Optimisation of an antenna-coupled LEKID for future ground-based CMB experiments

A. Hornsby[1], P. S. Barry[1, 2], S. Doyle[1], E. Shirokoff[2]

[1] School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, CF24 3AA, UK
[2] Department of Astronomy & Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA

Abstract

Optical coupling to a lumped-element kinetic inductance detector (LEKID) via an antenna and transmission line structure enables a compact and simple to fabricate detector architecture, easily optimised for sensitivity and multiplexing performance for applications in cosmic microwave background (CMB) experiments. Adding passive microwave structures, such as diplexers, between the antenna and a number of LEKIDs elements enables multi-chroic, polarisation-sensitive pixels to be realised highlighting why this coupling mechanism is ideal in such applications. We discuss how to optimise this architecture for multiplexing ability through considerations of the absorber volume and the impact this has on the predicted noise of the detector. We present the first experimental data acquired proving the overall design concept and fabrication process is suitable for these applications.

Introduction

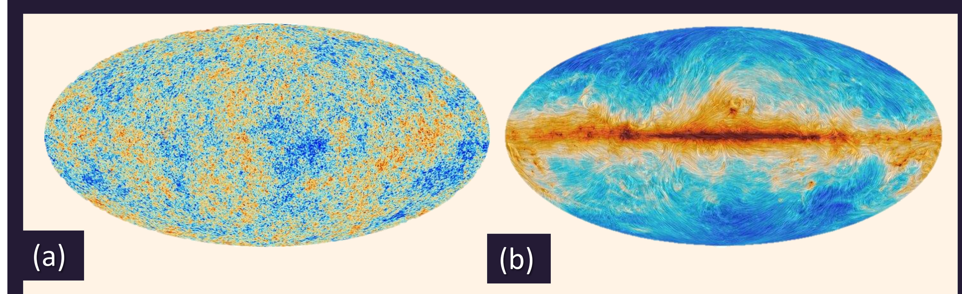


Figure 1: (a) Temperature anisotropies as measured by Planck [1] (b) Polarised dust emission dominated by Milky Way [3]

Planck [1] revolutionised our understanding of the universe through measurements of the CMB, yet the primordial gravitational waves hidden within B-modes [2] continue to remain elusive. Therefore in the post-Planck era, we will require thousands of detectors performing at the photon noise limit.

LEKIDs offer highly-multiplexable readout making them an attractive detector choice for future experiments requiring large detector arrays. With the addition of on-chip, band-defining structures (cf. Figure 4, 5) it is possible to create a multi-chroic, polarisation-sensitive pixel ideal for future studies of the polarised CMB.

Lumped Element Kinetic Inductance Detectors

LEKIDs are superconducting resonators with a resonant frequency which changes as a function of absorbed power [3].

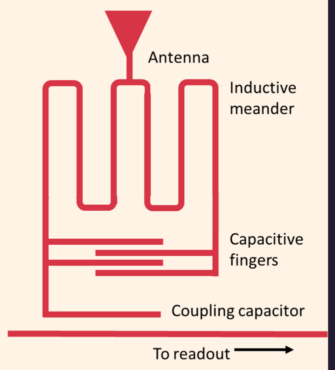
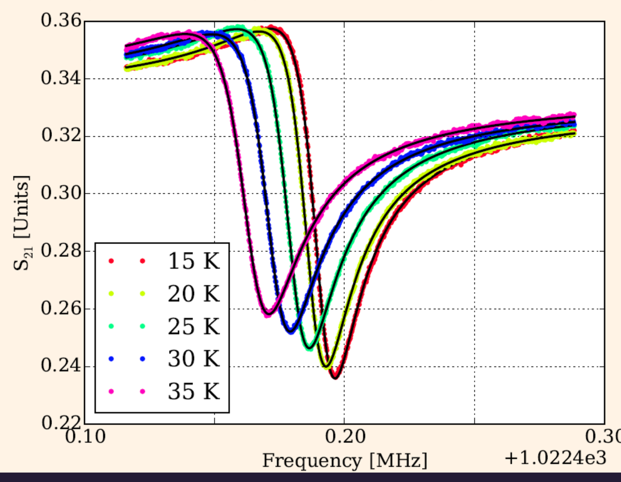


Figure 2: LEKID with the proposed optical coupling mechanism.

In a LEKID the discrete inductive, *L*, and capacitive, *C*, elements are spatially separated. This enables normally lossy dielectric materials to be added to the inductive element without reducing Q_i allowing efficient microstrip feedlines to be formed.

Control over the absorbing volume allows a trade-off between device noise and quality factor to be performed, enabling the mux ratios and device responsivity to be optimised for a given application



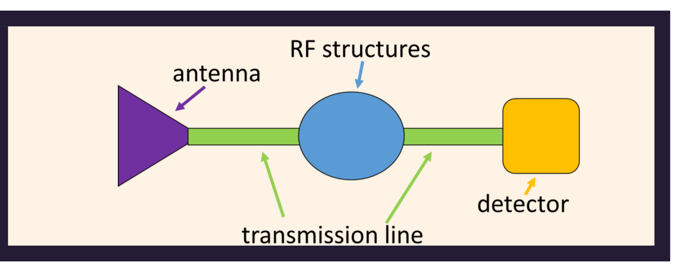
LEKID Operating Principle

With increasing optical power, the resonator

- bandwidth increases
- depth decreases
- frequency, f_0, decreases

Figure 3: A LEKID responding to incident radiation. As power is absorbed, the resonance curve becomes broader , the dip depth reduces and the resonant frequency reduces.

Figure 4: Block diagram of proposed pixel. Light is collected by the antenna, and travels down a transmission line, via optional RF structures separating light according to colour and polarisation, before being absorbed into the resonating detector.



RF structures

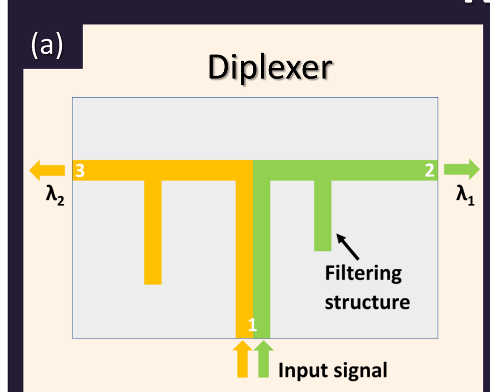
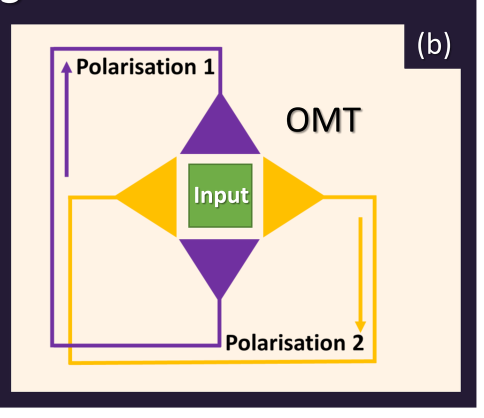


Figure 5: (a) Diplexer structure – splits signal into two frequency bands via filtering structures. (b) Orthomode transducer (OMT) – separates signal according to orientation of input signal's polarisation.



Test device

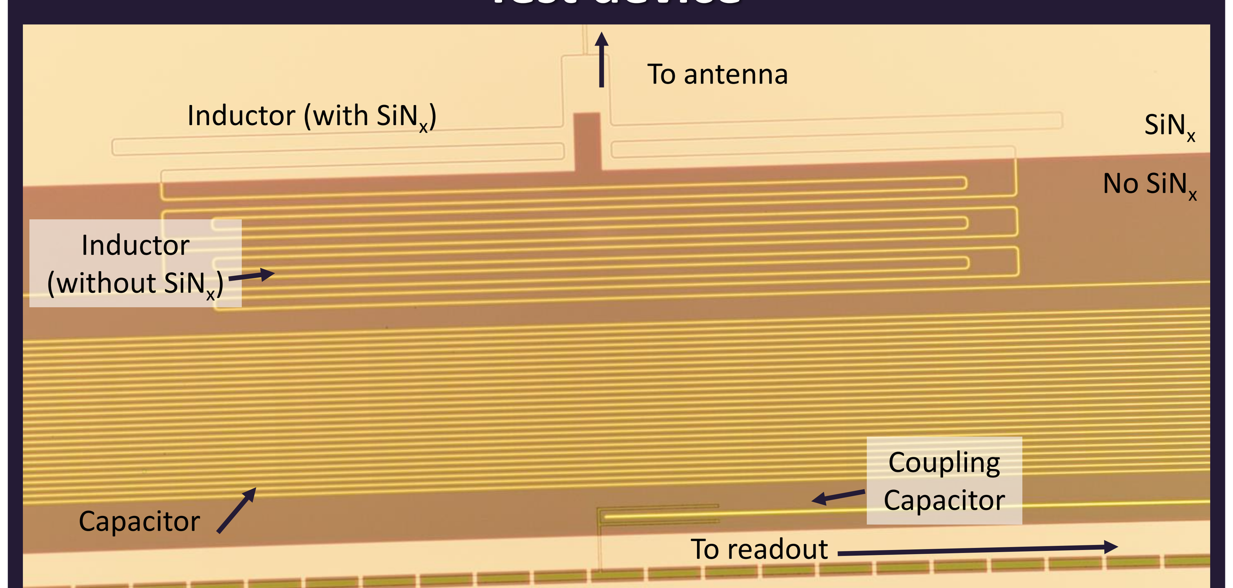


Figure 6: Image of test device. The darker areas have no SiN_x

Q factors

The number of resonators multiplexed on to a single channel is limited by the bandwidth of the readout system. To maximise the number of resonators per unit bandwidth, the individual resonator bandwidth needs to be minimised which is achieved by fabricating high-*Q* devices. Fundamentally the *Q* factor is limited by the intrinsic *Q* (Q_i) which is reduced by optical loading of the detector and material losses. Q_c quantifies the coupling capacitor which is tuned by the value of the coupling capacitance.

Q factor

$$\frac{1}{Q} = \frac{1}{Q_c} + \frac{1}{Q_i}$$

Investigating the impact volume has on device performance

There are multiple contributions to the noise observed in LEKIDs (**see E. Shirokoff's poster PA-13**). The goal is to ensure the noise in the LEKID is dominated by the photon noise from the sky/CMB ~ 10^{-17} W Hz $^{-1/2}$.

Thermal generation

$$NEP_{\mathrm{G,th}} \propto \sqrt{V_{\mathrm{L}}}$$

Recombination

$$NEP_{\mathrm{R}} \propto \sqrt{V_{\mathrm{L}}}$$

Assuming $N_{qp}\tau_{qp}$ is constant.

Figure 7 shows simulations of the *Q* factor and NEP for a range of absorber volumes as a function of optical power. To maintain a constant ratio of kinetic to geometric inductance, the increase in the volume is achieved by increasing the meander length, while keeping the film thickness constant.

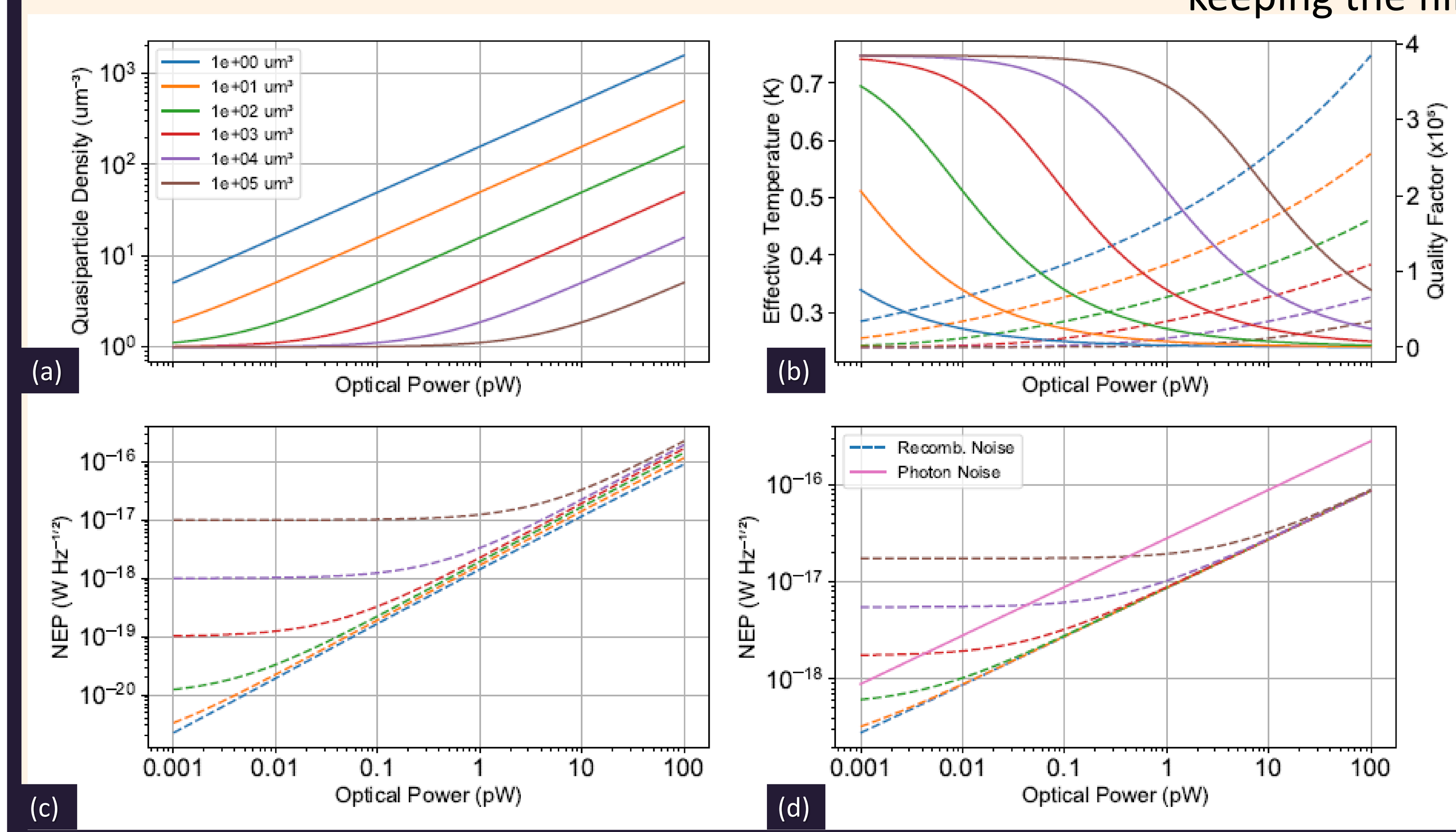


Figure 7: (a) Quasiparticle density as a function of optical power for an array of absorbing volumes. (b) Quality factor (–) and effective quasiparticle temperature (--) as a function of optical power. (c) Total noise predicted for the detector as a function of power. (d) Comparing (c) to the photon noise limit.

Requirement 1: High *Q* factors for maximum multiplexing ratio

- Large Q factors maintained for typical optical loads expected from CMB experiment (~5 pW @ 150 GHz [5])

Requirement 2: Detector noise to remain background limited

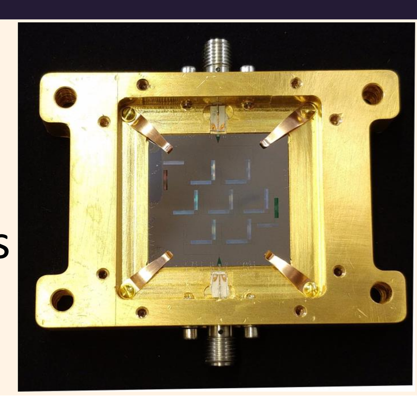
- Detector NEP for the largest volume remains below photon noise NEP

Large film volumes are required for high performance detectors for CMB applications

Silicon Nitride study

Applying a dielectric around the capacitive elements in a LEKID results in a major loss mechanism because this is where electric fields are highest. However coupling to a transmission line requires a dielectric be present in the device.

We have tested devices where the SiN_x dielectric layer is over the inductor, and other devices where it is over both the capacitor and inductor. **See Q. Tang's PA-2 for device fabrication.**



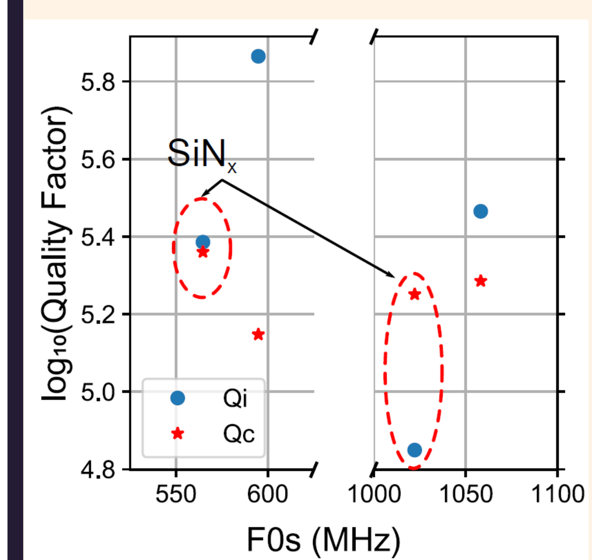


Figure 8: Quality factor for four resonators. The SiN_x resonators have been circled. Removing the SiN_x improves the Q of the LEKID.

Key results:

- Q_i is high in devices where SiN_x is on the inductor only
- Q_i is lower where SiN_x dielectric layer is on the inductor and capacitor
- Q_i is better in low f_0 devices where TLS have less of an effect [6]
- Significantly more back bending in devices where SiN_x is over the capacitor in Figure 9

Having SiN_x over inductor does not degrade Q_i

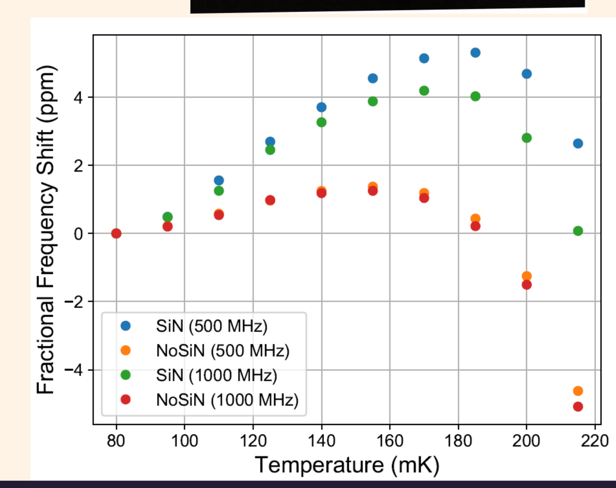


Figure 9: Fractional frequency shift for four resonators – two with, and two without SiN_x over the capacitor. There is more back bending present with SiN_x due to TLS, but this can easily be removed.

Conclusions

- Separating out *L* and *C* allow for losses caused by the dielectric interacting with electric fields in the capacitor to be mitigated.
- Relatively simple fabrication process allows *Q* factors to be maximised, and is therefore suitable for this purpose.
- Increasing the meander length can result in a high-*Q* resonator whilst remaining background limited
- Optical coupling to a LEKID via an antenna and transmission line structure is a promising candidate for future experiments requiring large detector arrays, with potential for multi-chroic, polarisation-sensitive capabilities.

Future work

Full characterisation of array including:

- Verify performance of antenna with spectral data
- Measure performance under optical loading
- Verify performance as a function of volume to corroborate model

Overall aim is to combine the optimised detectors with RF structures to create a multi-chroic, polarisation-sensitive pixel suitable for large arrays to study the CMB.

References

[1] Planck Collaboration XXXVIII. "Planck 2015 XXXVIII. E- and B-modes of dust polarization from the magnetized filamentary structure of the interstellar medium". A&A (2015)
[2] Huber, S.J. et al. "Detectable gravitational waves from very strong phase transitions in the general NMSSM". JCAP 1603 (036 2016)
[3] Doyle, S et al. "Lumped Element Kinetic Inductance Detectors". J Low Temp Phys 151 (530 536 2008)
[4] Khalil, M.S et al. "An analysis method for asymmetric resonator transmission applied to superconducting devices". JAP 111 (054510 2012)
[5] Ade, P.A.R et al. "BICEP 2 II: Experiment and three-year data set". Phys. Rev. let. 112(24 2014)
[6] Gao, J. et al. "A semi empirical model for two-level system noise in superconducting microresonators". Appl. Phys. Lett. 92 212504 (2008)

Acknowledgements

This project is supported by the NSF Advanced Technologies and Instrumentation program. A. Hornsby is supported by the Science and Technology Facilities Council PhD studentship programme. Device fabrication is conducted at the JPL Microdevices Laboratory. This work made use of the Pritzker Nanofabrication Facility of the Institute for Molecular Engineering at the University of Chicago, which receives support from SHyNE, a node of the National Science Foundation's National Nanotechnology Coordinated Infrastructure (NSF NNCI-1542205). Testing of the device was made possible by facilities in the Astronomy Instrumentation Group, based at Cardiff University, and was supported by T. Brien, J. Parrianen, and S. Rowe.