Summer research report:
Readout system for MKIDCam

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ABSTRACT

This document describe my involvement on an instrumentation project as part the group lead by Profs. J. Zmuidzinas and S. Golwala. The long term goal of the project is to develop a submillimeter camera with 600 pixels and 4 colors, using Microwave Kinetic Inductance Detectors (MKIDs) and a readout strategy that makes use of frequency multiplexing. This camera will be a very useful survey tool in the submm/mm-wave region and will increase the capabilities of the Caltech Submilliter Observatory. The short term goal is to build a test camera with 6x6 pixels and 4 colors and make an engineering run by May 2008. This will be a significant improvement with respect to the current system of 4x4 pixels and 2 colors, that was tested at the CSO on April 2007. I have been working on the development of a new readout system to be used on the May 2008 engineering run, that can be easily scaled to the final camera. The main products of this work are a detailed electronic design with complete specifications for the principal components and a simulation of the readout system that with improvements could be used to the design and testing of signal processing strategies.

1. Introduction

Submillimeter astronomy makes use of the electromagnetic radiation received at frequencies between 200μm and 1mm. Astronomy at these wavelengths is developing rapidly due to the advances in detector technologies. The science that can be done at these wavelengths includes many areas of galactic and extragalactic astronomy that deal with cold material, specially during the early evolution of planets, stars and galaxies.

Driven by the interesting perspectives for submillimeter astronomy, our group lead by Profs. S. Golwala and J. Zmuidzinas from Caltech, in colaboration with researchers from JPL and the University of Colorado at Boulder, has been working on the development of a new submm/mm-wave camera, MKIDCam, for the Caltech Submillimeter Observatory. This new multipixel-multicolor instrument will be an excellent survey tool, and as such will provide targets for follow-up observations with the ALMA interferometer. It will also contribute to the development of instrumentation for the proposed Cornell-Caltech Atacama Telescope and other future projects.

I have been particularly involved on the design of a new readout system for MKIDCam and on the drafting of an observational project to be carried out during the next engineering run planned for May 2008.

The scientific motivation is briefly described in the next section. This is followed by a description of MKIDCam and the MKIDs technology. A description of the readout system and an account of the advances made in the readout system is made. Finally a short description of future goals is presented.

2. Scientific motivation

There are many astronomical applications for MKIDCam, among them we can mention star formation and submm galaxy surveys. It is the submm galaxy surveys the main goal of the camera, but due to the proximity of Galactic sources it is interesting to consider early science related with Galactic star formation.

Submm galaxies are a population of very luminous high-redshift galaxies, that contribute a significant fraction of the energy generated by all galaxies over the history of the Universe. The redshift determinations are complicated by the fact that they are usually faint in the optical but current knowledge is that $z > 1, z_{mean} \sim 2 - 3$. The bulk of the emission in submm galaxies corresponds to thermal emission from dust, which can be approximated to a modified black-body $f_\nu \propto \epsilon_\nu B_\nu$, where ϵ_ν is the dust emissivity and B_ν is the Planck function. The evidence indicates that high-mass star formation is the main source of energy that heats the dust. The inferred luminosities are greater than $10^{12} - 10^{13} L_\odot$, with star formation rates of $10^2 - 10^3 M_\odot/year$ (Blain et al. 2002).

Due to the multicolor capability, this instrument will be appropriate to identify candidate submm galaxies without the uncertainties introduced by using multiple instruments. A submm galaxy with a typical spectrum at $z \sim 8.5$ will have the maximum of its SED in the MKIDCam bands (section 3), providing very important information to galaxy formation models. For lower redshift we will measure the Rayleigh-Jeans tail of the spectrum. The 4 color camera would allow to constrain the dust emissivity spectral index β, providing better constrains to the dust temperature-redshift product allowing a more detailed study of their physical properties.

Star formation surveys can also be done with the camera. The multicolor capability will allow the identification of star formation sites and the study of the physical properties of the dust. Specifically, the hypothesis that the dust emissivity changes significantly with temperature (Dupac et al. 2003; Boudet et al. 2005) can be studied in detail.

The large-area maps and multicolor capabilities of the instrument will make it a invaluable survey tool.

3. MKIDCam

MKIDCam is a submm/mm-wave camera with 600 spatial pixels each one sensing four colors at 750μm, 850μm, 1.1mm and 1.3mm, angular resolution between $19''$ to $34''$ and a sensitivity one order of magnitude better than previous CSO instruments.

This instrument will make use of MKIDs, photolithographic phased-array antennae and filter designs, revolutionary new technologies developed recently at Caltech and JPL.

3.1. MKIDs technology

MKIDs are a new type of superconducting detector pioneered at Caltech (Day et al. 2003; Mazin 2004), in which quasiparticles created by incident radiation are sensed by measuring the change in the surface impedance of a strip of superconductor. The change in surface impedance is measured by making the superconductor part of a microwave resonator and measuring the phase of a microwave signal transmitted through the resonator. The detection principle is illustrated in figure 1.

An absorbed photon breaks a number of Cooper pairs in the superconductor which is at a temperature much lower than the critical temperature T_c (a). These quasiparticles produce a change in the surface impedance of the superconductor, which is part of the resonator (b). The change in the impedance modifies the amplitude and phase of the transmission curves of the resonance. It is through this effect that we can detect the incidence of a photon (c and d).

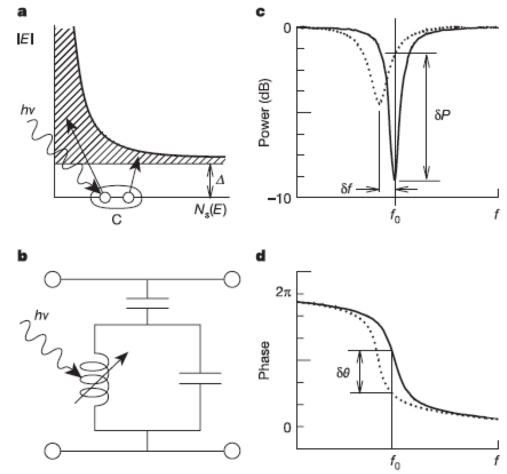

Fig. 1.— Illustration of the detection principle for MKIDs as part of a microwave resonator. From Day et al. (2003)

This choice of circuit design, with a high transmission away from resonance is what allows the readout of several resonators with slightly different resonant frequencies coupled to a common transmission line.

The possibility of frequency multiplexing many resonators is what makes MKIDs so attractive as an alternative for large submillimeter arrays. This produces a great simplification over traditional readout approaches that make use of separate cold readout electronics for each pixel, moving all the readout electronics to room temperature where it is possible to use commercial components and to share it among multiple elements.

3.2. Readout system

To implement the frequency multiplexing, each resonant circuit is designed to have a different resonant frequency and is coupled to a transmission line. Using high quality factor resonators it is possible to multiplex a hundred of them in a bandwidth of a few hundreds of MHz.

Starting from the concept, I made (in collaboration with Dr. B. Mazin Caltech/JPL) a detailed electrical design that is represented schematically in figure 2.

The digital-to-analog converters (DAC) are used to generate the input signals. These signals (I and Q) are the sum of sinusoids of particular frequencies each one associated with a resonator. I is the in phase component and Q is the quadrature component, that is 90^o out of phase with respect to I. The use of this two signals allow us to measure the phase and amplitude of the transmitted signal. The signals are up-converted using an IQ mixer and a local oscillator at microwave frequencies. This up-converted signal goes through the MKIDs and is modified by the resonant circuits. The signal is down-converted using other IQ mixer and then is digitized using a pair of analog-to-digital converters (ADC). Further signal processing is necessary to recover the phase and amplitude of the IQ signal and to determine the photon energy flux in the resonators (Pozar 2004; Oppenheim et al. 1999).

The main components of the system were completely specified and vendors identified and contacted. At this moment we are evaluating some detailed aspects related with the implementation of the last stages of the readout system.

After the signals are digitized by the ADCs, a series of signal processing operations must be performed in order to measure the phase and amplitude change of the signals. This signal processing, which is basically taking a Fourier transform, will be done using a Field Programable Gate Array (FPGA). The implementation of this stage will be done by RF Engines, a UK based company specialized in signal processing for FPGA. It is our task to make a complete specification of the requirements.

As a tool to help in the design stage, I am developing a Matlab simulation of the system. This simulation has the capability to represent the up-conversion, down-conversions, amplification stages, analog-to-digital conversion stages and some signal processing operations. The idea is to take into account the most important effects that can affect the output of the system, and to create a tool to allow quantitative comparison of various signal processing strategies.

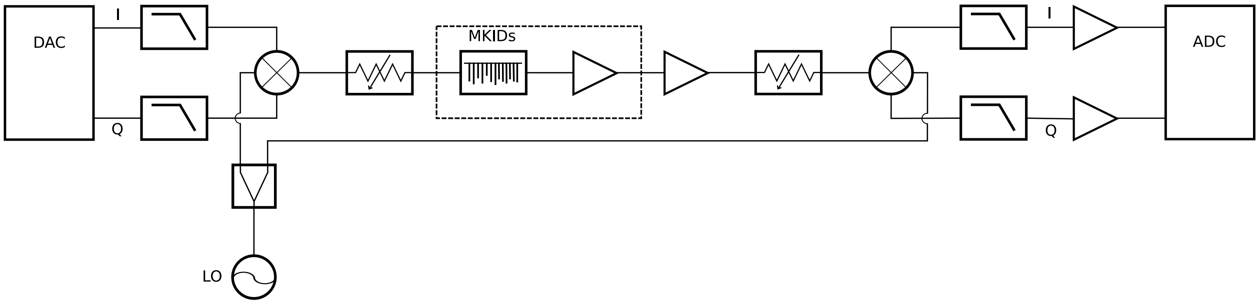

Fig. 2.— Block diagram for the readout system. The only components in the cool stage are the MKIDs microwave resonators and the HEMT amplifier, the rest of the components are commercial room temperature devices.

The hardware implementation of the system is planned to start by November, and the simulation is proving to be very useful as a learning and design tool.

4. Future goals

Some finer details of the electronic design have to be addressed before implementing the system in the laboratory in November. Some effort will be made in improvements to the Matlab simulation, because this can help in the design stage, however it is possible that an experimental characterization of the electronics components might be a better choice. Starting in November most of the effort will be dedicated to the integration of the system in the laboratory.

An engineering run of the camera in the Caltech Submillimeter Telescope is programed for May 2008. It is possible to make use of these early observations to study the SEDs of local starburst galaxies as M82. These galaxies and LIRGs/ULIRGs are very similar to submm galaxies so it can be interesting to study the properties of their dust while we don't have enough sensitivity for more distant sources. A list of targets will be made based on the SCUBA Local Universe Galaxy Survey (Vlahakis et al. 2005).

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