Submitted to the Ninth International Symposium on Space Terahertz Technology, Pasadena, March 1998

SUPERCONDUCTING CORRELATORS FOR RADIO ASTRONOMY

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The proceedings of this conference attest to the striking progress in front-end receiver technology during the last ten years. This puts great demands on back-end technology. Because of this, high-speed low-power superconducting correlator technology is an attractive alternative to the complex hybrid semiconductor correlators currently employed. It is described how superconducting autocorrelators can be used today and in the next few years. Large scale superconducting correlators have the potential to replace semiconductor correlators to the benefit of future millimeter array observatories.

I. INTRODUCTION

Autocorrelation spectroscopy is widely used in radio astronomy to take a time series of a very small signal buried in noise and produce a time-averaged frequency spectrum. Many single-dish observatories still use acousto-optical spectrometers or even filter banks as they provide high resolution and bandwidth at reasonable cost [1]. Today, digital autocorrelators are becoming more prevalent as their benefits outweigh their cost. The autocorrelator for a modern single-dish telescope such as the Green Bank Telescope (GBT) consists of very many equipment shelves filled with VLSI semiconductor correlator chips, connected by intricate cabling. This is the current state-of-the-art.

Nevertheless it is evident that much more correlation throughput could be profitably employed. A focal-plane array receiver with M independent pixels requires a multi-bank autocorrelator M times as large as the single-pixel receiver. Consider the millimeter array observatories (BIMA, IRAM, OVRO, NRO, SMA), which use digital correlators exclusively for spectral observations. To take full advantage of an N-dish array each baseline must be separately correlated, and so N(N-1)/2 times the correlator throughput is required compared to the single dish [2]. Therefore the correlators under design for future large arrays (MMA, LMSA) which will have 40, 50, or more dishes must push the current state-of-the-art, but must also make severe compromises.

The proceedings of this conference attest to the striking progress in front-end receiver technology for millimeter-wavelength astronomy during the last ten years; however the standard design of heterodyne receivers has changed little during this time. It consists of an externally pumped SIS (and lately, HEB) mixer operated at 4.2 K followed by a cooled semiconductor IF amplifier, room-temperature postamplifiers, an analog-to-digital converter (ADC), and some spectrometer. This scheme has been very successful, and such receivers are responsible for most of the recent striking achievements in this spectral range [1].

Nevertheless, this scheme has several limitations. First, SIS receivers are single-pixel devices, with few exceptions (such as [3]). Among other reasons for this [4] are that multichannel spectrometers are complex and expensive. Second, the instantaneous bandwidth of almost all SIS receivers has been limited to 1 GHz. This is not due to the SIS mixers themselves, which are capable of 20% to 30% fractional bandwidth [5]. One problem is that SIS mixers operate at 4.2 K while the HEMT IF amplifiers are usually mounted some distance away with an isolator in between. A great improvement on this, to 4 GHz bandwidth, was demonstrated when Padin et al. [6] positioned a HEMT much closer to the SIS junction. Padin's 1994 accomplishment has been widely cited in plans for future observatories, for example, the Millimeter Array specification calls for **8 GHz** bandwidth per sideband based on Padin's work [7]. This is a striking indication of the thirst for greater bandwidth.

Thus one might say that the correlator is the limiting instrumental subsystem for radio astronomy today. Here we consider using high-speed low-power superconducting technology to replace the complicated hybrid semiconductor correlators currently employed. Is this worth the effort? -- in principle, any size correlator can be built with today's semiconductor technology by further multiplexing. In practice however the limitations are reliability, power dissipation, cost, and complexity of interconnections. The largest correlators today fall comfortably within these constraints, but not by a large margin. Also, semiconductor VLSI appears to be approaching its maximum clock speed according to the authoritative semiconductor industry "Roadmap" [8].

After introducing superconducting correlators we will describe how these can be used today (Sec. IV, Large Focal Plane Arrays), in the near future (Sec. V, Protogalaxy Search Receiver), and if a state-of-the-art fabrication facility becomes available (Sec. VI, General Correlators for Radio Astronomy).

II. SUPERCONDUCTING DIGITAL ELECTRONICS

The potential virtues of superconducting digital electronics are impressive. The intrinsic switching time is very short, on the order of a picosecond. Perhaps even more important is the low power dissipation, on the order of a microwatt per gate, a thousand times less than CMOS circuits. There has been a long and significant research effort in this area, most notably the IBM supercomputer project ending in 1983 and the MITI project (Japan) in the 1980's. These projects and most others chose to emulate semiconductor technology in using a "voltage state" logic -- data is represented by steady voltage levels. This choice was unfortunate. Superconducting voltage state logic cannot operate faster than a few GHz (10 GHz with considerable error rate) for reasons that are intrinsic, in fact topological [9], and the maximum speed can be little increased by better technology.

Today there is a renewed research effort in superconducting digital electronics based on RSFQ (rapid single flux quantum) logic, first proposed in 1985 [10]. Among the accomplishments of this technology are a simple digital circuit operating up to 370 GHz [11], a 64-bit circular shift register with data clocked around at 18 GHz [12], and an oversampling ADC with 18-bit decimation filter composed of 2100 Josephson junctions operating above 10 GHz clock frequency [13]. Note that this combination of digital speed and complexity cannot be approached in any other technology.

It must be stated that no Josephson junction digital devices have yet left the laboratory. One limitation is the requirement to operate at 4 K, a severe disadvantage for many applications. Also, high-speed output from an SFQ circuit is difficult because of the small energy scale. The best result to date is output to room temperature of 8 GHz RSFQ data [14]. Likewise, chip-to-chip SFQ transmission has not yet been demonstrated; the emphasis has been to develop multi-chip modules [15], which is much harder. Perhaps the most severe problem has been integration scale. A useful digital circuit should require many Josephson junctions with well-controlled properties and complex interconnections. To realize such a circuit puts great demands on fabrication tolerances.

III. SUPERCONDUCTING CORRELATORS

During the past few years there have been a number of designs advanced for superconducting digital correlators, but no concerted development effort. An early 256-lag 1-bit correlator used 4350 Josephson junctions and operated at a clock frequency of 10 GHz [16]. There was no prescaler, however, and the output from the correlator was analog. A fully digital RSFQ correlator was proposed in [17], and different modifications of this [18-20] have converged to a common design. In one of these projects [19] a 16-lag RSFQ autocorrelator complete with on-chip ADC, high-speed clock, and counters (1650 Josephson junctions total) was successfully demonstrated at a clock frequency of 11 GHz [21]. It resolved a sinusoid buried in -40 dB signal/noise.

These are 1-bit autocorrelators with double-Nyquist sampling. The basic architecture is well-known, identical to [22], for instance. 1-bit correlator schemes were a standard tool in early days of radio astronomy [23] and are appropriate for an immature technology where device-count is a greater limitation than switching speed.

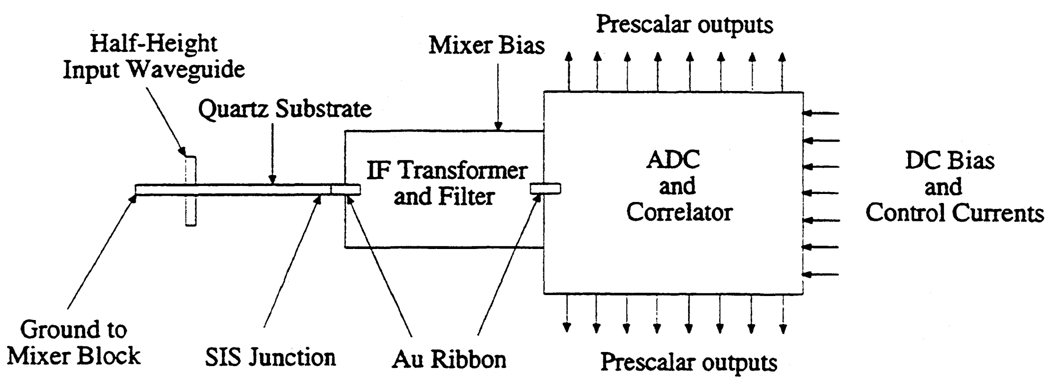

Fig. 1. Possible scheme for an integrated superconductor mixer / back end.

Figure 1 is a sketch of a possible heterodyne receiver. A 1-bit ADC measures the sign of the (almost) random signal X(t) coming from the SIS mixer at intervals $\tau = 1/f_c$, where f_c is the clock frequency; it gives the data stream sign(X(t_i)), where i is the sample number. In double-Nyquist sampling the nominal bandwidth is $f_c/4$. The autocorrelator lag number k must compute the product of sign(X(t_i)) and sign(X($t_i+2k\tau$)), which is the sample taken 2k clock periods later, and accumulate the result over many samples i = 1 to N. Since the SFQ ADC codes sign+ as "1" and sign- as "0", this product is simply the XNOR function of a given sample and another sample delayed by $2k\tau$. In practice, the XOR function provides the same information.

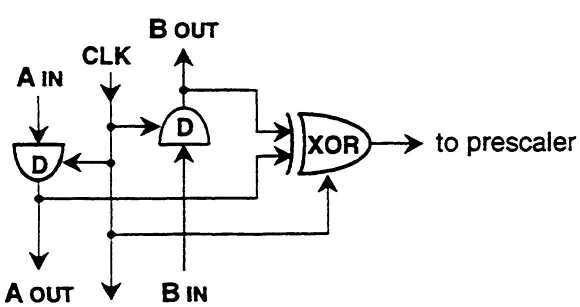

Fig. 2. A single correlator lag.

A single lag stage of this autocorrelator is shown in Fig. 2. The clocked delay line consists of RSFQ destructive read-out (DRO) cells ("D"), which are the simplest RSFQ gates. After the k=1 stage the A_{out} is connected back to the B_{in} (with a single delay). The XOR is a standard , and the prescaler is an SFQ T-flip-flop binary counter whose length (8-13 stages) depends on the clock rate, integration time, and desired output rate. This is an extremely simple RSFQ circuit.

The only "interesting" challenge in this circuit is the timing requirements. The A arm uses concurrent clocking (clock flows with data) while the B arm uses counterflow clocking (clock flows opposite data), and as drawn the circuit suffers from the worst aspects of both: susceptibility to race faults in the A arm and low speed because of the B arm [24]. It is likely that this circuit can be made considerably more robust and also faster by an optimization of the timing interconnections [25]. This basic design however is an excellent trade-off between speed and circuit area. It can be made with very few Josephson junctions, and the accuracy lost by the one-bit digitization is partially compensated by the oversampling [26].

III.1 Circuit area and power dissipation

The major design constraint for superconducting correlators today is the necessity to use only a single chip. The correlator design described above will require roughly 100 Josephson junctions per lag. A literature survey shows that current RSFQ design practices use about 2000 μm^2 area per junction. This implies that a 256-lag autocorrelator will fit on a standard 1 cm^2 chip. The area requirements of RSFQ circuits have never been pushed and could be reduced by perhaps 4x today with an aggressive design. They certainly will be reduced with future fabrication improvements. Note that a future specification (Sec. VI) is 100 μm^2 per junction.

A literature survey shows that current RSFQ circuits dissipate on the order of 0.2 μW per junction. Therefore a 256 lag correlator will dissipate about 5 mW at 4.2 K, and so one hundred such chips would require only a standard 1 W cryocooler. This power dissipation is entirely due to static loss in the dc bias resistors and can certainly be reduced. A preliminary estimate is that 0.03 μW per junction is possible with little decrease in reliability [19]. (Note that a future specification from Sec. III.4 is 7.5 nW per junction.) Thus the cryogenics capacity should not limit the ambitions of future superconducting correlators.

IV. LARGE FOCAL PLANE ARRAYS

Recent technological advances have put the construction of a large focal plane array of submillimeter-wave mixers within technical and financial feasibility. It is now standard to incorporate tuning structures directly on the same substrate as the SIS junction, alleviating the need for cumbersome adjustable tuners. Micromachining technology offers the possibility of fabricating large numbers of waveguide / mixer blocks in a single unit [27, 28, 29]. A new laser milling technique has been developed to fabricate high quality submillimeter waveguide components and feedhorns with almost any cross section [30]. Under computer control, the construction of high performance large-format (~10 x 10) waveguide array receiver front ends becomes tractable.

Unfortunately, there is no backend technology to efficiently process the vast quantity of a data that would be gathered by such an array. Using current correlator or acousto-optical components, an entire room of equipment would be required. Superconducting correlators are ideal for this application. A 256-lag single-chip version of the autocorrelator described above, clocked at 1 to 10 GHz, gives a frequency resolution of 1 to 10 MHz. The size of the array would be limited by the requirements for the multiple low-noise HEMT amplifiers. It may however be possible to use superconducting ADC's to digitize the SIS mixer output without intervening amplification, as sketched in Fig. 1. Superconducting ADC's have been the focus of much research for many years, as reviewed in [31, 32]. For instance, a fully SFQ "quasi-one-junction SQUID" ADC [33] consists of only several Josephson junctions. The superconducting mixer / ADC / autocorrelator combination would enable an entire 10 x 10 array receiver (frontend + correlators) to be housed in a standard 1 W cryostat.

V. PROTOGALAXY SEARCH RECEIVER

Last year at this conference it was suggested that observations of protogalaxies are "THE future of millimeter-wavelength astronomy" [34]. It is likely that there is a large class of early objects which are heavily obscured by dust [35],[36]. For instance, Charlot and Fall maintain that there is only a brief period at the beginning of star formation between the generation of Lyα emission and complete attenuation by dust [37]. Protogalaxy model light curves fall within the sensitivity limit of the Hubble Space Telescope (HST) only because of the extended ultraviolet brightness of the irregular galaxy spectrum; for high-z objects the HST sees the flux of a few naked O stars which do not represent the stellar population as a whole -- most of the luminosity appears in the submillimeter [35]. To resolve these issues, some sort of submillimeter-wave search is needed.

The $^2P_{3/2} \rightarrow {}^2P_{1/2}$ line of C^+ at $\lambda = 158\,\mu m$ is long recognized as a sensitive probe of protogalaxies [38, 39]. This CII line will be most prominent in protogalaxies undergoing a burst of star formation. Cold-dark-matter galaxy formation models (i.e. [40]) predict such bursts occur at $z \sim 2.2$ and decay afterward at a roughly exponential rate. Adopting this redshift, one finds the most promising frequency range to detect protogalaxies in the CII line is between ~ 500 and 700 GHz. Atmospheric absorption narrows this window to 620-710 GHz.

To locate such protogalaxies, a sensitive sub-millimeter SIS receiver is desirable. The instantaneous bandwidth of the receiver should be as large as possible, but high resolution is *not* required. The integrated superconducting receiver described above and sketched in Fig. 1 is just such a receiver, if the back-end is operated at a high clock rate. In fact, the bandwidth is limited by the maximum clock rate of the autocorrelator.

All RSFQ circuits use the same material system as SIS mixers -- Nb/Al_2O_3/Nb Josephson junctions. Although more than 10 laboratories in the world fabricate superconducting digital circuits (as reviewed in [41]), few make both competitive SIS mixer junctions and also digital circuits. SIS mixers commonly use junctions with 1 μm^2 area and critical current density (j_c) 10 kA/cm^2. Digital circuits however are generally made with 3.5 μm linewidth, minimum junction area 10 μm^2, and j_c = 1 kA/cm^2. These parameters are more conservative for good reason; it is because the fabrication-induced parameter variations, the differences between design and chip, are by far the limiting factor which determines the maximum clock rate of complex RSFQ circuits. Were it not for this, one could design complex RSFQ circuits which run at almost 100 GHz, today [42].

The correlator is a very simple RSFQ circuit and so a clock rate of 20 GHz is probably possible today using the j_c = 1 kA/cm^2 specification. Almost all of the most successful complex RSFQ circuits to date have been fabricated at the Hypres, Inc., foundry [43]. Hypres is now in the process of upgrading their fabrication facility and anticipate a 1.0 μm linewidth with j_c = 10 kA/cm^2 by Summer 1999 [44]. This should allow the construction of an autocorrelator clocked at 64 GHz, giving an IF bandwidth of 16 GHz. 256 lags implies a spectral resolution of 62.5 MHz, and the broad ~ 600 MHz emission lines expected from protogalaxies at 680 GHz will be easily resolved. It is seen that superconducting correlator technology is an ideal match to the spectrometer requirements of a protogalaxy search.

VI. GENERAL CORRELATORS FOR RADIO ASTRONOMY

In light of the strong need for greater correlation throughput presented in the Introduction, one asks whether high-speed low-power superconducting correlators can ever compete with the massive semiconductor correlators used at radio astronomy observatories. In fact, future plans for RSFQ logic are far beyond the needs of radio astronomy!

For instance, a large DARPA-sponsored trial project has recently begun development of a petaflops computer (10^{15} floating point operations per second) based on RSFQ logic, under the title "Hybrid Technology Multithreaded (HTMT) Architecture." Many believe that this can not be accomplished with future CMOS technology. One HTMT specification projected 10,000 RSFQ processors, each providing 100 gigaflops. Each processor will consist of about 30 chips in a multi-chip module. Each 2 cm x 2 cm chip will have 4,000,000 Josephson junctions (0.8 μm linewidth with $j_c = 20\,kA/cm^2$), run at a clock speed of 100 GHz, and dissipate 30 mW at 4 K. The plan is to complete this in ten years. Most recent results and specifications are given in [45].

This is a breathtakingly ambitious project. For comparison, one design for the Millimeter Array correlator requires 204,800 256-lag sub-correlators with a clock rate of 125 MHz [46]. To realize this in RSFQ with 100 Josephson junctions per lag at 125 MHz would require 5 Billion junctions, more than two orders of magnitude less than the HTMT specification. And of course a 1000 x increase in clock rate would simplify the MMA correlator enormously.

One can be certain that superconducting correlators will be widely used in radio astronomy long before other large-scale superconducting digital electronics applications receiving intense interest, such as the HTMT project; for three reasons. First, there is less competition. A large hybrid autocorrelator can provide a correlation bandwidth of perhaps 16 GHz using semiconductor chips with clock rate of only several hundred MHz. It does this by subdividing the input and taking the cross-correlation functions of all the subdivisions. This means that the complexity of a hybrid correlator decreases as the *square* of the clock speed, and so superconducting correlators compete with much more complex semiconductor correlators. Second, the correlator functions without frequent communication to the (room temperature) external world, unlike the other large projects. Third, superconducting correlators have the advantage of a much simpler architecture than other large superconducting circuits, without need of contingent high-speed decisions. Computer circuits are much more difficult to design and to realize.

Many technical advances will be required before this can occur, in particular a large improvement in superconductor circuit fabrication. However, any progress towards the HTMT or other ambitious project goals will require a large investment in Josephson junction fabrication technology, to the benefit of future superconducting correlators for radio astronomy.

VII. CONCLUSION

Single-chip superconducting autocorrelators can enable large focal plane array and/or very wide bandwidth submillimeter wavelength receivers for radio astronomy. This is an extremely simple superconducting digital circuit, the 4 K operating temperature requirement is an advantage rather than a liability, and high-speed output is not required. In the future, large superconducting correlators may allow the information throughput of millimeter array observatories to be fully utilized.

Let us define a figure of merit for a correlator chip F = (number of lags)•(clock rate). Then the GBT chips have F = 128 lag-GHz [46]. Superconducting correlator chips of this performance have already been demonstrated [21]. In several years it should be possible to realize superconducting correlator chips suitable for a protogalaxy search receiver (Sec. V), for which F will be 128 times higher than this. The HTMT specifications (Sec. VI) imply F can be 30,000 times higher than the GBT chips.

The author gratefully acknowledges the substantial contributions of Chris Walker and Tony Kerr to this paper.

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