Detection of Terahertz radiation using large Niobium detector arrays

Simon Doyle, Chris Dunscombe, Philip Mauskopf
Department of Physics and astronomy
Cardiff University
Cardiff
Email: Simon.Doyle@Astro.cf.ac.uk

Zaid Aboush, Adrian Porch
Department of Electrical Engineering
Cardiff University
Cardiff
Email:PorchA@cf.ac.uk

***Abstract*— Kinetic Inductance Detectors (KIDs) made from Niobium are an attractive solution for constructing large detector arrays working at temperatures achievable using only modest cryogenic equipment. In a high Q resonant structure, generation of non-equilibrium quasiparticles upon photon absorption causes a change in complex impedance of the superconducting thin film making up the resonator. This change in complex impedance is observed through a shift in the resonant frequency or a phase change of a microwave probe signal. Fabricating KIDs of varying resonant frequencies means they can be easily multiplexed and therefore lend themselves to use in large detector arrays. Here we present results from the fabrication and testing of simple resonant structures created from Niobium thin films and cooled to 4.2 K. We discuss the design and optimisation of antenna coupled and lumped element Niobium KIDs for use in the detection of THz radiation.**

I. Introduction

Kinetic Inductance Detectors (KIDs) are capacitively coupled superconducting transmission lines that effectively measure the quasiparticle density of the superconductor. The equilibrium quasiparticle density can be perturbed by a change in temperature of the resonator or by direct absorption of a photon above the gap energy $2\Delta/h$. This change in quasiparticle density will alter the complex impedance of the resonator and hence its resonant frequency. The change in resonant frequency is proportional to the kinetic inductance L_k which is increased with reduction of the centre strip width or thickness. This change in resonant frequency will also give rise to a change in the phase of a fixed tone microwave probe signal of frequency equal to that of the resonator's resonant frequency f_0. This change in phase for a given shift in resonant frequency is enhanced by the overall unloaded Q factor of the resonator and its coupling coefficient g[1].

The fundamental limiting factor of a KID is the noise associated with the random generation and recombination of quasiparticles in the resonator. This noise is proportional to the quasiparticle life time τ_{qp}, which depends on the superconducting material and temperature[2]. The quasiparticle lifetime also provides a lower limit for the time constant of a KID. However this limit is realistically inaccessible due to the electronic ring-down time of high Q circuits. Owing to the longitudinal current distribution of a half wave resonator the response of a KID demonstrates a position dependence which is greatest for an absorption event occurring half way along the centre strip. For a quarter wave resonator the optimal position for photon absorption occurs at the shorted end of the centre strip. There have been various solutions proposed for both antenna coupling and quasiparticle trapping using quarterwave resonators. In this paper we discuss the theoretical performance of a Niobium KID operating at modest cryogenic temperatures.

II. Microwave details of a KID

The favoured resonator geometry for KIDs is the coplanar waveguide resonator (shown in fig1). Unlike microstrip or stripline devices, the impedance of the coplanar waveguide resonator (CPWR) can be set by altering the gap width (s) alone provided that the substrate thickness $d \gg s$. The flexibility of such a structure allows us to set a centrestrip width (w) to whatever we desire and still have control over the impedance of the resonator for matching to an antenna or our microwave probe source. For most applications a characteristic impedance Z_0 of 50Ω is desirable which requires a s/w ratio of 0.142 for a CPWR on sapphire ($\epsilon_r \approx 9.4$) . The impedance of the resonator is further modified by the fact it is decoupled from the line by a gap of capacitance C_g. This now give an input impedance on resonance of Z_0/g where g is the coupling coefficient given by $g \approx 8\pi Q(f_0 C_g Z_0)^2$ [1]

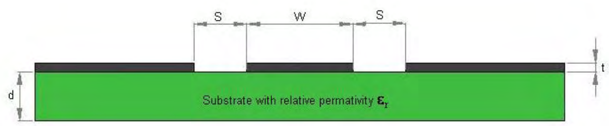

Fig. 1. Schematic of a Coplanar waveguide cross section

The resonant frequency of a half wave CPWR or any transmission line resonator is set by the centre strip length (l) and effective dielectric constant (ϵ_{eff}) and can be calculated by

$$f_0 = \frac{c}{2l\sqrt{\epsilon_{eff}}} \qquad (1)$$

Equation 1 contains a factor of 4 in the denominator for a quarter wave resonator. For a CPWR where the substrate thickness $d \gg s$, ϵ_{eff} is given by $(1+\epsilon_{substrate})/2$.

At resonance $\mid S_{11} \mid = (1-g)/(1+g)$ giving zero reflection for a critically coupled resonator. The phase shift of S_{11} close to resonance is given by

$$\Delta\phi \approx \frac{4gQ}{1-g^2}\frac{\Delta f}{f_0} \tag{2}$$

Equation 2 shows the change in phase of S_{11} for a given shift in frequency from resonance is scaled by Q and $1/1-g^2$. Although g and Q are not independent variables g can in principal be set to any value by altering the size of the capacitive gap. This potentially gives us a large shift in phase for a relatively small shift from the resonant frequency. Making use of this control of g provides a measurable phase shift for a given shift from resonant frequency without the need for ultra high Q resonators.

III. Detector performance

The performance of a KID depends ultimately on two parameters; the shift in resonant frequency (Δf_0) upon photon absorption and the microwave response to Δf_0. The microwave response has been explained in the last section and demonstrates a need for a high Q resonator close to being critically coupled. The shift in resonant frequency is governed purely by the change in kinetic inductance ΔL_k. The total kinetic inductance for a CPWR can be calculated from the Cooper pair density in the centre strip and by considering a change in superconducting electron density (n_s) by -1 in a small volume of the centre strip δV we calculate the ratio of $\Delta L_k/L_k$ to be:

$$\frac{\Delta L_k}{L_k} = \frac{1}{n_s}\frac{J_0^2}{\int J^2 dV} \tag{3}$$

Here the value J_0 is the local current density at the point where n_s is reduced by 1. The volume integral of$J^2 dv$ accounts for the non-uniform current distribution across the strip width. Equation 3 is modified to take in to account the non-uniform current distribution along the centre strips length to give:

$$\frac{\Delta L_k}{L_k} = \frac{1}{n_s}\frac{2}{s_{eff} l} \tag{4}$$

Here s_{eff} gives an effective cross-sectional area of the centre strip and is given by $\int J^2 dv/J_0^2$. Due to the long diffusion length of a quasiparticle once created (up to 1mm [3]), means that for a thin narrow strips s_{eff} becomes the cross-sectional area of the strip Wt. Equation 4 can now be written as

$$\frac{\Delta L_k}{L_k} = \frac{1}{n_s}\frac{2}{V} \tag{5}$$

where V is the volume of the centre strip. The resulting shift in resonant frequency can be calculated by $\Delta f_0 \approx -f_0 \frac{\Delta L_k}{2L}$ where L is the total inductance of the strip [1]. L is dominant over L_k so we can write

$$\frac{\Delta f_0}{f_0} \approx -\frac{\beta k}{2 n_s V} \tag{6}$$

Here $k = \Delta L_k/L$ and β is a dimensionless factor that accounts for the proportion of L_k not provided by the centre strip and is typically in the range of 0.6 to 0.85 for CPWR geometries [1]. Re fering back to equation 2 we can calculate the phase shift of S_{11} for $n_s \rightarrow n_s - 1$ as

$$\Delta\phi \approx \frac{4gQ}{1-g^2} - \frac{\beta k}{2 n_s V} \tag{7}$$

Values for Q can be derived from the Mattis-Bardeen result for complex conductivity and shows a suppression of Q with a increase in L_k; $Q_c = (2/\pi k)\exp(\Delta(0)/k_b T)$. This suppression of the conductor quality factor (Q_c) is offset by the larger shift in f_0 for stuctures with a larger L_k so does not effect the overall phase shift for a change in n_s. Rewriting equation 7 in terms Q_c we can write the complete expression for $\Delta\phi$ as:

$$\Delta\phi \approx \frac{4g\beta}{\pi(1-g^2)}\frac{1}{n_s V}\exp\left(\frac{-\Delta(0)}{k_b T}\right) \tag{8}$$

Equation 8 holds well until Q_c reaches the limit set by the surface resistance ($R_{s,0}$) of the resonator. In high quality Nb films $R_{s,0}$ can be as low as $10n\Omega$ which modifies Q_c by $Q_c \approx \omega\mu_0\lambda/2kR_{s,0}$ which is $\approx 10^6$ to 10^7 at 10GHz. The total Q for the resonator is also reduced by radiative losses and substrate losses. The latter can be reduced by using low loss substrates such as sapphire.

The fundamental noise source in a KID comes from the random generation and recombination of quasiparticles in the superconducting resonator and is governed by the quasiparticle life times (τ_{qp}) and densities (N_{eq}). The generation-recombination noise equivalent power (NEP_{gr}) is given by $NEP_{gr} = 2\Delta\sqrt{N_{eq}\tau_{qp}}$ [2]. Theoretical values for τ_{qp} as a function of T are given by Kaplan [3]

$$\frac{1}{\tau_{qp}} = \frac{\pi^{1/2}}{\tau_0}\left(\frac{2\Delta}{k_b T_c}\right)^{5/2}\left(\frac{T}{T_c}\right)^{1/2} exp\left(\frac{-\Delta(0)}{k_b T}\right) \tag{9}$$

$\tau_0 = 0.149 \times 10^{-9} s^{-1}$ for Niobium [3]. Calculating the NEP_{gr} from equation 9 for a strip of volume $\approx 1000\mu m^3$ predicts an NEP_{gr} of $10^{-19}W\sqrt{Hz}$ at 1K. This result is consistent with Sergeev and Karasik [2] . τ_{qp} will also dictate the fundamental time constant for the detector. Fig 3 shows a decrease in $\tau_{qp}$with a reduction in temperature. The value of τ_{qp} can be as short as 10^{-9} at 4.2K however the electronic ringdown time is scaled by Q ($\tau_{ring} = Q/\pi f_0$). In order to make the electronic ringdown time comparable with τ_{qp} for a 10GHz resonator we would need to suppress Q down to about 30.

IV. Applications

For terahertz radiation, Niobium resonators are capable of providing low noise detectors at modest cryogenic temperatures. At 1K a Nb KID can have an NEP_{gr} as low

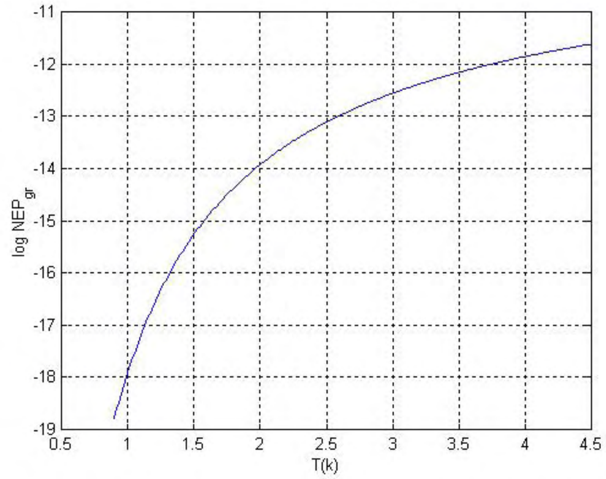

Fig. 2. calculated NEP_gr for a $1000\mu m^3$ strip from 0.9 to 4.5K

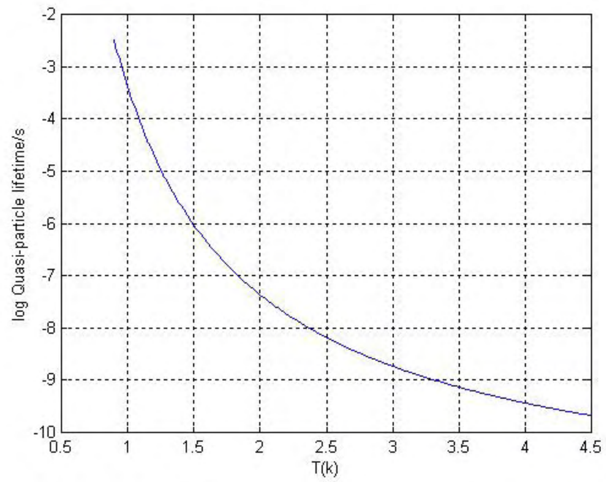

Fig. 3. calculated NEP_gr for a $1000\mu m^3$ strip from 0.9 to 4.5k

as $10^{-19}W/\sqrt{Hz}$ whereas an Aluminium equivalent would need to be cooled to around 130 mK to achieve the same NEP_{gr}. Aluminium KIDs have been considered for mm wave applications and arrangements have been proposed for Aluminium KIDs using Niobium antennas and microstrip lines to couple in photons of energy $2\Delta_{Al} < h\nu < 2\Delta_{Nb}$ [4]. For a Niobium KID working in the terahertz region we would need to use an normal metal antenna and microstrip line to couple in the photon power. This arrangement would be lossy at THz frequencies so keeping the microstrip lines short would be necessary in order to detect low power signals. Another solution to couple power on to the centre strip is to use slot antennas etched in to a gold layer deposited on to the ground planes of the CPWR but seperated by a dielectric layer. This gold layer will suppress the Q by a factor proportional to the dielectric thickness and the quality of the gold film. This suppression of Q could be offset by altering the coupling coefficient g to regain a phase sensitivity to Δf_0. Finally using a lumped element resonator can provide an absorbing area with a uniform current distribution, hence removing the position dependance of the detector. Lumped element resonators tend to have lower Q values compared to their distributed component counterparts, which again could be offset by altering g. A lumped element resonator could be used with a feed horn or a hemi-spherical lens in an arrangment similar to that of the spiderweb bolometer.

V. Results

Measuring the unloaded Q factor of a resonator (Q_u) requires an accurate measurement of the insertion loss (IL). Q_u can be deduced from the loaded Q (Q_L) using the following

$$Q_u = \frac{Q_L}{1-|S_{21}|} \quad \text{where} \quad |S_{21}| = 10^{\frac{-IL}{20}} \tag{10}$$

$|S_{21}|$ is governed by the coupling and for a strongly coupled CPWR will heavily load Q. The results shown in fig 4are for the loaded Q of a 12mm Niobium resonator. Although this line is superconducting and should have a theoretical Q_u of order 10^4 we can see the effects of being over coupled. The measured Q_L for this line is around 100. To avoid over coupling and measure a value closer to Q_u far weaker coupling is required. This can be achieved by increasing the capacitive gaps at each end of the resonator.

The resonant frequencyf_0 for this line was 4.7 GHz which is in accordance with equation‘1

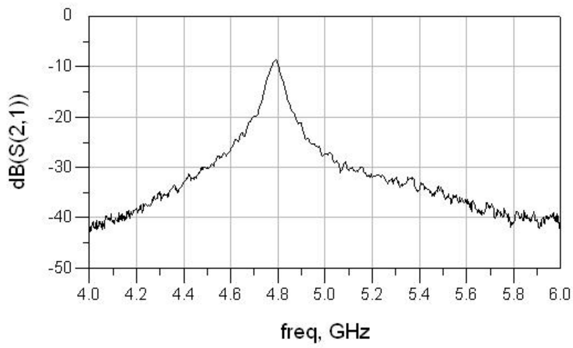

Fig. 4. Example of a over-coupled Nb resonator at 4.2K

VI. Conclusion

Niobium KIDs theoretically have very low noise at 1K and would make an ideal terahertz detector. Along with low noise properties, KIDs have the potential to be multiplexed in to large arrays reducing the electronic complexity on the cold stage to a simple 2-port RF coupling. In comparison to an Aluminium KID the Niobium KID requires simpler cryogenics and could be run using simple sorption coolers running in an open cycle (permanent 1K stage) mode. Gold slot antennas could allow efficient coupling of THz radiation to a Nb resonator providing the Q factor is not suppressed beyond a point we can adjust for by altering (g). Alternatively lumped element resonators could act a multimode free space absorbers for terahertz radiation. We are currently simulating various Nb THz KID geometries to optimise both the coupling and quality factors for distributed and lumped element devices.

ACKNOWLEDGMENT

Mr Vic Haynes, Miss Nicola Whitehouse and Mr Douglas Haig

REFERENCES

[1] S. Porch, P. Mauskopf, S. Doyle, and C. Duscombe, "Calculations of the characteristics of coplanar resonators for kinetic inductance detectors," in *Applied Super Conductivity*, October 2004.

[2] A. Sergeev, B. Karasik, I. Gogidze, and V. Mitin, "Ultrasensitive hot-electron kinetic-inductance detectors," *AIP Conf. Proc. 605: Low Temperature Detectors*, vol. 605, pp. 27–30, Feb. 2002.

[3] S. B. Kaplan, C. C. Chi, D. N. Langenberg, J. J. Chang, S. Jafarey, and D. J. Scalapino, "Quasiparticle and phonon lifetimes in superconductors," vol. 14, pp. 4854–4873, Dec. 1976.

[4] B. Mazin, "Microwave kinetic inductance detectorsl," Ph.D. dissertation, Californian Institute of Technology, Nov. 2004.