1 Background

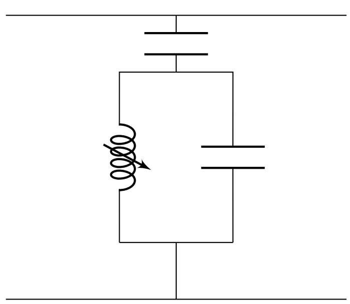
Particle dark matter detection has been an ongoing field of research for decades, and over time there have been many different proposed designs to build a machine capable of detecting the weak interactions between hypothesized dark matter particles and ordinary matter. As a non-collider detector, experiments like SuperCDMS and TESSERACT use cryogenic solids and liquids as target materials to detect the interactions between dark and ordinary matter.

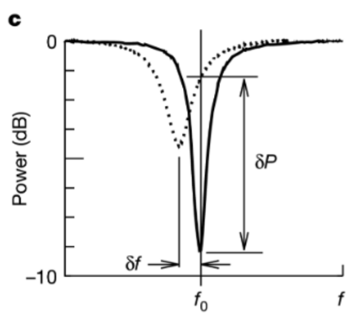
Currently, the detector operates by detecting collisions between cosmic particles and the target atoms in the detector. When such a collision happens, a small vibration, i.e., phonons, are generated, which propagate throughout the material. Then, superconducting devices called Transition Edge Sensors (TES) detect these vibrations, which are converted to electrical signals and read out.

This project I am interested in focuses on a new kind of phonon sensor, called a kinetic inductance detector (KID). Similar to the TES, these are superconducitng circuits placed onto the target material. The motivation for coming up with a new detector is manyfold, but one simple reason is that the physical circuitry for a KID-based detector is much simpler, making it much easier to diagnose and fix issues when things malfunction. To add, the components used largely consist of commercial RF hardware, which is much cheaper than those used for TES. As a result, a system with KID-based detectors is competitive for this and multiple other reasons, see here for more details.

2 KID-based detector

At its core, the KID is really nothing more than a simple LC circuit:

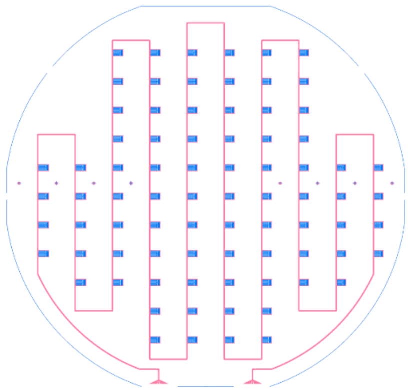


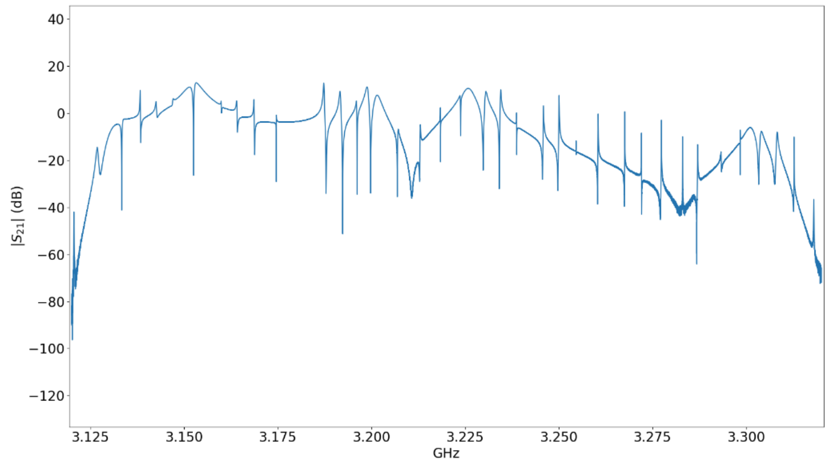


Its frequency response is shown on the right, where we see a very narrow dip at $f = f_0$, a parameter we can control. The dip at $f = f_0$ means that this particular KID suppresses sine waves with exactly $f = f_0$, but leaves other frequencies untouched. So, the idea for a KID-based detector is as follows: we line many KIDs in series connected with a feed line, each one calibrated to attenuate at a specific frequency $f = f_0$. Then, we send a linear combination of sine waves at the frequencies we chose through the circuit, and read its output. Under normal circumstances, this will return a suppressed signal. Then, when a phonon is absorbed by the superconductor, it alters the value of L slightly, causing a momentary shift in the frequency response. As a result, the signal that used to be attenuated by that particular KID is now less suppressed, producing a pulse in the signal we can detect. Depending on the frequency of the detected signal, we can also determine which KID was hit, and thereby reconstruct where the collision took place in the target material.

3 Project Description

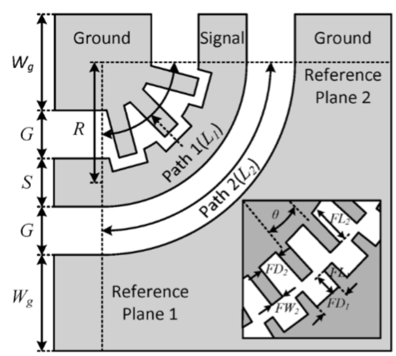
What was described above is an extremely idealized picture of what a KID-based detector looks like. Unfortunately, current prototypes for this detector has proven to be ineffective, one of the issues being the amount of impedance interference present in the circuit. To illustrate this point, we take a schematic of the full circuit, shown below:





The image on the left is the schematic, and its frequency response is shown on the right. Each blue square represents a KID, and the red line represents the feed line that we send sine waves through. Currently, the issue with this implementation is that whenever there is a sharp corner in the feed line, which causes interference that distorts the frequency response of all KIDs. The evidence for this distortion can be seen in the frequency response curve, as the degree to which each KID attenuates the signal is non-uniform, and also the overall shape of the curve (so disregarding the spikes from the KIDs) is not as uniform as we would ideally want. As a result, these effects make some KIDs more sensitive than others, and overall makes the device a weaker detector.

To solve this problem, we follow an approach developed by Kim (2009). In the paper, they attempt to solve this issue by introducing a phenomenon called "slow wave compensation", shown below:



In essence, the interference in the system is thought to be caused by a phase difference between the two travelling waves, since the wave along the inner radius of the corner travels less distance than the outer. The introduction of "forks" on the inner track generates some capacitance, and serves to slow the inner wave down so that both waves remain in phase upon exit. The required capacitance to do this is also well known, since we know exactly how much further the outer wave travels. This paper also provided some very basic simulations of the proposed solution, and it has shown to greatly reduce the effects of impedance interference, which shows that this method is indeed promising.

For this honors project, our goal is to further develop these simulations to closely replicate the detector geometry, and ultimately try to understand the interactions that happen between the feed line and its surroundings. Investigation into this not only helps us get one step closer to developing new ways to detect dark matter, but it also has large implications on other fields as well, since cryogenic RF transmission lines are employed in other cryogenic devices such as quantum computers. My project will be largely done in an FEA software called Ansys HFSS, a program specially designed to simulate 3D electromagnetic systems. I will be primarily working with Dr. Yen-Yung Chang, co-sponsored by Prof. Matt Pyle.