

# Digital Readouts for Superconducting Microresonators

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**Abstract.** A large community has converged on the idea of using high quality factor superconducting microresonators to achieve dense frequency domain multiplexing at microwave frequencies. This technique uses wide bandwidth high electron mobility transistors (HEMTs) to provide several GHz of bandwidth with noise temperatures below 5 Kelvin, potentially allowing thousands of detectors to be read out through a single transmission line. This technique, developed originally for microwave kinetic inductance detectors (MKIDs), is also applicable to transition edge sensors (TESs) coupled to resonators through rf SQUIDs, and Normal-Insulator-Superconductor (NIS) detectors. This paper will describe the challenges and benefits of this readout technology.

## 1. Technical Approach

A large community has converged on the idea of using high quality factor superconducting microresonators to achieve dense frequency domain multiplexing at microwave frequencies. This technique uses wide bandwidth high electron mobility transistors (HEMTs) to provide several GHz of bandwidth with noise temperatures below 5 Kelvin, potentially allowing thousands of detectors to be read out through a single transmission line. This technique, developed originally for microwave kinetic inductance detectors (MKIDs)[1], is also applicable to transition edge sensors (TESs) coupled to resonators through rf SQUIDs [2], and Normal-Insulator-Superconductor (NIS) detectors[3].

In a MKID [4], shown to the right in Figure 1, a high Q ( $10^4$ - $10^6$ ) superconducting resonator with a resonant frequency between 1-20 GHz is fabricated lithographically. Incident photons (panel b) change the surface impedance of the superconductor, causing a change in the amplitude (panel c) and phase (panel d) of a microwave probe signal sent past the resonator at the resonant frequency. Since the transmission far away from the resonance is

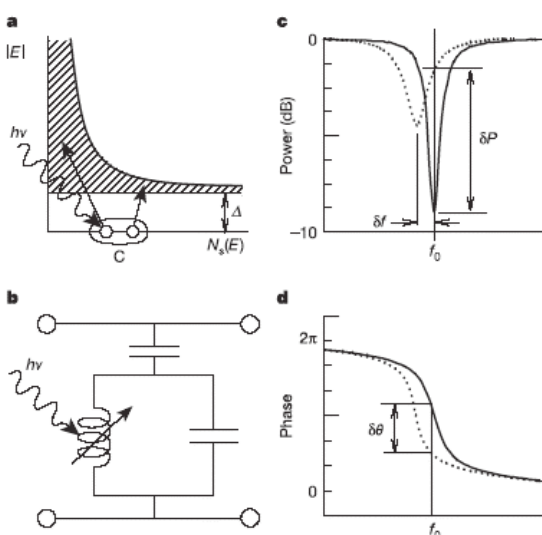


Figure 1. The mechanics of a MKID.

unity, we can multiplex many MKIDs off a single transmission line by setting each MKID's resonant frequencies to be slightly different with lithography. This is analogous to the different tones produced by different length pipes in a pipe organ. Using this approach, groups have recently demonstrated resonator-to-resonator frequency scatter below 1 MHz (Figure 2).

In a microwave SQUID array each high-Q resonator is loaded with a dissipationless rf-SQUID. The flux-variable inductance tunes the resonance frequency without affecting Q. Any detector that a SQUID can read out can be multiplexed this way, in particular the TES. To linearize the response one can apply flux feedback if the number of detectors is small. If the number of detectors is large one can utilize the SQUID flux periodicity to modulate the signal, for example by applying a common flux ramp to all SQUIDs in the array. This is a form of phase modulation and it both linearizes the SQUID response and up-converts the detector signal to higher frequencies in the bandwidth of the resonance. It requires more bandwidth per detector and additional room temperature computation but allows us to modulate above the  $1/f$  noise of the resonators and the HEMT. The lithography for defining closely spaced resonances is essentially the same as for MKIDs and the SQUIDs can be fabricated on the same wafer as the TESs.

In order to read out an MKID or microwave SQUID array, one must generate a comb of frequencies with a sine wave at the resonant frequency of each individual resonator. This comb is then sent through the device, where each detector imprints a record of its illumination on its corresponding sine wave. The comb is then amplified with a cryogenic HEMT and brought outside the cryostat. The comb is then digitized, and the phase and amplitude modulation of each individual sine wave is recovered in room temperature electronics. Aside from a simple HEMT amplifier, there are no cryoelectronics. Compared to existing low frequency TES SQUID multiplexers, much of the complexity is moved from the base temperature to room temperature, where the full power of modern microwave electronics is available. The readout of TES devices with resonator-coupled SQUIDs will be very similar, except the signal will be entirely in the phase direction, and higher readout data rates will be required to sample an external magnetic modulation signal required to linearize the SQUID response.

The technique described above, where a comb of frequencies is created, modified, then digitized and analyzed, is very common in modern wireless communications, where it is usually

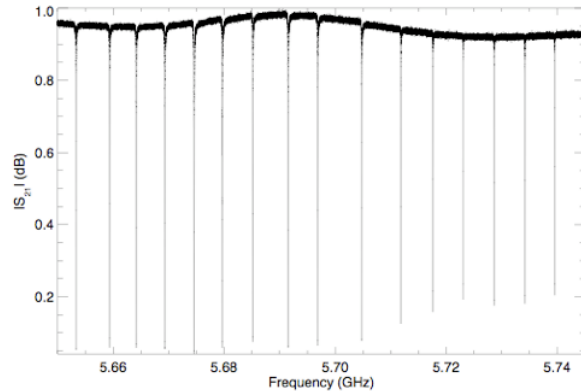


Figure 2. Transmission past a microwave MKID array.

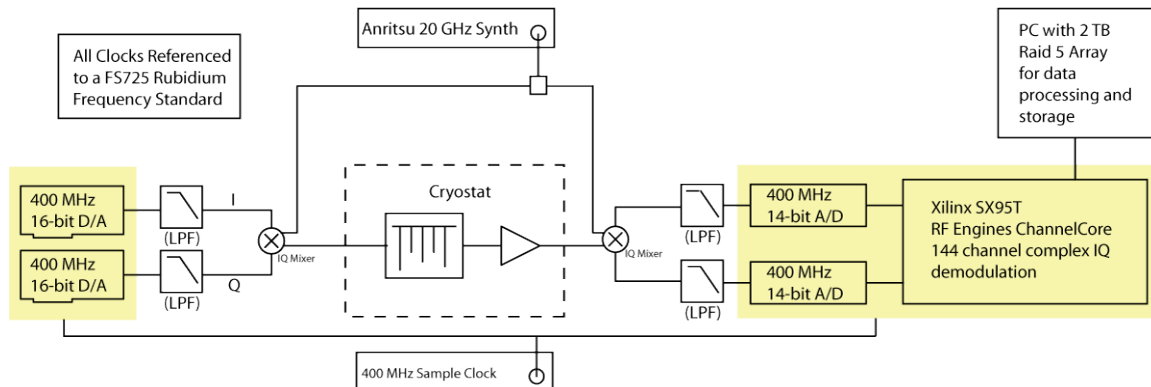


Figure 3. A block diagram of a SDR readout.

referred to as software-defined radio (SDR). An implementation suitable for reading out detectors is shown in Figure 3. In this implementation, dual 400 MHz, 16-bit digital to analog converters play back a pre-computed waveform to generate the comb. Since two D/As are used, we can use an IQ modulator, which allows us to produce signals within a 400 MHz wide band centered on our LO frequency (usually 2-6 GHz). After the comb passes through the detector, it is mixed back down to baseband with another IQ modulator, low pass filtered, then digitized with dual 400 MHz, 14-bit analog to digital converters. After digitization, the signals are passed to a fast field programmable gate array (FPGA). There are many algorithms that can be run in the FPGA to demodulate the signals. The simplest is a direct digital downconverter (DDC) that simply digitally multiplies the complex input signal by sine wave at the desired frequency. This shifts the frequency of interest to 0 Hz. A digital filter followed by decimation gives the desired output data stream.

## **2. Maturity**

The first SDR readout for LTDs was demonstrated in the lab in 2006 [1]. In April 2007, Caltech and the University of Colorado brought a SDR readout to the Caltech Submillimeter Observatory (CSO). This MKID demonstration camera proved the technology viable for ground-based operations [5]. This work has brought the readout to a TRL of 5, and has enabled Caltech and Colorado to successfully propose to the NSF for a much larger camera for the CSO. The MKID camera on the CSO will read out approximately 2400 pixels in 8 GHz of bandwidth, making it by far the largest microwave FDM readout. This camera will push the readout to TRL 6.

## **3. Benefits and Disadvantages**

A SDR readout allows a drastic simplification of the focal plane. This simplification cascades through the system, lowering costs at every stage. For instance, a MKID based focal plane will only need several wires leaving the detector wafer, while a TDM TES multiplexer will require thousands between the detectors and the cryogenic multiplexer elements. This drastically simplifies the construction of the focal plane.

The advantage of moving the readout complexity from 4 Kelvin to room temperature is significant. The entire hardware set developed to allow SCUBA-2 is extremely powerful, but large and very expensive due to the requirement of having one SQUID per pixel. Also, since conventional TDM TES multiplexers are completely custom, they do not gain much from external developments. In the two years since experimentation on these readouts first started, there has been a factor of 4 four improvement in the speed of 14-bit A/D converters. The ability of SDR readout power to scale with Moore's law ensures that they will grow significantly more powerful with time.

The drawback of these systems for space applications is that they require flying fast and precise A/Ds, D/As, and FPGAs. Flight ready versions of these components tend to lag their ground-based counterparts, so the bandwidth of space-based SDR readouts will be lower than ground-based systems. The complex signal processing may also consume a significant amount of power at room temperature, in the worst case as high at 0.1 Watts/pixel, but likely much lower.

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