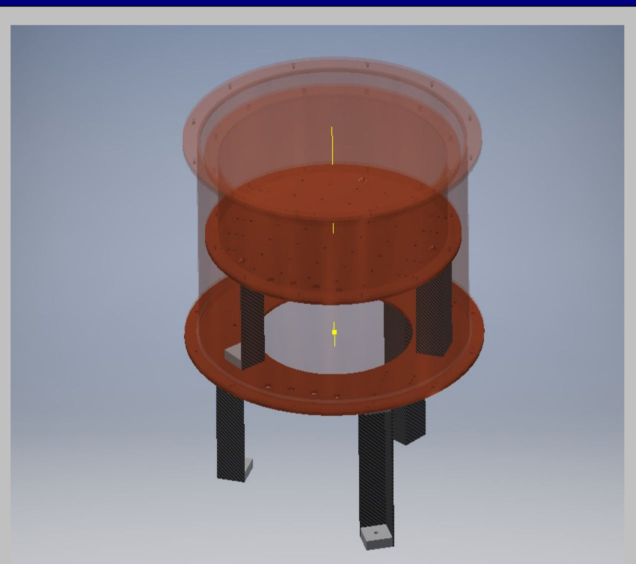




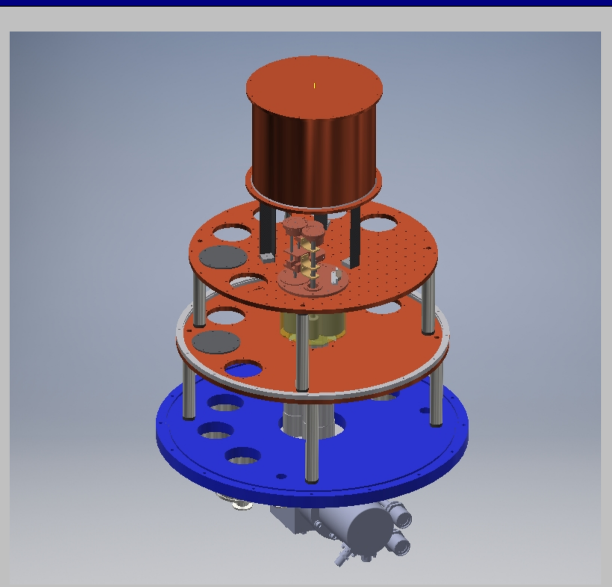
mK Stage Design



SolidWorks Model Full Assembly Without mK Stage



SolidWorks Model of mK Stage



SolidWorks Model Full Assembly With mK Stage

The mK stage is designed to be able to house a six inch wafer and be fully enclosed. The final temperature of the mK stage is 250mK, with a maximum heat load of 3μW. Carbon fiber is used for the supports due to their low heat conductivity and thermal expansion.

Next Steps

•Create Homodyne noise characterization setup (design is finalized, construction and testing currently in process)
•Construct and test the full mK Stage

References

[1] Zmuidzinas J 2012. Condens. Matter Phys. 3:169-214
[2] Tholén E A, Ergül A, Stannigel K, Huter C, and Haviland D B Nov 2009. cond-mat.supr-con
[3] Wallraff A, Schuster DI, Blais A, Frunzio L, Huang RS, et al. 2004. Nature 431:162–67
[4] Muaskopf P Accepted to PASP

Acknowledgments

• I would like to thank Dr. Mauskopf for giving me the opportunity to join his research lab and work on this project. None of this would have been possible without his generosity and leadership throughout my time in his lab. The opportunity he granted me has taught me a lot about performing scientific research and scientific instrumentation.
• I would also like to thank Hamdi Mani. Hamdi was instrumental in getting the cryostat up and running and taught me many lab skills including but not limited to soldering, wirebonding and coding.
• Lastly, I would like to thank Sean Bryan. He helped me greatly with the coding for the data analysis portion of the thesis.