A study of the performance of Microwave Kinetic Inductance Detectors

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Microwave kinetic inductance detectors (MKIDs) are cryogenic photon detectors used for astronomical observation. Initiated by Drs. Rick LeDuc and Jonas Zmuidzinas at the California Institute of Technology and the NASA Jet Propulsion Laboratory, MKID technology provides an alternative to semiconductor-based detectors, a technology whose advancements are quickly plateauing. MKIDs use microwave frequencies to measure the change in surface impedance of a superconductor. They operate at cryogenic temperatures, thereby decreasing sources of thermal noise and dark current[1]. In order to more thoroughly understand the functionality of the device, it was necessary to test the performance of individual pixel detectors, and to determine the energy resolution of the observed photons. Tests were run using different input parameters, and the output frequency data for analyzed and interpreted. The results are presented here. Further implications of MKID technology on the field of astrophysics are considered.

I. Introduction and Background

The research on MKIDs (microwave kinetic inductance detectors) at Fermilab was conducted using a cryogenic pixel detector, which operates at temperatures around 100 mK to facilitate superconduction. The low inductance property of superconductors allows for sensitive detection of incident photons. These incident photons change the resistance and inductance of the superconducting material, which in turn changes the frequency of the resonate device. This is measured and analyzed by the detector and transmitted to computers. The frequency shifts are then further analyzed and calibrated using analysis software, which goes through each signal picked up in the detection process and uses input data to calibrate noise threshold and local oscillation frequency levels.

The investigations done this summer were aimed to improve pixel performance in the MKID array. This was accomplished by investigating the contributing factors to high noise levels, crosstalk phenomena, and local frequency contributions. A primary problem with pixel performance included issues with the noise levels in the detection device. Many of the sources were speculated to come from the technical design and construction material of the detector, which were inaccessible during the scope of this study.

The detector at Fermilab is currently in the primitive stage of testing, however tests indicate that there is great potential for MKIDs as a powerful astronomical tool. MKID detector technology is highly scalable, and around 10^3 resonators can be connected using one coaxial transmission line[2]. It is the ultimate goal of the project to improve the consistency and precision of this device so that it may be widely employed as a means of both ground and space- based astronomical observation.

i. Fermilab's involvement in MKIDs

Fermilab is working in collaboration with a team at the University of California, Santa Barbara to improve the process of data collection and analysis using MKID detectors. Through this collaboration, significant developments have been made in creating an analysis program pipeline. Currently, the Fermilab Detector Development and Operations Department is investigating factors that effect the spectral resolution. Tests are being done to determine how to increase the performance of the device.

ii. The Dark Energy Survey

It is believed that the universe is comprised of 4, 23, and 73 percent baryonic matter, weakly interacting particle dark matter, and dark energy, respectively. It is also proposed that one of the observational effects of dark matter appears in the form of gravitational lensing[3]. This phenomenon causes light to distort as travels from an object to a terrestrial detector source. Measuring this effect would provide insight into the behavior of dark matter. This is because lensing causes galaxies to orient in a non-random manner, and any deviation from a random orientation pattern is indicative of gravitational lensing, and consequently of the presence of dark matter. It is therefore necessary to measure the geometry of a wide extrasolar expanse, and to obtain precise galaxy redshift measurements. MKIDs possess the capability to survey the vast sweep of space required by this study.

iii. Limitations of Current Techniques

Astrophysics is an observational science; as such, advancement in the field depends on the development of detection equipment. Detector sensitivity is proportional to exposed surface area, something that, in 50 years, has increased in size by only a factor of four[4] in conventional detectors.

In addition to increasing the area of light-exposed detection regions, greater precision could be achieved by eliminating sources of electronic noise. In CCDs, noise exists from dark current, a phenomenon that occurs as a result of inherent photon movement within the detector[5]. MKIDs perform with reduced thermal noise because of the difference in operating conditions.

A prominent advantage of MKID over CCD technology is their greater sensitivity. The MKID detector at Fermilab uses TiN as superconducting material, which has a band gap in the order of 1 meV. Typical CCDs, however, use silicon with a band gap of around 1.1 eV. This means that when a photon strikes the TiN in an MKID, less energy is required to elicit a break in Cooper pairs[6]. Therefore, a greater number of electrons are excited by an incident photon in superconducting material than in traditional detector materials. Not only is this the key to MKIDs sensitivity, but it also allows for the energy of the incident photon to be calculated, which is not possible in CCDs due to the low level of excited electron activity.

II. Methods

i. Setup

MKIDs are essentially superconducting inductors that have been deposited onto a silicon substrate[7]. They work on the principle of the kinetic inductance effect[8], the idea that super current is stored in a superconductor, and when an incident photon strikes, it elicits a change in the current, and therefore a change in the kinetic energy. The result is a change in inductance. Inductors are placed in a resonator with a tuned microwave probe, and any changes in the inductance are recognized as changes in phase and amplitude of the probe signal. Multiplexing facilitates the transmission of individual probe signals, as each pixel is tuned to a unique resonant frequency during the manufacturing process.

In order to create the cryogenic conditions necessary for superconduction, an adiabatic demagnetization refrigerator is used. The ADR uses the properties of heat transfer and entropy to create the required temperature conditions. The 'cool down' process consists of several phases[9]: first, compressed helium is introduced into a dewar, where temperature decreases as the gas expands. A paramagnetic salt is then introduced into the inner chamber of a dewar, which contains the helium gas surrounded by a helium bath. Surrounding the chamber is an electromagnet, which is powered with an electric current, thereby causing the magnetic poles of the salt to realign. The process is thermally controlled so that isothermal conditions are achieved. The alignment of the salt at a constant temperature causes a decrease in entropy, which is then offset by heat transfer to the helium bath. The demagnetization takes place in the next step, when the helium gas is pumped out to stop any further heat transfer, and the current to the magnet is removed. The magnet reverts back to it's original alignment, causing an increase in entropy. Without an outlet for heat transfer, the salt itself decreases in temperature to offset the change in entropy. The final temperature achieved is around 100 mK.

ii. Readout Hardware

The 2024 pixels that make up the MKID are attached to two feedlines, which connect to 1012 pixels each. To obtain data from the MKID, resonators are excited with a resonant microwave signal. Probe signals are then sent through the array using a ROACH (reconfigurable open architecture computing hardware) board, which is located outside of the cryogenic setup at room temperature. When the array is exposed to a light source, photons are absorbed and increase the surface inductance, which in turn contributes to a lower resonant frequency. Individual detectors then resonate with the corresponding probe signal. The signal is amplified by the HEMT (high electron mobility transistor) at 3K, and then transferred to the FPGA (fast field programmable gate array), where the phase and amplitude information is then recorded. Because the resonant frequencies produced by the detectors are above the range of conventional DACs (digital-to-analog converters), a LO (local oscillator) frequency is used to modulate the amplitude.

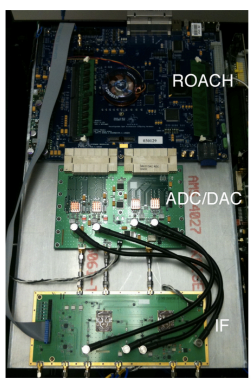

Figure 1
Hardware used to send comb frequency signals to the MKID array

iii. Software

The process of acquiring data from the resonators is complex and multi-step. It consists of running a chain of programs written largely in Python and C by Dr. Benjamin Mazin's team at University of California, Santa Barbara. Initially, frequency data is separated into four groups, because at the time of these investigation, it was only possible to access one IF board, and the frequency comb used to probe the detectors is limited to 256 resonators in 512 MHz of bandwidth[10]. This is done in a LabView program, and the raw frequency data can be viewed visually in the lab using a network analyzer device. The experimenter is then able to communicate with the ROACH board using a series of programs, where the appropriate LO frequency and attenuation is calculated and set. These programs initialize communication with the ROACH and send out probe signals. Radiation is detected by comparing the phase shifts of incident photons with those of electronic noise, so a program is used to effectively calibrate noise levels by calculating individual threshold levels without exposure to light. Next, the resonator array is subjected to a monochromatic light source via an integrating sphere (see fig. 2 as a reference to the light setup), and an observation data file is created. This raw data can then be processed further by analysis programs, known collectively as the ARCONS Pipeline. Here, information about individual phase shifts can be used to determine photon energy levels, arrival times, and more.

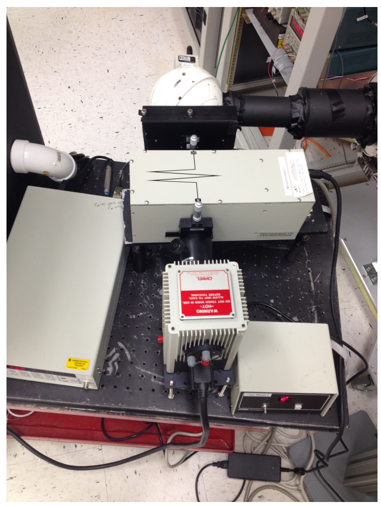

Figure 2
The light setup, including the variable power lamp, wavelength control box, integrating sphere, optical power meter, monochrometer, and optical input to the cryogenic dewar.

III. Analysis

i. Local Oscillation Frequency Testing

As previously described, the probe signal is mixed with a LO frequency to reach appropriate frequency range levels. A data collection program calculates an optimal LO frequency before sending out probe signals, however it is hypothesized that there are flaws in the algorithm. The LO frequency was varied over a range of 2.7 to 3.1 GHz, in .1 GHz intervals. The data was analyzed both by looking at variations in quality of the phase shift histograms, and by looking at the average resolution of the resonators at each LO frequency. It was found that resolution with LO frequency, which seemed to indicate that an optimal LO frequency indeed existed.

ii. Pixel Grouping Testing

Micro variations within the TiN energy gap are believed to cause ‘grouping’ of resonators, which causes grave issues with the performance of the detector. Abnormally grouped resonator frequencies were looked at visually, and it was noted that at around 250 kHz, the resonators exhibited very poor quality.

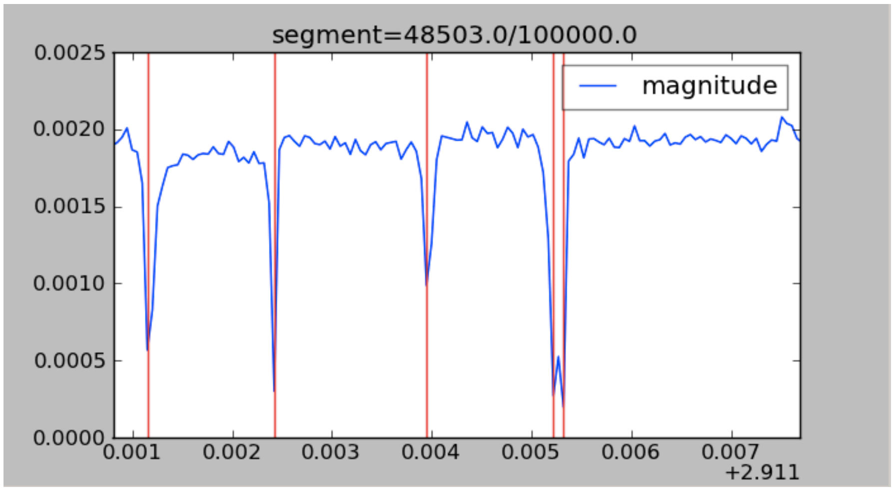

Figure 3
A pair of grouped pixel frequencies.

iii. Lamp Testing

It was noted that many of the phase shift histograms generated from observation data contained two 'peaks' at different phase energies. Because phase shift is proportional to photon energy, and thus wavelength, this was unexpected for a monochromatic light source. It was hypothesized that these multiple peaks were occurring due to a leak in the light filter setup, so a monochrometer was installed. The monochrometer selectively transmits certain wavelengths to the integrating sphere using a diffraction grating. Tests were done comparing observation files taken for 900 seconds at 400 nm wavelengths first with the monochrometer installed and then without it. Figure 4 indicates the second, lower energy 'peak' observed in trials without the monochrometer, compared to the single peak in trials with the monochrometer.

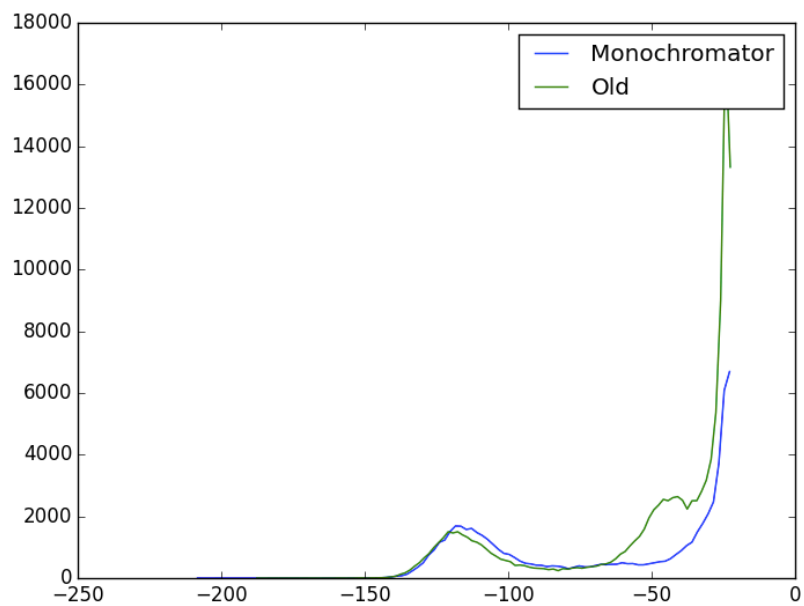

Figure 4
A histogram of pixel phase shifts. Data collected without the monochrometer is indicated by a green line, while data collected with the monochrometer is indicated by a blue line.

iv. Further Problems

A great deal of time and effort was used to correct issues that arose in hardware operation. The lab setup is complex and the performance of the resonator array is highly dependent upon the organization of the equipment. In addition to the lamp leak, many other problems arose and were carefully documented so that MKIDs could be more easily operated by future users.

III. Conclusion

MKID devices have great potential due to their sensitivity and ability to be multiplexed into large-scale arrays. Sky imaging projects such as the Dark Energy Survey (DES) and Large Synoptic Survey Telescope (LSST) aim to document around 3 billion galaxies and quasars [11], however the method of multi-filtering and image superposition required by CCD detectors contributes to uncertainty in redshift estimations. MKIDs aim to reduce the redshift uncertainty by a factor of ten[12].

It is ultimately proposed that large-scale MKID arrays be implemented in these dark energy surveys as a means of reducing redshift uncertainties. They also have a wide variety of applications as ultraviolet, optical, and near infrared terrestrial detectors. Designing new generations of hardware and fine-tuning pixel resolution issues will help introduce this promising technology as a standard tool in astronomical observation.

IV. Acknowledgments

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