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# THERMOELECTRIC TRANSFER DIFFERENCE OF THERMAL CONVERTERS MEASURED WITH A JOSEPHSON SOURCE

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## Abstract

We have measured the thermoelectric transfer difference of two thermal voltage converters using a Josephson source and compared the results to similar measurements made with a conventional semiconductor source. Both sources use the fast reversed DC method. The Josephson source is an array of 16 384 superconductor-normal-superconductor Josephson junctions that is rapidly switched between voltage states of +0.5 V, 0 V, and -0.5 V. A marginally significant difference is detected between measurements with the two different sources.

#### Introduction

We have measured the thermoelectric transfer difference of both a single junction and a multi-junction thermal voltage converter (TVC) using a programmable Josephson voltage source [1, 2] and compared the results to similar measurements using a conventional semiconductor source. Both sources utilize the fast reversed DC (FRDC) method [3]. The measurement compares the response of the thermal converters to the three different waveforms shown in Fig. 1. Each waveform is derived by switching



Fig. 1. FRDC waveforms.

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 effects in the FRDC waveform. The Josephson source eliminates uncertainties related to the fluctuations in the output voltage level and offsets induced by the switches.

Figure 2 is a block diagram of the measurement system that uses the Josephson array. To synthesize the FRDC waveform, the computer loads the waveform memory with

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

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 bias source generates transients that have a significant probability of trapping magnetic flux in the Josephson array. To avoid this problem, we used only those array segments with the largest resistance to flux trapping. As a result we were able to use only half of the 32 768 Josephson junctions (JJ) resulting in a maximum output voltage of 0.5 V.

#### Measurements

FRDC-DC difference measurements were made by recording the TVC 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. Figure 3 shows the FRDC-DC difference as a function of frequency for a single junction thermal converter (SJTC), and a multi-junction thermal converter (MJTC). Each was measured at 0.5 V with both the Josephson and semiconductor sources. Each point represents the average of many difference measurements. The total measurement time for each thermal converter was about 8 hours.



Fig. 3. FRDC measurement results. The upper pair of least-sumsquares (LSS) fit lines correspond to the MJTC. The lower pair of LSS fit lines are for the SJTC. Data from the Josephson source is shown with open squares, and data from the semiconductor source is shown with solid circles.

The Josephson source has the advantage that its output is intrinsically stable, and the positive and negative voltages are perfectly matched. However, a mismatch in the Josephson array switching transients when the waveforms in Fig. 1 are generated gives rise to a frequency dependent component in the curves of Fig. 3. This component of the FRDC-DC difference can be uniquely identified because it has a linear frequency dependence, which results in a slope of the 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 curves 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-sumsquares fit line [4].

	Multi Junction TVC	Single Junction TVC
Josephson Source	$-0.05 \pm 0.13 \times 10^{-6}$	$-2.51 \pm 0.12 \times 10^{-6}$
Semiconductor Source	$+0.29 \pm 0.27 \times 10^{-6}$	$-1.94 \pm 0.06 \times 10^{-6}$

Table 1. Comparison of FRDC-DC differences.

The Type A uncertainties of the FRDC-DC measurement for the Josephson and semiconductor source are comparable. There is, however, a marginally significant difference in the two measurements. This suggests the existence of Type B uncertainties in either or both of the two sources, not an unexpected result.

### Conclusion

The level of agreement between the Josephson and semiconductor FRDC sources provides evidence that the Type B uncertainty in both of these methods is less than 1 part in  $10^6$ .

Based on these experiments, we believe that the flux trapping problem that limited the Josephson array output to 0.5 V can be solved with a bias system that uses low impedance (constant voltage) bias drivers. Repeating the experiment at 1 V will give a factor-of-four increase in the TVC output and a consequent reduction in the uncertainty of the FRDC-DC measurement.

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It is a well accepted hypothesis that the frequency independent part of the AC-DC difference in TVCs (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 under way to create such an AC standard using a pulse driven Josephson array [5] and a rapid-single-flux-quantum digital-to-analog converter.

#### References

 C.A. Hamilton, C.J. Burroughs, S.P. Benz, and J.R. Kinard, "AC Josephson Voltage Standard: Progress Report," <u>IEEE Trans.</u> <u>Instrum. Meas.</u>, vol. 46, pp. 224-227, April 1997.

[2] S.P. Benz, C.A. Hamilton, C.J. Burroughs, T.E. Harvey, and L.A. Christian, "Stable 1-Volt Programmable Voltage Standard," <u>Appl. Phys. Lett.</u>, vol. 71, no. 13, pp. 1866-1868, Sept. 1997.

[3] M. Klonz, G. Hammond, B.D. Inglis, H. Sasaki, T. Spiegel, B.Stojanovic, K. Takahashi, R. Zirpel, "Measuring Thermoelectric Effects In Thermal Converters With A Fast Reversed DC," <u>IEEE Trans. Instrum. Meas.</u>, vol. 44, pp. 379-382, 1995.

[4] N. Draper, H. Smith, <u>Applied Regression Analysis 2<sup>nd</sup> Ed.</u>, New York, Wiley, pp. 82-83, 1981

[5] S.P. Benz, C.A. Hamilton, C.J. Burroughs, L.A. Christian, and T.E. Harvey, "AC and DC Voltage Source Using Quantized Pulses," this conference.

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