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Digital readouts for large microwave low-temperature detector arrays

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Abstract

Over the last several years many different types of low-temperature detectors (LTDs) have been developed that use a microwave resonant circuit as part of their readout. These devices include microwave kinetic inductance detectors (MKID), microwave SQUID readouts for transition edge sensors (TES), and NIS bolometers. Current readout techniques for these devices use analog frequency synthesizers and IQ mixers. While these components are available as microwave integrated circuits, one set is required for each resonator. We are exploring a new readout technique for this class of detectors based on a commercial-off-the-shelf technology called software defined radio (SDR). In this method a fast digital to analog (D/A) converter creates as many tones as desired in the available bandwidth. Our prototype system employs a 100 MS/s 16-bit D/A to generate an arbitrary number of tones in 50 MHz of bandwidth. This signal is then mixed up to the desired detector resonant frequency (~10 GHz), sent through the detector, then mixed back down to baseband. The baseband signal is then digitized with a series of fast analog to digital converters (80 MS/s, 14-bit). Next, a numerical mixer in a dedicated integrated circuit or FPGA mixes the resonant frequency of a specified detector to 0 Hz, and sends the complex detector output over a computer bus for processing and storage. In this paper we will report on our results in using a prototype system to readout a MKID array, including system noise performance, X-ray pulse response, and cross-talk measurements. We will also discuss how this technique can be scaled to read out many thousands of detectors.

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1. Introduction

The field of low-temperature detectors (LTDs) has advanced to the point where single pixel devices reach sensitivity levels easily adequate for all but the most challenging space-based applications. The primary challenge is now making arrays that are large enough to fulfill important science goals like detection of the polarization of the microwave background and mapping large areas of the sky in the millimeter and submillimeter wavebands. Developing large format imaging spectrometers for optical, UV, and X-ray wavelengths is also a priority of the scientific community. This paper will discuss a new all-digital microwave technique to read out LTDs that has been implemented using off-the-shelf components developed for the wireless communication industry. Using this technique it will be possible to read out thousands of microwave kinetic inductance detectors (MKIDs) [1] using inexpensive room temperature components. It is likely that this approach can be adapted to many different types of detectors in addition to MKIDs, such as microwave SQUID readouts for transition edge sensors (TES) [2] and NIS bolometers [3].

2. Frequency domain multiplexing

The primary idea behind this readout is that every detector is part of a microwave resonant circuit with high

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transmission off resonance. Every detector is designed to have a different resonant frequency, and the whole array can be read out with a comb of frequencies. For example, we could design an array with detectors (resonators) at 6.0 6.02, 6.04 GHz, etc. We measure the response of the detector by looking at the phase and amplitude change of a microwave probe signal sent through the resonator at its resonant frequency. We can send in a comb of frequencies to excite all the resonators, then use room temperature electronics to sort out the signals. A fully analog version of this technique has been used extensively in our lab, and more details can be found in Mazin's thesis [4].

In this work we explore using a fully digital version of the readout. In this version, and arbitrary waveform generator creates a comb of frequencies, then this comb is block up-converted to the frequency range of interest. The comb is sent into the cryostat, excites the resonators, then is block down-converted back to baseband, where it is sampled by a very fast analog to digital converter (A/D). A numerical mixer on a dedicated integrated circuit or a multipurpose FPGA can be used to recover the detector response by tuning the known resonator frequency.

3. Software defined radio hardware

We are using off-the-shelf products from Pentek and National Instruments to realize this digital readout. A block diagram of the system we used is shown in Fig. 1.

In this method a fast digital to analog (D/A) converter creates as many tones as desired in the available bandwidth. Our prototype system employs a 100 MS/s 16-bit D/A to generate an arbitrary number of tones in 50 MHz of bandwidth using a National Instruments 5421 card. This signal is then mixed up to the desired detector resonant frequency ($\sim$10 GHz) with a single sideband mixer (SSB), sent through the detector, then mixed back down to baseband with another SSB. The baseband signal is then anti-alias filtered and digitized with a fast analog to digital converters (80 Ms/s, 14-bit) residing on a Pentek 7131 board. Next, a numerical mixer in a dedicated integrated circuit (TI Graychip 4016 on the Pentek 7131) mixes the frequency of a specified detector to 0 Hz, and sends the complex detector output over a computer bus for storage.

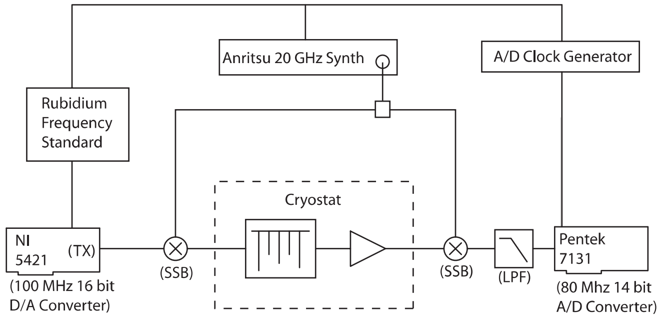

Fig. 1. The physical hardware of the software radio readout used for data acquisition in this paper.

This is a prototype system. We have a Pentek 7640 board on order, which contains both the transmit and receive functions on a single board. This board also contains a fast VIRTEX FPGA. Software is currently being developed that will allow this FGPA to read out up to 256 resonators in the 105 MHz of bandwidth that the two 105 MS/s A/D converters provide.

4. Results

We have used the system described in Fig. 1 to take data on a aluminum on sapphire CPW MKID resonator. Please see the captions of Figs. 2–4 for more details.

The basic result is that the SDR readout has superior performance to our conventional readout in almost all aspects. It has better noise performance, is much more flexible, and the output data set is easier to interpret since it does not contain many of the features inherent in an analog system, like phase imbalance between the I and Q sides in the IQ mixer, frequency-dependent DC offsets in the IQ mixer, etc.

It will be possible to extend this readout technique to a multi-GHz bandwidth by constructing a microwave system that will slice the multi-GHz bandwidth of the HEMT amplifier into 50 MHz blocks, which then down convert these blocks to baseband for digitization. With a very reasonable resonance spacing of 2 MHz, this means that a single HEMT amplifier with a 4–12 GHz bandwidth could read out 4000 resonators through a pair of coaxial cables. Using optical/UV/X-ray strip detectors with their inherent multiplexing means a 64 kilopixel array could be read out through a pair of coaxial cables.

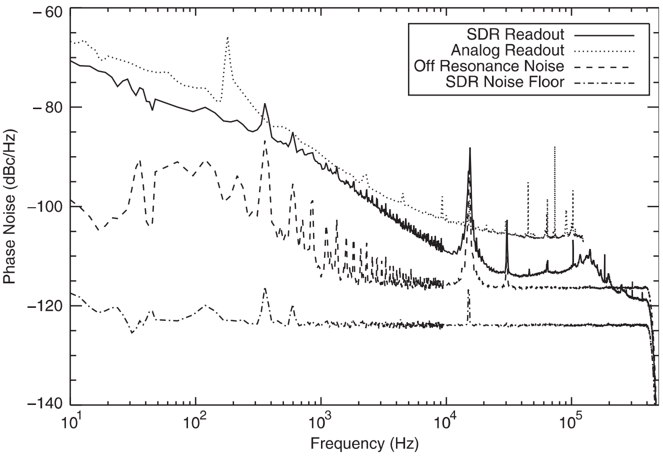

Fig. 2. Measured phase noise of a $Q\sim20,000$ aluminum on sapphire resonator. The top two curves show that we get similar noise from our analog and digital readouts, with the digital readout having slightly better performance at high offset frequencies. The off resonance noise curve shows the performance limit of the digital readout at this power level. The noise floor is the best the digital readout can do if all other components were noiseless.

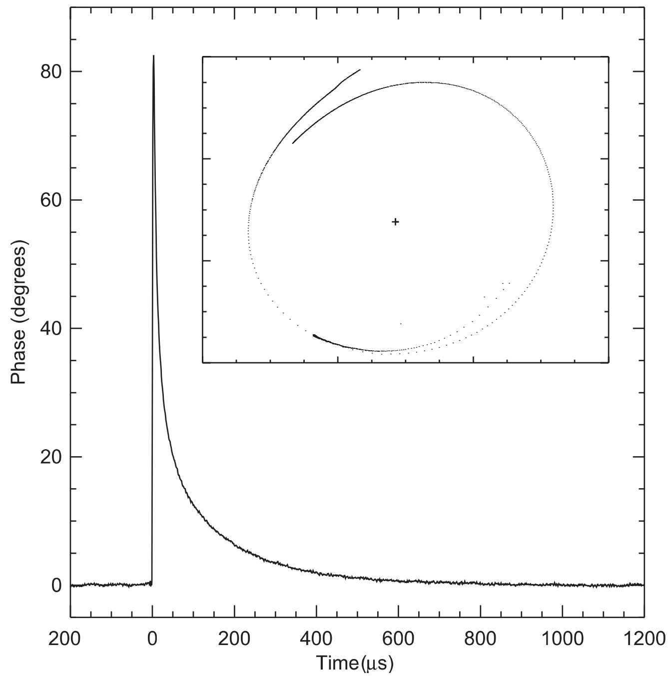

Fig. 3. A single 6 keV X-ray pulse read out with the digital readout. The inset shows the actual IQ trajectory of the X-ray pulse. The sample rate is 1 MS/s.

5. Conclusions

This data set shows that a SDR solution is an excellent candidate for extremely large array readouts. It has excellent noise performance, often exceeding the capabilities of a fully analog system, and is very simple to implement and scale up to a very large number of channels.

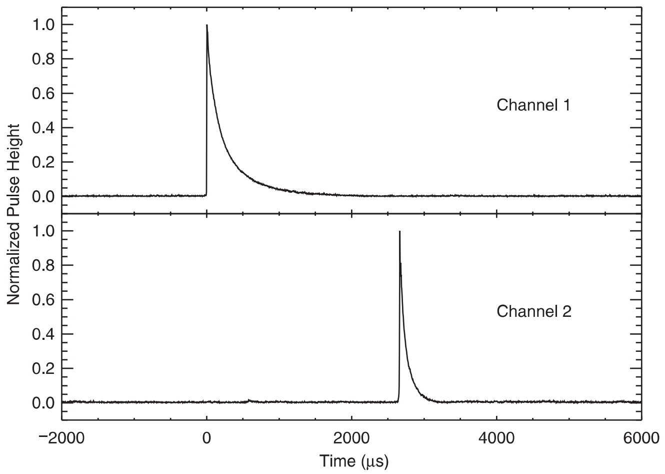

Fig. 4. Nearly simultaneous X-ray events observed on two different resonators with the digital readout. This plot shows that there is essentially no crosstalk between resonators spaced 14.2 MHz apart.

As the digital components continue to improve—a 2 GHz 10 bit A/D from Atmel has just been introduced to the market—this readout technique's utility will increase. We plan to base all our future large MKID readouts on this technology.

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