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High density processing electronics for superconducting tunnel junction x-ray detector arrays

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ABSTRACT

Superconducting tunnel junctions (STJs) are excellent soft x-ray (100–2000 eV) detectors, particularly for synchrotron applications, because of their ability to obtain energy resolutions below 10 eV at count rates approaching 10 kcps. In order to achieve useful solid detection angles with these very small detectors, they are typically deployed in large arrays – currently with 100+ elements, but with 1000 elements being contemplated. In this paper we review a 5-year effort to develop compact, computer controlled low-noise processing electronics for STJ detector arrays, focusing on the major issues encountered and our solutions to them. Of particular interest are our preamplifier design, which can set the STJ operating points under computer control and achieve 2.7 eV energy resolution; our low noise power supply, which produces only 2 nV/$\sqrt{\text{Hz}}$ noise at the preamplifier's critical cascode node; our digital processing card that digitizes and digitally processes 32 channels; and an STJ *I–V* curve scanning algorithm that computes noise as a function of offset voltage, allowing an optimum operating point to be easily selected. With 32 preamplifiers laid out on a custom 3U EuroCard, and the 32 channel digital card in a 3U PXI card format, electronics for a 128 channel array occupy only two small chassis, each the size of a National Instruments 5-slot PXI crate, and allow full array control with simple extensions of existing beam line data collection packages.

1. Introduction

Superconducting tunnel junctions (STJs) are being developed as x-ray detectors in the 100–2000 eV range for synchrotron applications because of their demonstrated capability for obtaining energy resolutions below 10 eV at count rates approaching 10 kcps [1–3]. Detector sizes, however, are restricted to dimensions of approximately 250 μm by 250 μm or less by the presence of Fiske mode resonances in their *I–V* curves, which become too closely spaced at larger dimensions to allow an acceptable bias point to be found [4]. Therefore, to achieve good detection efficiencies, they are generally deployed in arrays to achieve larger solid detection angles. Arrays of 100+ elements have been produced and arrays of 1000+ elements are being contemplated [5–7]. Experience with smaller arrays, of up to 32 elements, which mimics the experience with similar sized HPGe detector arrays 25 years ago [8], makes it clear that instrumenting these arrays using multiple copies of single channel processing electronics causes unacceptable operational difficulties for array sizes much in excess of 30 detectors. Achieving the promise of STJ detectors therefore requires the development of processing electronics that can place detector setup, calibration, and data collection under computer control. This essentially replicates the history of producing digital data systems for HPGe detectors, except at much higher channel counts, with more stringent limitations on energy resolution, and for a detector type that requires a significantly more complex procedure to set its operating bias.

We have recently completed a 5-year effort to develop compact, computer controlled, low-noise processing electronics for STJ detector arrays that preserve the detectors' inherent energy resolution, make their use accessible to non-specialists, and interface with only minor modifications to the various data collection packages found at synchrotron beam lines. In the following sections we focus on the major issues and developments in the project as follows: Section 2: our preamplifier design, which sets STJ operating points under computer control and achieves ~2 eV energy resolution; Section 3: a novel method for identifying Fiske modes that allows automated bias point setting; Section 4: an ultra-low noise power supply that delivers 16 V to the preamplifier's critical cascode circuit with only 2 nV/$\sqrt{\text{Hz}}$ noise; Section 5: the system preamplifier and digital processing cards; Section 6: control software; Section 7: system performance showing 2.7 eV resolution at 250 eV and conclusions.

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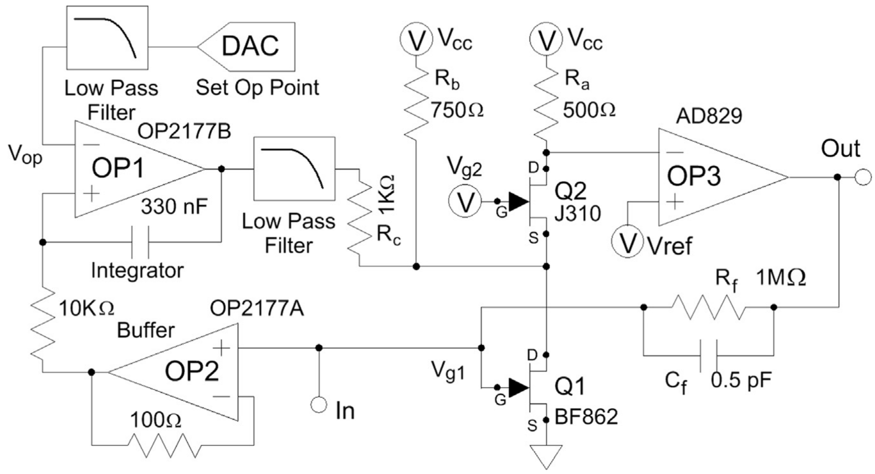

Fig. 1. Schematic of a single preamplifier channel.

2. Preamplifier design

A preamplifier optimized for STJ operation has several unusual requirements. First, it should be a transimpedance amplifier with a low input impedance at dc, since the STJ must be biased stably between Fiske mode resonances. Second, the preamplifier must be stable despite the STJ's relatively low dynamic resistance of ~1–10 kΩ and its relatively high capacitance of several nF. Third, STJ detectors are biased at a few hundred microVolts, but their bias points need to be individually determined and then held stably and reproducibly at the level of 1 μV. For large arrays it is also a necessity that the bias determination process be computer controlled. Fourth, as the detectors output currents of order 100 nA/keV of x-ray energy and are capable of energy resolutions of a few eV, the preamplifier's input referred noise should be 1 nV/$\sqrt{\text{Hz}}$ or less. Finally, the design should allow high density, relatively low cost scaling to large array sizes.

Fig. 1 shows a simplified schematic of our preamplifier design which adds ideas from Fabris et al. [9] to an earlier design by Friedrich et al. [10]. It's overall operations are as a two stage amplifier (the 1st stage being the Q2–Q3 cascode, the 2nd stage being OP3) with a feedback network comprising R_f and C_f. Changes in the STJ detector's current when it absorbs an x-ray are supplied through the 1 MΩ feedback resistor R_f, for an output of ~0.1 V/keV. C_f stabilizes the feedback loop against the STJ detector's 2 nF capacitance.

In the Q1–Q2 FET cascode, the input transistor Q1 is the inexpensive, fairly high gain ($g_m=40$), and very low noise (0.8 nV/$\sqrt{\text{Hz}}$) BF862, which is operated close to its I_{DSS} value, with the current being supplied through 3 resistor legs—R_a, R_b, and R_c. The value of R_a is set by the desired first stage gain $G_1=g_mR_a$, where g_m is transistor Q1's transimpedance. With the voltage at Q1's drain set by V_{g2} minus the gate–source voltage drop of Q2, R_b is chosen to supply the remainder of Q1's nominal 14 mA I_{DSS}. The current difference between this nominal value and Q1's true I_{DSS} value, which varies on a part-by-part basis, is supplied through R_c.

A novel feature of the circuit is that the detector's bias point, which is in the microvolt range, is set by adjusting the gate–source voltage V_{g1} of Q1, where V_{g1} is controlled by the amount Q1's drain–source current differs from I_{DSS}, I_{DSS} being the current I_{ds} that flows when V_{g1} is zero. In our design, V_{g1} is set using the OP1–OP2 feedback loop. In this circuit OP2 buffers Q1's gate voltage V_{g1}; OP1 compares that to a filtered DAC output value and integrates the difference, thus changing the current through R_c until V_{g1} matches the set point established by the DAC. Both the DAC voltage and OP1 outputs are heavily low pass filtered (order 1 s time constants), since any noise in the current through R_c appears as attenuated signal noise (see [9] for the analysis). The resulting circuit uses only commercial grade surface mount parts and it thus both inexpensive and very compact, occupying only about 6 cm^2 of board space. Of critical importance, sweeping the DAC voltage across a range of STJ bias voltages allows both the STJ's characteristics to be determined and its bias point determined under full computer control.

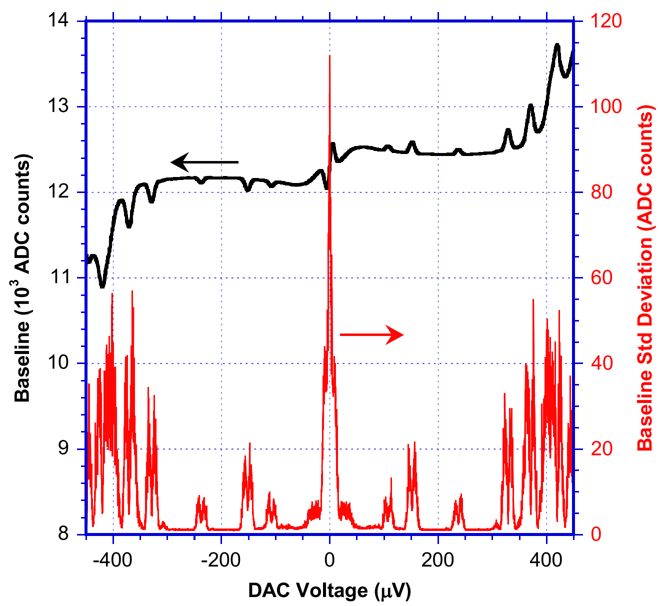

Fig. 2. Scans of STJ current and current noise versus bias voltage.

3. Noise curves for finding Fiske modes

Because the STJ's current is supplied by OP3 through R_f, one can generate I–V curves for the detector by recording V_{out} as a function of V_{DAC}. Fig. 2 shows a typical STJ I–V trace (upper curve) generated this way. The small peaks are Fiske mode resonances in the STJ that are known to degrade energy resolution [11,12]. Because they are small, they are not well suited to machine identification processes of the sort required to automate the bias setting process.

Fiske modes are cavity oscillations in the STJs that increase the electronic noise in the external measuring circuit. See [11] and references therein for details. However, in working with the detectors, we realized that the same increase in electronic noise at a Fiske mode that damages resolution could also be used to identify its presence. Recalling that STJ detector current I_d is just