Preliminary tests of a phonon-mediated Kinetic Inductance Detector with phonon-funneling volume

L. Pesce(1)(2)(*), M.Calvo (3), M. Cappelli (1)(2), U. Chowdhury(3), A.L. De Santis(1)(2)(**), G. Del Castello(2), D. Delicato(3)(1)(2), M. Folcarelli(1)(2), M. del Gallo Roccagiovine(1)(2), D. Quaranta(1)(2), A. Cruciani(2), A. Monfardini(3), and M. Vignati(1)(2)

(1) *Dipartimento di Fisica - Sapienza Università di Roma - Piazzale Aldo Moro 2, 00185, Roma, Italy*
(2) *INFN - Sezione di Roma - Piazzale Aldo Moro 2, 00185, Roma, Italy*
(3) *Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France*

Summary. — Cryogenic phonon detectors are adopted in light dark matter searches or coherent elastic neutrino-nucleus scattering experiments thanks to the low energy threshold they can achieve. The phonon-mediated detection of silicon particle absorbers has been already proved with Kinetic Inductance Detectors (KIDs), acting as phonon collectors and sensors at the same time. We present a first prototype of a KID coupled to a separate structure of phonon absorbers in order to increase the sensitivity. It consists of a thin KID with a trilayer wire of Aluminum/Titanium/Aluminum coupled to larger aluminum phonon collecting volume. Phonons absorbed in the collecting volume create Quasi-Particles which are trapped in the lower-gap trilayer after diffusion. The performance of the device is compared with a standard phonon-mediated KID. We report the results of preliminary tests, which showed that the KID with collection structures had a greater response.

1. – Introduction

Experiments searching for direct light dark matter [1-3] interaction or Coherent Elastic neutrino-Nucleus Scattering (CEνNS) [4-8] need detectors achieving very low energy thresholds due to the small nuclear recoil energy releases. For this reason, cryogenic detectors, such as Transition Edge Sensors (TESs) [1, 4, 9] or Neutron Transmutation Doped (NTDs) Ge sensors [2,6], can be used used as phonon absorbers coupled to target

(*) leonardo.pesce@uniroma1.it
(**) now at Gran Sasso Science Institute (GSSI), 67100, L'Aquila, Italy

crystals to detect sub-keV nuclear recoil processes. Detector units with baseline energy thresholds of around 20 eV have been achieved [4, 9]. Conversely, it is important to build mass-scalable instruments since experiments with larger targets are more sensitive to smaller dark matter interaction cross sections for Weakly Interacting Massive Particle (WIMP) searches [10]. While detectors using cryogenic detectors with target masses up to tens of grams have already been developed [1, 4, 11], scaling up to the kilograms scale remains an experimental challenge.

The BULLKID project developed an innovative type of particle detector which is designed for tackling the mass scaling problem [12]. It consists of a monolithic array of 64 silicon dices of 0.36 g each and $5.4 \times 5.4 \times 5\,\mathrm{mm}^3$. Each one of them is carved into a wafer with 3" diameter and 5 mm thickness. The single dices are sensed with Kinetic Inductance Detectors (KIDs) acting as phonon absorbers. These detectors are well suited for use in large arrays thanks to the intrinsic multiplexing they can ensure [13] and can be therefore adopted to design mass-scalable instruments. While the best analysis energy threshold was set at around 160 eV [14], there remains a vast field to explore in the design and development of new sensors aimed at minimizing baseline energy thresholds as much as possible. Therefore, one possible strategy is the improvement of the phonon-mediated KIDs baseline energy resolution.

2. – Description

A KID is a superconducting LC resonator in which the kinetic inductance L_k contributes to the total inductance of the resonator L [15]. In more detail, the kinetic inductance can be associated to the energy stored by the Cooper Pairs (CPs) motion inside the superconductor. An energy release in the substrate leads to phonon generation which can break CPs, whose number density variation could be responsible for a shift of L_k and, thus, of the resonance frequency f_r. Such a shift changes the transmission function S_{21} both in phase and magnitude [15-19] and de-tunes the resonance frequency with respect to the readout frequency of the quantity Δf_r. Such a variation changes in time, giving origin to a pulse whose amplitude is regulated by the detector responsivity for a fixed value of energy release.

Starting from [15, 20] it is possible to state how the baseline energy resolution for a single phonon-mediated KID scales:

$$\sigma_E \propto \frac{\Delta_0}{\eta}\sqrt{\frac{V_{\mathrm{KID}}}{\alpha}} \tag{1}$$

where $\Delta_0 \approx 1.75 k_B T_c$ is the superconducting gap [15], with k_B the Boltzmann constant and T_c the superconductor critical temperature, $\eta \propto V_{\mathrm{ph}}/V_{\mathrm{sub}}$ the phonon collection efficiency (with V_{ph} being the phonon collection volume in contact with the substrate and V_{sub} the substrate volume), V_{KID} is the active volume of the resonator and $\alpha = L_k/L$ the fraction of kinetic inductance. Notice that eq.1 does not include other terms related to superconducting theory and electrical noise, but only those that can be primarily tuned through the design studied in this work. A possible strategy to improve the baseline energy resolution is therefore maximizing the phonon collection volume V_{ph} and reducing the active volume V_{KID} at the same time.

In a standard phonon-mediated KID, phonons are directly absorbed by the sensor, hence the phonon collection volume coincides with that of the resonator. We designed and tested a first prototype of phonon-mediated KID with separate phonon-collection

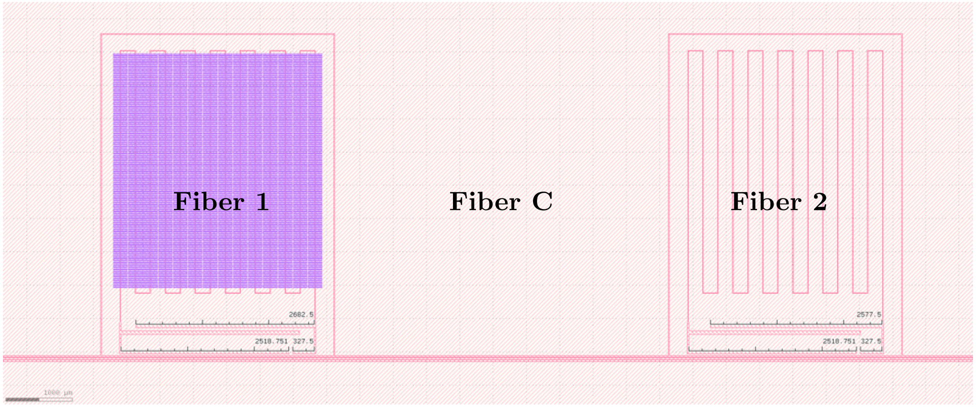


Fig. 1. Design of the two tested KIDs. They are identical but for the presence of funnels on the left one. The inductive part is on the top of the sensor, while the capacity is coupled to a coplanar waveguide. The first two fingers of the capacity differ by 105 μm to space the two resonance frequencies. At the back of the two resonators and at the back of the central part of the substrate between them three optical fibers are placed.

structures (funnels). These are large aluminum structures coupled to the inductive meander of the KID (see fig.1). The resonator is composed of a trilayer wire of Aluminum/Titanium/Aluminum (AlTiAl), that has a smaller superconducting gap than aluminum. With this design, phonons are (mostly) absorbed by the collection structures, where they break CPs, generating a large amount of Quasi-Particles (QPs). Therefore, proximity effects [21] between metals are exploited to trap the QPs: as funnels are composed of an higher superconducting gap metal (aluminum) than the meander (AlTiAl), there creates an effective potential slope at the metals' interfaces which causes QPs to accumulate into the sensor from the collection structures. The overall AlTiAl critical temperature is lowered by proximity effects [22-25] between the two aluminum layers ($T_c \approx 1.2\,\mathrm{K}$) and the central titanium layer ($T_c \approx 0.40\,\mathrm{K}$) [24] and a critical temperature of about 0.81 K was measured by the CALDER project [22].

We shot 400 nm photons generated at room temperature [26] on the substrate by means of three optical fibers, two close to the two resonators and one in the center, always at the back of the KIDs, in order to characterize the pulses and interaction position effects. The scheme of the three fibers is also reported in fig.1. We performed preliminary tests of the two KIDs at a base temperature of about 35 mK, well below the critical temperature of AlTiAl.

3. – Preliminary tests

We used an Ettus X310 Board [27, 28] to generate the readout waves for the two KIDs. The transfer function amplitude $|S_{21}|$ has been reported in fig.2 as a function of the readout frequency. Both the two resonances are visible as the deep minima on the transmission line and are spaced by more than 60 MHz. The KID with funnels is spotted as that producing the first resonance, while the other KID generates the second one.

In fig.3a we report a pulse event in the frequency response for the two KIDs generated by a burst of photons with total energy of $\sim 55\,\mathrm{keV}$ and shot with the central fiber in

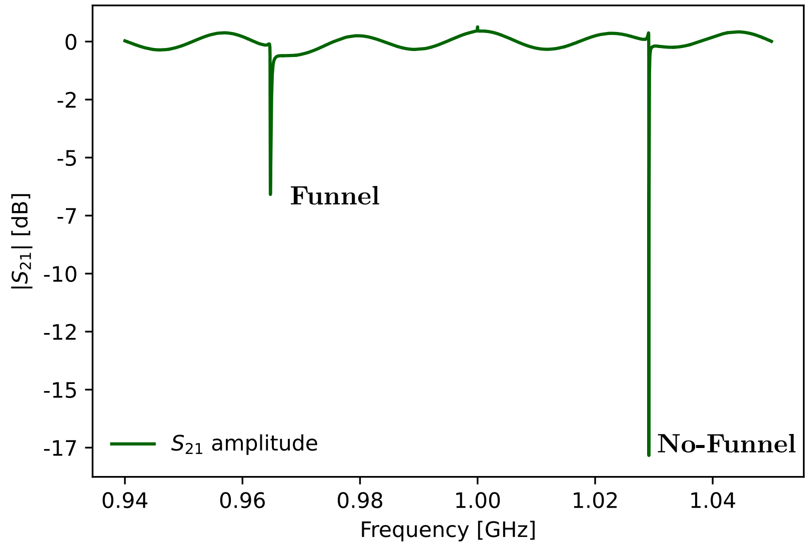
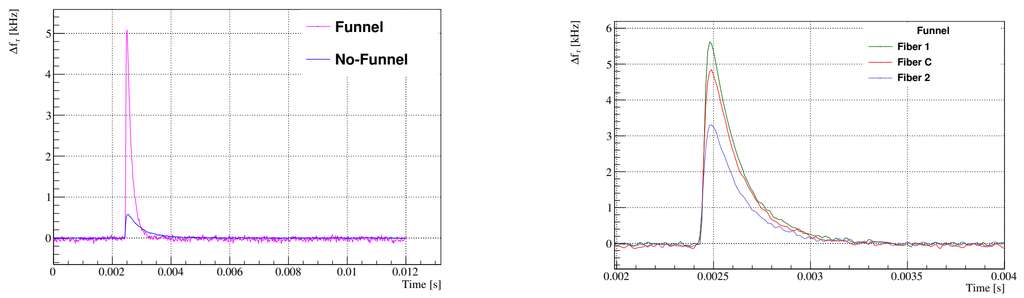


Fig. 2. The transfer function amplitude $|S_{21}|$ as function of readout frequency. The two minima are the resonance frequencies, while the central spike is related to the interference introduced by the board local oscillator.

between. We measured a greater response for the KID with funnels.

In fig.3b three different pulses measured by the KID with funnels are shown. They were generated by the same amount of energy release of about 55 keV deposited in the three different positions covered by the fibers. The response is dependent on the position where the energy was released. If the distance between the deposit point and



(a) (b)

Fig. 3. (a) Pulses of the two KIDs generated by a energy release of about 55 keV between the two resonators. (b) Three pulses measured by the KID with funnels relative to the same amount of energy release of 55 keV deposited on the resonator with funnels (green), in the center (red) and on the opposite resonator (blue), always at their back.

the resonator increases, phonons are more diluted into the substrate and a smaller fraction of them is therefore absorbed by the KID and the amplitude of the signal is smaller. This procedure was used to identify the two resonators unambiguously (as the fibers' positions were known).

These preliminary tests highlight the perspectives for the KID with funnels, resulting in a much more responsive detector. Further data will therefore indicate the real potential of such a new device both in terms of detector response and baseline energy resolution.

4. – Conclusions

We presented the first tests of a prototype phonon-mediated KID with funneling volumes. Preliminary results proved a stable functioning and greater signal amplitudes compared with those of the same KID without funnels. Further data could establish the performance of such a new device and the possibility to pave the way for a new design of phonon-mediated KID.

* * *

We thank the team of Laboratorio di Rivelatori Criogenici of Sapienza University of Rome for the support. This work was partially supported through the European Research Council through the Consolidator Grant DANAE No.101087663. We acknowledge the support of the PTA platform [29] for the fabrication of the device. We thank A. Girardi and M. Iannone from INFN Sezione di Roma for technical support.

REFERENCES

[1] Abdelhameed et al., *Physical Review D*, **100** (2019) 102002.
[2] Armengaud et al., *Journal of Cosmology and Astroparticle Physics*, **2016** (2016) 019.
[3] Agnese et al., *Physical review letters*, **120** (2018) 061802.
[4] Strauss et al., *Physical Review D*, **96** (2017) 022009.
[5] Billard et al., *Journal of Physics G: Nuclear and Particle Physics*, **44** (2017) 105101.
[6] Augier et al., *Journal of Low Temperature Physics*, **212** (2023) 127.
[7] Agnolet et al., *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **853** (2017) 53. URL `https://www.sciencedirect.com/science/article/pii/S0168900217302085`
[8] Akimov et al., *Science*, **357** (2017) 1123.
[9] Alkhatib et al., *Physical review letters*, **127** (2021) 061801.
[10] Roszkowski et al., *Reports on Progress in Physics*, **81** (2018) 066201.
[11] Armengaud et al., *Physical Review D*, **99** (2019) 082003.
[12] Cruciani et al., *Applied Physics Letters*, **121** (2022) .
[13] Day et al., *Nature*, **425** (2003) 817.
[14] Delicato et al., *The European Physical Journal C*, **84** (2024) 353.
[15] Zmuidzinas, *Annual Review of Condensed Matter Physics*, **3** (2012) 169.
[16] Mazin, *Microwave kinetic inductance detectors*, Phd thesis, California Institute of Technology (2005).
[17] Khalil et al., *Journal of Applied Physics*, **111** (2012) .
[18] Swenson et al., *Journal of Applied Physics*, **113** (2013) .
[19] Vignati et al., *arXiv preprint arXiv:2102.09431*, (2021) .
[20] Battistelli et al., *The European Physical Journal C*, **75** (2015) 353.
[21] Riwar et al., *Physical Review B*, **100** (2019) 144514.
[22] Cardani et al., *Superconductor Science and Technology*, **31** (2018) 075002.
[23] Catalano et al., *Astronomy & Astrophysics*, **580** (2015) A15.

[24] Zhao et al., *Superconductor Science and Technology*, **31** (2017) 015007.
[25] Brammertz et al., *Journal of Applied Physics*, **90** (2001) 355.
[26] Del Castello, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **1068** (2024) 169728.
[27] Minutolo et al., *IEEE Transactions on Applied Superconductivity*, **29** (2019) 1.
[28] Ettus Research, *Ettus research – the leader in software defined radio (sdr)*, `https://www.ettus.com/` (2025).
[29] Plateforme technologique amont, *Our Facilities Overview*, `http://pta-grenoble.com/our-facilities/overview`.