The cryogenic detector for cosmology observation

IOP Conf. Series: Materials Science and Engineering **502** (2019) 012060 doi:10.1088/1757-899X/502/1/012060

The cryogenic detector for cosmology observation

Baurzhan ALZHANOV[1], Mehdi SHAFIEE[1], Zhaksylyk KAZYKENOV[1], Marzhan BEKBOLANOVA[1], George SMOOT[1,2] and Bruce GROSSAN[1,2]

[1] Nazarbayev University, Energetic Cosmos Laboratory, Astana, Kazakhstan.
[2] University of California, Berkeley, USA.

E-mail: baurzhan.alzhanov@nu.edu.kz

Abstract. This paper will present the implementation of the Microwave Kinetic Inductance Detectors (MKID) for mm/submm astronomy purposes in our cryocooler at the Energetic Cosmos Laboratory (ECL). Authors have used the robust cryocooler 106 Shasta from HPD Company. The refrigerator can cool down the temperature to 30 millikelvin. In this report, authors describe our experiences about millikelvin refrigerator, implementation challenges of MKIDs in refrigerator and the evaluation results.

1. Introduction

Microwave Kinetics Inductance Detectors (MKID) are a new type of superconducting sensor capable of measuring the arrival times, quantities and energies of individual photons simultaneously; this is something that Charge-Coupled Devices (CCDs) can do only after the light is split with a prism or a grating, an extra step that adds to the loss of photons [1].

One major advantage of MKIDs is the possibility to couple several hundreds of absorbing micro resonators to a single transmission line to read them out by frequency division multiplexing (FDM) which makes it faster than all current cameras. MKIDs can be designed at different frequency ranges from around 30 GHz up to several THz, which makes it interesting for different applications such as medical imaging for cancer detection [2], full body scanners for security systems [3], material science and especially for radio astronomy. One of the challenges in cosmology is studying cosmic microwave background (CMB) with a temperature of $T \approx 2.74$ Kelvin more precisely, which corresponds to emitted radiation in the mm-wave range, giving important information about the formation of the universe back to the Big Bang, 15 billion years ago. By using MKIDs as a fast and precise detector for understanding more about CMB as well [4,5].

2. Microwave Kinetics Inductance

MKIDs are made of thin layer of superconductors (20 – 60 nm) on pure Silicon substrate. Superconductors have bandgap energies roughly 1000 times lower than that of silicon, allowing for the detection of much lower energy photons. The superconducting charge carriers, called Cooper pairs, break up into normal conductive quasi-particles for absorbed energies (photons) (Figure 1 (a)) that are higher than the superconductors energy gap ($E = h\nu > 2\Delta = 3.526\ K_B T_C$) leading to a change in surface impedance.

The nonzero AC impedance of the superconductor due to the inertia of the Cooper pairs gives rise to an almost purely inductive reactance in addition to the conventional reactance caused by the magnetic inductance Lm, which is the so-called *kinetic inductance* L_{kin} that MKIDs are famous for (Figure 1 (b)) [6]. Incident photons cause a change in L_{kin} and thus in surface impedance, leading to a shift in resonance frequency of the micro resonator measurable by standard radio frequency techniques in amplitude and phase (Figure 1 (c), (d)). By measuring changes in phase, we can calculate the energy of the/an incident photon. Photon frequency range can be from 30 GHz to several THz but resonance frequency is of the order of 1-6 GHz depending on the MKIDs geometrical parameters. [4, 5].

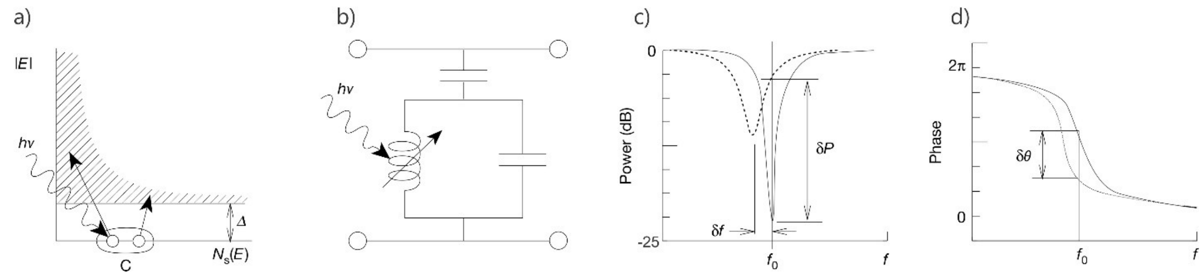

Figure 1. Photon striking the MKID circuit breaks apart one or more Cooper pairs shifting the resonant frequency and increasing energy losses.
(a) Schematic of Superconductor quasiparticle excitation. (b) MKIDs equivalent circuit (c) and (d) showing the expected results after incident photon to one MKIDs pixel [7]

3. Cryogenic facility for MKIDs measurement

Cryogenic system: It consists of a Pulsed Tube Refrigerator (PTR) and Adiabatic Demagnetizing Refrigerator (ADR). A Cryomech PTR provides cooling for the 60 K and 3 K stages (HPD Shasta 106[8]). It consists of a compressor, remote motor, cold head, bellows, and helium flex lines.
The pulse tube cooler is a closed-loop system using gaseous helium. No liquid cryogens are used (Figure 2, Left). The ADR generates the coldest stage temperatures (500 mK and 50 mK) (Figure 2, right). The ADR contains a superconducting 4 T magnet, a Gadolinium Gallium Garnet (GGG) paramagnetic salt pill, a Ferric Ammonium Alum (FAA) paramagnetic salt pill, a Hiperco 50 magnetic shield, and a Kevlar suspension system. The ADR generates cooling through adiabatic demagnetization of the paramagnetic salt pills. The Kevlar suspension isolates the salt pills from warmer stage temperatures.

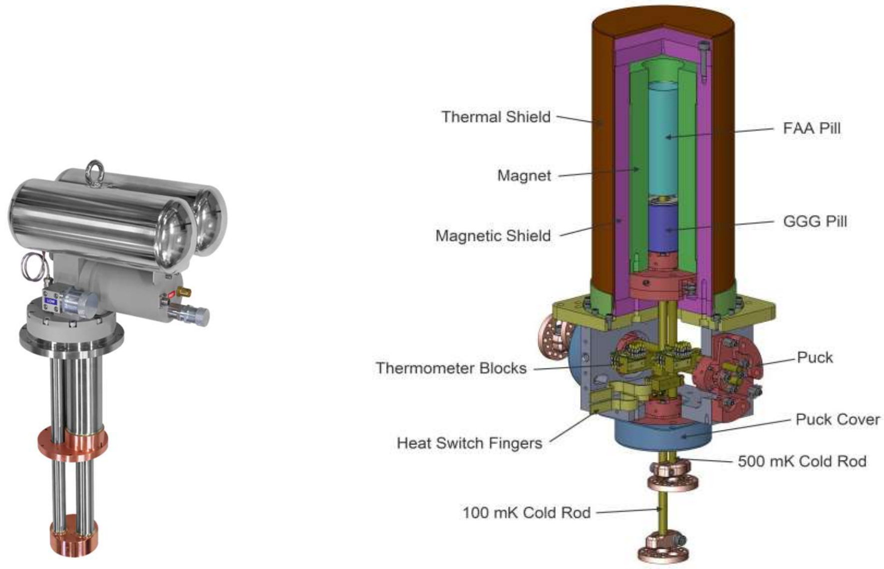

Figure 2. (Left) Pulse tube refrigerator (Right) Schematic of ADR system

4. MKIDs readout system

In order to measure the instantaneous resonance frequency and dissipation of superconducting micro-resonators of the MKID arrays, authors have developed a data acquisition system with emphasis on precision, readout speed and digital processing capabilities [9]. The Ettus X310 was used for Software Define Radio (SDR) [10]. The IQ mixer was used to down convert the MKIDs signal in the range of 20 – 80 MHz, then digitize them by 250 MSPS (millions of samples per second) ADC.

Processed data at field programmable gate array (FPGA) – Kintex 7 will be transferred to the PC for further analysis by the rate of 10 Gbit/sec.
Authors used also data reduction analysis to reduce the number of data in order to make system faster while keeping main information [11]. Figure 3 shows FPGA implementation.

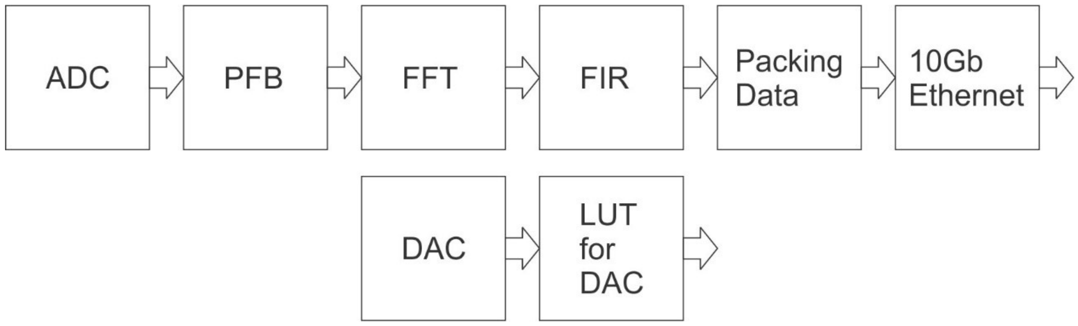

Figure 3. FPGA Firmware Diagram Implementation for measuring MKIDs signals [11].
ADC – analog-to-digital converters; PFB – polyphase filter bank; FFT – fast Fourier transform; FIR - finite impulse response (digital filters); DAC - Digital-to-Analog Converter; LUT for DAC – lookup table for DAC.

5. MKIDs Design and Results

Authors are designing different type of MKIDs with different bands at ECL. Already Authors are designing MKIDs centered at different frequencies of 140 GHz, 150 GHz, 1.2 THz (Infra-red) and optical range both single and dual polarization for studying CMB and optical and radio astronomy. SONNET and CST software were used for simulation. They are made with a tiny single layer of superconducting film (20 – 60 nm) deposited on a substrate and patterned using optical or electron beam lithography. In order to do experiments required an extremely cold area lower than 1K. ECL has super cold cryogenic system capable of cooling down to 30 mK.
Authors have developed MKIDs readout system by using robust scalable SDR, Ettus USRP X310 board, including a powerful FPGA - Kintex 7.

Figure 4. (Left) our MKIDs measurement setup (Right) Mounting MKIDs inside of cryogenic system

One pixel of our design by Sonnet software is shown in Figure 5. It consists of 60 nm Aluminum on 4 µm Silicon substrate including inductor and interdigitated capacitors. The resonance frequency for this pixel is designed to be 1.344 GHz. The MKIDs fabricated by Astroparticle and Cosmology laboratory in Paris (APC). Picture has taken by Atomic Force Microscopy (AFM) shows part of surface including aluminum feed line. Based on design it is supposed to have a thickness around 60 µm but pictures show some deviations (Figure 6).

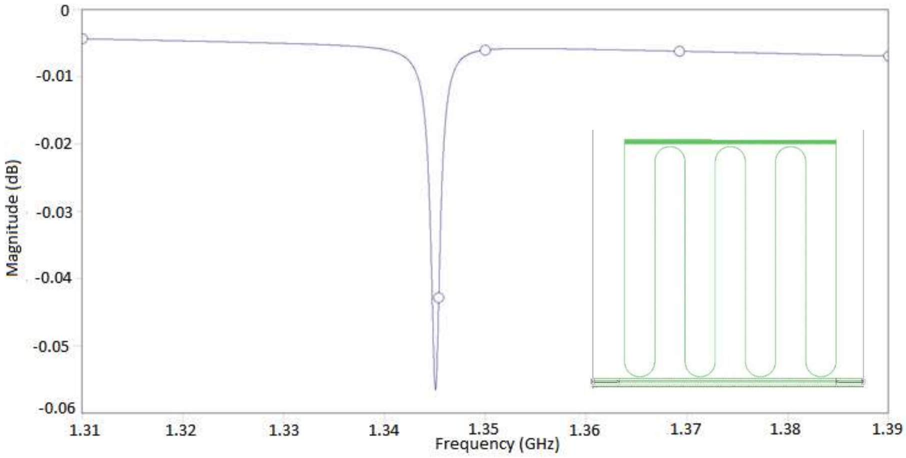

Figure 5. Resonance frequency of one pixel, which was designed by SONNET software.

After installing MKIDs and cryo amplifier inside refrigerator, resonance frequencies was measured *(S_{21})* by Vector Network Analyzer (VNA), which is sweeping frequency from 1.3 GHz to 1.4 GHz and digital electronic readout system. One of resonance frequencies measured to be 1.343 GHz, 1 MHz far from expected value via simulation (Figure 7).

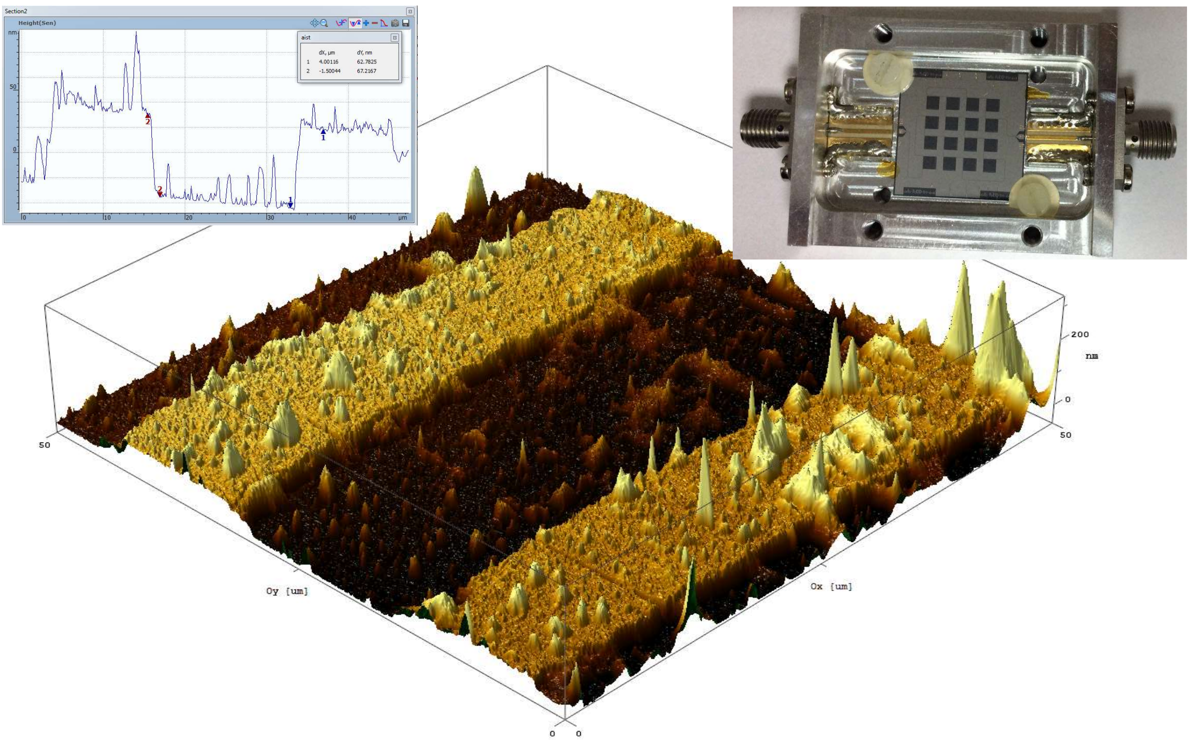

Figure 6. Surface picture of MKIDs by AFM

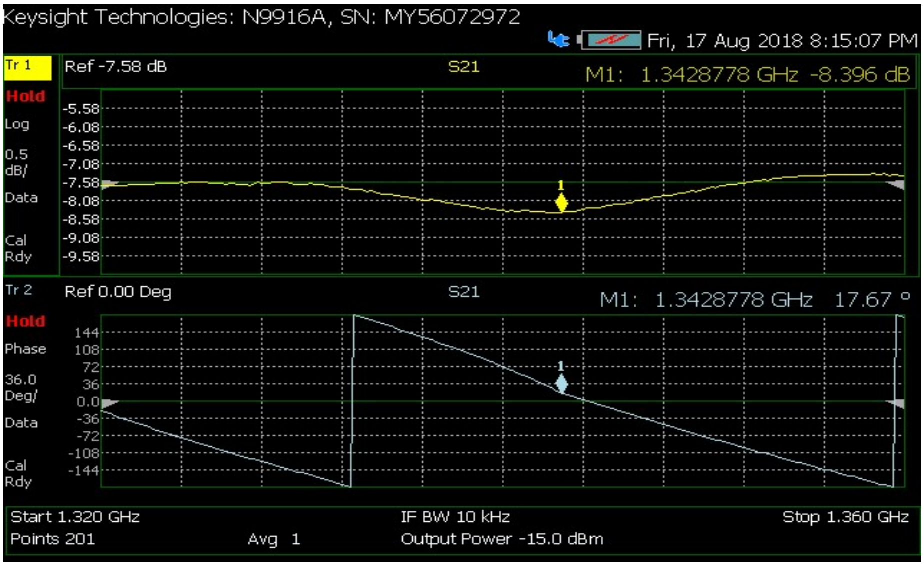

Figure 7. One pixel of MKIDs resonant measurement by VNA

6. Conclusion

MKIDs are one of the possible next generation detectors that will be used widely. At ECL are studying to develop and improve large array MKIDs with higher resolution, precision and quality factors while covering larger frequency bands of incident photons.

References

[1] P. Day, H. LeDuc, B. Mazin, A. Vayonakis, and J. Zmuidzinas. "A broadband Superconducting detector suitable for use in large arrays". Nature, 425:817–821, 2003.
[2] M. Afsar, M. Obol, K. Korolev, and S. Naber. "The use of microwave, millimeter wave and terahertz spectroscopy for the detection, diagnostic and prognosis of breast cancer". *33rd International Conference on Infrared, millimeter and Terahertz waves, IRMMW-THz*, pages 1–3, 2008.
[3] T. May, G. Ziegler, S. Anders, V. Zakosarenko, M. Starkloff, H.-G. Meyer, G. Thorwirth, and E. Kreysa. "Passive stand-off terahertz imaging with 1 hz frame rate". *Proceedings of SPIE*, 6949(69490C), 2008.
[4] Markus Rosch, Development of lumped element kinetic inductance detectors for mm-wave astronomy at the IRAM 30 m telescope, 2013.
[5] Monfardini A. et al. NIKA: A millimeter-wave kinetic inductance camera. Astronomy and Astrophysics, A29 521, (2010).
[6] Zmuidzinas A. Superconducting microresonators: Physics and applications. Annual Review of Condensed Matter Physics, 3, 2012.
[7] J.J.A.Baselmans, S.J.C.Yates, P.de Korte, H.Hoevers, R.Barends, J.N.Hovenier, J.R.Gao, T.M.Klapwijk, Development of high-*Q* superconducting resonators for use as kinetic inductance detectors, Advances in Space Research, Volume 40, Issue 5, 2007, Pages 708-713
[8] High Precision Devices Co.
[9] M. shafiee, S.A.H.Feghhi, J.Rahighi, "Experimental Performance Evaluation of ILSF BPM Data Acquisition system", Measurement, 2017.01.003.
[10] National Instrument, Ettus Resrach Co.
[11] M. shafiee, S.A.H.Feghhi, J.Rahighi, "Analysis of de-noising methods to improve the precision of the ILSF BPM electronic readout system", Journal of Instrumentation, 28 December 2016.