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Expanding the Capability of Microwave Multiplexed Readout for Fast Signals in Microcalorimeters

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Abstract

Microwave SQUID multiplexing has become a key technology for reading out large arrays of X-ray and gamma-ray microcalorimeters with mux factors of 100 or more. The desire for fast X-ray pulses that accommodate photon counting rates of hundreds or thousands of counts per second per sensor drives system design toward high sensor current slew rate. Typically, readout of high current slew rate events is accomplished by increasing the sampling rate, such that rates of order 1 MHz may be necessary for some experiments. In our microwave multiplexed readout scheme, the effective sampling rate is set by the frequency of the flux-ramp modulation (f_r) used to linearize the SQUID response. The maximum current slew rate between samples is then nominally $\Phi_0 f_r / 2M_{in}$ (where M_{in} is the input coupling) because it is generally not possible to distinguish phase shifts of $> \pi$ from negative phase shifts of $< -\pi$. However, during a pulse, we know which direction the current ought to be slewing, and this makes it possible to reconstruct a pulse where the magnitude of the phase shift between samples is $> \pi$. We describe a practical algorithm to identify and reconstruct pulses that exceed this nominal slew rate limit on the rising edge. Using pulses produced by X-ray transition-edge sensors, we find that the pulse reconstruction has a negligible impact on energy resolution compared to arrival time effects induced by under-sampling the rising edge. This technique can increase the effective slew rate limit by more than a factor of two, thereby either reducing the resonator bandwidth required or extending the energy range of measurable photons. The extra margin could also be used to improve crosstalk or to decrease readout noise.

Keywords Microwave SQUID multiplexing · Transition-edge sensors · Flux-ramp modulation

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1 Introduction

Microwave superconducting quantum interference device (SQUID) multiplexing has proven to be a successful and scalable technology for the readout of large arrays of cryogenic microcalorimeters. In microwave SQUID multiplexing, rf-SQUIDs are inductively coupled to cryogenic sensors to modulate the frequency of high-Q microwave resonators. The resonators are coupled to a common feedline with each resonator tuned to a different frequency. A superposition of microwave tones, one for each resonator, can measure all sensors simultaneously. Readout of 128 gamma-ray transition-edge sensor (TES) microcalorimeters on a single pair of coaxial cables has been demonstrated [1], and current technology provides a clear path toward scaling to upwards of 500 sensors per pair of coaxial cables [2].

The number of detectors that can be multiplexed is limited by the available readout bandwidth. The bandwidth of each resonator limits the sampling rate for the detector signals. In our implementation of microwave SQUID multiplexing, the SQUID response is linearized via flux-ramp modulation [3]. Each ramp period provides a single measurement of the detector signal, so the effective sampling rate is equal to the flux-ramp rate. The maximum flux-ramp frequency is generally limited to half the resonator bandwidth. The resonant frequencies must be spaced sufficiently far apart relative to the resonator bandwidth to avoid unacceptable levels of crosstalk between frequency neighbors [4]. Low-noise, high-bandwidth cryogenic HEMT amplifiers are commonly used to transmit signals from the cold resonators to room-temperature electronics. These amplifiers typically provide a few GHz of total bandwidth, which then limits the total number of resonators. Therefore, there is a trade-off between the total number of resonators that can be placed on a single feedline and the bandwidth of each individual resonator, which must allow a high enough sampling rate to read out the fast-slewing signals produced by X-ray and gamma-ray pulses. Future experiments like the LCLS-II soft X-ray spectrometer [5] and the LYNX X-ray microcalorimeter [2,6] are expected to require sampling rates of 1 MHz or faster in order to meet count rate, mux factor, and X-ray energy range requirements.

The sampling rate required to read out a pulse is set, in part, by the maximum current slew rate between successive samples. The flux-ramp demodulation algorithm must identify phase shifts of the flux-ramp response caused by the detector signal between one ramp period and the next. For an unknown signal, it is not possible to distinguish a phase shift of more than π from a negative phase shift of less than $-\pi$. Therefore, the maximum signal slew rate between samples for accurate signal demodulation is nominally $\Phi_0 f_\mathrm{r}/2M_\mathrm{in}$ A/s, where Φ_0 is the magnetic flux quantum, f_r is the flux-ramp frequency, and M_in is the SQUID input coupling strength. However, during a pulse, we know which direction the current ought to be slewing, which breaks the degeneracy between phase shifts of $> \pi$ and $< -\pi$. By treating the flux-ramp modulation response as linear, that is, assuming that the demodulated value reported is correct modulo 2π, we can accurately reconstruct pulses. In the subsequent sections, we describe a simple algorithm for identifying and correctly demodulating pulse events that exceed the nominal slew rate limit. We demonstrate this algorithm using X-ray TESs with maximum slew rates that exceed the nominal limit by up to a factor of 2.7

and show that pulse reconstruction does not appear to significantly degrade the energy resolution of the TES.

2 Biased Unwrapping

The flux-ramp demodulation algorithm extracts the phase shift that occurred during each ramp period, so each sample passed from firmware to the data collection software contains a normalized value representing a phase shift between $-\pi$ and π. Since a typical pulse will traverse more than 2π (more than one Φ_0), the data are unwrapped before being sent to the client that collects and stores pulse data. If consecutive samples differ by more than π, we subtract 2π, and if they differ by less than $-\pi$, we add 2π. During a typical pulse, the rising edge slew rate is greater than the falling edge slew rate. Therefore, we know that largest sample-to-sample differences we observe must be occurring on the rising edge of a pulse, as long as the pulses all have the same polarity. Then, we can bias the unwrapping algorithm to correctly reconstruct these pulses. If the ratio of the falling edge to rising edge slew rates is equal to X, then we can bias the range such that differences of $< -X\pi$ are corrected by 2π, and $> 2(1 - X/2)\pi$ by -2π (or vice versa, depending on the direction of pulses). This effectively changes the slew rate limit from $\Phi_0 f_r/2M_{in}$ to $(1 - X/2)\Phi_0 f_r/M_{in}$.

Biasing the unwrapping algorithm relies on the assumption that high current slew rates only occur in one direction. However, this may not always be the case. In, for example, a hybrid code-division/microwave SQUID multiplexed readout scheme [7] where multiple sensors may be coupled to the same resonator with different coupling polarities, the fast rising edges of the pulses would be both upward and downward going. As another example, if the sensors are AC biased, signals will also slew rapidly in both directions. In these cases, biasing the unwrapping algorithm is not useful.

3 Correction Using Pulse Records

If the current slew rate during a pulse produces phase shifts between samples that are $>2\pi$, biasing the unwrapping algorithm is not sufficient to correctly reconstruct the event. Furthermore, if the slew rate on the falling edge is a significant fraction of $\Phi_0 f_r/2M_{in}$, biasing may cause unwrapping errors on the falling edge. However, pulses that produce phase shifts in excess of 2π between samples on the rising edge can still be recovered by using the recorded pulse data.

The first step is to identify events where the demodulation algorithm has failed. In this work, we assume that the slew rate on the falling edge of a pulse never exceeds the nominal $\Phi_0 f_r/2M_{in}$ limit. Then, demodulation may fail on one or more samples on the rising edge, but the algorithm will successfully track the entire falling edge. In this case, when the sensor returns to quiescence following the pulse, the equilibrium level will be one (or more) Φ_0 lower than the pre-trigger baseline (see Fig. 1). To identify such events, we compared the mean pre-trigger level to the last sample of the record. If the last sample was less than the pre-trigger level by more than $\Phi_0/2$, then the event was categorized as needing correction. This threshold was chosen because although

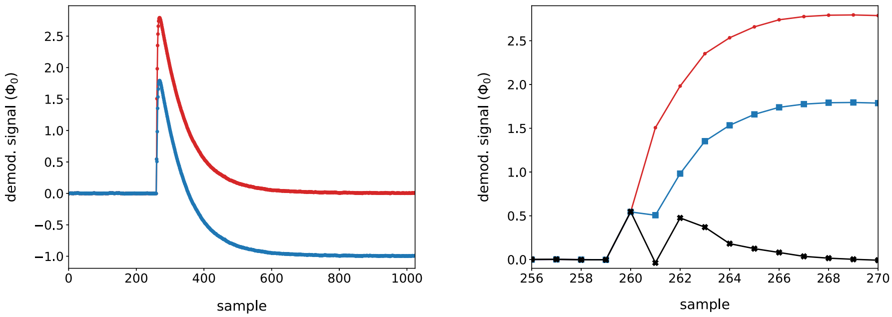

Fig. 1 *Left* The blue trace shows an Al Kα (1.49 keV) X-ray event measured by a TES optimized for soft X-ray energies. The event exceeds the nominal slew rate limit, causing a phase shift of more than π between samples and resulting in a demodulation error. The red trace has been corrected using the method described in Sect. 3. *Right* The blue trace shows the leading edge of the un-corrected pulse from the left-hand plot. The black trace is the difference between sample n and sample n-1, which should decrease monotonically after the trigger sample (260) until the peak. Therefore, sample 261 is identified as the location of the demodulation error, and 1 Φ_0 is added to this and all subsequent samples to produce the red (corrected) trace (Color figure online)

the new quiescent level should be exactly one Φ_0 lower, based on our assumption that the flux-ramp modulation response is linear, for shorter record lengths the sensor may not have completely returned to the quiescent state by the last sample. Therefore, the threshold for event identification should be $< 1\ \Phi_0$ but much larger than the noise.

Having identified the events where the demodulation algorithm failed, the next step is to identify which samples in the record require correction. By limiting ourselves to cases where the demodulation algorithm tracks the falling edge, we can limit our attention to samples on the rising edge of the pulse, which reduces the amount of computation required. To correct the events, we assume that the slew rate is highest at the start of a pulse and decreases as the pulse approaches the peak. For the samples between the trigger and the pulse peak, we compute the difference between subsequent samples. The difference should be largest immediately following the trigger and then decrease monotonically until the peak. If this is not the case, then the demodulation algorithm must have failed between those samples (see Fig. 1). If the difference between post-trigger samples is monotonically decreasing but the difference between pre- and post-trigger quiescent levels indicates that an error has occurred, then we assume that the error occurred on the triggering sample. This was a good assumption for our X-ray TES data, but it may not be true in all cases; for example, piled up pulse events in high rate experiments may violate the assumption that the slew rate decreases monotonically on the rising edge, causing demodulation errors that may not be appropriately corrected by this simple algorithm. Once the sample that requires correction is identified, applying the correction is accomplished by adding 1 Φ_0 to that sample and every subsequent sample in the record.

If the slew rate is very high, multiple samples may exceed the nominal limit and require correction. It is also possible that the phase shift between samples could exceed 4π, which means that two or more Φ_0 must be added. In these cases, an iterative process can be used to correct the data. The difference between pre- and post-trigger levels indicates how many Φ_0 must be added to correct the event. Then, working backward from the pulse peak, samples can be corrected by 1 Φ_0 until the corrected data conform to the assumption that the slew rate is monotonically decreasing and the appropriate number of Φ_0 has been added.

4 Demonstration with X-Ray TES Data

To demonstrate that high-slew-rate events can be reconstructed without degrading energy resolution, we used a Mo/Au bilayer transition-edge sensor (TES) designed for detection of X-rays up to energies around 5 keV to measure the spectrum of titanium Kα X-rays (4.51 keV). The X-rays were produced using a commercial X-ray tube to fluoresce a titanium target. The sensor was read out using a microwave SQUID multiplexer chip with 2 MHz bandwidth per resonator. Flux-ramp modulation was used to linearize the SQUID signal. Nominally, the flux-ramp frequency f_r is limited to half the resonator bandwidth. However, the sharp falling edge of the sawtooth wave used to provide the flux ramp creates a brief transient signal that distorts the shape of the SQUID modulation. Therefore, we typically set the amplitude of the flux ramp to sweep out $2\Phi_0$ per ramp period, using the second modulation period to fit and extract the phase signal. This limits f_r to 1/4 the resonator bandwidth, or 500 kHz for the multiplexer chip used in this work.

At $f_r = 500$ kHz, the maximum possible sampling rate, the average maximum slew rate of pulses produced by Ti Kα X-rays was 0.44 Φ_0/sample. This was less than the nominal slew rate limit of $\Phi_0/2$, so no correction was needed. We found the energy resolution of the detector was 2.99 ± 0.13 eV FWHM (see Fig. 2). Next, the sampling rate was reduced to 250 kHz, and the average maximum slew rate of Ti Kα X-rays was 0.8 Φ_0/sample. These events could be corrected using the biased unwrapping method described in Sect. 2. The resolution was not degraded: 2.85 ± 0.11 eV FWHM. At 125 kHz, the average maximum slew rate is 1.36 Φ_0/sample, a phase shift of greater than 2π. The detector resolution was 3.73 ± 0.17 eV. However, the degradation in resolution can be accounted for by the effects of under-sampling the rising edge of the pulse. As the sampling rate is reduced, the measured pulse height becomes dependent on the subsample arrival time of the pulse. This effect occurs regardless of readout technology; it has been observed in time- and code-division SQUID multiplexing [8] as well as in the microwave SQUID multiplexer. The exact nature of the correlation will depend on the sensor, readout, and the sampling rate. We use an entropy-minimizing correction to account for pulse height/arrival time correlation [8], but as there are fewer and fewer samples on the rising edge, the structure of the correlation becomes more complex and the correction becomes less effective. To verify that this effect accounts for the degradation we observed when sampling at low rates, we downsampled the pulse records taken at 500 KHz and then re-processed them to produce X-ray spectra. At 250 kHz (downsampled), the resolution was 3.05 ± 0.13 eV. But, at 125 kHz (downsampled), it worsens to 3.46 ± 0.15 eV. This suggests that at 125 kHz the sampling rate is not high enough to capture the shape of the pulse with the accuracy needed for the best possible spectral resolution, and demonstrates that the contribution of demodulation correction to the degradation of the energy resolution is minimal.

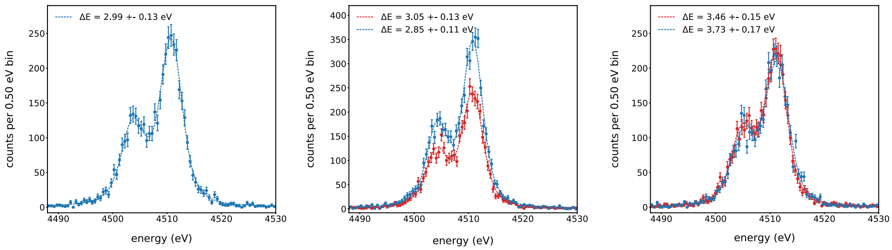

Fig. 2 Energy spectra of Ti Kα X-ray emission recorded at 500 kHz, 250 kHz, and 125 kHz sampling rates. Each data set was acquired at the same incident photon rate, although the length of data collection varied between data sets. The dashed lines show fits to the intrinsic line shape of the Ti Kα complex with a Gaussian component for broadening due to the detector resolution. *Left* At 500 kHz sampling rate, where the maximum per pulse slew rate is 0.44 Φ_0/sample, the detector resolution is 2.99 $\pm$ 0.13 eV FWHM. *Center* At a 250 kHz sampling rate (blue data), where the maximum per pulse slew rate is 0.8 Φ_0/sample, detector resolution is 2.85 $\pm$ 0.11 eV FWHM. Downsampling the 500 kHz pulse records to 250 kHz (red data) and then re-analyzing the data yield similar resolution: 3.05 $\pm$ 0.13 eV. *Right* At 125 kHz sampling rate (blue data), where the maximum per pulse slew rate is 1.36 Φ_0/sample, detector resolution is 3.73 $\pm$ 0.17 eV FWHM. Downsampling the 500 kHz data to 125 kHz (red data) yields energy resolution of 3.46 $\pm$ 0.15 eV, suggesting that demodulation correction is not responsible for much, if any, of the degradation (Color figure online)

5 Conclusion

We have shown that pulse events read out by a microwave SQUID multiplexer that exceed the nominal input current slew rate limit of $\Phi_0 f_r/2M_{\text{in}}$ by more than a factor of two can still be accurately demodulated. The techniques described require that the slew rate on the falling edge of the pulse does not exceed the nominal limit. In this case, two simple techniques can be used to identify and correct pulse events that exceed the nominal limit on the rising edge without degrading the energy resolution. Biased unwrapping works for sample-to-sample phase shifts up to $2|\pi|$ (slew rates up to $\Phi_0 f_r/M_{\text{in}}$). We have implemented this correction to work in real time, so no post-processing is needed. We also described a simple algorithm to identify and correct pulse records where the sample-to-sample phase shift exceeds 2π. This algorithm assumes that the highest slew rate occurs at the beginning of the pulse, and that the slew rate decreases monotonically until the pulse peak. This is generally a good assumption for TES microcalorimeter data. Although this correction was made offline in software, in principle the computations are simple enough to implement in real-time data collection. We have shown un-degraded resolution of TES pulses for slew rates exceeding $\Phi_0 f_r/M_{\text{in}}$. Eventually, as the sampling on the rising edge of the pulse becomes too sparse, correlations between pulse height and arrival time begin to degrade the energy resolution. Although this effect is not caused by slew rates in excess of the nominal limit, it becomes increasingly important as the sampling rate approaches the time constant of the rising edge, and so must be taken into consideration when choosing the sampling rate.

The extra slew rate margin provided by this technique could be used in several different ways because the sample-to-sample slew rate in the final readout configuration depends on the detector, the sampling rate (and consequently the resonator bandwidth), and the SQUID input coupling. For example, (i) since higher energy pulses tend to have higher slew rates, the energy range that can be read out could be extended without any change to the multiplexing setup. (ii) By using a slower sampling rate, the resonator bandwidth could be reduced. This allows the inter-resonance spacing to be reduced, enabling more sensors to be multiplexed per pair of readout cables. (iii) The spacing between resonances can be kept fixed as their bandwidth is reduced, which improves crosstalk between frequency neighbors. (iv) The strength of the SQUID input coupling could be increased, which decreases the SQUID noise level as referred to the detectors. As future experiments require larger sensor arrays and higher count rates, a higher slew rate budget will allow for less complex, less expensive microwave SQUID readout.

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