Superconductor Analog-to-Digital Converters and Their Applications

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Abstract — A wide variety of applications, ranging from radio-frequency (RF) receivers for broadband communications and signal detection, on earth and in space, would benefit from high-performance superconductor analog-to-digital converters (ADCs), based on magnetic flux quantization and fast switching Josephson junctions. Superconductor ADCs are capable of very high sample rates (100 GHz or more), very high linearity, and high sensitivity. Nyquist-rate ADCs use the high sample rate to digitize a wide instantaneous bandwidth (tens of GHz) and are useful for wideband spectrum monitoring as well as high-end scientific instrumentation. Delta and delta-sigma oversampling ADCs use the high linearity to achieve programmable trade-off between dynamic range and instantaneous bandwidth. These lowpass and bandpass ADCs have been used for direct digitization of narrower (tens to hundreds of MHz) RF bands in the 1-20 GHz range for a variety of communications, intelligence, electronic warfare, and radar applications. Another application area of these cryogenic ADCs is for outputs of cryogenic sensor arrays and terahertz mixers. Recent advances in various classes of ADCs for different applications are described.

Index Terms — Digital-RF, RSFQ, Mixed Signal, Wireless.

I. INTRODUCTION

The convenience and compelling advantages of digitally copying, processing, analyzing and storing information have inexorably altered the preferred format from analog to digital. However, a substantial fraction of information transport, as well as many information sources, resides in the analog domain. Therefore, there is a growing demand for better converters between analog and digital domains. Depending on the application, the system demands an analog-to-digital converter (ADC) with one or more of the following parameters: higher instantaneous bandwidth, higher analog signal frequency, higher linear dynamic range, higher sensitivity, and lower power consumption. These demands are not easily met and the ADC improvements have been much slower than that of digital processors [1]-[2]. Thermal noise, timing jitter in sampling, and comparator non-idealities all contribute towards making ADC improvements harder to achieve than that which is possible with Moore’s law growth in circuit complexity. Low temperature superconductor single flux quantum technology [3], featuring quantization of magnetic flux and ultrafast Josephson junction (JJ) comparators, offers an attractive alternative for building high-performance ADCs [4]. Furthermore, these ADCs can be integrated today with medium-scale digital circuitry (~10,000-15,000 JJs/chip) on the same chip running at the same clock frequency. Clock speeds up to 50 GHz have been demonstrated with 1.5-µm device technology and scaling to well over 100 GHz is projected with sub-micron devices [5, 6]. On-chip digital circuit complexity is also projected to increase by an order-of-magnitude. In general, one can build superconductor ADCs with very wide instantaneous bandwidth (tens of GHz), very high linear dynamic range (exceeding 100 dB), high sensitivity, and very low power consumption [4]. A further feature for space applications is the radiation immunity of these devices with respect to both hard and soft errors.

In this article, we analyze different superconductor ADCs from the perspectives of three different classes of applications: radio frequency (RF) systems, cryogenic sensor/detector readout, and high-end instrumentation.

II. DIGITAL-RF RECEIVERS

RF systems encompass broad application areas such as telecommunications, monitoring and dynamic allocation of spectrum, signals intelligence, electronic warfare, and radar. The RF spectrum is a precious resource. Its efficient use is valuable for the commercial communication service providers and its dominance is critical for the military. The enabling concepts for better spectrum utilization, such as software and cognitive radio, demand better ADCs. The insatiable demand for greater information exchange, especially high-resolution video and images, is forcing future RF systems to migrate to higher frequencies, from X/Ku/Ka/Q band to V and W bands where more bandwidth is available, with concomitant requirements on digital processing.

Direct digitization of RF signals enables generation, distribution, and simultaneous processing of multiple copies without loss of power or fidelity, and with the full flexibility and programmability afforded by digital circuitry. Superconductor ADCs offer compelling advantages at all frequencies, and can be optimized to deliver the maximum performance in a given band-of-interest. A digital-RF receiver, incorporating a bank of superconductor ADCs, accommodates multiple RF functions; a conceptual diagram is shown in Fig. 1. Whereas the individual ADCs are matched to the RF bands, the digital processing units are band-independent. Taking advantage of high sampling rates, it is natural to design lowpass (LP) and bandpass (BP) oversampling ADCs, incorporating delta (∆) and delta-sigma (∆Σ) modulators, for this application. Superconductor oversampling ADCs with sampling rates up to 50 GHz have been demonstrated [7].
Another ADC design employs multiple quantizer thresholds [12] and has been clocked up to 25.6 GHz (Fig. 2). Bandpass ADCs have been employed to build digital-RF receivers for X-band (7.5 GHz) and Ka/EHF-band (20 GHz) satellite communication, commercial wireless communications (850 MHz, 2.5 GHz) and tactical data links (1 GHz).

Another class of ADCs uses $\Delta$ modulation, of which the predominant variety is called phase modulation-demodulation (PMD) (Fig. 3) [13]. Here, the phase of an SFQ pulse stream is modulated by the derivative of the input analog signal. A clocked sampling circuit (called the synchronizer) that generates a '1' or a '0' indicating whether or not an SFQ pulse arrived during that clock interval performs the phase demodulation. These ADCs are slew rate limited and particularly useful for very high dynamic range (>100 dB) applications at the lower end of the RF spectrum (0-100 MHz). Further dynamic range enhancement may be obtained by extending the slew rate limit of the ADC; two- and four-fold increases have been demonstrated with half-rate and quarter-rate quantizers [14]. Even further enhancement of dynamic range necessitates multi-modulator architectures, such as a subranging ADC [14]. Fig. 4 compares proven and projected performance of these ADCs with the state of the art.
A series of cryocooled digital-RF receiver systems (Fig. 5) have been built with various superconductor ADCs addressing a variety of RF functions [15].

III. CRYOGENIC DETECTOR READOUT

Digital readout systems for cryogenic energy and particle detector arrays are particularly attractive since they can take advantage of the existing cryogenic platforms to provide digitization at or close to the focal plane. Sensitive SQUID-based signal digitizers help preserve the quality of low-level, fast detector responses, facilitate digital processing, and provide immunity from noise-pickup and crosstalk during transport to warmer temperature. The application space ranges from arrays of transition-edge sensors (TES) [16] and microwave kinetic inductance detectors (MKIDs) [17] to THz mixers (SIS and hot-electron bolometers [18]).

The most common ADC uses a SQUID front-end followed by a digital counter [19]. The SQUID quantizes the magnetic flux induced by the detector current pulse, producing a train of SFQ pulses that are counted over an interval. By summing these digital counts over the entire pulse duration, one obtains a measure of the integrated charge in the current pulse. Counts over finer time intervals provide information about the pulse shape. The same digital counter may be used to count the number of clock pulses between successive events (called ‘hits’) to produce a multi-hit time-to-digital converter (TDC). Charge sensitivity of 250 electrons [20] and time resolution of 6 ps [21] have been demonstrated.

This application, especially when employing detectors in the mK range, demands extremely low power dissipation and even few mW of static power dissipation in traditional rapid single flux quantum (RSFQ) circuitry may not be acceptable. Several schemes for minimizing and eliminating static power dissipation have been developed recently. These include reciprocal quantum logic (RQL) [22], and energy-efficient RSFQ (ERSFQ and eSFQ) logic families [23]. Since switching energy of a JJ is very small ($2 \times 10^{-19}$ J for a 100 µA JJ), the dynamic power dissipation even at 100 GHz clock frequency is over an order of magnitude smaller than the static power dissipation. Recently, a 20-stage ERSFQ binary counter, with zero static power dissipation, was demonstrated to operate with ±16% operating margins up to 67 GHz [24].

Using such a circuit, one can implement an extremely low-power cryogenic detector readout scheme, especially in an event-driven configuration [25] where no power is dissipated in the digital readout circuitry until the detector sends a pulse. The availability of such low power logic enables further digital operations to be performed before transferring data to room-temperature. For example, outputs from several detectors may be digitally multiplexed to reduce the number of leads between warm and cold temperature stages. Alternatively, one can digitize the analog multiplexed signal from a detector array with a broadband superconductor ADC, to facilitate noise-immune digital transport.

IV. HIGH-END INSTRUMENTATION

Instruments require the highest performance electronics. Therefore, instrumentation has been one of the earliest application drivers for superconductor ADCs. Extremely high sampling rates (100 GSps and higher) are possible with JJ technology. Transient digitizers and digital oscilloscopes are the natural products for measurement of ultrafast phenomena and performing diagnostics on wideband optical communication systems.

Superconductor flash ADCs use periodic quasi one-junction SQUID (QOS) comparators, and need only one comparator per gray-coded bit. The current through the QOS junction is digitized by the comparator, and ideally is a sinusoidal function of the input signal. The QOS comparator suffers from
dynamic errors, manifested as a non-sinusoidal asymmetric transfer function. This problem was alleviated by the SFQ-version of QOS, integrated with a SQUID and a negative feedback resistor [26]. Further improvement with a real-time look-back error correction algorithm was implemented using a pair of comparators, offset by $\Phi_0/4$, for each bit [27]. More recently, a symmetric comparator was demonstrated using a pair of complementary quasi-one-junction SQUIDs (CQOS) [28]. A 5-bit Flash CQOS ADC design, employing look-back error correction and bit-interleaving, has been demonstrated for $I_c = 2.5$ kA/cm$^2$ and 10 kA/cm$^2$ at 32 GHz and 50 GHz clock frequencies respectively (Fig. 6) [29].

V. CONCLUSION

Superconductor ADCs offer superior solutions to a variety of applications. Although the fundamental performance advantages of a superconductor ADC are incontrovertible, the need for cryogenics has hindered commercial applications in the past. Recent improvements in cryocooler, data link, and interface software and hardware are complementing the advantages of superconductor ADCs. Complete digital-RF receiver prototypes with superconductor ADCs have been demonstrated in user facilities. Although the ADCs to date are relatively simple circuits they compete well with much more complex semiconductor ADCs. With recent improvements in fabrication technology, more complex ADCs are being built and are expected to deliver unprecedented sensitivity, linearity, and bandwidth for progressively higher RF bands.

REFERENCES