Initial investigation into the susceptibility of antenna-coupled LEKIDs to two level system affects

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Abstract Optical coupling to a lumped-element kinetic inductance detector (LEKID) via an antenna and transmission line structure enables a compact detector architecture, easily optimised for the required sensitivity and multiplexing performance of future cosmic microwave background (CMB) experiments. Coupling in this way allows multi-chroic, polarisation-sensitive pixels to be realised through planar on-chip filtering structures. However, adding the necessary dielectric layers to LEKID structures to form the microstrip-coupled architecture has the potential to increase two level system (TLS) contributions, resulting in excess detector noise. Using a lumped-element resonator enables coupling via a microstrip to the inductive section only, whilst leaving capacitive elements clear of potentially noisy dielectrics. Here we present the preliminary data acquired to demonstrate that a microstrip transmission line structure can be coupled to a LEKID architecture with minimal additional TLS contributions. This is achieved through a simple fabrication process, which allows for the dielectric to be removed from capacitive regions of the LEKID. As a result we have produced resonators with the high quality factors required for large multiplexing ratios; thus highlighting the suitability of the separated KID architecture for future observations of the CMB.

Keywords CMB, instrumentation, kinetic inductance detectors

1 Introduction

\textit{Planck} has revolutionised our understanding of the universe through measurements of temperature anisotropies in the afterglow of the big bang – the cosmic microwave background (CMB). Polarimetry allowed for the extraction of E-modes, but has yet to yield the degree-scale B-mode signature from primordial gravitational waves, as predicted by inflation [1, 2]. Currently, many ground-based experiments have successfully implemented Transition Edge Sensors (TESs) to measure the small-scale temperature anisotropies of the CMB [3, 4]. With many instruments now approaching the background-limit, the only way to improve...
sensitivity is to continue to increase the size of focal planes and consequently detector numbers. However, such arrays are difficult to fabricate and will prove a significant technical challenge to scale to multiplexing ratios required for future CMB experiments.

With their high multiplexing capabilities and simple fabrication process, kinetic inductance detectors (KIDs) are an attractive detector choice for future experiments requiring large arrays. Optical coupling to a KID via an antenna and transmission line structure enables a compact detector architecture, easily optimised for the required sensitivity and multiplexing performance of future CMB experiments. KIDs are superconducting resonators whose resonant frequency and quality factor are modified with absorbed power [5]. For this coupling mechanism to be realised, we employ LEKIDs because the discrete inductive ($L$) and capacitive ($C$) elements are spatially separated [6]. This separated architecture enables lossy dielectric materials to be added to our devices whilst maintaining the high intrinsic quality factors, $Q_i$, required for multiplexing performance.

Coupling the LEKID to a microstrip transmission line is an important step towards realising the large arrays of multi-chroic, polarisation-sensitive pixels required for future studies of the CMB. In this paper we present the preliminary data to study the effects of the deposited dielectric silicon nitride (SiN$_x$) over the LEKID architecture. We compare three LEKID resonators with various coverage of SiN$_x$ to study the affects on $Q_i$ and resonant frequency as a function of temperature, as a first look at TLS contributions.

2 Motivation

For the high sensitivity required for improved observations of the CMB, we must implement large arrays of detectors operating at the photon-noise limited under typical sky loads of $\sim 1$–$10$ pW at 150 GHz[7]. This requires arrays of close to $10^5$ detectors with NEPs of order $10^{-17}$ WHz$^{-1/2}$ [8]. Achieving this with KID devices requires high-$Q$ resonators in order to maximise the number of detectors in a given readout bandwidth whilst minimising the potential of resonator clashes. Current arrays have achieved multiplexing ratios of around 1000 [9], and are commonly read out with commercially available readout hardware [10].

Amorphous dielectrics, like SiN$_x$, have a tendency to degrade $Q_i$s of resonators through dielectric loss tangents and the introduction of two level systems (TLSs) [11,12]. These capacitance fluctuations can be characterised by a temperature-dependent shift in resonant frequency $f_r$ [13] as

$$\frac{\Delta f_r}{f_r} = -\frac{F \Delta \epsilon}{2 \epsilon},$$

where $\epsilon$ is the dielectric constant parametrised as,

$$\frac{\Delta \epsilon}{\epsilon} = 2 \delta_0 \Re \Psi \left( \frac{1}{2} + \frac{1}{2 \pi i kT} \right) + \log \frac{h \omega}{kT},$$

and the fill factor, $F$, is described by,

$$F = \frac{\int_V \epsilon |\mathbf{E}(r)|^2 d\mathbf{r}}{\int_V \epsilon |\mathbf{E}(r)|^2 d\mathbf{r}} = \frac{w_0^2}{w^2},$$

where $\omega$ is the frequency, $\Psi$ is the complex digamma function and $\delta_0$ is the TLS-induced dielectric loss tangent at $T = 0$ for weak, non-saturating fields [13]. $F$ is the ratio of electric fields stored in the TLS-loaded volume, $w_0^2$, to the total electric energy stored in the
Initial investigation into the susceptibility of antenna-coupled LEKIDs to two level system affects resonator, \( w^\cdot \). Therefore, the fill factor accounts for the fraction of electric field contained within the TLS host material. Thus if we limit the deposition of dielectric to regions of low electric field i.e the inductor, then the fill factor of the dielectric material will be low, resulting in a lower \( \delta_0 \). This is a crucial step in reducing the additional losses which occur due to dielectric requirements of our proposed optical coupling mechanism.

Measurements of the resonator frequency as a function of temperature provide a first qualitative look at how adding SiN\(_x\) to the LEKID affects the device performance. In addition, a complimentary measure is provided by the intrinsic quality factor of the resonator as a direct probe of the dielectric loss. For the preliminary results presented here, we make a relative comparison of both the frequency shift and quality factor of resonators with different dielectric coverage.

### 3 Prototype test device

The prototype device presented here is a seven-element, single-polarisation array, of thin-film Al LEKIDs (cf. Fig. 3. A lenslet array comprising seven anti-reflection (AR) coated alumina lenses focuses light on to a planar twin-slot antenna. An Al/Nb bilayer transmission line connects the antenna to the LEKID, and it is here where filtering structures can be easily accommodated to create multi-chroic, polarisation-sensitive devices. The motivation and design of this prototype device is discussed thoroughly in Barry et al. [14]. The details of the device fabrication process is discussed in Tang et al. [15].

For the inverted microstrip transmission line design used here [16], the Al layer is deposited before the SiN\(_x\) and Nb groundplane layer. This allows maximum control over processing of the Al, aiding the reduction of TLS noise from the original substrate. We further reduce our susceptibility to TLSs by removing the SiN\(_x\) from the capacitive regions of the LEKID, as depicted in Fig. 1 (KID02).

Outside of the lens footprint sit a number of ancillary detectors with no antenna coupling and various SiN\(_x\) coverage. Fig. 1 shows a schematic version of the devices and highlights
Fig. 2 (a) Image of the prototype test array. (b) The lenslet array which focuses light on to planar twin-slot antennae. (Colour figure online)

our three different scenarios. The lowest frequency resonator, at $\sim 540$ MHz, is completely free of dielectric (Fig. 1, left). While this does not allow for optical coupling via a microstrip, this structure serves as a reference device for our proposed design, providing insight into how our resonator is affected by the necessary dielectric. The next resonator, located at 553 MHz, for comparison, is completely covered by SiN$_x$ and is expected to have the highest loss (Fig. 1, centre). At 605 MHz, our resonator has SiN$_x$ over the mm-wave absorbing length only (Fig. 1, right) – this is the desired dielectric coverage for the proposed coupling scheme.

4 Preliminary Results

As means of a preliminary investigation into how the performance of the prototype device is impacted by the addition of SiN$_x$, we explored the dark response of the resonators outlined in Fig. 1. The prototype device was placed in a gold-plated OFHC copper sample box, installed on the the 80 mK baseplate of a cryostat, which is cooled via a miniature dilution system [17]. We measured $S_{21}$ of the resonators as a function of base temperature between 80 - 320 mK using a Vector Network Analyser (VNA). To extract the $Q_i$ and resonant frequency, the $S_{21}$ data was fitted following the procedure outlined in Khalil et al. [18].

All of the resonators in Fig. 3(b) have limiting, low-temperature quality factors in excess of $10^5$, maintained up until $\sim 180$ mK. However adding SiN$_x$ to the capacitive region of the KID01 has limited its performance, as this resonator has the lowest measured $Q_i$ across the 80 - 320 mK range. In terms of $Q_i$ the best performing KID is the bare resonator KID00, closely followed by KID02. This suggests adding the required dielectric to the mm-wave absorbing length does have a small, but not prohibitive affect on the resonator $Q_i$.

For a second measure of performance, we investigated the fractional frequency shift of each resonator as a function of temperature. These values are normalised to the first data point to allow for a direct comparison. From Fig. 4(a), we observe the so-called back-bending in all devices, where the resonant frequency increases with temperature instead of decreasing, typical of the TLSs perturbation described by Eq. 2. This is highlighted in Fig. 4(b), when we zoom in to the low temperature region, where back-bending is greatest in KID01 (SiN$_x$ covered). Removing SiN$_x$ reduces back-bending substantially here, however there is no discernible difference between KID00 and KID02 at temperatures below 170 mK.
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Fig. 3 (a) $S_{21}$ data of KID02 as a function of base temperature. The calculated fit is shown overlaid in black. (b) $Q_i$ as a function of base temperature for the three different resonators described in Fig. 1. (Colour figure online)

Fig. 4 (a) The fractional frequency shift as a function of temperature for our resonators. All values are normalised using the first data point to allow for a direct comparison. (b) A closer look at (a) between 80 - 240 mK to highlight back-bending due to TLSs. (Colour figure online)

Thus, introducing SiN$_x$ to the LEKID architecture, via the mm-wave absorbing length, does not introduce a significant additional TLSs frequency response relative to the completely bare resonator.

The combination of the frequency and dissipative TLS response suggest that this design is viable from the point of view of resonator loss from the addition of dielectric over the inductor. Furthermore, the performance of these devices is expected to be background-limited at representative power loading [14], and, with $Q_i > 10^5$ enabling multiplexing ratios in excess of $10^3$, this design presents a compelling architecture for CMB applications.
5 Conclusion

Optical coupling to a LEKID via an antenna and transmission line structure is a promising candidate for future experiments requiring large detector arrays, making possible the addition of structures needed for multi-chromatic, polarisation-sensitive capabilities. Separating out the inductive and capacitive elements allows for additional TLSs losses, caused by placing dielectric over the resonator, to be minimised. For a non-optimised device, we have demonstrated that we can meet the dielectric requirements of the microstrip transmission line coupling, whilst maintaining high Q factors and minimal additional parasitic dielectric response.

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