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KINETIC INDUCTANCE DETECTORS DEVELOPMENT FOR MM-WAVE ASTRONOMY

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Abstract. Throughout the last decades, development of low-temperature detectors focused mainly on the design of high-sensitivity, single-pixel devices. This includes such devices as semiconductor-based photodetectors and bolometers, Magnetic Metallic Calorimeters (MMC), Superconducting Tunnel Junctions (STJ), and Transition Edge Sensors (TES). However, these devices have had limited success in achieving the simultaneous large-scale array sizes and large-bandwidth operation necessary for high-speed, high-resolution detection. To overcome this performance limitation, it is advisable to focus on low-temperature detectors which are intrinsically adapted to giant-array multiplexing and ultra-fast readout. To adopt large scale frequency-domain multiplexing for low-temperature detectors, it is necessary to find detectors which “broadcast” at microwave frequencies. Superconducting microwave resonators naturally lend themselves to this task. One recent demonstration is an implementation known as Kinetic Inductance Detectors (KIDs). This detection mechanism can be adopted for low-energy EM radiation (radio, mm, THz) in continuous mode, or in pulsed mode for higher energy radiation and particles. We present an ongoing development for a KIDs instrument dedicated to millimetric ground-based observations at the 30m IRAM telescope at Pico Veleta. The Neel IRAM KIDs Array (NIKA) project is coordinated in Grenoble and involves groups in Holland (SRON), UK (Cardiff) and Italy (Roma).

1 Kinetic Inductance Detectors - Introduction

When a current I is established in a conducting strip, most of the input energy is stored in the B-field. Associated with this energy is the usual geometric induc-

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tance, L_g . The remaining fraction of the energy is used to accelerate the current carriers. If this energy is stored and not dissipated, it is reasonable to associate an inductance with this energy as well - this is known as the kinetic inductance, L_k . While resistive losses dominate in normal metals and severely limit the kinetic inductance, the kinetic-to-geometric inductance ratio is non-negligible for superconductors. The AC current carriers in which energy can be reversibly stored and are responsible for the large L_k are Cooper pairs (supercurrent). The other current carrier present in a superconductor, the residual quasi-particles, undergo irreversible energy loss and can be predominantly associated instead with a real resistance.

For flat geometries (e.g. coplanar transmission lines), L_k depends on the B-field penetration length λ_L , related to the quasi-particle concentration. Incident Cooper-pair-breaking photons can directly affect the quasi-particle concentration and thus result in modulation of L_k for a mesoscopic slab. The cutoff photon frequency ν_{min} is determined by the superconducting gap: $\nu_{min} = 2\Delta_g/h = 3.528kT_c/h$ according to the BCS theory at $T \ll T_c$ [Tinkham 1996]. Obvious options for mm-wave or THz detection are Aluminium ($T_c = 1.2$ K, $\nu_{min} = 115$ GHz), Titanium ($T_c = 0.5$ K, $\nu_{min} = 48$ GHz) and Niobium ($T_c = 9$ K, $\nu_{min} = 865$ GHz). Real cutoffs can be slightly different due to small deviations with respect to the BCS microscopic theory.

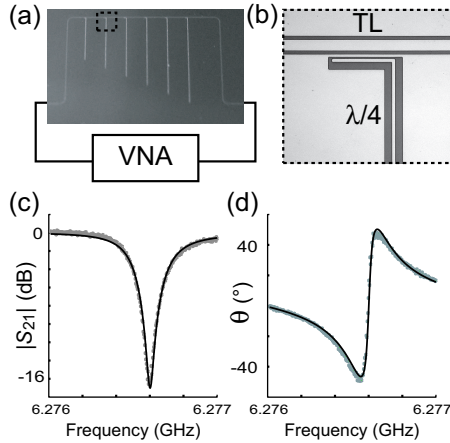


Fig. 1. Example of high-Q resonators designed, fabricated and tested in Grenoble [Grabovkij 2008]. (a) A vector network analyzer (VNA) with an output power of -50 dBm was used to measure the transmission coefficient S_{21} . (b) The coupling capacitance to the feed-line is estimated to be 4 fF. (c) Typical resonance curve $|S_{21}|$. The black line is a fit which takes into account the resonance frequency, the internal and external quality factors, and parasitic impedances introduced by the measurement circuitry. (d) Phase θ measured simultaneously with the amplitude data in (c).

In order to harness the sensitivity of the kinetic inductance to incident radi-

ation, it is necessary to embed the superconducting strip in a high-quality-factor resonant circuit (i.e. $Q=10^5$ - 10^6). A transmission line can then be coupled to the superconducting resonator and driven with a high-frequency wave at a frequency near the resonance frequency of the superconducting circuit $f = f_c$. In order to match commercially available amplifiers and RF components and also to remain on a reasonable size-scale, the resonating frequencies are usually designed to fall within the 0.5 to 20 GHz range. Suitable detection electronics can then be used to monitor the amplitude (A) and phase (θ) of the transmitted wave. Near the resonance frequency, any change in the L_k/L_g ratio will result in a significant change in the measured signal.

KIDs, in their current version, were first proposed less than 10 years ago by Caltech-JPL [Day 2003]. In the standard mode of operation, a photon flux will result in an increase in the quasi-particle concentration. This will result in a change in the L_k/L_g ratio and subsequently the detected amplitude and phase. As each resonator occupies a small portion of frequency space and can be controlled lithographically, a large number of high-Q “pixels” can be coupled to the same transmission line. An off-the-shelf low-noise cryogenic amplifier, necessary for achieving the high sensitivity required for low-photon-flux detection, can cover a band as wide as 8 GHz. Assuming a rather realistic spacing of 2 MHz between resonators, up to 4,000 channels can be multiplexed using just two coaxial cables in a cryostat (In/Out).

Current research is focused on three main challenges facing KID sensitivity:

1. It can be demonstrated that the Noise Equivalent Power at low frequency is [Mazin 2004]:

$$NEP = S_x \cdot \left(\frac{\eta \tau_{qp}}{\Delta_g} \cdot \frac{\delta x}{\delta n_{qp}} \right)^{-1}, \quad (1.1)$$

where $x = [A, \theta]$, S_x the phase or amplitude noise, n_{qp} the number of quasi-particles and τ_{qp} the lifetime of quasi-particles at the operating temperature T and η the efficiency of quasi-particle generation. The sensitivity is directly proportional to τ_{qp} , that plays the role of the thermal relaxation constant for classical bolometers. In absence of recombination channels other than electron-phonon interaction, τ_{qp} should grow up exponentially as T approaches zero. In that case, the sensitivity of the detector could be adjusted simply by varying the cryostat temperature T . However, this has not proven to be the case. Experimental studies demonstrate that τ_{qp} flattens out around $T/T_c = 0.15$ [Barends 2008]. A clear identification of the additional relaxation channel is still lacking.

2. A second, open problem is the observed excess phase noise [Gao 2007]. Encouraging results, demonstrating a phase noise reduction by up to an order of magnitude, have been recently achieved by changing the coupling geometry of the resonators.
3. Finally, the power handling capabilities of superconducting resonators remains uncertain. The resonances are deformed at unexpectedly low power

levels - around 2% of the current needed to drive the inner conductor normal. Since the S/N ratio is directly proportional to the readout power, a better comprehension of this behavior could lead to a decisive improvement of KIDs performances.

Despite these limiting factors, currently under investigation by a growing number of research groups, NEP of the order of $6 \times 10^{-19} W/Hz^{0.5}$ have been demonstrated for THz detection. Those values are already comparable with state-of-the-art Transition Edge Sensors (TES).

2 NIKA: the Néel IRAM KIDs Array

For a suitable measurement platform, we have designed and fabricated an optical dilution cryostat adapted to the IRAM 30-m telescope optics. The optical design is based on an innovative reflecting baffle placed on the coldest stage (60 mK) and a telecentric, two lenses (HDPE) system. For further details see [Benoit 2008]. The University of Cardiff is providing the filters to be mounted on the several radiation screens, and the band-defining filter for observations centered around the cosmologically interesting frequency of 150 GHz ($\lambda = 2$ mm).

Our collaboration encompasses two complementary efforts for the detection array:

1. SRON, in the framework of the NIKA project, has designed and fabricated a 20×20 array of antenna-coupled KIDs. The curved, double-slot antenna is placed at the grounded end of a distributed $\lambda_c/4$ resonator. The pixels pitch is 1.6 mm, calculated for Nyquist sampling of the focal plane at a wavelength $\lambda = 2$ mm. Moreover, SRON is developing read-out electronics based on fast FFTS boards able to acquire/digitise/FFT at a frequency up to 1.5 GHz. A commercial board is used to generate the tones to excite all the resonators. Resonances are in the 4 to 6 GHz band. The absorbing area of the first prototype is small compared to the geometrical pixel footprint. The single antenna have to be replaced, in future versions, with a small array feeding a single resonator. As an alternative, an array of silicon micro-lenses could focus the radiation on a single, small antenna.
2. We have designed, in collaboration with Cardiff and Roma, an alternative 15×15 pixels focal plane based on Lumped Element resonators (LEKIDs) [Doyle 2008]. In this case, taking advantage of the fact that the resonator itself can absorb the mm-wave radiation, the filling factor is much higher. The detectors are still in fabrication, and the first optical tests are scheduled in February 2009 in Cardiff.

In both cases, a $\lambda/4$ anti-reflecting slab is used, and the detectors are back-illuminated through the substrate. A final selection of detectors for the IRAM technical run is foreseen in July 2009.

3 Conclusion and Outlook

We have presented a particular application of KIDs for ground-based mm-wave astronomical observations. A European collaboration, coordinated by Grenoble and including SRON (Utrecht and Groningen), University of Cardiff and La Sapienza Roma has recently been signed. The goal is to perform, in Summer 2009, a first technical run at the IRAM 30m radio-telescope. Two alternative focal planes (225-400 pixels) are under development. The field-of-view on the sky will be 2.4 arc-min.

In the longer term, we plan to participate in the announced IRAM call for a new bolometric instrument (4000-6000 pixels) intended to optimally fill a field-of-view of at least 8 arc-min.

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