

**School of Physics and Astronomy**

**Year 3 Final Project Report**

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Declaration:

I have read and understand Appendix 2 in the Student Handbook: “Some advice on the avoidance of plagiarism”.

I hereby declare that the attached report is exclusively my own work, that no part of the work has previously been submitted for assessment (although do note that material in “Interim Report” may be re-used in the final “Project Report” as it is considered part of the same assessment), and that I have not knowingly allowed it to be copied by another person.

**Characterizing Arrays of Kinetic Inductance Detectors**

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Date:

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**Abstract**

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# **Introduction**

## **1.1 Characterizing a Detector**

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## **1.2 Overview and Significance of Kinetic Inductance Detectors**

## **1.3 Aims and Objectives**

## **1.4 Overview of Supporting Literature**

The project is based on a topic that was covered by my supervisor Dr. S. Doyle, therefore principles of KIDs discussed in *Chapter 1* is based on Doyle’s Thesis on LEKIDs [1], along with supporting materials [3], [4] and [5]. Non-academic supplementary material [11] and [12] from Doyle also helped understand the workings of the detector.

# **Kinetic Inductance Detector Theory**

## **2.1 Superconductivity in KIDs**

**2.1.1 Principles of Superconductivity**

For superconductors below a critical temperature the DC resistance falls to zero. The zero resistance can be attributed to a new path for the current through a new density of superconducting electrons, . [1] Bardeen, Cooper and Schrieffer explains this in the BCS Theory [3]. When the temperature decreases below , electrons start to form pairs known as Cooper-pairs with a binding energy of . An important property of these pairs is that they do not scatter in the material. This scatter-less property gives rise to zero resistance, which superconductors are known for.

Expanding on this, we can start from the conductivity of normal metals in the Drude Model. Based on Ashcroft and Mermin [4] on the Drude Model, the conductivity of a metal can be expressed as follows:

|  |  |  |
| --- | --- | --- |
|  |  | *(1)* |

where is normal electron (quasi-particle) density, j equals to , is the elementary charge, is the scattering time, m is the mass of the electron and is the angular frequency.

Following this, F. London and H. London put forward explanations for the behaviour of electrons in superconductors [5]. As explained, will accelerate in an electric field without being scattered by the ions in the lattice. Within the Cooper-pairs, there exists no scattering events and therefore . Substituting this value of into *equation 1*, the conductivity for becomes:

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  | *(2)* |
|  |  |  |

This gives us a relationship between and the superconducting conductivity , which only comprises of an imaginary part that will be further explained in the Two Fluid Model.

**2.1.2 Meissner Effect**

Another important property of superconductivity is the Meissner effect, where the bulk of the material expels any magnetic field or displays complete diamagnetism [5]. For a perfect conductor, when an external magnetic field is applied, it will work to prevent a change in magnetic field . This is given by:

|  |  |  |
| --- | --- | --- |
|  |  | *(3)* |

However, London [5] explains that superconductors display complete diamagnetism and cannot be modelled as perfect conductors. London’s solution was to define an expression for the magnetic field as a function of distance from the superconducting material surface . This gives the expression for for a superconductor:

|  |  |  |
| --- | --- | --- |
|  |  | *(4)* |

where is the magnetic field at the surface of the material. *Equation 2 and 4* are collectively known as the London Equations and are not derived from any fundamentals of superconductors but are relations for the observed effects. A complete description will be given by the Mattis-Bardeen Theory.

Within the material surface, the magnetic field will fall to of the value of when at a distance . This distance is known as the London Penetration Depth (LPD) :

|  |  |  |
| --- | --- | --- |
|  |  | *(5)* |

is used for characterizing the effects of photons on superconductors such as a KID, therefore *equation 5* is crucial as shown in the following section.

**2.1.3 Two Fluid Model**

Following from the formation of Cooper-pairs below , Gorter and Casimir [6] explains that the 2 electron populations, and gives rise to the Two Fluid Model [6] of superconductors. The model considers that a current in a superconductor will have 2 paths it can propagate, which are the 2 populations. From [1], temperature dependence of ratio is given by:

|  |  |  |
| --- | --- | --- |
|  |  | *(6)* |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  | *(7)* |

is inversely proportional to , whereas also falls due Cooper-pair formation. This relationship can be observed in the graph:

|  |  |  |
| --- | --- | --- |
|  | A picture containing chart  Description automatically generated |  |
|  | ***Figure 1*** *Graph of ratio of and to total electron population n vs the ratio of temperature to* |  |

This relationship will be useful in modelling a KID as its response is dependent on the populations [1].

The variation in with temperature means that also varies with temperature. The expression for as a function of temperature can be obtained with *equation 5 and 6*:

|  |  |  |
| --- | --- | --- |
|  |  | *(8)* |

where is the LPD at 0K.

For this report, the effects of varying temperature is used to model KID detection. Fundamentally, increasing temperature has the same effect as incident photons, as it provides energy to break Cooper-pairs. The detection of the KID is modelled by temperature changes instead of photon counting as it simplifies the models.

[1] provides an explanation for the effects of varying frequencies incident on a superconducting material; From *equation 2*, at low frequencies is far greater than . However, at higher frequencies, especially in the microwave region, is no longer negligible. This can be attributed to an inertia of as the energy drawn from is stored as kinetic energy, and this inertia produces a reactance which gives a large impedance at high frequencies. As such, this stored kinetic energy relates to the kinetic inductance of . The effect also causes the current to lag by , which explains why only comprises of an imaginary part. This increase in with decrease leads to a larger proportion of flowing through the resistive quasi-particle path at higher frequencies. This can be illustrated in a circuit-equivalent diagram in *Figure 2*:

|  |  |  |
| --- | --- | --- |
|  | Diagram  Description automatically generated |  |
|  | ***Figure 2*** *Circuit-equivalent diagram of current density J through 2 electron densities and at high frequencies* |  |

For a KID, the superconducting path is important as its changes in inductance can be characterised to give information on the detection.

## **2.2 Internal Inductances**

A KID measures a detection through a change in the internal inductance. Building on previous sections, [1] explains that the inductances of a superconducting material can be characterized as it changes with temperature as does . Kinetic inductanceis associated with the kinetic energy of and magnetic inductance is due to the magnetic field energy density by stored in the volume. The derivation is length and beyond the scope of the project, as such we quote [1] for the inductance expressions. The expression for:

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  | *(9)* |

where is current and is the LPD.

The surface integral that is performed over the cross-section of the strip considers the non-uniform current distribution. Considering the variations in , the surface integral can be evaluated and the expression for quoted [1]:

|  |  |  |
| --- | --- | --- |
|  |  | *(10)* |

where t is the thickness and W is the width. The magnetic inductance can also be found with a similar procedure, and the expression was quoted [1]:

|  |  |  |
| --- | --- | --- |
|  |  | *(11)* |

and are in per unit length; by setting length = W, the W term can be eliminated from *equations 10 and 11,* giving in per unit square. The internal inductance is simply the sum of the inductances. Quoting from [1]:

|  |  |  |
| --- | --- | --- |
|  |  | *(12)* |

where is in per unit square.

*Equations 10, 11 and 12* are used to model a KID since a change in inductance indicates a detection, varies as the temperature varies, as described by in *equation 8*.

Using *equation 10, 11 and 12*, we can generate models of how the varies with thickness:

|  |  |  |
| --- | --- | --- |
|  | Chart, line chart  Description automatically generated |  |
|  | ***Figure 3*** *(Top) Ratios of and to . (Bottom) and in pH per square. Both plots were created using a fixed* |  |

This relationship will be useful, as [1] shows that varies with thickness; as drepresents a change in temperature from *equation 8* and represents the detection, the sensitivity of the KID is therefore dependent on the thickness. This will be explored in a future section discussing the sensitivity of KIDs.

## **2.3 Mattis-Bardeen Theory**

As mentioned earlier, the results derived for the conductivity is not based on any fundamentals of superconductivity. In BCS Theory [3], the band gap is not introduced and the electrons are accelerated independently if E applied whereas due to finite size of Cooper-pairs, it is not the case. The expressions derived previously holds very well under experimental conditions, but to study the underlying properties of a KID, it would be useful to use expressions for conductivity that consider the band gap and non-local treatment of Cooper-pairs.

Pippard [7] gives a non-local treatment of the London Equations and combined with the band gap, the full effects of the above-mentioned properties lead to the Mattis-Bardeen Approximations for within the limit [8]:

|  |  |  |
| --- | --- | --- |
|  |  | *(13)* |
|  |  |  |
|  |  | *(14)* |

and are the modified Bessel functions of the first and second kind respectively. is the temperature dependent binding energy, and is the binding energy at . The derivations and underlying theories are beyond the scope of this project, only the conductivity expressions are important.

and  can be plotted against T to show the temperature variation using *equation 13 and 14*:

|  |  |  |
| --- | --- | --- |
|  | Chart  Description automatically generated with medium confidence |  |
|  | ***Figure 4*** *and against T for an Aluminium sheet at 7GHz* |  |

can be observed to increase and decreases with increasing T, which agrees with the Two Fluid Model as Cooper-pairs break.

By using from the Mattis-Bardeen Approximations, combined with the real part of *equation 2* for and *equation 5* for , the Mattis-Bardeen LPD is found:

|  |  |  |
| --- | --- | --- |
|  |  | *(15)* |

Using *equation 13,14* *and 15*, a graph of against T can be obtained:

|  |  |  |
| --- | --- | --- |
|  | A picture containing chart  Description automatically generated |  |
|  | ***Figure 5***  *variation with T for an Aluminium sheet at 7GHz using Mattis Bardeen Approximations* |  |

[1] shows that the resistance R of a superconducting strip can then be calculated from the real part of the impedance. Quoting the expression for R from [1]:

|  |  |  |
| --- | --- | --- |
|  |  | *(16)* |

Using *equation 14 and 16*, R variation with T can be observed:

|  |  |  |
| --- | --- | --- |
|  | Chart  Description automatically generated |  |
|  | ***Figure 6***  *variation with T for an Aluminium sheet at 7GHz using Mattis Bardeen Approximations* |  |

The variation in R for different T is useful in modelling a KID as the resistance gives the loss of the detector. The result of this will be explored in the Ideal KID Model section.

## **2.4 Kinetic Inductance Detector**

**Schematic**

With all the fundamentals established, it is now possible to define a KID. The detection of photons is accomplished on a KID Resonant Circuit. It is a circuit that sits on an aluminium sheet along with a silicon wafer that acts as the ground [11]. A schematic is shown below:

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  | ***Figure 7*** *Schematic of a single KID, with an aluminium sheet (Dashed) which contains the circuit on a silicon ground plate (White) (Image from [12])* |  |

The detector operates at [1], well below; as we will see later that lower system temperatures lead to lower circuit-noise contribution and more accurate readouts. The inductive meander has a total inductance , which is coupled to the interdigital capacitor IDC. is the geometric inductance, that is dependent on the dimensions and material of the meander, its derivation is beyond the project and since the KID dimensions and material remain constant, remains constant and will be taken as such. The circuit behaves as an LC circuit that has resonant frequency . The diagram can be illustrated as a circuit diagram as shown in *Figure 10* below:

|  |  |  |
| --- | --- | --- |
|  | Chart, box and whisker chart  Description automatically generated |  |
|  | ***Figure 8*** *Circuit diagram of the KID resonant circuit where Ltot is the inductive meander (Image from [12])* |  |

There are 2 coupling capacitors, the first coupling capacitor is coupled to the transmission feedline and the second is coupled to ground. [11]

When a photon is incident on the detector, it provides energy for Cooper-pairs to overcome . decreases as Cooper-pairs break, and therefore will vary according to *equation 12* and therefore varies as well.

The capacitance of the coupling capacitors and the total capacitance is given [11]:

|  |  |  |
| --- | --- | --- |
|  | \ | *(17)* |
|  |  |  |
|  |  | *(18)* |
|  |  |  |

As mentioned, the circuit is modelled as an LC circuit with a resonant frequency [11] that can be found from from *equation 18* and :

|  |  |  |
| --- | --- | --- |
|  |  | *(19)* |

Since varies with respect to photon intensity incident on the inductive meander, varies accordingly. is coupled to the transmission feedline, thus a change in the frequency can be measured.

**Microwave Electronics Readout**

[11] explains a common phenomenon faced by microwave electronics, such as KIDs, where electronic components’ dimensions become comparable to signal wavelengths. Due to this, signals might be out-of-phase when reading out leading to an error. Therefore, treatment of the signal must be of a wave instead of voltage and currents. An illustration is shown below:

Length / m

|  |  |  |
| --- | --- | --- |
|  | Diagram  Description automatically generated |  |
|  | ***Figure 9*** *Diagram illustrating**phase difference of microwave frequency readouts at different length of a wire (Image from [12])* |  |

As such, it is useful to define a microwave circuit based on the scattering parameters. Scattering parameters is defined as the ratio of voltages on 2 ports [10]. For a KID it is the ratio of input signal through the feedline into the KID to its respective output signal. A circuit-equivalent diagram of a single KID on a transmission line is shown:

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  | ***Figure 10*** *Schematic of a single KID on a transmission feedline with the blue section representing a KID resonant circuit (Image from [11])* |  |

The scattering parameter that gives the change in is S21. Its derivation is beyond the scope of this project, therefore the expression for S21 is quoted from [11]. S21 is a complex number, it would be intuitive to express this as an amplitude and phase . These values are given [11]:

|  |  |  |
| --- | --- | --- |
|  |  | *(20)* |
|  |  |  |
|  |  | *(21)* |

where and Q is the real and imaginary component of S21 respectively. A KID will measure and output I and Q values in units of Volts. We can use the above expressions to characterize the measurements.

## **2.5 Ideal KID Simulation**

Combining the microwave properties of superconductors and the KID resonator circuit readout, it is now possible to model a KID with temperature variation, corresponding to a detection. The model was created using Python with several values quoted as constant parameters for a superconducting aluminium sheet:

The is defined as follows [1]:

|  |  |  |
| --- | --- | --- |
|  |  | *(22)* |

approximated to as a fixed value since is small and has insignificant changes to .

The model was created with the following steps:

1. From *equation 13 and 14,* the Mattis-Bardeen Approximations can be found for and can be found from the expression for LPD using equation 8.
2. Using the *equation 10, 11 and 12* for the inductances, the temperature variation of can be found and therefore was found after.
3. Using the resonant circuit *equation 19,* was found along with |S21|
4. Using *equation 16*, determine variation in the resistive part with temperature, which increases the loss as temperature increases.

The resulting plot is as follows:

Diagram

Description automatically generated ***Figure 11*** *Tone Frequency variation of a single KID for 2 temperatures with the fixed parameters given above, with dF0 labelled. For real measurements, plots like these where |S21| plotted against frequency is known as Sweep data/plots.*

dF0

The shift in tone frequency, for the minimum of |S21| corresponds to photon detection as increasing temperature changes. This will be characterized further in the responsivity section. In a constant system, the |S21| does not vary with temperature and will be the same as the base temperature (lowest), the increase is due to varying R contributing to loss.

An intuitive way of understanding the I and Q variations (measured quantities) is by plotting I vs Q for varying temperatures, given below:

A picture containing circle

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***Figure 12*** *I vs Q plot for 2 temperatures. The crosses represent the I and Q values corresponding temperature plot at.*

Figure 12 shows the shift I and Q for different temperature, where the cross represents a shift in I and Q at frequency . In real KID measurements, the data typically consists of I and Q values for both the sweep and time-steams (across time) for a set tone frequency *Figure 12* illustrates how the I and Q values vary at the tone frequency, and can be related to the response of the detector.

[11] explains that to characterise , we can utilize a formula that considers *and*  as they can be found for the change in I and Q (measured quantities) from the base temperature. The formula was quoted [11]:

|  |  |  |
| --- | --- | --- |
|  |  | *(23)* |

where and are the changes in I and Q values for a particular data point. and can be calculated by taking numerical derivatives at the minimum point of the sweep data at the tone frequency (In the above case, the base temperature).

*Equation 23* is crucial, as it makes it possible for the conversion of I and Q measurements of time-stream and sweep data, to changes in . The change in corresponds to a detection and is important in characterizing the response of the detector. This will allow usto do noise analysis and sensitivity measurements, which will be explored in the experimental section.

*Equation 23* holds well for small deviations in , after which the formula starts to deviate from real data. This limit can be observed by plotting the formula along with the minimum of |S21| from the model. This is shown below:

|  |  |  |
| --- | --- | --- |
|  | Chart, line chart  Description automatically generated |  |
|  | ***Figure 13***  *formula plotted alongside the minimum of |S21| from the model for varying T* |  |

*Figure 13* shows that the formula holds remarkably well up till 0.21K. As such, the formula is appropriate for low temperature variations, therefore the maximum change in for the approach to still be valid is . This is finding imperative as this is the maximum variation that should be taken when doing future measurements.

# **Experimental**

## **3.1 Detector Data**

## **3.2 Conversion of Detector Data to dF0**

## **3.3 Modelling the Measured Power**

## **3.4 Response of the Detector**

## **3.5 NEP of the Detector Array**

# **Results and Discussion**

## **4.1 Noise Sources and Contributions**

## **4.2 Experimental NEP and Implications**

## **4.3 Characterizing the KID**

# **Conclusions**

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