# 1 VOLT JOSEPHSON FAST REVERSED DC SOURCE

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## Abstract

We have made several improvements to the NIST Josephson FRDC (fast reversed dc) source so that it now operates at 1 Volt. We have made a precision comparison to a conventional semiconductor FRDC source by measuring the thermoelectric transfer difference of a known thermal voltage converter. The agreement between the two sources was measured to be better than 1 part in $10^7$.

## Introduction

The NIST programmable 1 V Josephson voltage standard chip [1, 2] has been employed to develop a Josephson FRDC source. We have recently improved this FRDC source, which is now able to utilize all junctions on the Josephson chip to produce 1 Volt. The Josephson source utilizes an array of 32 768 superconductor-normal-superconductor (SNS) Josephson junctions that are rapidly switched between voltage states of +1.018 V, 0 V, and -1.018 V. To demonstrate its capabilities, we measured the thermoelectric transfer difference of a known multijunction thermal voltage converter (MJTC), and compared the results to similar measurements using a conventional semiconductor source. Both sources utilize the FRDC method [3], and the timing of the FRDC waveforms was nominally the same for both instruments.

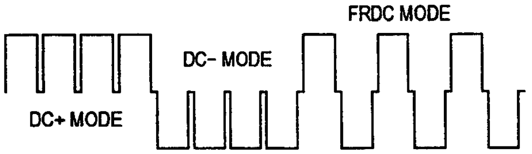

Fig. 1. FRDC waveforms.

The FRDC measurement technique compares the response of the thermal converter to the three different waveforms shown in Fig. 1. Each waveform is derived by switching between stable dc levels. For the waveform labeled "FRDC Mode," the voltage is alternately reversed in polarity. The dc waveforms have a constant output level except for brief transitions to zero that duplicate the transient portions of the FRDC waveform. The Josephson source eliminates uncertainties related to the fluctuations in the output voltage level and offsets induced by the switches.

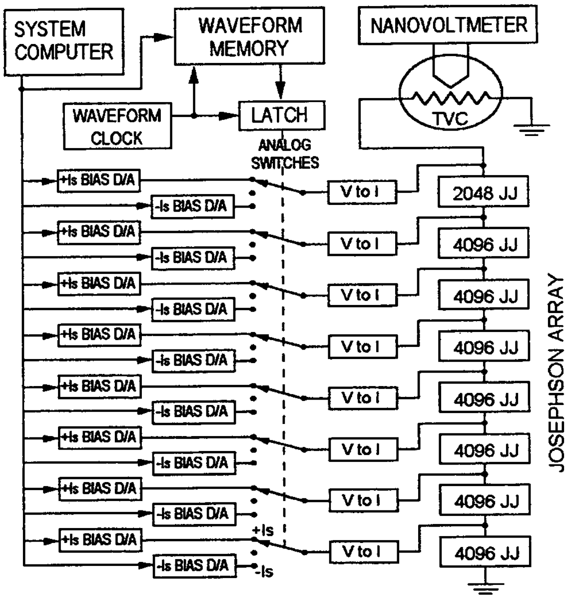

Fig. 2. Block diagram of the Josephson array system.

Figure 2 is a block diagram of the Josephson FRDC measurement system. To synthesize the FRDC waveform, the computer loads the waveform memory with the required state (-1, 0, +1) of the array for up to 65 536 time steps of the specified waveform. When the waveform clock is started, the memory steps through the time sequence, and its outputs drive the analog switches that select the bias appropriate to the -1, 0, or +1 constant voltage steps for each array segment. The outputs of the analog switches control fast constant-current drivers for the array bias lines. A latch on the digital inputs to the analog switches ensures that all switches change state within a few nanoseconds. The settling time of the bias current drivers is 400 ns.

At this bandwidth (approximately 1 MHz), the current drivers can generate transients that are sufficiently large to trap magnetic flux in the Josephson array. To eliminate this problem, we have tuned the values of components in the current drivers to minimize overshoot and prevent oscillations, but at the same time provide a reasonably quick settling time.

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## Measurements

FRDC-DC difference measurements were made by recording the MJTC output for a sequence of inputs: FRDC, DC+, DC-, FRDC, and computing the difference between the means of the two FRDC and two dc measurements. Fig. 3 shows the FRDC-DC difference as a function of frequency for the MJTC. It was measured at 1.018 V with both the Josephson and semiconductor sources. Each point represents the average of many FRDC-DC difference measurements. The total measurement time for each source was about 8 hours.

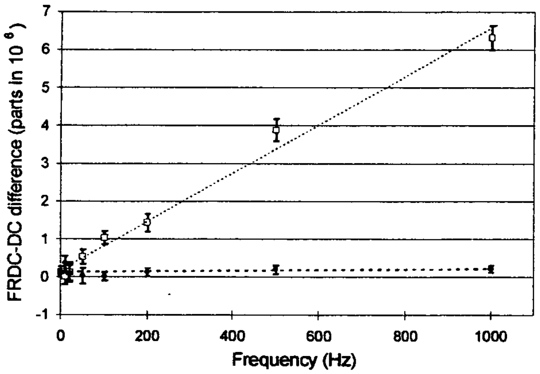

Fig. 3. FRDC measurement results. Data from the Josephson source is shown with open squares, and data from the semiconductor source is shown with solid circles. A least-sum-squares (LSS) fit line is shown for each source.

The Josephson source has the advantage that its output is intrinsically stable, and the positive and negative voltages are perfectly matched. However, due to a mismatch in the Josephson array switching transients when the waveforms in Fig. 1 are generated, the Josephson source has a frequency dependent component in the line of Fig. 3. This component of the FRDC-DC difference can be uniquely identified because it has a linear frequency dependence [3], which results in a slope of the least-sum-squares (LSS) fit line. Thus, the thermoelectric transfer difference is given by the extrapolation of the curves to zero frequency. In the case of the semiconductor FRDC source, the switching transients have been very carefully matched so that there is essentially no frequency dependence. Table 1 lists the measured FRDC-DC differences based on the extrapolation of the LSS fit lines of Fig. 3 to zero frequency. The Type A uncertainties use a coverage factor $k = 2$ and are based on the standard formula for the extrapolation of a least-sum-squares fit line [4].

Table 1. Comparison of FRDC-DC differences.

| | FRDC-DC Difference |
|---|---|
| Josephson Source | $+0.14 \pm 0.14 \times 10^{-6}$ |
| Semiconductor Source | $+0.12 \pm 0.07 \times 10^{-6}$ |

The difference between the measurements given by the two sources is only $0.02 \times 10^{-6}$, with a combined uncertainty of $0.16 \times 10^{-6}$ (again, $k = 2$). These results show no significant difference between the two sources.

## Conclusion

The level of agreement between the Josephson and semiconductor FRDC sources was measured to be better than 1 part in $10^7$, with a combined uncertainty of the same order. By tuning the components of the current driver stages and eliminating ground loops in the system, we were able to eliminate the flux-trapping problems that limited us to half the chip output voltage in earlier experiments [5], and operate the Josephson chip at its full output voltage of 1 V.

It is a well-accepted hypothesis that the frequency independent part of the AC-DC difference in thermal voltage converters (including measurement with the FRDC method) is the result of thermal effects and thermoelectric voltages in the DC mode. To verify this hypothesis and identify other contributions to AC-DC difference, it is necessary to realize a sinusoidal waveform that is directly derived from the Josephson effect. Efforts are underway to create such an AC standard using pulse driven Josephson arrays [6] and rapid-single-flux-quantum digital-to-analog converters [7, 8].

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