Lumped Element Kinetic Inductance Detectors

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ABSTRACT

Kinetic Inductance Detectors (KIDs) provide a promising solution to the problem of producing large format arrays of ultra sensitive detectors for astronomy. Traditionally KIDs have been constructed from superconducting quarter-wavelength or half-wavelength resonator elements capacitivly coupled to a co-planar feed line. Photons are detected by measuring the change in quasi-particle density caused by the splitting of Cooper pairs in the superconducting resonant element. This change in quasi-particle density alters the kinetic inductance, and hence the resonant frequency of the resonant element. This arrangement requires the quasi-particles generated by photon absorption to be concentrated at positions of high current density in the resonator. This is usually achieved through antenna coupling or quasi-particle trapping. For these detectors to work at wavelengths shorter than around 500 μm where antenna coupling can introduce a significant loss of efficiency, then a direct absorption method needs to be considered. One solution to this problem is the Lumped Element KID (LEKID), which shows no current variation along its length and can be arranged into a photon absorbing area coupled to free space and therefore requiring no antennas or quasi-particle trapping. This paper outlines the relevant microwave theory of a LEKID, along with theoretical performance for these devices.

INTRODUCTION

The principal of operation for any KID device is to measure the change in quasi-particle population within the volume of a superconducting film upon photon absorption. Any photon with an energy $hf > 2\Delta$, if absorbed will break apart Cooper pairs resulting in an excess quasi-particle population (n_{qp}). The result of this event is to alter the complex impedance of the film by increasing the kinetic inductance (L_k). In practice the variance in L_k with change in quasi-particle density is very small and requires the film to be fabricated in to a high Q, microwave resonance circuit to sense this variation. In this regime we can monitor the change in phase of a fixed tone microwave probe signal centred on the resonant frequency. The variation in L_k upon photon absorption is now scaled by Q, which can be of order 10^6 for a low loss superconducting resonator operating well below the superconducting transition temperature of the film (T_c) [1]. The theoretical noise limit of these devices is governed by generation-recombination noise, which scales with temperature and film volume [2]. For a typical coplanar aluminium KID device operating at 100mK this noise is estimated to be around 10^{-20} W√Hz.

The approach to date for creating high Q microwave resonators from superconducting films for the purpose of photon detection has been to fabricate distributed half-wave or quarter-wave resonators from CPW geometries. For these devices to act as photon detectors power must be coupled in to area of high current density using antenna structures or quasi-particle traps [3]. In this paper we discuss the concept of a new idea for a lumped element KID which shows no current variation along its length and also serves as a free space absorber. This new approach provides an elegant solution to the problem of coupling THz radiation to the sensitive element of a KID device, combining the properties of the absorbing area, detection and readout elements of the KID.

DISTRIBUTED KID DEVICES

In a resonant circuit fabricated from superconducting elements (L, C), varying the Cooper pair density in the superconductor will alter the resonant frequency ω_0. The change in ω_0 is proportional to α which is the ratio of kinetic inductance L_k to normal inductance L ($\alpha = L_k/L$). A schematic of a quarter-wave KID is shown in fig (1). The resonant frequency for a quarter-wave KID constructed from a coplanar geometry can be approximated by:

$$f_0 \approx \frac{c}{4l\sqrt{\frac{1+\varepsilon_{sub}}{2}}} \tag{1}$$

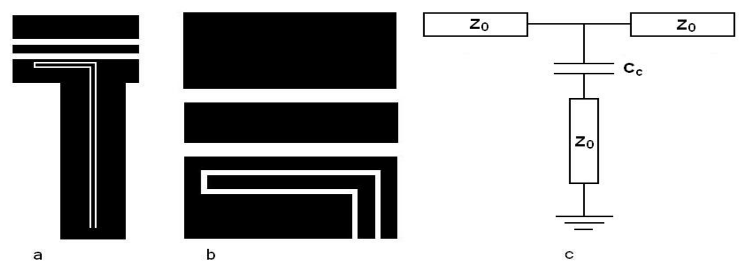

Fig 1, a) A schematic of a elbow coupled quarter-wave resonator. b) Close up of the elbow coupling section. c) Equivalent transmission line model.

Where ε_{sub} is the substrate permittivity. Close to resonance the impedance of the quarter-wave section can be written as:

$$Z_{res} \approx \frac{Z_L}{g}(1 + 2jQ_u x) \tag{2}$$

Here Z_L is the characteristic impedance of the resonance section, Q_u is the unloaded quality factor, g is the coupling coefficient and *x* is given by (ω-ω_0/ω_0). The coupling coefficient is dependent on the coupling capacitance which is set by the geometry of the elbow section. The coupling is also set by Q_u and the frequency at resonance.

$$g = \frac{2Q_u}{\pi}(\omega_0 C Z_L)^2 \tag{3}$$

The effect of g is to reduce the measured (loaded Q) Q_L in such a way to give:

$$\frac{1}{Q_L} = \frac{1}{Q_u} + \frac{g}{2Q_u} \tag{4}$$

If the characteristic impedance of the resonant section is made to be the same as the characteristic impedance of the feed line then the power transmitted past the resonator at frequencies close to resonance can be calculated using a standard ABCD matrix approach [3] for a shunted impedance to ground giving

$$S_{21} = \left(\frac{2}{2+g}\right)\frac{1 + 2jQ_u^2 x^2}{1 + (4jQ_u x/2 + g)} \tag{5}$$

$$|S_{21}| = \left(\frac{2}{2+g}\right)\frac{1 + 4Q_u^2 x^2}{1 + (4Q_u x/2 + g)^2} \tag{6}$$

The change in phase close to resonance is given by the argument of S_{21}. For a quarter-wave resonator the resonant wavelength is fixed by geometry, the resonant frequency however is dependent on the line impedance which varies with kinetic inductance. From basic transmission line theory it can be shown that the change in resonant frequency upon changing L_k is given by:

$$\Delta f = -\frac{1}{2}\frac{\alpha}{L_k} f_0 \Delta L_k \tag{7}$$

The change in resonant frequency is measured using a fixed tone microwave probe signal set equal to the resonant frequency f_0. As f_0 varies with photon absorption a shift in phase of the probe signal is observed. ΔL_k for a change in quasi-particle density can be calculated by looking in the change in the complex component of the conductivity (σ_2). Using Mattis-Bardeen theory the change in σ_2 with the change in quasi-particle density yields the result for the change in phase of the probe signal with change in quasi-particle density:

$$\frac{d\theta}{dN_{qp}} = \left\lfloor \sqrt{\frac{2}{\pi}} \cdot \frac{\hbar\omega I_0(\varsigma) - (2\Delta + \hbar\omega) I_1(\varsigma)}{\sqrt{\Delta k_B T(2\Delta + k_b T)}} \right\rfloor \frac{\alpha Q_L}{N_0 V} \qquad (8)$$

where ς is given by

$$\varsigma = \frac{\hbar\omega}{2k_B T} \qquad (9)$$

N_0 is the single spin density of electron states. N_0 for Niobium is 6.93×10^{10} μm^{-3} eV^{-1} [4]. For Aluminium N_0 is 1.72×10^{10} μm^{-3} eV^{-1}, where V is the effective volume of the resonator. This effective volume accounts for the fact that only the areas of the film where current is flowing will be sensitive to pair breaking. I_0 and I_1 are modified Bessel functions. From (8) it is clear that in order to maximise the response of the device one needs to maximise α and Q_L while minimising the film volume V.

OPTICAL COUPLING TO A DISTRIBUTED KID

The current distribution along the length of a quarter-wave distributed KID follows a sine distribution with a current node at the coupling end of the line and a peak at the shorted end. This condition means that the response of a distributed KID to a pair breaking event will be position dependent, having a maximum at the shorted end and zero at the coupling end. For this reason optical power must be coupled in to the shorted end. There are two ways currently used to do this. The first is to take a KID fabricated from an Aluminium superconducting film with a bandgap of $2\Delta_{Al}$ and a Niobium antenna and microstrip line of band gap energy $2\Delta_{Nb}$ [5]. Coupling is achieved by running the microstrip line coupled to the antenna over the centre strip of the resonator using it as a ground plane. Any optical signal with photon energy $2\Delta_{Al} < E_{ph} < 2\Delta_{Nb}$ will now travel through the antenna and microstrip with very low loss. However once the signal reaches the KID it will break Cooper pairs in the resonator and be dissipated. This defines a band in which we can operate that is limited to be between the two bandgap energies of the resonator and antenna structure. Using an Aluminium KID with Niobium antenna sets this band to approximately 100 – 700 GHz.

Antenna coupled KIDs are limited by the bandgap energy of Niobium and therefore cannot be used for the detection of THz radiation. An alternative solution is to use a quasi-particle trap [5]. Here we use a superconducting film as an absorber and fabricate a KID from a superconductor with a lower bandgap energy to that of the absorbing film. The shorted end of the KID is placed in contact with the absorbing pad. Quasi-particles generated in the absorbing superconductor can now diffuse in to the KID, where owing to their higher energy will break further pairs and lose energy. The quasi-particle are now unable to diffuse back in to the superconducting absorber due to the energy gap created by the two materials. This method has been used to demonstrate the absorption of optical and X-ray photons [6] but will prove difficult to work for THz radiation. The reason for this is impedance matching. In order to get good coupling to free space the superconducting absorber must be of order $\lambda/4$ in size and have a normal impedance matched to that of free space. To impedance match to free space the films must be made thin to increase the sheet resistance, by doing this the diffusion length, *l* of the quasi-particles is reduced. Combined with the large absorber size it becomes very difficult to create a film of high enough quality to insure that the quasi-particles generated can diffuse in to the KID sensing element.

THE LUMPED ELEMENT KID (LEKID)

One way of solving the problem of optical coupling THz radiation to a KID device is to use a lumped element resonator, which unlike its distributed counterpart shows no current variation across the device. This means the device itself can act as the absorber as well as the sensing element in a detector system. The device is based on a series LC circuit inductively coupled to a microstrip feed line. An example of a lumped element resonator is shown in fig (2).

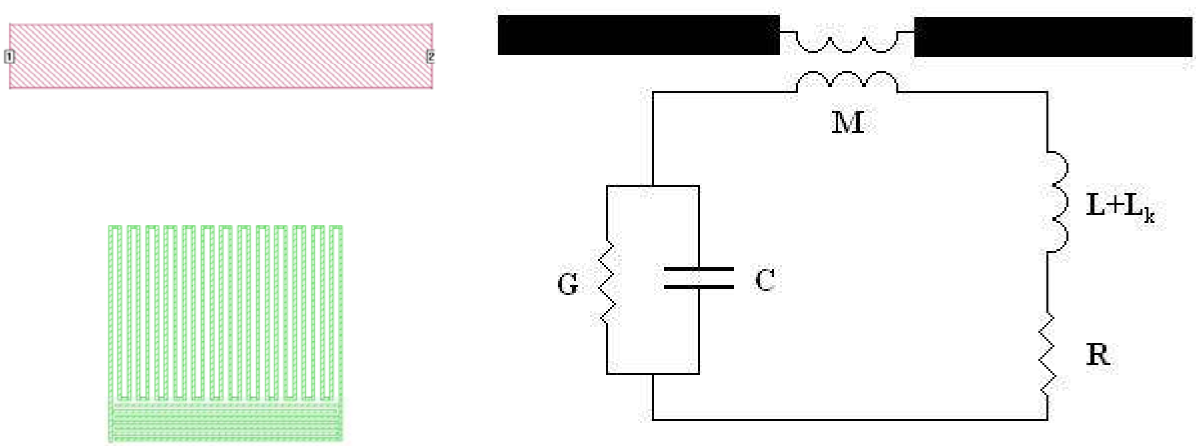

Fig 2: Left a schematic of a LEKID device showing the microstrip feedline (red) and resonant section (green). Right; the equivalent circuit of an inductively coupled LEKID device.

The inductor $L+L_k$ is formed from the self inductance of the meander, and the kinetic inductance of the superconducting film. The capacitor is formed from the interdigital structure connected to each end of the meander. The approximate resonant frequency of this device is simply:

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad (10)$$

The impedance of the resonant section is given by:

$$Z_{res} = j\omega(L+L_k) - \frac{1}{j\omega C} + R \qquad (11)$$

Around resonance an inductively coupled resonator with mutual inductance M, loads the feed line as if it were a lumped series impedance (Z_{eff}) on the feed line.

$$Z_{eff} = \frac{\omega^2 M^2}{Z_{res}} \qquad (12)$$

As in the distributed case the scattering parameters about resonance can be found from a simple ABCD matrix approach. About resonance S21 is described by:

$$S_{21} = \frac{1}{1 + \dfrac{\omega^2 M^2}{2Z_0 Z_{res}}} \qquad (13)$$

Where Z_0 is the characteristic impedance of the feed line. Away from resonance Z_{res} is very large hence and S_{21} is unaffected by the presence of the resonator. At frequencies close to the resonant frequency the resonator begins to load the line and reduces S_{21} reaching a minimum on resonance. As with the distributed KID we can define a coupling coefficient g.

$$g = \frac{M^2 Q_u}{Z_0 L}\omega \tag{14}$$

Q_u for a series resonant circuit is given ωL/R [3]. In practice we want Q_u to be as large as possible and therefore R to be as small as possible. R represents all the losses in the circuit, which are due to residual losses in the superconducting film brought about by quasi-particles as well as losses in the dielectric of the capacitor. We can rewrite Q_u as:

$$Q_u = \frac{\omega L}{R_{qp} + 1/\omega C \cdot \tan\delta} \tag{15}$$

Here R_{qp} is the residual quasi-particle loss and tanδ is the loss tangent of the capacitor. For an interdigital capacitor on sapphire at low temperatures tanδ is negligible so Q_u is governed by R_{qp}. One additional mechanism of loss in this structure is through radiation. This loss would depend the geometry of the resonant element. Q_L would now be written as

$$\frac{1}{Q_L} = \frac{1}{Q_u} + \frac{1}{Q_{rad}} \tag{16}$$

From the simulations performed radiation losses do not seem to be a problem for this structure, however Q_{rad} can be reduced by placing the device in a closed box if radiation losses proved to be a problem. This clearly would not be suitable for a free space coupled detector, however the lid of this box could be replaced with a high pass filter reducing the radiation losses.

SIMULATED RESPONSE

To determine the microwave response of a LEKID device we simulated several geometries using Sonnet EM. The device discussed from this point forward was designed on a 100μm thick sapphire substrate using a metal film with a real impedance 0.5μΩ/sq and a tanδ of 1×10^{-6}. These values are realistic for a superconductor of modest quality and have been compared with the results made from a measured distributed KID fabricated from a Tantalum film at 300mK. The mutual inductance and hence the Q_L value is proportional to the distance of the resonator from the feed line. Fig (3) shows the simulated results of a resonator placed 200μm from the feed line. The Q_L for this device was of order 10^5 and had a phase slope dω/df of order 17000.

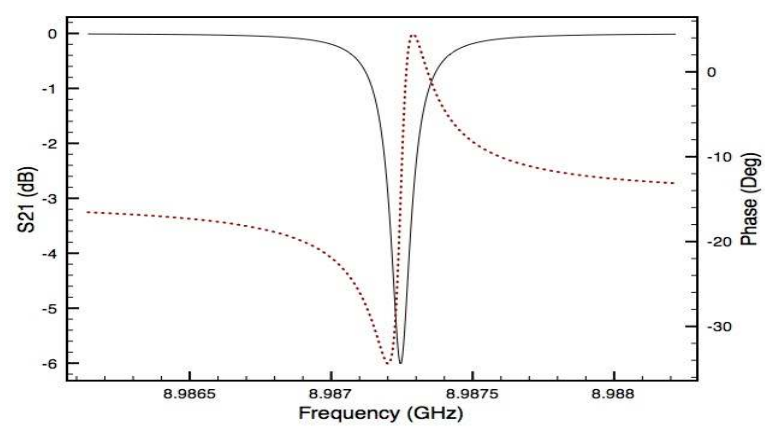

Fig 3, the simulated microwave response of a LEKID device

The response of this device to a change in quasi-particle density can be estimated in the same way as for a distributed KID using equation (8). An α value was calculated by performing a simulation on the meander structure alone to determine a value for the inductance of the meander section. L_k was calculated using London theory and assuming that the current flow through the entire volume of the meander. This is a reasonable estimate if the film thickness is of order $2\lambda_L$ where λ_L is the London penetration depth. Fig 4 shows the expected response of a typical LEKID device using a film thickness of 50nm fabricated from Aluminium and Niobium.

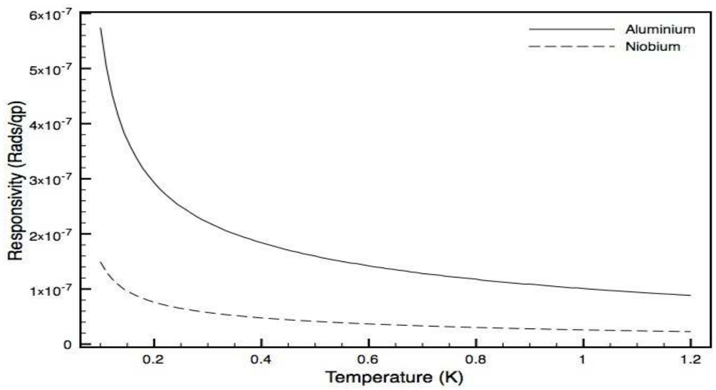

Fig 4, The predicted phase response to a single photon absorbed as a function of temperature for an Aluminium and Niobium LEKID device.

The results shown in fig (4) are comparable with the responsivity of a 50nm thick distributed KID with the same value of Q_L operating at the same resonant frequency. The LEKIDs responsivity is lower by about a factor of 3. This is due to the LEKID geometry having a higher film volume at this resonant frequency.

The limiting noise of any KID device is governed by the generation recombination noise [2] and takes the form:

$$nep_{qp} = 2\Delta\sqrt{\frac{n_{qp}}{\tau_{qp}}} \qquad (17)$$

This is the theoretical limit and will depend heavily on the film quality, which ultimately determines the number of quasi-particles at a given temperature (n_{qp}) and the quasi-particle life time at that temperature (τ_{up}).

The current distribution across the device was also simulated to look for signs of the device resonating in distributed modes. For the typical geometries the distributed mode started appearing at around 30 GHz which is well out side the bandwidth of the readout electronics.

6. Optical coupling to a LEKID device

A HFSS simulation was performed on the meander section of the LEKID in the absence of a substrate. By tuning the thickness of the meander alone an absorption of 50% can be achieved over a broad range of frequencies. This is shown in fig (5). Due to the geometry of the meander the optical coupling of the LEKID devices simulated in this paper has a dependence on polarisation. The coupling to free space in the favored polarization is determined by the impedance the meander presents to an incoming photon. This impedance can be tuned by altering the film thickness or number of lines in the meander.

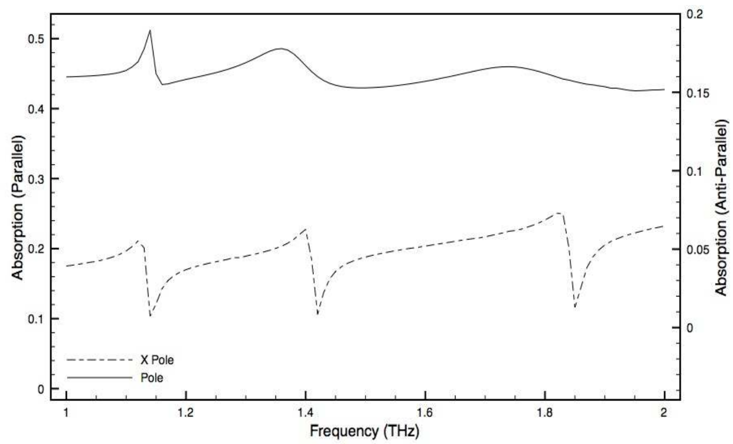

Fig 5, An HFSS simulation of the absorption of radiation with polarization parallel and anti-parallel to the meander absorbing structure in the absence of a substrate.

The presence of a substrate and ground plane behind the meander can be used to ones advantage by creating a λ/4 back-short. This in conjunction with a low loss anti-reflection coating can be used to maximise optical coupling. Using a quasi-optical analysis approach the optical coupling can be calculated to reach values close to 100% as shown in fig (6). An alternative approach is to remove some of the ground-plane of the device and illuminate the detector through the substrate. This approach has the advantage reducing the required impedance the meander needs to present to the incoming photon allowing for more leeway in the normal impedance of the of the meander structure. The approach also removes the need for a very low loss anti reflection coating, which would otherwise reduce the Q_u of the resonator.

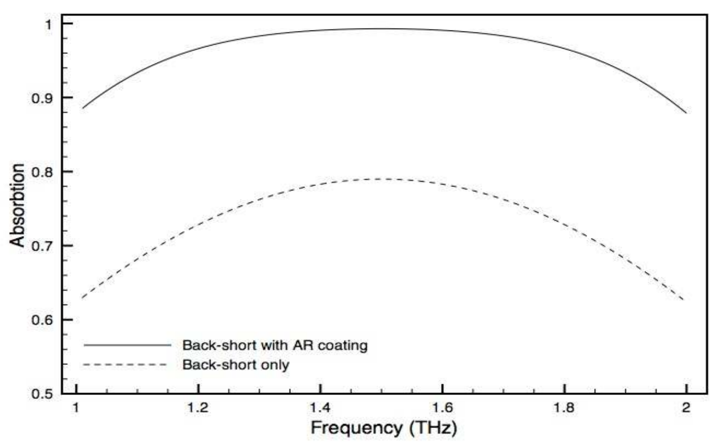

Fig 6, A Quasi-optical simulation showing the absorption of radiation with polarization parallel to the meander as a function of frequency in the presence of a substrate forming a λ/4 backshort.

MULTIPLEXING

One of the major advantages with KID devices is there natural ability to multiplexing in the frequency domain. Changing the length of a distributed KID or changing the value of the interdigital capacitor of a LEKID alters the resonant frequency of the device. This enables many devices to be coupled to a single feed line. Using this approach one can excite all the KID devices coupled to a single line simultaneously by probing the line with a complex probe signal made up from the resonant frequency of each device. This probe signal can be constructed in software and then realised using digital to analogue converters

(DAC). In practice the complex probe signal is constructed at a lower frequency, which is then up converted using a mixer and local oscillator to the resonant frequency of the devices on the chip. Once the devices have been probed the signal can be mixed down using the same local oscillator and read in to an analogue to digital converter (ADC) for analysis. Both the DAC and DAC are available as "off the shelf" technologies providing a simple solution to reading out large arrays of KID detectors. This approach means as many as 10000 devices can be read out using only two coaxial lines connected to the detector array. This simplifies the cryogenics considerably and reduces the cold (4K) electronics to a single HEMT amplifier [5].

7. CONCLUSION

The LEKID device simulated in this paper demonstrates a promising solution to the problem of coupling THz radiation in to kinetic inductance sensing elements. We have demonstrated a comparable theoretical response to that of a distributed KID operating at a similar temperature and resonant frequency. The coupling of radiation to these devices shows a strong polarization response which can reach almost 100% if used in conjunction with a λ/4 backshort and anti-reflection coating. It is worth noting that due to the simplicity of the LEKID geometry means an entire array could be fabricated using a single lithographic step and etch along with two film depositions. The ease of processing is in striking contrast with competing detector technologies such as Transition Edge Sensors (TES) which require multiple fabrication steps.

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Acknowledgments

Discussions with: Mr Dmirty Morozov, Dr Gustav Teleberg, Dr Jochem Beselmans and Dr Stephen Yates

Work funded by PPARC rolling grant. Grant code:PP/D001048/1