

2024 SURF Final Report

Improving Phonon Collection Efficiency in Kinetic Inductance Detectors (KIDs) by Attaching Aluminium Fin Phonon Guides and Minimizing Phonon Loss with New Detector Mounts

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1 Abstract

The lack of evidence for weakly interacting massive particles above 10 GeV has prompted investigations into lower keV mass scales, where dark matter interactions produce energy depositions under 1 eV—too small for standard detection techniques such as scintillation or ionization. Phonon-mediated microwave kinetic inductance detectors (KIDs), which are thin-film superconducting microwave resonators featuring an interdigitated capacitor and a meandering inductor, are effective for detecting these low-energy interactions. KIDs detect dark matter by capturing the energy deposited into the substrate from dark matter particle collisions. This energy generates phonons that disrupt Cooper pairs within the resonator, increasing the inductance and lowering the resonance frequency.

This project aims to improve phonon collection efficiency in KIDs, currently below 1%, through two main strategies: adding thin-film quasiparticle-trapping aluminum fins to maximize phonon collection area and guide phonons into the resonator, and redesigning the KID box mount to reduce phonon loss. We use Sonnet, an electromagnetic simulation software, to test and analyze these improvements along with circuit geometry modifications, focusing on current density distributions and changes in resonant frequency and Q factor. The redesigned box features a new mounting configuration with wire bonding to minimize phonon loss through surface area and provide thermal connection, ensuring effective thermal anchoring and enabling the detector to reach the low temperatures required in the cryogenic refrigerator.

2 Objective

Our project aims to increase the phonon sensitivity of the Kinetic Inductance Detectors (KIDs). We plan to do this in two ways: attaching thin-film aluminum fins onto KIDs and redesigning the O-ring mount on the KID box. Attaching thin-film aluminum fins onto the KIDs will be done by designing fins in Sonnet and attaching them to the simulated chip, and then running circuit simulations to understand the current density across the chip with fins attached, as well as evaluating the resonance frequency and quality factor of the chip as the fins are varied. Redesigning the O-ring mount on the KID box involves understanding wire bonds and using SolidWorks to design a new mounting orientation for the KID in the cryogenic refrigerator.

3 Introduction

The rotation curves in spiral galaxies as well as the Bullet Cluster provide strong support for the idea that the universe's matter density is dominated by dark matter. Theoretical physicists have proposed many candidates for dark matter, including the quantum chromodynamics (QCD) axion, a weakly interacting massive particle (WIMP), a "hidden sector", or perhaps something else.

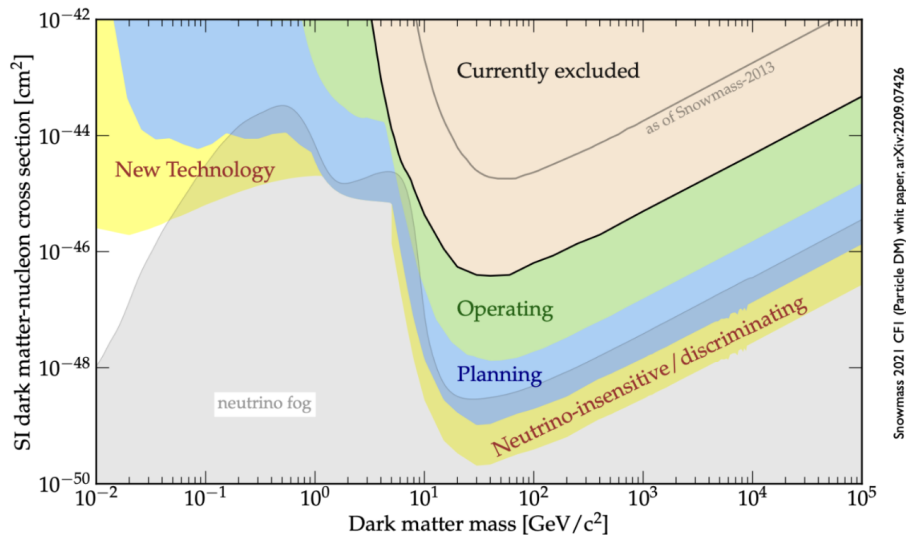


Figure 1: *This graph compares the dark matter cross-section in cm^2 and the dark matter mass in GeV/c^2 of particles that older, operating, and new technology can detect.*

So far, experiments searching for WIMPs greater than 10 GeV mass scales have found no evidence for such particles, motivating searches down to the keV mass scale, which is the limit from cosmology for thermally generated, fermionic dark matter. The expected energy depositions of these particles are less than 1 eV, which does not provide enough energy for scintillation or ionization. Therefore, new devices must be phonon-mediated to measure the vibrations caused by the dark matter colliding with a substrate. Thus, we propose

that the phonon-mediated microwave kinetic inductance detectors (MKID) using the kinetic inductance (KI) effect will be effective in searching for sub-GeV dark matter.

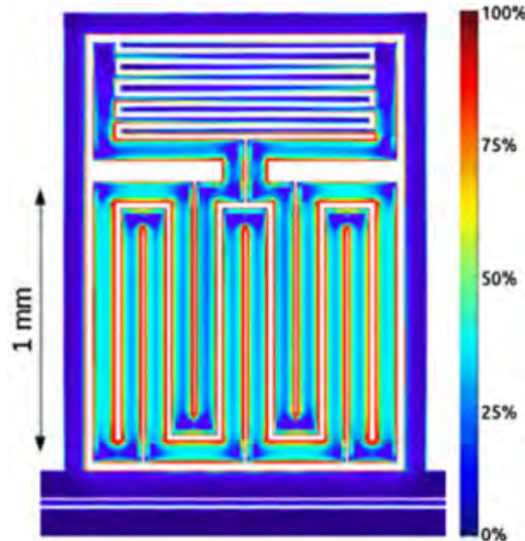


Figure 2: *KID design. The current density is shown through the color scale.*

KIDs are microwave LC resonators with a superconducting capacitor and inductor piece. When dark matter collides with the detector, the energy deposition into the substrate generates phonons, which propagate through the substrate and disturb Cooper pairs within the resonator.

As phonons move at a certain frequency, they encounter inertia of the Cooper pairs, known as kinetic inductance, which is directly proportional to the density of Cooper pairs. Therefore, a decrease in the number of Cooper pairs results in higher inductance and a lower resonance frequency, measured by $\frac{1}{2\pi\sqrt{LC}}$. Additionally, the experiment has to be shielded and conducted in a dilution fridge at 50 mK because KIDs must be operated around below their superconducting transition temperature, which is 1.2 K for aluminum, as well as to block blackbody radiation.

4 Methods and Approach

The energy resolution of the KIDs determines the lower limit of the energy detection spectrum, so we aim to decrease noise and increase phonon collection. Our original plan for SURF was to implement the Kinetic Inductance Traveling Wave Parametric Amplifier (KI-TWPA) from JPL for noise reduction and signal amplification, but due to our fridge breaking, we changed our focus on increasing phonon collection.

Currently, the phonon collection efficiency is around 1% of the input energy, and we would like to improve this by attaching thin-film aluminum fins onto the KID and redesigning the O-ring mount on the KID box.

The only part that carries cooper pairs in our detector is the inductor of the KID, so by adding thin-film aluminium fins that do not carry much current, we expect to see the

phonons to "bounce off" the fins back into the inductor rather than break cooper pairs or get lost to heat.

Additionally, with multiple design analysis of successful KIDs, it seems that the low phonon collection efficiency is not due to the actual KID design but rather the mounting, which is a gold plated copper box that surrounds the KID inside the dilution fridge. The silicone chip with the KID sits on the gold plated copper, which is a great conductor, so we theorize that the generated phonons are absorbed into the box rather than the inductor of our KID. Therefore, by changing the O-ring mount to wire bonds, where the KID hangs from its box rather than touching it, we hope to see an increase in phonon collection efficiency.

5 Acknowledgement

Thank you so much Brandon, Osmond, and Professor Sunil for guiding us and being a great mentor throughout the summer. I learned so much about KIDS and dark matter but also was able to grow as a person. I appreciated the kind explanations, unlimited encouragement, and constant support, making this summer an excellent time and experience for me.

Thank you to everyone in Cahill for making our work and lab environment so inclusive and encouraging.

Thank you Emily for being such a fun partner to work together with.

6 Progress

During the first month, we conducted a literature review on relevant work on KID readout design, resolution measurements, and KIPM-Detector development to grasp the background and purpose of our new SURF project. We dedicated time throughout the second week to work through SolidWorks Tutorials, and we started running Sonnet simulations of our KIDs with multiple different step-sizes, making plots to find the Q factor and f_r , the resonant frequency. However, the simulation took multiple days to run due, so we worked on implementing a new 3 port method requiring less computational power.

The main challenge of our SURF so far has been this 3 port method, which does not directly calculate the Q factor and resonant frequency and instead requires further calculation from the Sonnet simulation data. Our main source of this method is a single paper that has some instructions not specific to our device, so we resorted to online research and reading through Sonnet documentation. However, Sonnet is not a commonly used software, so most of the progress was made through experimenting with the settings in the program searching for similarities in our data and plots to those in the paper. From there, we extracted the f_r from the plots and used the following equation to find the Q factor

$$Q = \frac{kf_r}{2R}.$$

Over the second month, we worked on Sonnet simulations. We tested new inductor designs after attaching aluminium quasiparticle trapping fins to either side of the inductor. There were two designs of the fins, one resembling whiskers and one simple rectangle shape as shown in Figure 3.

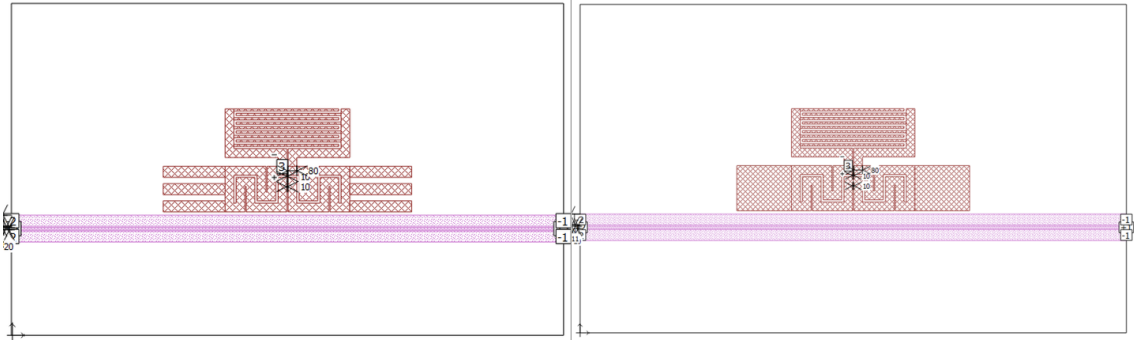


Figure 3: The left design reduced the distance between the capacitor teeth by 3 while increasing the , and the right design increased the number of capacitor .

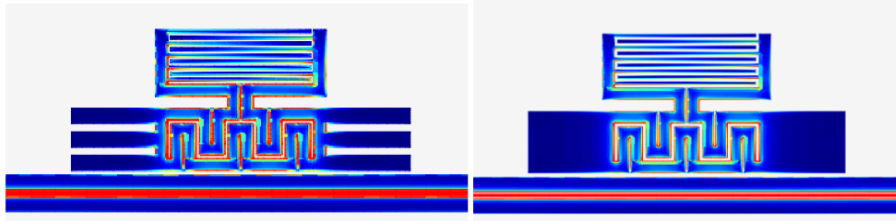


Figure 4: This figure shows the current density plot of the KID with the whiskers design on the left and the rectangle design with 412 nm by 560 nm quasiparticle trapping aluminium fins on either sides of the inductor. These plots have been generated at resonant frequency without the third port.

With the original KID inductor design without the waveguide around the KID, the whiskers design current density plots showed that the fins acted more as a capacitor, so we are only testing new designs with the rectangle fins. We actively used the 3-port method to find the resonant frequency and Q factor for the various inductor designs, but adding a new port into the KID seemed to affect the current density symmetry, so we ran an extra single frequency sweep at the resonant frequency to gather the current density plots.

To decrease the noise, we can decrease the volume of the inductor, but this change would case a change in the resonant frequency (f_r) as seen in the equation below:

$$f_r = \frac{1}{2\pi\sqrt{LC}}.$$

However, the detector is a thin film, so $L = L_{sq} \frac{length}{width}$. Then, we can change the length and the width of the inductor and still keep the same inductance. Therefore, we edited the shape of the KID by decreasing the width and the length by multiple different factors.

We gathered the resonant frequency and Q factor data for cases with and without fins and/or meanders as shown in the table above.

Even for the cases with where the inductance remains the same, there were changes in the resonant frequency. Additionally, 5.18511 was the largest factor that we can decrease the length and width of the inductor while keeping the shape of the rectangular fins (412 by 560 nm). This inductor resembles the shape of the KID in Figure 4.

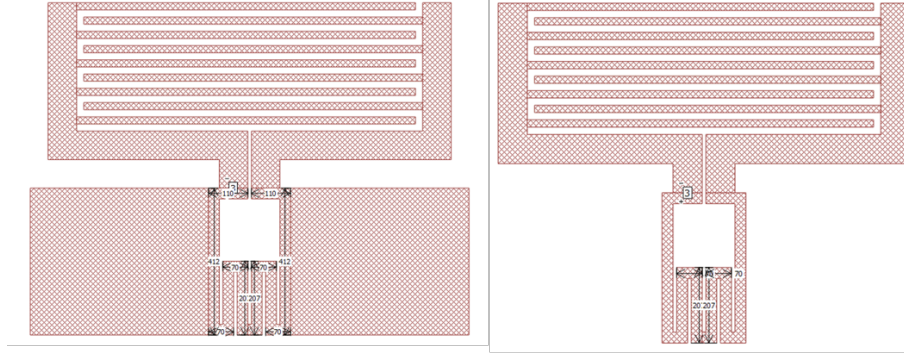


Figure 5: This figure shows the KID design with meanders for the 2.67 factor change in both length and width with and without the fins.

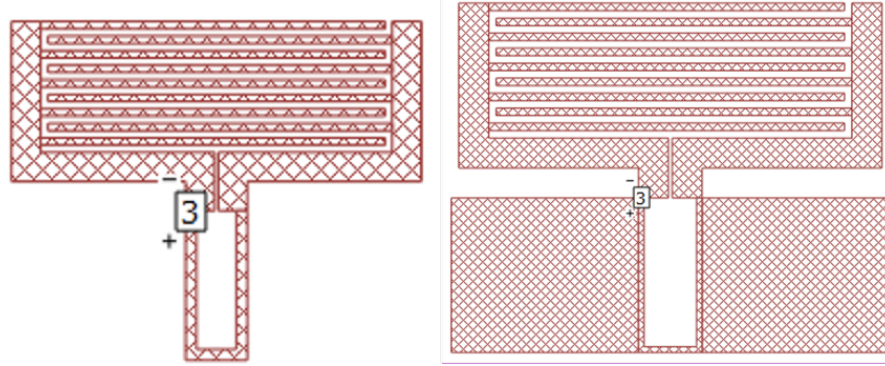


Figure 6: This figure shows the KID design (U-shape) for the 4 factor change in both length and width with and without the fins.

reducing factor	with vs without fi fin: ideal vs actu with fin			ideal f_r with fins	f_r with fins	<-- Q factor	without fin	f_r without fins	<-- Q factor	width	length	same factor?
1	-0.78%	0.00%		5.029983278	5.029983278	166680.298		4.9911503	239077.9808	80	4994	yes, meanders
2	-3.42%	-13.63%		5.029983278	5.715338207	312433.5415		5.526127146	774084.2782	40	2497	yes, meanders
2.67	-5.15%	-25.67%		5.029983278	6.15061005	496289.6515		5.849334895	2182028.476	30	1870	yes, meanders
2.67	-7.17%	8.64%		7.117776174	6.502996563	442325.9798		6.067880651	1551713.317	30	934	no, u-shape
4	-1.13%	-26.54%		5.030990786	6.366102717	453380.8883		6.294863516	711220.2757	20	1248	yes, meanders
4	-5.19%	-8.62%		5.754222187	6.250116292	1411381.58		5.94146921	3691387.035	20	954	no, u-shape
5.18511	-11.81%	-25.67%		5.029983444	6.321257671	109035.7034		5.6535054	1068341.11	15	963	yes, u-shape
8	11.32%	-34.37%		4.026858214	5.411062622	1179683.371		6.10146072	265573.5293	10	974	no, u-shape

Figure 7: This table organizes the percent change in resonant frequency, resonant frequency and Q factor with and without fins, the length and width of the inductor, and the shape of the KID.

Therefore, we are now trying two different methods: adding meanders and changing the inductance, or adding meanders while maintaining inductance and bringing down the KID closer to the feedline.

During this process, we struggled to show the current density of these simulations, but

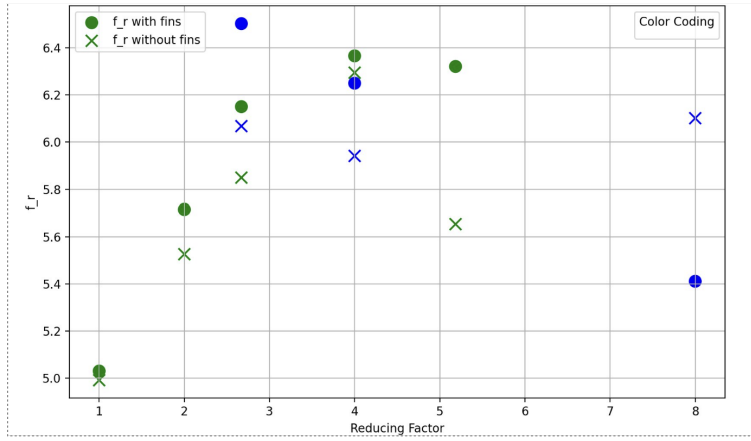


Figure 8: Plot of f_r with and without fins with different reducing factors.

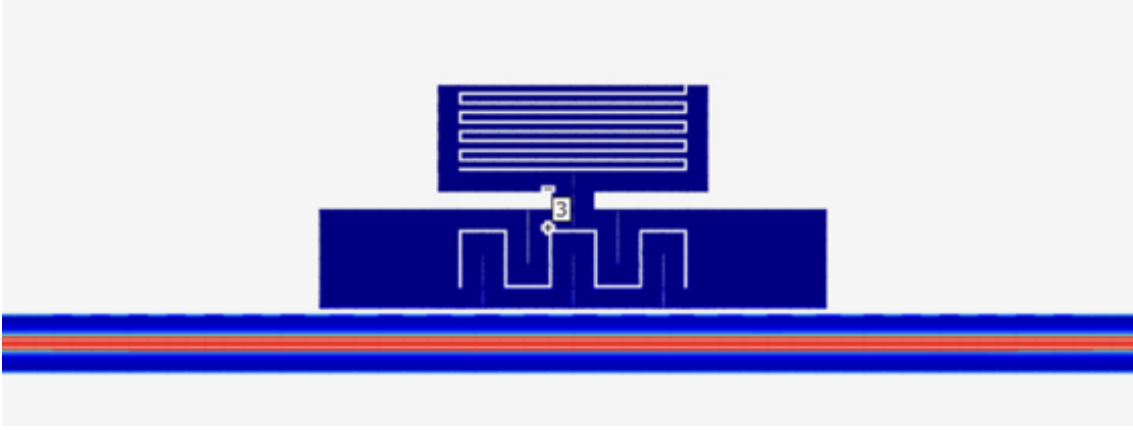


Figure 9: Notice the bright red signal line versus the dark blue KID, indicating the large difference in current density.

with the help of our mentors and other members of the Caltech community, we learned that the automatically set range of magnitude of the current density plot was too large for the smaller changes in current within the inductor due to the large difference between the current flowing through the signal line versus the circuit. After decreasing the range to 0 to 10, we were able to see the current density plots.

Additionally, we made changes in the capacitor design. We worked on two designs of the fins, with 2 additional capacitors as shown in Figure 10. Both designs has two more capacitors on the left and right side of the inductor. To maintain capacitance, we tripled the number of interdigitated capacitor teeth from 9 to 27. The right design has the distance between the interdigitated capacitor teeth decreased by a factor of 3 from 20 μm to 6 μm . The left design of the increased capacitor KID allows us to use the capacitor as quasiparticle trapping fins.

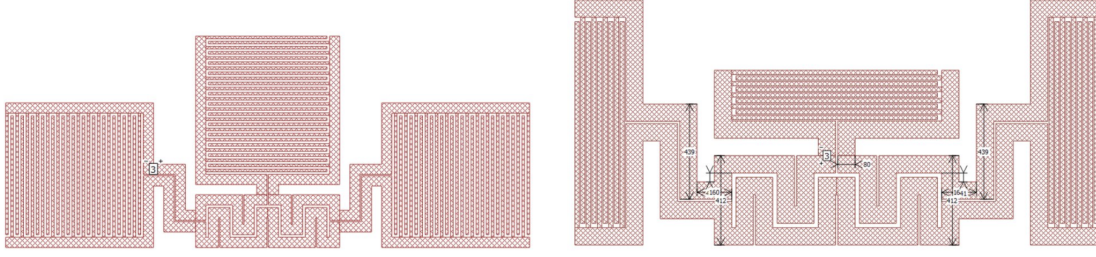


Figure 10: *The left design has triple the number of inter-digitated capacitor teeth, and the Right design has 3x smaller distance between each teeth.*

We also ran Sonnet simulations to find the current density plots of the new capacitor KID designs, and the results are as follows:

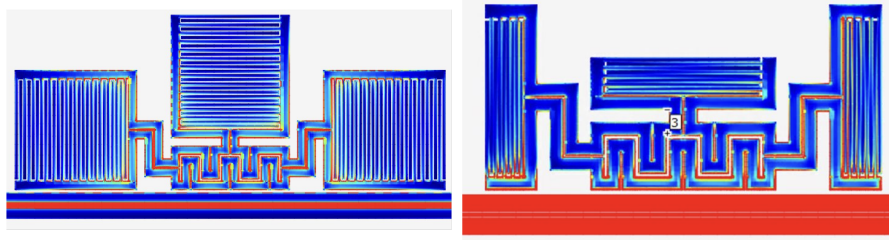


Figure 11: *This figure shows the current density plot of the KID with the additional capacitors. These plots have been generated at resonant frequency without the third port.*

In addition to the changed capacitor design, we also changed the inductor design and used the 3 port method to find that the resonant frequencies as shown in Figure 12.

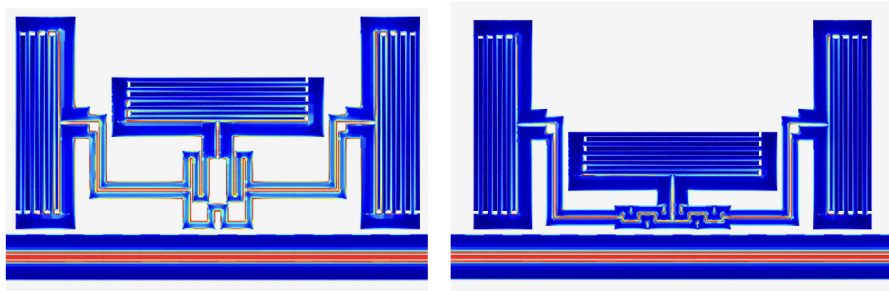


Figure 12: *We decreased the meandering inductor length by 2 for the left design, resulting in f_r of 5.238 GHz. We decreased the length of the meandering inductor by 2 for the right design, resulting in f_r of 5.563 GHz.*

However, while running simulations, we saw that the real component of the input impedance at port 3 wasn't linear as we assumed. This raised the concern whether our 3 port method is accurate, so we ran the 3-port method and our original 2 port method on the original KID design without the waveguide to find results shown in Figure 13.

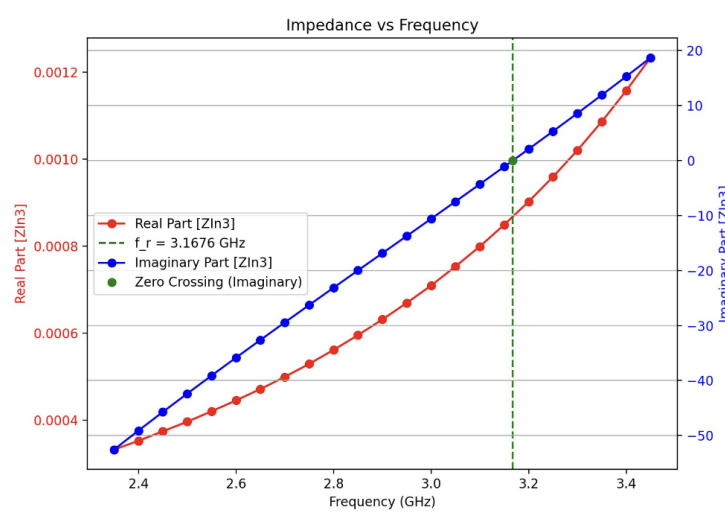


Figure 13: *The real component of impedance is nonlinear. Notice how the step size impacts the calculated Q factor.*

With the graph below, we can verify that the resonant frequency found through the 2 port and 3 port method is the same.

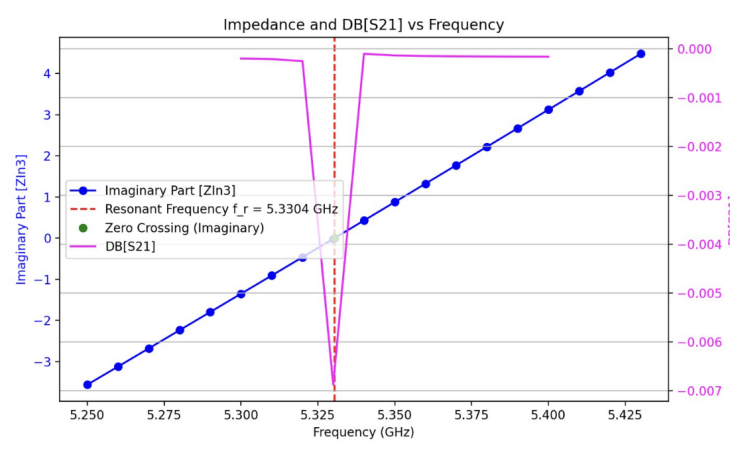


Figure 14: *Notice how the peak of the pink graph (s_{21} transmission) is located where the red dotted line (showing where the blue imaginary part of input impedance at port 3 crosses 0).*

The second part of our SURF project is working on the KID box mount and adding wirebonds. We modified parts of the original box design as well as making a new detachable supporting plate to secure the KID while wire bonding. Our first iteration of the box design is as follows, but there were concerns about the chip not being secured to the holder while wirebonding.

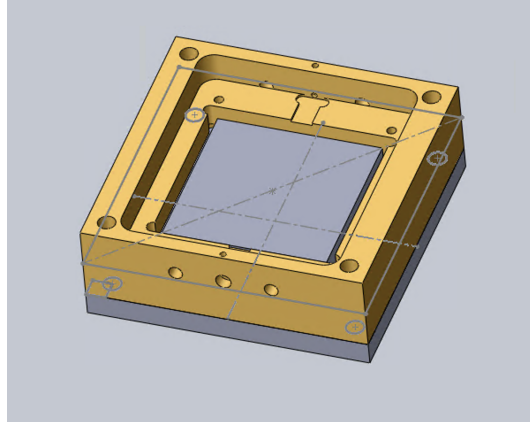


Figure 15: *The yellow part is the original gold plated copper mount of the KID. The gray part is the detachable supporting plate for the wire bonding process.*

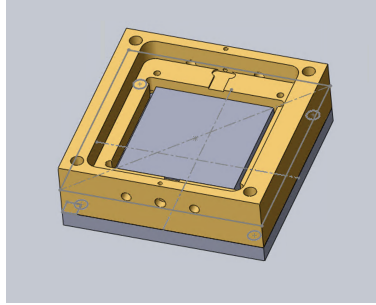


Figure 16: *The yellow part is the original gold plated copper mount of the KID. The gray part is the detachable supporting plate for the wire bonding process.*

Therefore, we added protruded edges to the corners of the holder, but hard corners are not machinable with circular drill bit, so we changed the design to have a smaller protruded edge on the four sides of the holder as shown in Figure 17 and 18. We also added slots onto all four sides of the box mount to block light more efficiently.

However, after 3D printing this design, we found that this holder shape in Figure 17 allowed the chip to rotate due to its design and also due the holder being too tight. For the third design (Figure 18), we returned to the having protruded edges in the corners but only on two opposite corners to also be able to use O-rings. We also increased the holder length and width by 0.5 mm, which allowed the chip to sit inside the holder comfortably and securely.

We plan to now test the wirebonding on the manufactured KID box mount of this most recent holder design and also continue to alter the circuit geometry and test more changes in



Figure 17: *First 3D printed box.*

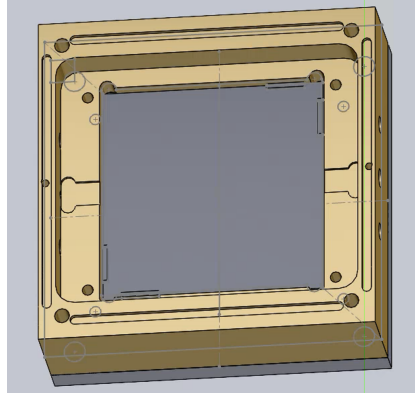


Figure 18: *Notice the slots on the four edges as well as the corners of the gray holder.*



Figure 19: *3D printed part of the third design with the chip inserted into the slot.*

the capacitor and the inductor to learn where the resonant frequency starts to largely deviate from the expected frequency.

7 References

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$$4\lambda_n - 1 = 4 \left(-\frac{1}{4} - \frac{n^2\pi^2}{\ln 22} \right) - 1 = -1 - \frac{4n^2\pi^2}{\ln 22} - 1 = -2 - \frac{4n^2\pi^2}{\ln 22}$$

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