A Fast, Ultra-Sensitive and Scalable Detection Platform Based on Superconducting Resonators for Fundamental Condensed-Matter and Astronomical Measurements

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Abstract. Low-temperature physics and astronomy have traditionally focused on developing exquisitely sensitive single-pixel detectors. While this has yielded considerable results, these technologies almost uniformly suffer from an inability to scale to large array sizes. In order to circumvent this barrier, frequency-multiplexing techniques have recently emerged as a suitable solution. Here we present a detailed description of a measurement platform based on frequency-multiplexed superconducting resonators along with the results from two distinct measurements that leverage this nascent technology to achieve multiple-device readout. The first application discussed is a seven-pixel array sensor of the permittivity of liquid helium suitable for quantum hydrodynamic experiments. The second implementation described is a prototype 16-channel mm-wavelength detector optimized for ground-based astronomical detection at the 30 meter Institute for Millimeter-Wave Radio Astronomy (IRAM) telescope in Pico Veleta, Spain.

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In the century since Heike Kamerlingh Onnes first liquified helium, low-temperature refrigeration has proven to be an indispensable tool for experimental physicists. However, cryogenic systems have traditionally suffered from relatively complex operation and low cooling-power. The first of these obstacles has been steadily ameliorated through computer automation and the advent of new cryogenic techniques such as adiabatic-demagnetization and cryogen-free refrigeration. However, the limited cooling power, ranging from nW to mW depending on system size, remains a major hurdle. This obstacle is manifest when scaling from the single-pixel device sizes characteristic of fundamental measurements to large arrays sizes typical of room-temperature electronics. The high wire-counts necessary for reading out many devices at low-frequencies present a limiting thermal pipeline, easily overwhelming the cooling-power of a cryogenic system. To address this issue, frequency-multiplexing of multiple devices on a single wire has been widely recognized as a convenient solution[1]. Employing this technique, we have developed a cryogenic detection platform based upon superconducting resonators continuously monitored with frequency-multiplexing electronics. Development was followed by testing on two measurement systems: a fast and sensitive array sensor of the permittivity of liquid helium and a prototype 16-channel mm-wavelength detector designed for ground-based astronomical detection at the 30 meter Institute for Millimeter-Wave Radio Astronomy (IRAM) telescope in Pico Veleta, Spain.

SUPERCONDUCTING RESONATORS

Due to their lithographically-controllable resonance frequencies, intrinsically high quality-factors, and versatility, superconducting microwave resonators are an ideal foundation for a scalable detection platform. The necessary measurement electronics for these devices are

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widely available due to the mature cellular phone industry and, more recently, the advent of the field programmable gate array (FPGA). These electronics can easily be integrated with a planar geometry transmission line to which the resonators can be inductively or capacitively coupled. Multiple geometries are realizable with single-layer lithography, with microstrip or coplanar waveguide (CPW) being the most common designs.

One property of superconducting resonators typically considered a disadvantage is the sensitivity of the device to the surrounding dielectric medium. This usually provides a loss-mechanism for the resonator and results in a decreased quality factor. However, this property can be exploited as well. For example, by measuring a series of half-wavelength CPW resonators covered with a variety of dielectrics, the high-frequency, low-temperature and low-energy properties of common insulating materials have recently been reported[2]. In a similar manner, we have recently demonstrated the ability of frequency-multiplexed CPW superconducting resonators to sensitively detect changes in the permittivity of surrounding helium at low temperatures (1.8 to 8.8 K)[3].

Another useful feature of superconducting resonators is their sensitivity to the complex surface-impedance. This reactance is due to the dissipation-less acceleration of the cooper-pairs in the presence of an electromagnetic field. As this process is lossless, the energy is merely stored by the charge carriers and not transferred to the lattice as is typical in a normal metal. With this stored energy it is possible to associate a kinetic inductance. This impedance is naturally sensitive to the density of cooper-pairs and gives rise to their well-established utility as photon detectors, commonly referred to as kinetic-inductance devices[4, 5]. Briefly, a photon absorbed by the resonator with an energy greater than 2Δ will result in a decrease in cooper-pair density and an increase in quasi-particle density. The resulting change in the kinetic inductance leads to a detectable shift in the resonance frequency. As part of an international collaboration called the Néel IRAM KIDs Array (NIKA), we are currently investigating the practicality of a giant-array, mm-wavelength detector for ground-based astronomy which exploits this effect.

FREQUENCY-MULTIPLEXED READOUT ELECTRONICS

State-of-the-art thin films provide the ability to engineer extremely high quality-factor resonators, in some cases exceeding a million, resulting in very sharp resonance peaks. The maxima of this peak, the resonance frequency, is lithographically controllable with standard optical techniques. This results in the ability to reliably pack a large number of resonances in a limited bandwidth. However, as it is often difficult to achieve electron temperatures below $T_e \sim 100$ mK in a standard dilution system, it is desirable for the resonance frequencies to substantially exceed $f = k_B T_e/(2\pi\hbar) \sim 2$ GHz to limit noise due to thermal excitation. Thus, in order to achieve simultaneous readout of a large number of resonators, it is necessary to synthesize and detect an equal number of continuous waves at high-frequencies within a bandwidth of order 100 MHz.

While the appropriate waveform could in principle be achieved by generating each tone from an individual high-frequency synthesizer, this very quickly becomes prohibitively expensive. An alternative is to generate the tones with the appropriate spacing at low-frequencies using digital electronics. These can then be shifted to the desired frequency band with a single high-frequency carrier and a mixer. This up-converted waveform then drives a transmission line to which the resonators are coupled. After interacting with the resonators, the amplitude and phase of the individual high-frequency sinusoids will be modified depending on the time-dependent state of the individual resonators. The signal is then suitably amplified and subsequently down-converted. Finally, the low-frequency signals can be digitally mixed and low-pass filtered to separate the individual tones. This is illustrated for two measurement frequencies in Fig. 1.

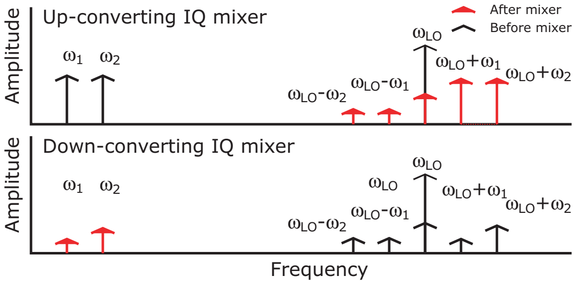

FIGURE 1. Illustation of up-conversion and down-conversion of two frequencies using IQ mixers and a carrier frequency at ω_{LO}. Notice that at the down-converting mixer, the upper-sideband signals have been reduced due to interaction with the superconducting resonators.

A circuit schematic of the readout electronics is shown in Fig. 2. In-phase (I) and quadrature (Q) copies of the low-frequency waves are generated digitally by a FPGA custom programmed using VHDL. These signals drive two DACs which, after passing through reconstruction filters, feed the the I and Q ports of an IQ mixers. A high-frequency source followed by a splitter generates two copies of the carrier. One copy of the carrier feeds the local-oscillator (LO) port of the up-converting IQ mixer. At the radio-frequency (RF) port of the mixer, the desired high frequency tones appear at frequencies above the carrier wave. By using an IQ mixer, spurious signals such as the lower sideband and the carrier wave are substantially suppressed with respect to the upper-sideband frequencies.

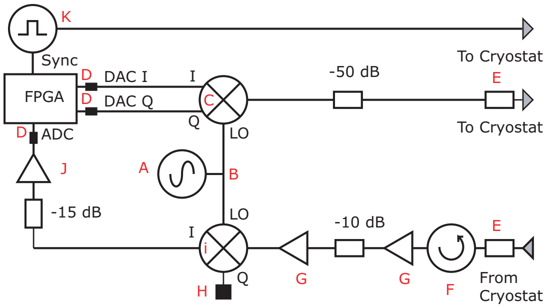

FIGURE 2. Readout electronics. A) High-frequency source, B) Splitter, C) Up-converting IQ mixer, D) Low-pass filter, E) DC Block, F) Circulator, G) High-frequency amplifier, H) 50 Ω, i) Down-converting IQ mixer, J) Low-frequency, high-power amplifier, K) Optional pulse source.

Inside the cryostat, a series of 50 Ω cryogenic attenuators are used to restrict thermal noise from the room-temperature electronics. At the lowest-temperature stages, NbTi superconducting coaxial cable is utilized to provide adequate thermal isolation. A band-pass filter and circulator before the first stage amplifier can be used to limit the effects of back-action noise on the resonators.

After amplification by a 65 K noise-temperature amplifier, the signal is fed to the RF port of the down-converting IQ mixer. The second copy of the carrier drives the LO port. For under-coupled resonators, the Q port can be terminated with a 50 Ω resistance. However, for strongly over-coupled resonators, it can be advantageous to use a 90° hybrid driven by the I and Q signals to suppress the lower-sideband signal. In either case, the waveform is then gained with a high-power amplifier before passing to an anti-aliasing filter and the ADC, which is connected to the FPGA. The phase and amplitude of the individual tones, which directly depend on the state of the corresponding resonators, can then be calculated with a specified level of filtering and read out.

QUANTUM HYDRODYNAMICS

Superconducting resonators are highly sensitive to their electromagnetic environment. Exploiting this feature, we have measured the response of quarter-wave NbN CPW resonators directly immersed in a helium bath as a function of temperature. As can be seen in Fig. 3, the resonance frequency is temperature dependent due to both a change in the internal kinetic inductance and a change in the external permittivity of the surrounding helium bath.

At temperatures significantly below T_c, the quasi-particle population is highly suppressed and the kinetic inductance is nearly constant. At these energies, the resonance frequency shift is predominantly due to changes in the surrounding dielectric medium. In this regime a resonator serves as a fast and sensitive probe of the local liquid-helium temperature. For example, a heat pulse can be applied to the helium bath by an in-situ heating resistor. This can subsequently be sensed by an array of resonant detectors in real-time. A measurement of this is displayed in Fig. 4. Here, a 70 Ω resistor was placed 3 cm from an array of resonators immersed in a helium bath at 1.8 K. Three heat pulses were then applied for varying duration and intensity while measuring the seven individual resonator states.

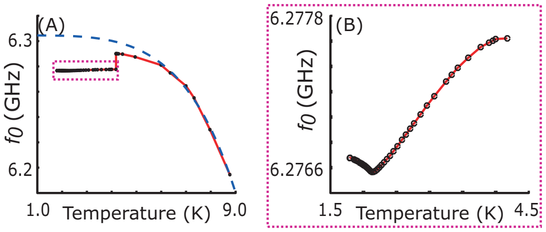

FIGURE 3. (A) Measured change in the resonant frequency of a superconducting resonator with temperature. The dashed line is the expected change due to the temperature-dependent kinetic inductance. (B) Measured change below 4.2 K (dashed box in (A)). Notice the lambda transition is clearly visible at 2.17 K.

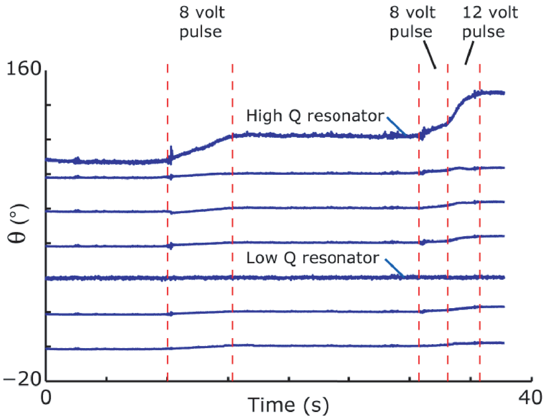

FIGURE 4. Measurement of resonators immersed in liquid helium. The resonator quality factors varied from 5×10^4 (low-quality resonator) to 10^5 (high-quality resonator). Three heat pulses were applied to a 70 Ω thin-film resistor situated 3 cm from the array. The initial 8 volt, ~5 second pulse was followed by a 15 second relaxation. This is subsequently followed by a 8 volt, ~2.5 second pulse and a 12 volt, ~2.5 second pulse.

As the electronics for this measurement were still unoptimized, the noise level was unfortunately high, resulting in the need to reduce the measurement bandwidth to ~100 Hz. As a future direction, we plan to implement a low-noise amplifier in the helium-bath and digital averaging of the resultant signal by the FPGA. This will significantly reduce the noise and allow for significantly increased measurement bandwidth, potentially resulting in the ability to perform time-of-flight measurements of second sound in superfluid helium and vortex detection in the turbulent flow regime.

NIKA

NIKA is an international collaboration focused on developing a prototype detector for the 30-meter IRAM telescope. This prototype uses an optical cryostat custom designed by Alain Benoit to mate with the telescope. The system is fitted with two coaxial cables and the necessary electronics to perform transmission measurements.

An example of a typical measurement with 13 channels is shown in Fig. 5. Initially, the resonators are calibrated with a 300 K black body placed in front of the lens. After calibration, the stop is removed and an x-y scan is initiated with a chopped circular image on the focal plane. The image alternates between 70 K and 300 K black bodies and the scan proceeds in steps, with each position being held for 20 seconds. During the raster scan, pixels can become partially or fully illuminated. While lit, the resonance will shift at the chopping frequency, with the depth of modulation dependent upon the incident power on the resonator and its quality factor. A close-in image of this behavior is shown in Fig. 6.

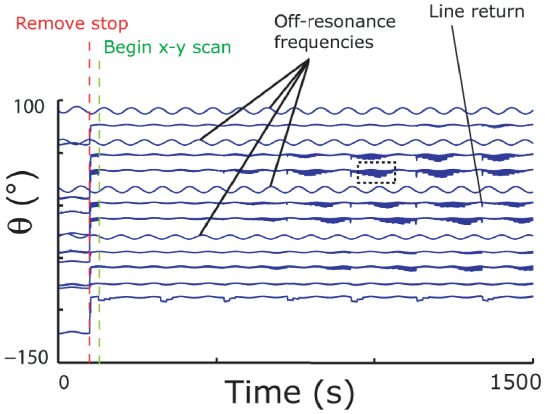

FIGURE 5. Response of 13 channels measured simultaneously. Four channels were placed off resonance to serve as controls. The response was taken while raster scanning an image over the detector, with the greatest response seen when the image is directly over a pixel.

For the measurement shown in Fig. 5, four off-resonance channels to serve as control signals. As is clear from these channels, our system currently exhibits spurious low-frequency noise which we expect to be able to eliminate in the near future. This is most likely due to synchronization issues with the high-frequency source and the FPGA or round-off error in the generation of the measurement waves. While we are working to reduce all noise-sources in the measurement chain, our current noise level is near that set by atmospheric fluctuations. Further, our current record of 16 channels simultaneous measured is limited by the resonator frequency spacing which presents no fundamental limit. We plan on scaling to a 32 and 64 pixel arrays in the near future, with larger arrays envisioned.

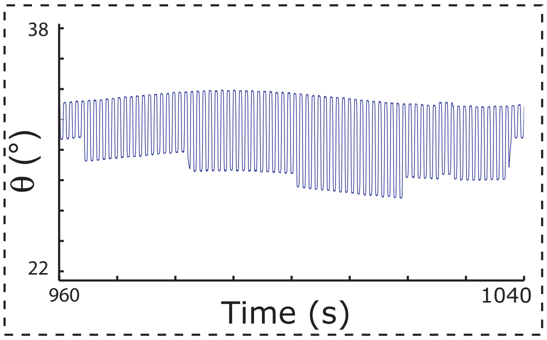

FIGURE 6. Inset from Figure 5. Response of a single resonator to a 1 Hz chopped image. The image was translated every 20 seconds.

CONCLUSION

Frequency-multiplexed superconducting resonators promise to be a revolution in low-temperature detection. While astronomical applications have served as a test bed and motivator for rapid early development, it is clear that numerous areas of cryogenic measurement can benefit. Material characterization studies, medical imaging, and fundamental physical measurements can all be enriched by the increased resolution and statistics achievable with a giant-array frequency-multiplexed resonator platform.

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