A Practical Josephson Voltage Standard at 1 V

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Abstract—**A series array of 1484 pairs of Josephson junctions, biased by microwaves at 72 GHz, is demonstrated to provide stable quantized voltages at the 1 V level. The niobium/lead-alloy junctions used in the array are not affected by thermal cycling.**

SINCE 1972 the U.S. Legal Volt has been defined in terms of the ac Josephson effect in which microwave radiation at frequency f generates quantized voltages at $V_n = nhf/2e$, where n is an integer, h is the Planck constant, and e is the elementary charge [1]. For this purpose a value of 483593.420 GHz/V has been adopted for the constant $2e/h$. Experiments which realize the Josephson volt typically use one or two junctions driven at 10 GHz to produce reference voltages between 5 and 10 mV. Such low voltage levels complicate the precise calibration of the 1.018-V Weston cells used as secondary standards.

In 1977 Levinsen *et al.* (2) suggested a simple method for using a series array of Josephson junctions to provide a reference voltage at the 1-V level. The method makes use of constant-voltage steps which cross the zero-current axis, allowing the array to be biased with a single current source at or near zero current. The zero-bias arrangement was demonstrated to produce quantized voltages first with a single junction [3], then with small arrays [4]–[6], and finally with an array of 1474 junctions [7], [8] which achieved voltages in excess of 1 V. The success of the 1474 junction array was incomplete, however, in that the voltage was unstable, jumping from one quantized level to another at intervals of a few minutes. Moreover, the lead-alloy junctions used in this array proved to have a shelf life of no more than one or two weeks.

This letter reports the first practical zero-bias series-array Josephson voltage standard at the 1-V level [9].[1] The quantized voltages produced are stable for periods of up to a few hours, and preliminary experiments have verified the accuracy of the standard to be within 2 parts in 10^6. In addition, the niobium/lead-alloy junctions used are almost unchanged after several tens of thermal cycles between room temperature and 4 K over a period of one year.

The increase in stability time which makes the present array fully practical is the result of a more nearly optimum choice for the critical-current density J_c and the dimensions $l \times w$ of the individual junctions of the array. Within the context of the Stewart–McCumber model for a point junction, the theoretical stability time [10] or an RF-induced step in the presence of thermal noise increases exponentially with critical current $I_c = lwJ_c$, provided the plasma frequency of the junction f_p is much less than the RF bias frequency f. Increasing J_c, l, or w will thus improve the stability as long as certain limits are not exceeded.

The limit on J_c is determined by the fact that instabilities associated with the onset of chaos [10], [11] appear when $f_p(=(eJ_c/\pi hC_s)^{1/2}$, where C_s is the specific capacitance of the junction) approaches f. Previous studies [3], [4], [7] indicate that the optimum value for J_c is that for which $f_p = 0.3f$ or about 70 A/cm^2 for niobium/lead-alloy junctions operated at 72 GHz, as in the present array.

The limits on l and w are determined by effects which cause variations in the junction phase across the area of the junction, invalidating the point-junction model. One such effect, phase bending produced by the magnetic field associated with the RF current, sets an upper limit on the length l of the junction in the direction of RF current flow [4], [7]. A second effect, believed to limit both l and w, is the excitation of Fiske resonances by the RF bias or its harmonics. Because the latter effect is not well understood, the junction dimensions of the present array were determined by trial and error.

The best geometry discovered for niobium/lead-alloy junctions operated at 72 GHz is shown in Fig. 1. Each section of the series array consists of a pair of $15 \times 20\ \mu m^2$ junctions connected in parallel. The strategy of using two small junctions in place of one large junction was adopted in an apparently successful attempt to reduce the problem of Fiske oscillations by moving the fundamental Fiske mode to a higher frequency. Junction pairs having this geometry produced stable zero-crossing steps at voltages of 1 mV or more for critical currents in the range from 150 to 500 μA for the pair. Critical currents significantly outside this range resulted in steps having insufficient stability for use in a voltage standard.

Two additional factors important to the successful operation of a series array are the uniformity of the junction critical currents and the uniformity of the RF-power distribution along the array. Critical-current uniformity assures that all junction pairs fall within the range which produces stable steps; even a single pair outside of this range will cause instabilities. Uniformity of RF power assures that all junction pairs receive the right amount of power to produce zero-crossing steps at high voltages.

In the present design, shown in Fig. 2, the array is folded into a compact arrangement which helps to minimize the variations in critical currents due to spatial variations in the sputter oxidation process. Fabricated on a 6.35×12.7 mm^2 silicon substrate, the series array includes 1484 junction pairs

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[1] Similar results have been obtained at the Physikalish-Technische Bundesanstalt in Germany.

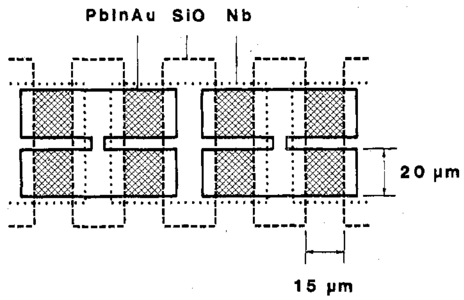

Fig. 1. A section of the array showing four junction pairs connected in series. SiO strips deposited over the Nb base electrodes help define the junction areas. The counterelectrodes consist of a PbInAu alloy of composition 84–12–4 percent by weight. Junction areas are indicated by cross-hatching.

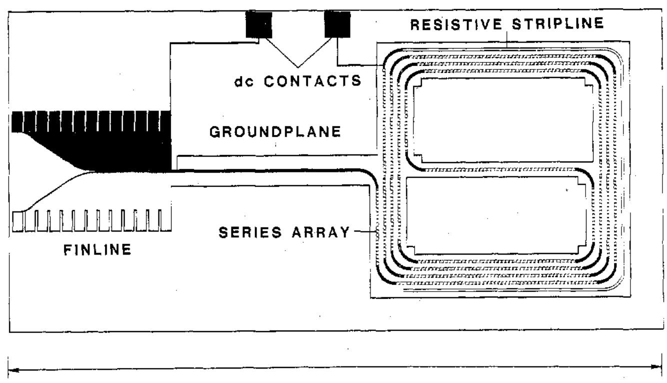

Fig. 2. Series-array microcircuit including 1484 junction pairs. The resistive stripline consists of an InAu alloy film with a sheet resistance of 0.16 Ω/sq.

arranged in a pattern which spirals inward and then outward again so that dc connections can easily be made to both ends of the array. In one successful array, all junction pairs had critical currents between 210 and 360 μA.

With regard to the distribution of RF power, the present circuit is similar in design to the previous 1474 junction array [7], [8]. The junctions are separated from a niobium ground plane by a 2-μm layer of silicon monoxide, making the array into a stripline along which RF power can propagate. Microwaves are coupled into one end of the array from a waveguide via a finline structure and absorbed at the other end by a section of resistive stripline. The resistive stripline acts as a matched load which helps to assure a uniform RF distribution by preventing reflections which would lead to standing waves. The RF-power uniformity is believed to be limited by the attenuation of the array rather than standing-wave effects. A comparison of the power required to produce the same step pattern on the first and last junctions of the array indicates an overall attenuation of about 6 dB. This attenuation implies that during normal operation the voltage of the highest-order step produced by the last junction will be about half that of the first junction.

A block diagram of the system used to generate reference voltages from the series array is shown in Fig. 3. The system uses a klystron which is phase locked to a crystal-controlled frequency counter to provide a few milliwatts of microwave power at an accurately known frequency near 72 GHz. An adjustable voltage bias with a source impedance of 100 Ω is used to select a voltage step near the desired voltage. The proper operation of the array is checked by modulating the bias current over a few microamperes and using an oscilloscope to verify that there is no change in voltage across the array. This procedure confirms that all of the junctions are on constant-voltage steps. The step order n of the array is determined by measuring the approximate voltage with a digital voltmeter, n being the integer closest to the ratio between this voltage and $hf/2e$. The array voltage is then accurately computed as $V_n = nhf/2e$. However, the voltage measured outside of the dewar will generally differ from the voltage across the array by a few microvolts due to the presence of voltages induced in the connecting wires by the thermal gradient between 4 K and room temperature. These thermal EMF's are compensated for by a small voltage source connected in series with the array and adjusted to produce a null when the array is in the zero-voltage state.

When operated at a fixed frequency near 72 GHz, the voltage standard is capable of providing a reference voltage at any one of more than 8000 voltage levels between 0.0 and 1.2 V spaced uniformly at intervals of $hf/2e = 149\ \mu$V. Fig. 4 shows the range of current bias for the 13 steps from $n = 6698$ to 6710 in the neighborhood of 1.0 V, induced by microwaves at 72.13506 GHz. As this figure suggests, more than 10 μA can be drawn from the array while it is biased on a quantized voltage step. In addition, because the RF source is tunable over a 200-MHz range, various combinations of frequency and step order can be used to select any desired reference voltage between 0.1 and 1.2 V. This tunability allows a Weston cell to be calibrated without a voltage divider, simply by adjusting the reference voltage to achieve a null. Digital voltmeters can be calibrated by direct connection to the reference voltage.

The accuracy of the array standard has been tested through an indirect comparison with the as-maintained NBS volt using a 1.000011-V Zener-diode transfer standard. Comparisons between the array and the Zener diode were made using various combinations of frequency and step order on two occasions, with the array stored at room temperature in the interim. All of these measurements agree to within 3 parts in 10^8, an uncertainty fixed by the drift of the null meter over the 2–3 min period required for a single measurement. The voltage of the Zener diode measured using the array proved to differ by 2 μV from that established by the as-maintained NBS volt, a discrepancy on the order of the shifts in Zener standards typically induced by transport. We conclude that the array standard has a accuracy of 2 parts in 10^6 or better, a level which establishes the array as a useful standard. The consistency of the measurements made with the array suggests, however, that a more direct comparison will demonstrate a much higher degree of accuracy for Josephson array standards.

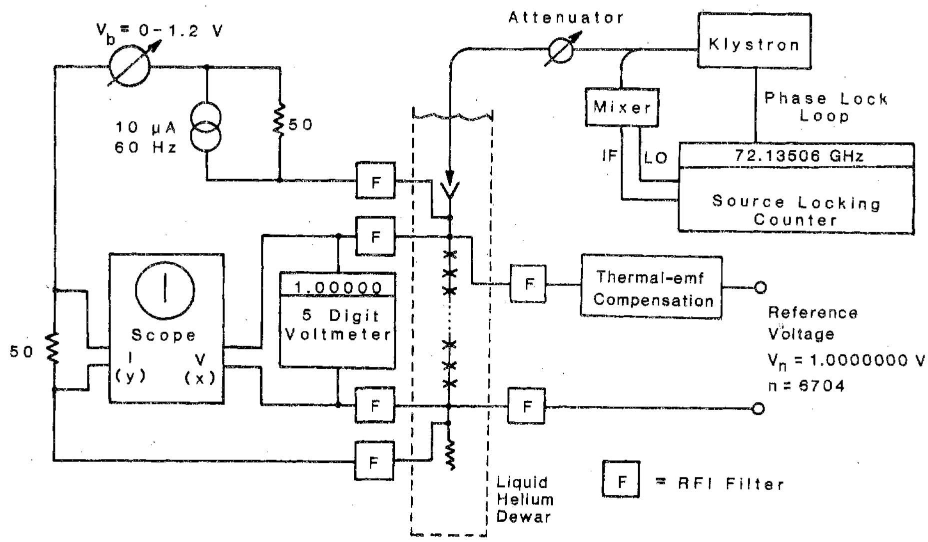

Fig. 3. Block diagram of the system used to generate quantized reference voltages.

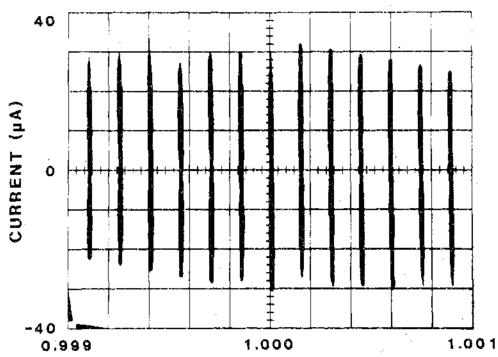

Fig. 4. Current-voltage characteristic of the array in the neighborhood of 1 V for a drive frequency of 72.13506 GHz. The current through the array has been swept to trace out all of the constant-voltage steps.

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