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A mm-Wave Polarisation Analyser Using LEKIDs: Strategy and Preliminary Numerical Results

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Abstract The context of this study is the development of polarisation sensitive detectors in view of future Cosmic Microwave Background experiments. Our goal is to demonstrate the possibility to make a mm-wave polarisation analyser at 150 GHz using Lumped Element Kinetic Inductance Detectors (LEKIDs). Although LEKIDs are very attractive for the relative ease of fabrication, they have an intrinsic optical response which is weakly polarisation-sensitive, i.e. orthogonal linear polarisations are absorbed with comparable efficiencies (with a separation typically not exceeding few dB). To overcome this difficulty, we achieve a polarised response by means of small ($\sim \lambda \times \lambda$) superconducting Nb wire-grids. Each grid is deposited on the rear side of the 300 micron Si substrate, on which 20 nm Al resonators are patterned, so that each pixel may in principle respond as an independent polarisation analyser. Simulations show encouraging results, with a deep (-20 dB) rejection of the unwanted polarisation. Although what we present here is not yet a polarimeter, this pilot study allows us to address some relevant questions that may be crucial in view of a full polarimetric

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architecture development. In particular, our first prototypes will allow to assess the behaviour of small grids, the interaction between adjacent polarised pixels, and to choose the most suitable resonator geometry. What we present here are preliminary design results about devices which are currently being realised, and soon ready for optical response characterisation.

Keywords Kinetic Inductance Detectors · Cosmic Microwave Background · Polarisation

1 Introduction

Accurate and sensitive measurements of Cosmic Microwave Background polarisation, on both small and large angular scales, can shed light on the physical processes occurring during the Inflation era, possibly leading to the formation of Large Scale Structure in the Universe that we observe today. In order to map CMB polarisation, large cryogenic detector arrays are essential to improve mapping speed, to fulfil demanding sensitivity requirements. The coupling of each detector to polarised radiation has to be designed in such a way the level of systematics does not hamper the final sensitivity achieved by an experiment. Ideally, the polarisation state of incoming light should not be altered by the instrument itself (polarimetric accuracy). In particular the unpolarised signal shouldn't leak into polarised channels. Lumped Element Kinetic Inductance Detectors [1] has already been demonstrated to be suitable for use in large arrays for mm-wave Astronomy (see for example NIKA [2]). Here we present a research program aimed at demonstrating their use in a polarisation sensitive focal plane architecture at $\lambda \sim 2$ mm. What we are going to describe here is a polarisation analyser, suitable to detect one linear polarisation component *per pixel*. Although this is not the best set-up for a CMB polarisation experiment, which ideally benefits from the absorption of the two polarisation components within the same focal plane area, this numerical study, which will be put through experimental verification soon, is intended to be a pilot study for further evolution towards a fully polarimetric architecture.

2 Method and Materials

Although an immediate way to obtain a polarisation selection is by means of antenna-coupled MKIDs, here we do not intend to explore this possibility, since we are aiming at a polarisation-sensitive absorption, while retaining the intrinsic simplicity of LEKID concept. Also we have discarded the opportunity of feed-horn coupling (followed elsewhere [3]) since, despite its potential polarimetric purity, and possible dual-polarisation response, it entails the manufacturing of a large format horn array, which is not readily available, and might be very expensive if we think for example to a kilo-pixel multi-band experiment, with mm and sub-mm channels. We are aware that horn-coupled MKIDs have recently been proposed for CMB polarisation experiments [4], although in a single-polarisation focal-plane architecture.

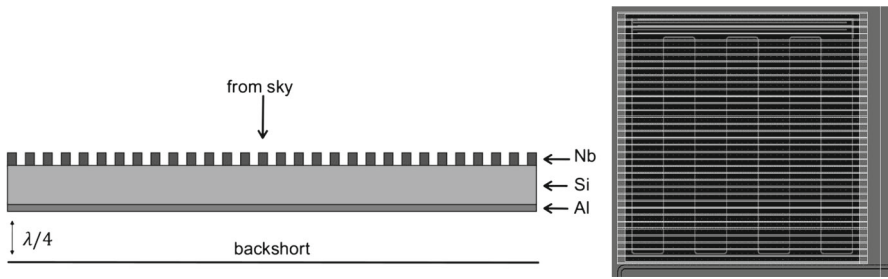


Fig. 1 *Left panel:* Layout of a polarisation-sensitive pixel. See the text below for a description. *Right panel:* an example of a single LEKID with superimposed pixel-sized polariser (a mask detail)

In our approach, aluminium LEKIDs are patterned on one side of a double side polished $300\ \mu\text{m}$ Si wafer. On the opposite side of the wafer, that one looking directly at the sky (as in Fig. 1), Nb wire grids are patterned in correspondence of each pixel, acting as individual polarisers, with characteristic dimension $\sim\lambda$. LEKID coupling to free space impedance is achieved as in [1], knowing substrate ϵ_r , the Al thin film sheet resistance R_{\square} , and acting on meander inductor geometry, in order to maximise absorption. Each LEKID, thanks to the grid, acts as an individual polarisation analyser. LEKID response is intrinsically weakly polarisation selective (only few dB dynamics in absorption for orthogonal polarisations), and the grid is used precisely to enhance selectivity, keeping its wires orthogonally aligned with respect to long meander arms. In a filled array configuration, in which several pixels can be hosted within the Airy spot of a telescope, the image can be sampled in both polarisations, although, with our current scheme, half of the signal is lost.

In order to model correctly the optical coupling and the readout, we have characterised the electrical properties of our superconducting films through a Van der Pauw measurement scheme [5], measuring DC conductivities from 3K to 300 K. Concerning Al films, thicknesses from 50 nm down to 12 nm have been studied on $4''$ Si substrates. Our first prototypes have been realised with 20 nm films, corresponding to normal state conductivity $\sigma_n \simeq 3.1 \times 10^7$ S/m at 3K, and $RRR = 2.3$. We have characterised also a 100 nm Nb film, finding a normal state conductivity $\sigma_n \simeq 1.2 \times 10^7$ S/m (at ~ 10 K) with $RRR = 3.7$.

3 Simulation settings and results

In our simulations, performed using CST Microwave Studio, we impose Floquet boundary conditions (therefore neglecting the effect of array borders), and we use plane-wave modes, in both TE and TM polarisations, at the input port. Reflected signals, which are the primarily computed quantities, are evaluated at the same port for both polarisations. The fraction of absorbed power, for each mode, is evaluated as $1 - R_{ii}$ (where R_{ii} is reflected power in the mode i , after injection in the same mode i , with $i = TE, TM$). Only normal incidence is considered. The E-field component labelled E_{\parallel} is that one parallel to the Nb wires, and should be completely rejected in the ideal case. The orthogonal one, which should be absorbed, is labelled E_{\perp} . For

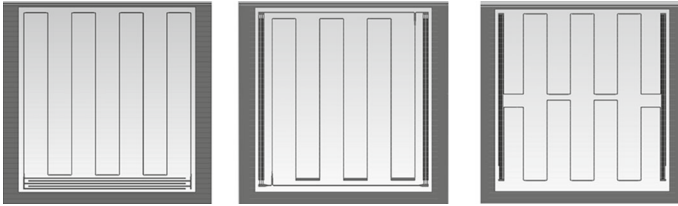


Fig. 2 Resonator topologies considered for this study. From *left to right*: 1 meander/1 capacitor (basically a standard NIKA pixel), 1 meander/2 capacitors (in parallel) and 2 meanders/2capacitors

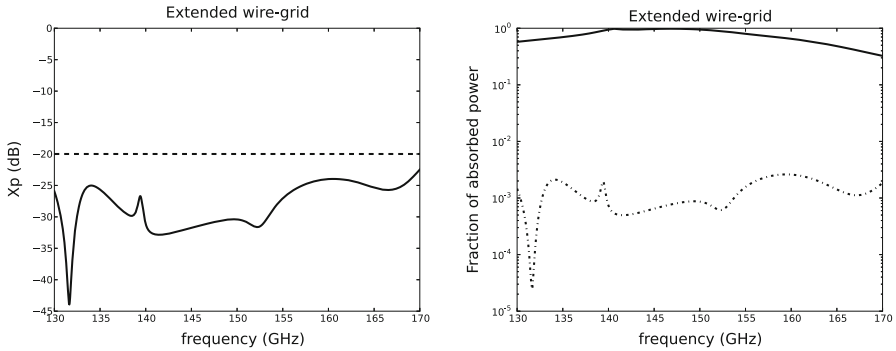


Fig. 3 *Left panel*: rejection of the unwanted polarisation in the case of an infinitely extended wire grid patterned on the opposite side of a LEKID array. *Right panel*: E_{\perp} (solid line) and E_{\parallel} (dash-dotted line)

each pixel we ask the ratio of rejected-to-absorbed power $Xp = (E_{\parallel}/E_{\perp})^2$ to be as small as possible. Although this is not a cross-pol definition in a rigorous sense, Xp quantifies the relative absorption efficiency between the two orthogonal polarisations, and tells us to which extent our focal plane is able to absorb a single E-field component in a given pixel . We consider two distinct cases: (I) a polariser of infinite extent and (II) small (pixel-sized, $\sim 2.3 \text{ mm} \times 2.3 \text{ mm}$) grids, associated to individual pixels, and aligned in the same direction. This two situations allow us to evaluate the effect of the size of the wire grid. Case (II), in turn, is studied for three different topologies of the resonator, as in Fig. 2: 1 meander/1 capacitor (basically a standard NIKA pixel), 1 meander/2 capacitors (in parallel) and 2 meanders/2capacitors.

In the case of an infinite extent polariser, patterned above the LEKID array, the rejection of the unwanted polarisation is rather deep ($Xp < -20\text{dB}$, as in Fig. 3) across a large bandwidth (130–170 GHz). No structures appear at a significant level.

When we study co-aligned small grids (entirely contained within a unit Floquet cell), in order to test individual pixel response in polarisation, we see that the dynamics in polarisation rejection is degraded with respect to the previous case, with deepest rejection value around -20 dB, but only on a small fraction of the frequency band (see Fig. 4). The most striking effect is that resonant structures appear (in particular around 152 GHz), and partly corrupt the response.

These structures survive, and with only slightly different amplitude, if we consider different topologies for the resonator, as we can see in Fig. 5, where we plot in linear

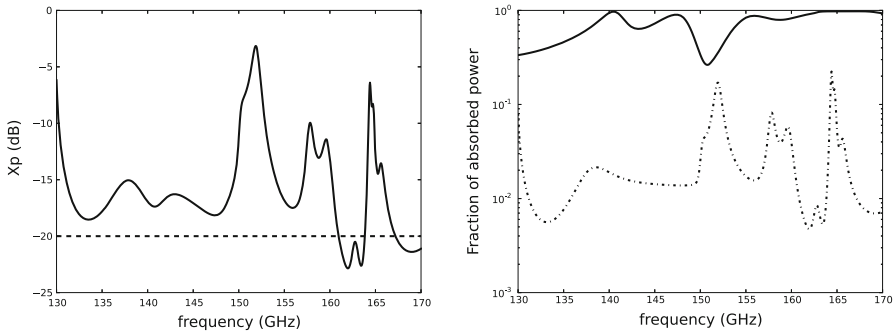


Fig. 4 *Left Panel:* We plot Xp as in the previous figure for pixel-sized grids. *Right panel:* E_{\perp} (solid line) and E_{\parallel} (dash-dotted line)

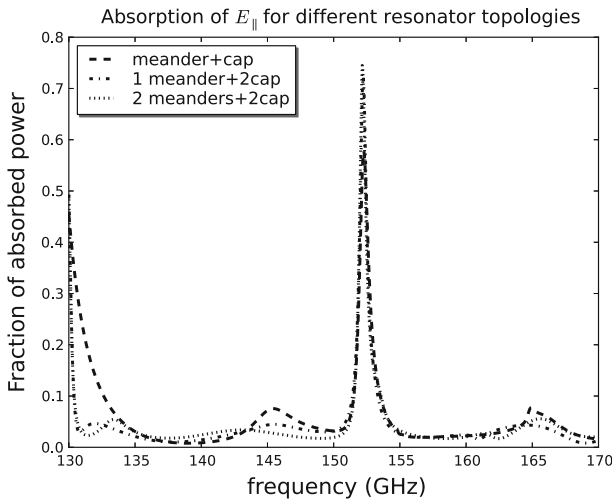


Fig. 5 Fraction of absorbed power in E_{\parallel} for different LEKID topologies. See text for details

scale the fraction of absorbed power in E_{\parallel} for three different cases. Therefore we conclude that what we observe is the result of the finite size of the grid, which is comparable to the wavelength, and to the array unit cell size. As a further numerical check, we have observed similar structures substituting LEKIDs with square absorbers perfectly matched to free space. Also in this case, the E_{\parallel} component is strongly dissipated in the metallisation behind the grid at a resonant frequency. A tentative interpretation is that the ensemble of wires deposited on the thick dielectric substrate, at a particular frequency, support oscillating currents and behave like an antenna. The numerical study for the case of orthogonally aligned nearest-neighbouring grids is more complicated, computationally more expensive, and is currently ongoing. The influence of the Nb grid on the position of each resonance has been evaluated by means of Sonnet simulations, and it is negligible.

4 Conclusions and Research program

The idea of using superconducting polarising grids coupled to LEKIDs seems a viable solution after first calculations, but it has still to undergo an experimental trial (imminent). We have found that this solution, which works well in the case of extended grids, is also feasible in the case of small grids (the most interesting case), although in the latter case strongly frequency-dependent features appear and partly degrade the performances in terms of polarisation selection. In general, we have found that the optical response is determined by the grids (or by the extended grid in the simplest case), whose size is comparable to the unit Floquet cell (the lattice constant of our periodic array). No particular role is played by the shape of the absorber. This strategy is relatively easy to implement, and deserve to be investigated carefully. For this reason, we are currently manufacturing 9 chips (on a single 4" wafer), each one with 25 pixels, in order to address all the issues arising from simulations:

- the effect of grid size on the resonant absorption of unwanted polarisation (the case of a unique grid serving all the array, to be compared with pixel-sized grids);
- the interaction among small nearest-neighbouring co-aligned grids, and the case of nearest-neighbouring orthogonally aligned grids;
- the effect of pixel cross-talk for different pixel spacings, for a given pixel kind.

Moreover, on each side (Nb and Al) of our 4" wafers, we have patterned also a cloverleaf structure dedicated to Van der Pauw measurements, in such a way that we will obtain the electrical properties of the superconducting thin films we are using for all our samples. After the first experimental trial we will be able to start the optimisation of our design, especially to increase the dynamics in the absorption of orthogonal polarisations (X_p). At that point, after spectropolarimetric measurement will be performed, we will have also hints to interpret correctly the problem of the resonant structures appearing in E_{\parallel} absorption, and eventually to solve it. In view of next generation devices, we have also to improve the absorption of the E_{\perp} polarisation, and to optimise grid dimensioning (wire width and spacing). A statistical electromagnetic field correlation analysis, as proposed in [6], and which seems important to understand the behaviour of polarisation-sensitive filled arrays [7] (with potentially dangerous polarisation artifacts), will certainly strengthen our comprehension about the response of our polarisation-sensitive LEKID array.

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