

## High-sensitivity high-resolution dual-function signal and time digitizer

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(Received 24 October 2001; accepted for publication 18 January 2002)

We have developed a dual-function high sensitivity/high-resolution digitizer. It consists of a superconducting digital integrated circuit, which can operate both as a time-to-digital converter (TDC) and a flux counting analog-to-digital converter (ADC). The TDC has a 30 ps multihit time resolution. The ADC has been designed with a superconducting quantum interference device based detector for a 1  $\mu\text{A}$  full scale range. This digitizer is extremely useful in many applications, e.g., for time-of-flight measurements, or as a radiation resistant, low-noise, low-power ADC for detector readout. © 2002 American Institute of Physics. [DOI: 10.1063/1.1459110]

Our digitizer is based on the rapid single flux quantum (RSFQ) approach of superconductor electronics, which is now undergoing rapid advancement and commercialization in many groups.<sup>1</sup> In RSFQ technology, digital information is stored and manipulated through the propagation of single quanta of magnetic flux. This dual-function digitizer was fabricated at HYPRES using the standard 3  $\mu\text{m}$  1 kA/cm<sup>2</sup> Nb fabrication process.<sup>2</sup> Digital RSFQ circuits based on this 3- $\mu\text{m}$  lithography process have already shown performance of better than 100 GHz. Scaling these chips to a submicron lithography process can further improve performance.<sup>3</sup>

This chip is targeted at two important functions of nuclear and high-energy physics detector instrumentation, analog-to-digital conversion (ADC) and time-to-digital conversion (TDC). Fast, low-power, low-noise, high sensitivity, and radiation resistant electronic instrumentation is essential for readout of detectors in numerous physics experiments. Detector readout instrumentation measures the timing, amplitude, integrated charge, and pulse shape of the detector response. By using traditional readout methods, with semiconductor room-temperature electronics, the information content of low-level, fast signals from a detector is distorted by noise pick up, cross talk in analog transmission lines and amplifier noise. In contrast, RSFQ chips are naturally radiation hard<sup>4</sup> and can thus be placed at the signal source, and through the direct digitization approach, allow preservation of the original signal quality. Conversion of the detector response into digital form also facilitates data acquisition and processing. In the targeted applications, the cryogenic requirements of this digitizer are not an issue as the detectors themselves are already cooled to  $\sim 4$  K or below. Moreover, the front-end requirements for both TDC and ADC applications can easily be adjusted for different detectors and applications.

Previously, we have separately demonstrated both ADCs and TDCs using the RSFQ approach, with performance far superior to conventional electronics.<sup>5</sup> These circuits take advantage of the intrinsic properties—high switching speed, quantum accuracy, dispersion-less transmission lines, radi-

ation hardness, and extremely low power dissipation—of superconductivity. Now these two circuits have been combined to create a single integrated circuit capable of both tasks. The integrated circuit consists of 750 Josephson junctions and fits on a 5 mm $\times$ 5 mm chip, dissipating less than 0.25 mW of power.

The digitizer can be switched from one mode to another via a simple enable switch (Fig. 1), and some simple changes in operational logic. In the TDC mode, we employ the aperiodic counting of a periodic stream of single flux quantum (SFQ) pulses to measure a time difference. In ADC mode, we employ the periodic counting of an aperiodic stream of pulses to measure an absolute charge (flux counting ADC).

Both applications use a common, all-digital counter, capable of measuring multiple counts/events on the same channel. The counter used in the dual-function digitizer consists of a three-hit, 16-bit buffer. A nine-hit version of this counter used in TDC mode has operated at 33 GHz reference clock frequency<sup>6</sup> (30 ps multihit time resolution).

The TDC works by counting SFQ clock pulses, between two successive input events (hits): each hit restarts the counter and shifts the data (accumulated counts or time stamps) to the multihit buffer, where it is stored in a shift register until it can be read out asynchronously by a readout clock.

To test our digitizer in TDC mode, events are applied using a HP-80000 1 GHz pattern generator and measure-

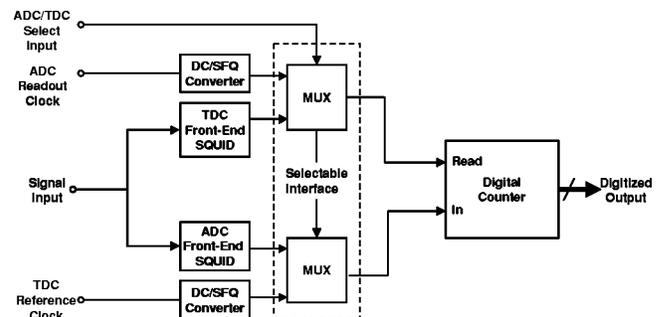


FIG. 1. Selectable interface applies appropriate TDC or ADC inputs to a common digital counter.

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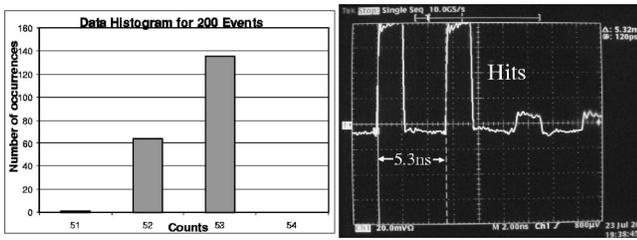


FIG. 2. At a TDC clock frequency (count rate) of 10 GHz, data is shown for 200 distinct events. We measured 52 and 53 counts, corresponding to 5.2 ns and 5.3 ns, respectively. Since the TDC clock and the hit signals are not synchronized, the 100 ps (one clock period) variation is expected.

ments are recorded on the number of counts accumulated in the counter between these events. Because the phase noise in our pattern generator is approximately 200 ps, it is difficult to accurately measure distinct events at high clock frequencies. To eliminate this time jitter and thus to verify correct TDC operation, we split each single event pulse and then recombined the pulse after a passive delay. Figure 2 shows the results for this experiment at a 10 GHz clock frequency/count rate (i.e., 100 ps time resolution).

To operate the digitizer as an ADC a high sensitivity superconducting quantum interference device (SQUID) front end was designed. The SQUID acts as a charge-to-flux converter, which is connected to the common digital counter described to create a flux-counting ADC. In this ADC, a 100:1 transformer coil amplifies an input current pulse, and this current is fed into the SQUID. The SQUID then produces a stream of SFQ pulses. The number per unit time (i.e., frequency) of SFQ pulses produced is proportional to the electrical charge applied at the input detector. By counting the number ( $N$ ) of pulses over a specified time interval (sampling or integration time,  $T$ ), a digital count is produced which is proportional to the charge in that time interval.

The major advantages of our implementation of this standard “counter-type” ADC are high sensitivity (4 nA/LSB at 100 M samples/s, corresponding to  $4 \times 10^{-17}$  C or  $250e$ ) and the perfect proportionality between the charge ( $Q$ ) and the magnetic flux ( $Q \propto \Phi = N\Phi_0$ , where  $\Phi_0 = h/2e = 2.07 \times 10^{-15}$  Wb is a quantum of magnetic flux) of the SFQ pulse stream. The dc voltage output at the detector can be monitored directly while varying the input current in the coil to obtain the classic periodic transfer function of the SQUID [Fig. 3(a)].

As mentioned before, in ADC mode, the digital counter is used to count an asynchronous stream of SFQ pulses from the SQUID detector over a given integration time ( $T$ ). If we vary the analog input current in the input coil, and measure the output at the counter, this experiment should reproduce the same  $V-\Phi$  curves in digital count form as in Fig. 3(a). Figure 3(b) shows how this digital data is taken with a 200 ns counting period (5 MHz sampling rate). The results are shown in Fig. 3(c). Here, the measured digital “counts” ( $N$ ) can be converted to the equivalent voltage using

$$V = \frac{N}{T} \Phi_0.$$

To verify that the ADC can be used to integrate the total charge in a pulse, we also performed a pulsed input test. A

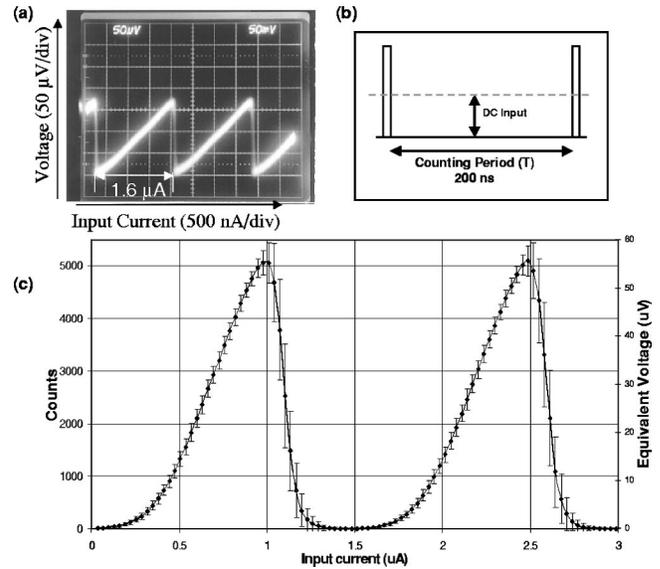


FIG. 3. (a) Periodic transfer characteristic of the SQUID front end. (b) dc input applied over a 200 ns counting period. (c) Reconstructed  $V-\Phi$  curves from the counter.

current pulse of variable width ( $T_{\text{pulse}} < T$ ) and amplitude ( $A_{\text{pulse}}$ ) was applied. Here, the output of the counter represents the total charge of the pulse. Figure 4 shows the ADC output for three different pulse amplitudes, each for five different pulse widths. These results show excellent agreement with the theory. The linear curve fits through the count outputs for the same amplitude and different widths are also shown. This test confirms the ability to digitize the charge of a pulse.

The digitizer contains a parallel-to-serial converter, for the counter readout. This design element limits the number of samples to the buffer length. A new design that reads out the data in the counter in parallel has been developed. This version allows continuous ADC operation and will be installed at RIKEN (Institute for Physical and Chemical Research) in Japan to measure data from superconducting tunnel junction x-ray detectors.<sup>7</sup>

This dual-function digitizer has tremendous potential for applications in many areas requiring high speed, low amplitude digitization. Since ADC measurements are limited by SQUID noise in the front end, lowering operation tempera-

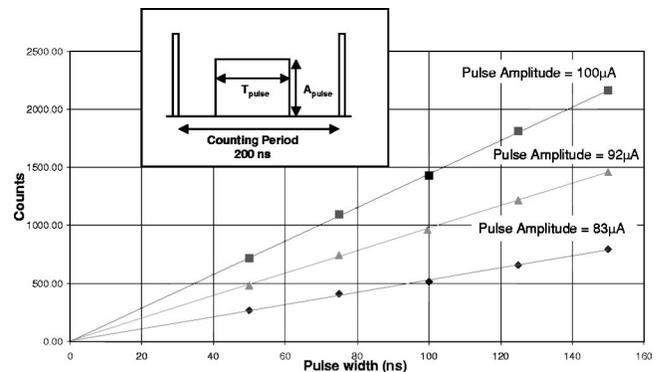


FIG. 4. Time integral of several current pulses of varying widths and amplitudes (without the amplification coil) were digitized. The linear fits for each data set corresponding to three different pulse amplitudes ( $A_{\text{pulse}}$ ) are shown.

ture could further increase sensitivity. With this dual-function digitizer, it is now possible to create a multichannel system capable of measuring both charge and timing information simultaneously, with the option of switching any individual channel between the two functions in real time. If additional timing resolution is required in the TDC mode, an additional analog prescaler<sup>8</sup> can be integrated to the digital counter, which can increase time resolution to 5 ps.

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<sup>2</sup>HYPRES Inc. Nb design rules, available at <http://www.hypres.com/>

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<sup>7</sup>Takayuki Oku and Hirohiko Shimizu, *IEICE Trans. Electronics* (in press).

<sup>8</sup>S. B. Kaplan, A. F. Kirichenko, S. Sarwana, and O. A. Mukhanov, *IEEE Trans. Appl. Supercond.* **11**, 513 (2001).