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Preliminary Assessment of Microwave Readout Multiplexing Factor
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1. Introduction

Ultra-high resolution microcalorimeter gamma spectroscopy is a new non-destructive assay technology for measurement of plutonium isotopic composition, with the potential to reduce total measurement uncertainty to a level competitive with destructive analysis methods [1-4]. Achieving this level of performance in practical applications requires not only the energy resolution now routinely achieved with transition-edge sensor microcalorimeter arrays (an order of magnitude better than for germanium detectors) but also high throughput. Microcalorimeter gamma spectrometers have not yet achieved detection efficiency and count rate capability that is comparable to germanium detectors, largely because of limits from existing readout technology.

Microcalorimeter detectors must be operated at low temperature to achieve their exceptional energy resolution. Although the typical 100 mK operating temperatures can be achieved with reliable, cryogen-free systems, the cryogenic complexity and heat load from individual readout channels for large sensor arrays is prohibitive. Multiplexing is required for practical systems. The most mature multiplexing technology at present is time-division multiplexing (TDM) [3, 5-6]. In TDM, the sensor outputs are switched by applying bias current to one SQUID amplifier at a time. Transition-edge sensor (TES) microcalorimeter arrays as large as 256 pixels have been developed for X-ray and gamma-ray spectroscopy using TDM technology. Due to bandwidth limits and noise scaling, TDM is limited to a maximum multiplexing factor of approximately 32-40 sensors on one readout line [8]. Increasing the size of microcalorimeter arrays above the kilopixel scale, required to match the throughput of germanium detectors, requires the development of a new readout technology with a much higher multiplexing factor.

2. Microwave Readout

The most promising readout technology to enable kilopixel TES arrays is microwave frequency-division multiplexing [7-9]. It was originally developed for microwave kinetic inductance detectors, a type of low-temperature detector used for sensing single photons in the ultraviolet to near-infrared range [10]. Microwave multiplexing is now being applied to TES microcalorimeters, and has been shown to overcome important limits of existing readout technologies. It is based on the same principles as broadcast radio or television. Fig. 1 shows a schematic of the basic elements for microwave multiplexing. Each microcalorimeter sensor modulates a unique sine wave carrier, and can be read by "tuning in" to that specific frequency. In response to incident energy, the TES resistance changes. The corresponding current change through the TES modulates the microwave transmission of its resonator through the action of an RF SQUID. If the resonators have distinct and well-spaced resonant frequencies, many sensors can be connected to a single microwave feed line and continuously measured by a set of sinusoidal probe tones. Compared to TDM readout, cryogenic components for microwave multiplexing are relatively simple. Instead, complexity is moved outside the cryostat, where it is possible to leverage high-bandwidth commercial components and implement many functions using software-defined radio methods.

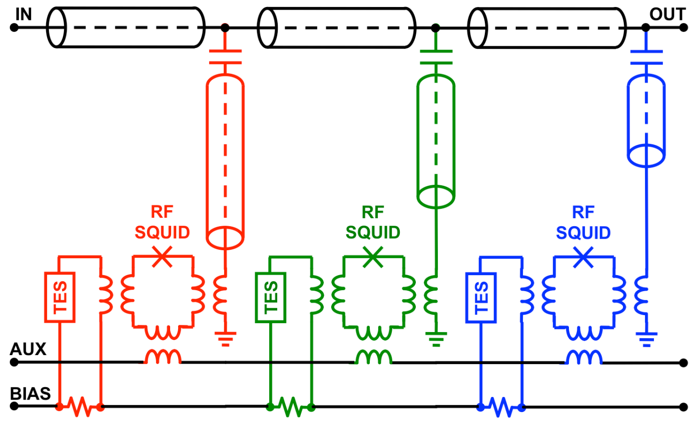

Fig. 1: Basic elements of microwave frequency division multiplexed TES readout.

3. Implementation, present limits, and scalability

Figure 2 shows an early two-channel demonstration of microwave frequency division multiplexed readout of transition-edge sensors, and is useful to illustrate a complete readout system [7]. Many functions can now be implemented with highly scalable software-defined radio methods, discussed later in this section. Two sinusoidal microwave probe tones are produced by signal generators labeled "μw source". These tones are summed ("Σ") and sent to the input of the microwave feedline in the detector package, which is outlined in blue. At equilibrium, the resonator frequencies are matched to the probe tone frequencies, and so each resonator acts as a short to ground. Energy deposited by gamma rays is detected by changes in the TES resistance, which modulates current ("I_{TES}") in the TES bias cell. An RF SQUID (drawn in purple) acts as a flux-variable inductor that modulates the resonator transmission in proportion to the TES signal. The responses of all RF-SQUIDs are linearized by a flux modulation line drawn in green [11]. The change in resonator transmission corresponds to an increase in power transmitted through the feedline for the corresponding probe tone. A cryogenic high electron-mobility transistor ("HEMT") amplifies the transmitted microwave signals. IQ mixers are used to monitor the in-phase and out-of-phase signal components ("V_I" and "V_Q") corresponding to each modulated probe tone, thus allowing reconstruction of the TES responses.

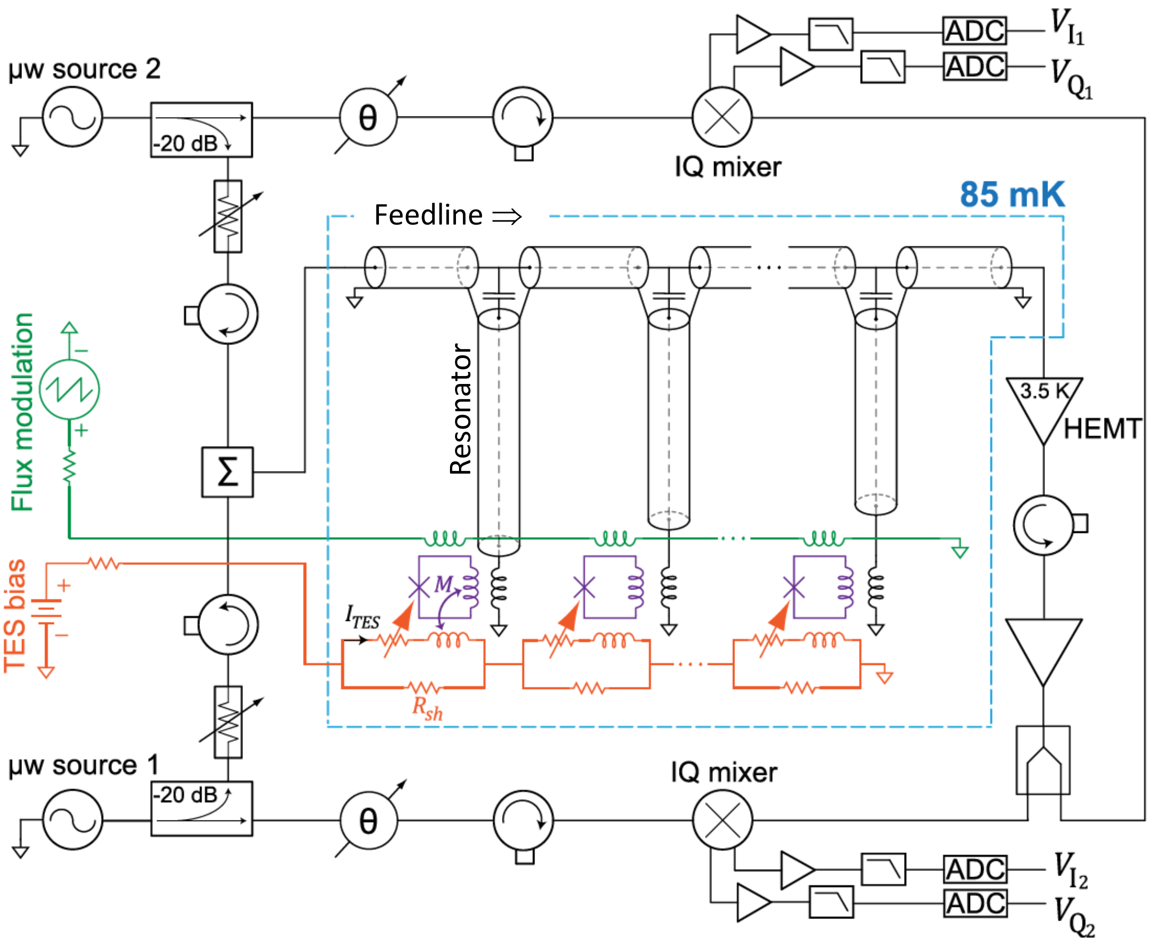

Fig. 2: Two-channel demonstration of a complete microwave frequency division multiplexed TES readout system using discrete microwave components [7].

To achieve 0.1% statistical error for measurement of plutonium isotopic composition, a microcalorimeter gamma spectrum requires 10^6 counts in the energy peaks of interest and approximately 10^8 total counts. Currently, TES microcalorimeters can provide single-pixel count rates of 50 cps. A 1,000-pixel array would then provide a total count rate of 50 kcps, and the ability to acquire 10^8 total counts in 33 minutes. A per-pixel readout bandwidth of 300 kHz would enable adequate sampling of the detector pulses. Readout noise must be below approximately 40 pA/√Hz so that it does not degrade energy resolution.

Resonator and RF SQUID chips have now been made (Fig. 3) that meet these key requirements. Resonator bandwidth of 300-500 kHz is achievable (Fig. 4) [12]. Readout noise levels as low as 17 pA/√Hz have been measured, which is far below the TES noise level (Fig. 5) [8]. Resonator center frequency spacing of 6 MHz appears to be practical with current fabrication processes, and 128 resonators have been demonstrated in 1 GHz of bandwidth with > 90% yield (Fig. 6). The bandwidth available on each cryogenic microwave feedline is set by the HEMT amplifier, which operates from 4-8 GHz. Therefore, a multiplexing factor inside the cryostat of 600:1 should be achievable with current technology. As fabrication processes are refined, yield will increase, and resonator spacing could be reduced to as low as 3 MHz. This is expected to enable multiplexing factors over 1000:1.

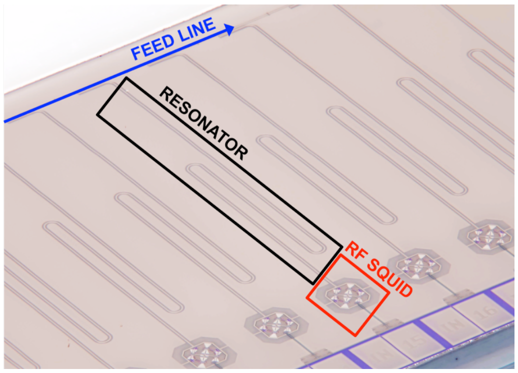

Fig. 3: Microwave feedline, resonators, and RF SQUIDs are fabricated on a single chip that is wire bonded to the TES array.

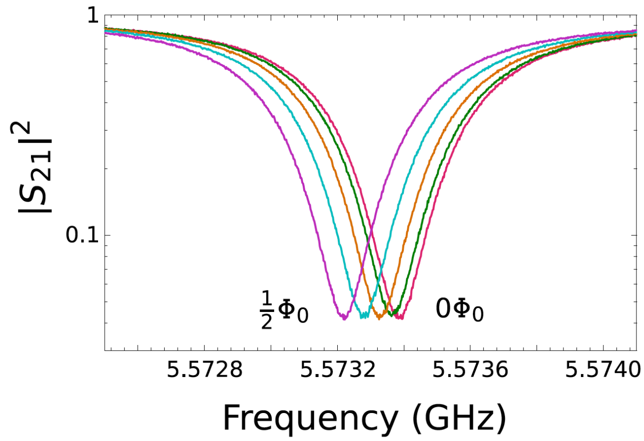

Fig. 4: Typical resonator bandwidth and response to RF SQUID flux.

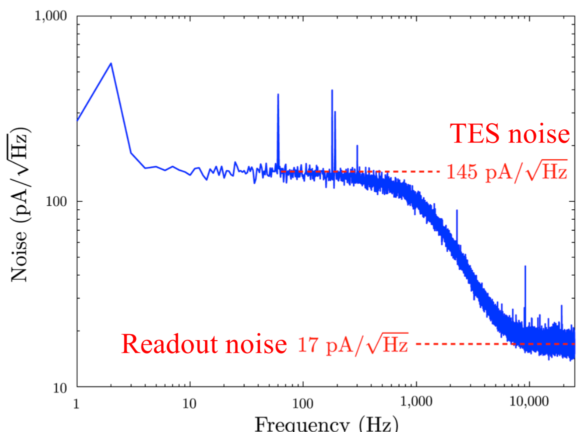

Fig. 5: Readout noise as low as 17 pA/√Hz has been demonstrated, which is far below the TES noise level [8].

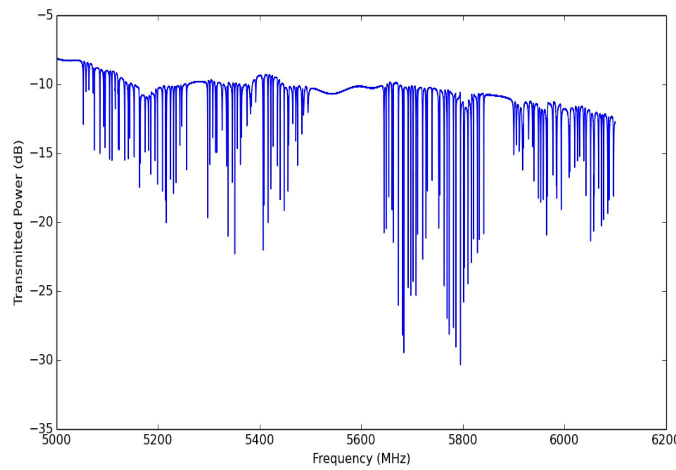

Fig. 6: 128 resonators have been demonstrated in a ~1 GHz band. Cryogenic bandwidth of 4 GHz is available with commercial HEMT amplifiers.

A key enabling technology for large-scale microwave multiplexing is software-defined radio (SDR). Digital processing replaces analog components to implement many function of microwave-frequency communications. The power and flexibility of SDR is ideally suited for the challenge of microwave multiplexed readout for large microcalorimeter arrays. High-speed digital to analog converters and analog-to-digital converters enable the generation and sampling of probe tones. Digital signal processing algorithms on a field-programmable gate array (FPGA) can synthesize probe tones and reconstruct individual sensor signals. A set of open-source electronics based on the Xilinx Virtex-6 FPGA have been developed by a collaboration of research groups to perform SDR for microwave frequency division multiplexers [13].

An implementation of SDR for microwave readout of a TES array is shown in Fig. 7. Much of the complexity is implemented in FPGA firmware, which is key to enabling readout at the kilopixel scale. A set of sinusoidal probe tones is calculated by the FPGA ("DDS"), generated by a digital-to-analog converter ("DAC"), then mixed up to GHz frequencies on the Discrete IF board. The tones are sent through the cryogenic feedline in the detector package, and the modulated tones are mixed down to baseband on the Discrete IF board and measured by an analog-to-digital converter ("ADC"). The FPGA firmware then reconstructs each sensor response from the modulated tones ("DDC", etc.) by extracting the amplitude and phase at each resonator frequency and deconvolving the flux ramp modulation. Data is transferred to a separate computer via Ethernet and processed to generate an energy spectrum. The FPGA firmware illustrated in Fig. 7 is an early version that uses a relatively simple channelization method. This firmware allowed initial testing of 32 channel microwave readout, and used approximately 14% of the Virtex-6 resources. Recently, a much more efficient firmware has been developed that uses a polyphase filter bank instead of direct digital synthesis and downconversion. The most recent firmware is capable of reading out 128 channels using only 9% of the Virtex-6 resources [14]. This suggests that reading out a kilopixel array on a single microwave feedline will be possible.

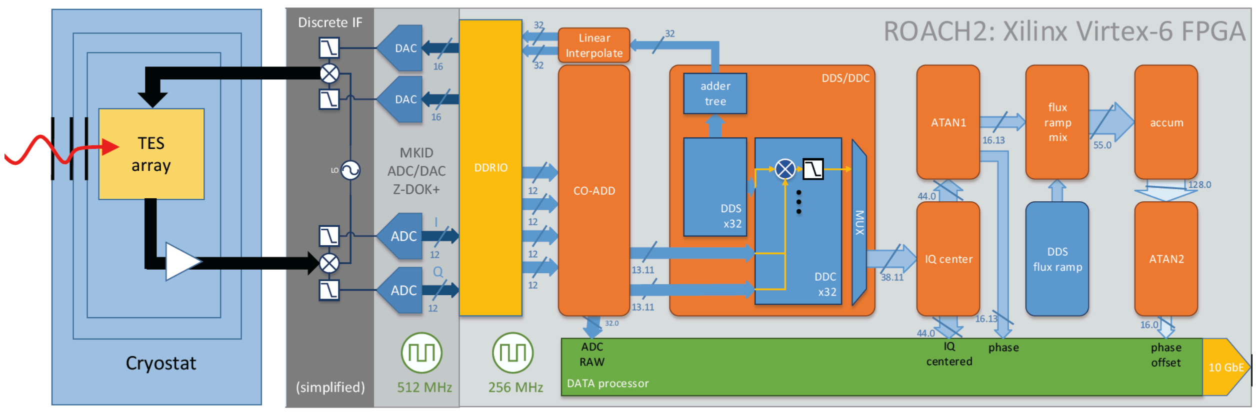

Fig. 7: Microwave readout using software-defined radio methods is highly scalable, because many functions are implemented in FPGA firmware.

4. Summary

Ultra-high resolution microcalorimeter gamma spectroscopy has the potential to close the uncertainty gap between non-destructive assay and destructive analysis methods for plutonium isotopic composition. Achieving this performance in practical applications requires increasing microcalorimeter spectrometer throughput to be comparable with germanium detectors. This can be achieved by scaling up to kilopixel arrays with increased detection efficiency and count rate capability. Microwave frequency-division multiplexing is the most promising technology for readout of kilopixel-scale arrays, and has been demonstrated to overcome important limits of existing methods. At the present time, cryogenic multiplexing factors as high as 600:1 appear to be practical using microwave readout. With improved resonator fabrication processes, multiplexing factors over 1000:1 are expected. Software-defined radio methods for generating microwave probe tones and demodulating sensor signals have recently been demonstrated with 128 channels and can be expected to operate at the 1000-channel scale in the near future.

5. References

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