Programmable Josephson Arrays for Impedance Measurements

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***Abstract*—Arbitrary impedance ratios can be determined with high accuracy by means of a programmable Josephson system. For a 1 : 1 resistance ratio at 10-kΩ level, we demonstrate that the novel system allows measurements over a wide frequency range from 25 Hz to 6 kHz. Uncertainties are in the range of a few parts in 10^8 and thus comparable to those of conventional impedance bridges. Two methods for four-terminal-pair impedance measurements have been investigated, i.e., the potential comparison circuit and the coaxial setup. Both methods are capable of measuring from dc to 6 kHz with uncertainties to a few parts in 10^8. The potential comparison circuit has an upper bound at 6 kHz due to the use of the sampling method. The four-terminal-pair coaxial setup has the potential to decrease the relative uncertainty down to 10^{-9} once systematic errors are analyzed and canceled.**

***Index Terms*—Impedance bridge, impedance measurement, Josephson array, signal synthesis.**

I. INTRODUCTION

JOSEPHSON arrays have been widely used by national metrology institutes for the realization of the dc volt for decades. Recent advances have opened up the possibility of using binary programmable Josephson junction arrays for quantum-based ac voltage standards with synthesized waveforms [1], [2]. By rapidly switching a series of Josephson junctions between their quantized voltage steps, ac waveforms with calculable rms voltages can be generated.

A four-terminal measurement is the technique that uses separate pairs of current-carrying and voltage-sensing wires for making more accurate measurements than two-terminal systems. When the condition is met such that there is no current flowing through the voltage leads, the resistance value can be defined at the point of connection between the voltage and the current lines on both sides of the resistor. At the same time, electrical and magnetic interferences are eliminated, and the problem of contact resistance that is seen in the two-terminal setup does not exist in the four-terminal-pair setup.

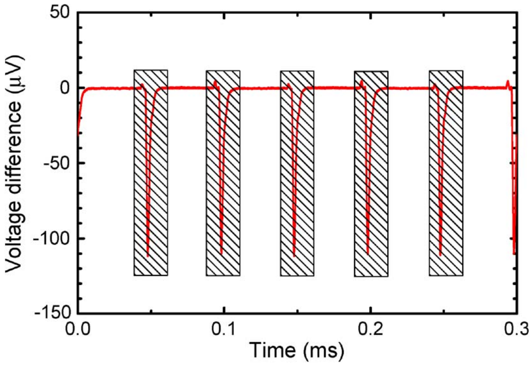

Fig. 1. Shaded portions of the synthesized waveform are not measured in the sampling method. The voltmeter only measures the parts where voltage steps are quantized.

In this paper, we present two configurations of four-terminal-pair bridges using two Josephson systems for measuring impedance ratios, including preliminary results for a 1 : 1 resistance ratio in the frequency range between 25 Hz and 10 kHz.

II. POTENTIAL COMPARISON CIRCUIT

The four-terminal-pair configuration in this section is a setup of a potential comparison circuit making use of the ac quantum voltmeter (ac-QVM). The ac-QVM is an instrument for measuring ac waveforms by comparing them to a Josephson waveform. It has been successfully tested, and first measurements at the $\pm 2.4\ \mathrm{V_{p\text{-}p}}$ level provided an uncertainty of 5×10^{-8} $(k = 1)$ [1]. The concept is to use a sampling digital voltmeter (DVM) connected together with a Josephson waveform synthesizer (JWS) to measure the difference between the generated waveform and the source waveform. For simplicity, we will name this circuit configuration as J4TP-PCC for Josephson four-terminal-pair potential comparison circuit.

By using sampling techniques with DVMs, the uncertainties due to transients can be avoided. Sampling allows measurements to be made in time slices of a "window."

Instead of measuring the whole waveform as it is done with a lock-in amplifier, a sampling DVM such as the Agilent 3458A[1] collects data within a designated period of a given waveform. This method can be simply demonstrated in Fig. 1, where only the windows of the quantized waveform are measured. The grayed-out area containing the unwanted transients of the synthesized waveform can be completely ignored.

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[1] Identification of commercial equipment does not imply an endorsement by PTB or that it is the best available for the purpose.

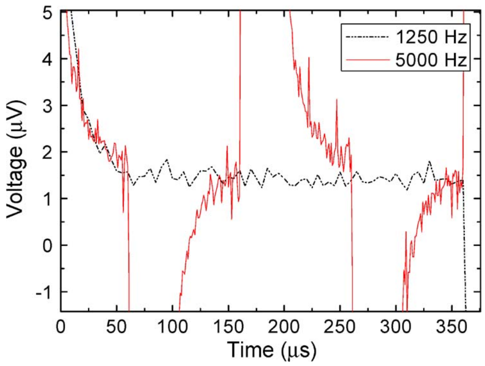

Fig. 2. Time trace of a 5-kHz waveform compared with a 1250-Hz waveform showing that the width of measurable quantized steps reduces as sample frequency increases.

The downside of this method is that the time window accommodating quantized step measurements becomes shorter and shorter as the signal frequency increases. As shown in Fig. 2, the time trace of a 5-kHz sample waveform is compared with a 1250-Hz waveform. The 5-kHz waveform has a narrow measurable width with an aperture time that is less than 20 μs as opposed to the 1250-Hz waveform that allows a long integration time of more than 200 μs.

The long settling time of the transients is caused by the relaxation of the sampling DVM input filters, which are charged by the transients [3]. The settling time limits the sampling rate to 6 kHz in this present setup. This can be improved if the settling time of transients seen by the sampling DVM is shortened or by having a faster analog-to-digital converter with high precision.

A. Experimental Setup and Procedure

The two Josephson systems generate voltage waveforms of the same frequency but opposite polarities to null the voltage difference, which is measured by a sampling DVM. The Josephson voltage amplitudes for each system develop according to $V_{\mathrm{J}} = n\,f/K_{\mathrm{J}}$, where n is the number of Josephson junctions, f is the microwave frequency, and $K_{\mathrm{J}} = 2\mathrm{e}/\mathrm{h}$ is the Josephson constant, which was fixed in 1990 to $K_{\mathrm{J}-90} = 483597.9$ GHz/V.

The system was operated using two NPL Josephson bias electronics [4] and the transmission line method to achieve fast transients without ringing [5].

The pair of two 10-kΩ resistors has been placed in a temperature enclosure, which can be stabilized to about ±1 mK. Measurements of the resistance ratio have been made at 18 frequencies ranging from 25 Hz to 10 kHz. A computer program automatically sets the frequency by changing the repetition frequency of a pulse synthesizer inside the trigger arrangement of the measurement system.

Fig. 3 shows the schematic used for this setup. The JWS$_{\mathrm{source}}$ depicted on the left acts as a source for driving the two standard resistors, whereas the JWS$_{\mathrm{meter}}$ on the right plays the role as a meter for balancing a null on the detector. The JWS$_{\mathrm{source}}$ in this setup uses a stacked Josephson array of 2.4 V [6] and generates 2.4 V$_{\mathrm{p\text{-}p}}$ across both resistors. The null detector connected in between the resistors measures the difference voltage between the source and the JWS$_{\mathrm{meter}}$.

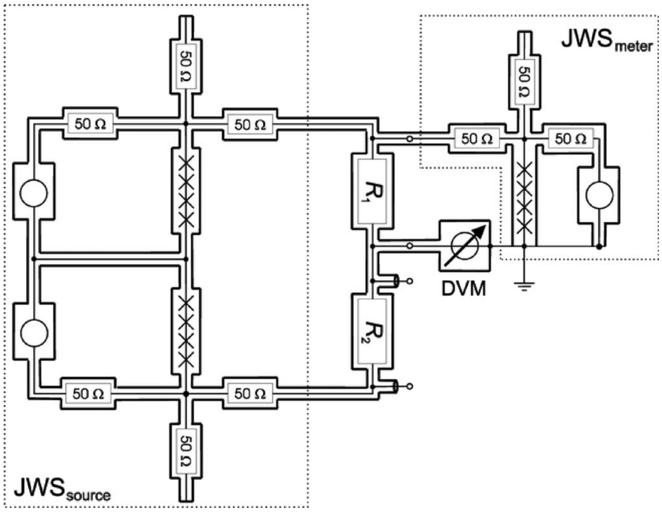

Fig. 3. Schematic diagram of the four-terminal-pair measurement setup using ac-QVM as a potential comparison circuit.

TABLE I

TABLE OF THE FREQUENCIES MEASURED AND THE CORRESPONDING APERTURE TIME USED

Frequency (Hz)	Aperture time (μs)
20	5000
40	2000
139	1000
400	700
1250	200
2500	100
4000	20
6250	10

The Josephson waveform amplitudes and the phase difference between the two systems are adjusted such that the null detector reading is close to zero. Subsequently, a series of measurement parameters are given to the sampling voltmeter for collecting readings at different frequencies. Next, the JWS$_{\mathrm{meter}}$ is shifted, together with the sampling DVM, to the connections of resistor R_2. The same procedure is followed.

The resistance ratios between the standards can be calculated as [7]

$$\frac{R_1}{R_2} = \frac{U_{\mathrm{meter}} - U_{\mathrm{reading}}}{U'_{\mathrm{meter}} - U'_{\mathrm{reading}}} \tag{1}$$

where U_{meter} is the voltage generated by JWS$_{\mathrm{meter}}$, and U_{reading} is the voltage measured by the sampling DVM at the connection to R_1. The prime symbol ($'$) is used to denote the voltages when the ac-QVM is moved to the connection of R_2.

For each measurement frequency, the sampling DVM is programmed with a different aperture time, as given in Table I, since the width of the measurement window decreases with increasing frequency. The highest frequency of 6250 Hz reaches the minimum measurement window time of 10 μs integration time, which is limited by the long settling time that

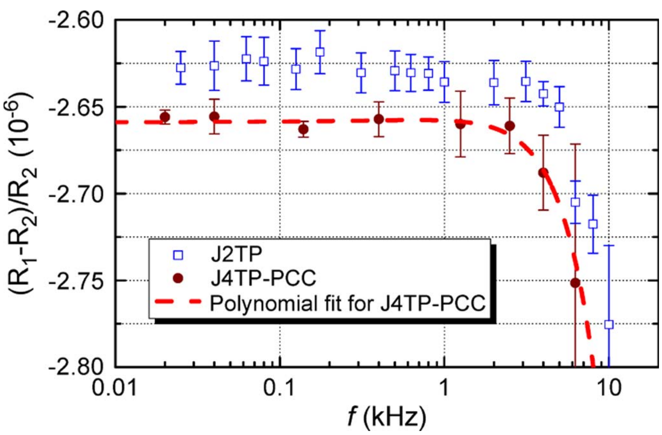

Fig. 4. Preliminary measurement results of the Josephson four-terminal-pair potential comparison circuit (J4TP-PCC), compared with measurement results from the Josephson two-terminal pair impedance (J2TP) bridge.

is experienced by the DVM input filter after the transients (as shown in Fig. 2). The DVM readings are averaged for 2 min.

B. *Results and Discussion*

Fig. 4 shows the measurement results of the J4TP-PCC, as compared with measurement results from the Josephson 2-terminal-pair (J2TP) bridge [8]. Each result point per frequency is the average over ten measurements, of which each single measurement is the reading of the sampling DVM over 120 s. Type-A uncertainties $(k = 1)$ for frequencies below 1 kHz are less than one part in 10^7, which demonstrates a successful outcome for the sampling technique.

The setup as a potential comparison circuit is very good for measuring at low frequencies since the accuracy of the sampling method greatly increases due to longer measuring time on the quantized step. Unlike two-terminal bridges, the J4TP-PCC does not suffer from discrepancies due to contact resistance. However, the limit of this setup is a highest measurable frequency of 6 kHz due to the lack of effective measurement window.

The slight lower shift in the sampling measurements by 3×10^{-8}, compared with measurements made by the J2TP bridge, equates to a change of 0.3 mΩ. The value is reasonable to account for the contact resistances seen in the J2TP bridge. Furthermore, an impedance measurement would be given by

$$Z = \frac{U}{I} = R \cdot (1 + j\omega RC + \omega^2 LC). \qquad (2)$$

The J4TP-PCC setup disregards the measurements from the transients, i.e., it is like a fast-reverse dc measurement that does not measure the last two components $j\omega RC$ and $\omega^2 L$. Therefore, the results previously shown only account for the real component of the resistors.

III. JOSEPHSON FOUR-TERMINAL-PAIR BRIDGE

A. *Experimental Setup and Procedure*

For making a true four-terminal-pair impedance measurement, the whole waveform has to be measured with a lock-in amplifier. One concept is to have a completely symmetrical coaxial bridge circuit. As shown in Fig. 5, each resistor in the coaxial setup has four leads connecting to it, two current leads and two voltage leads, hence fulfilling the four-terminal-pair definition of a resistor. The current-carrying leads of the resistors are the horizontal lines across the resistors, whereas the voltage leads are the vertical lines from the resistors. The two systems JWS1 and JWS2 comprised the same components as $\mathrm{JWS}_{\mathrm{meter}}$ of Fig. 3, which consists of the bias electronics and the 50-Ω resistors for canceling reflections.

Figure 5 shows that the JWS drives the resistors on their current leads with the full array voltage (1.2 $\mathrm{V}_{\text{p-p}}$) and runs half of the array voltage (0.6 $\mathrm{V}_{\text{p-p}}$) on the voltage-sensing leads of the resistors. A switch (Switch 1, Switch 3) is connected to one end of the voltage-sensing leads of a resistor, and an adjustable 10 kΩ is connected to the current lead on the same end of the resistor.

This part of the bridge is balanced by tuning the value of the 10-kΩ adjustable resistor such that the detector (lock-in amplifier) registers no change when opening or closing Switch 1. At this point, there will be no current on the voltage lead, as indicated in the schematic diagram $(i = 0)$. The same situation applies after balancing the loop on the side of JWS2 using Switch 3.

At the center of the bridge, a similar approach is applied by using a Kelvin Double Bridge [9]. A switch (Switch 2, which is normally closed) is installed between the potential leads of both resistors, and a pair of 100 Ω is connected in the loop to the lock-in amplifier. This section of the bridge is balanced in the same manner as above: the adjustable 100 Ω is tuned to a value at which opening or closing Switch 2 does not cause a change in the lock-in reading. When this is achieved, the impedance of the coaxial cable connecting the current terminals of R_1 and R_2 between points A and B will not affect bridge accuracy.

Since both Josephson arrays are set in two different Dewars and attached to two different cryoprobes, there are dissimilarities in the resistances of the outer-conducting cables on the probes. We measured the resistances of the outer conductors on the two cryoprobes to approximately 500 mΩ. Assuming a 2% difference on the resistances of the cryoprobes, together with a 50-μA current flowing in the system, results in 10 mΩ $\times$ 50 μA$/0.6$ V $=$ 833 nV/V, which is a huge difference compared with the uncertainty that is aimed to be at the nanovolt level. This problem can be solved in two ways: by either ensuring no resistance differences on the cryoprobes or performing a reversal by swapping the two JWS.

When all balancing conditions are met, the lock-in amplifier measures voltage in a forward configuration. A following reversal is made, and the bridge has to be rebalanced once more due to the differences in the 50-Ω resistors. The ratio of R_1 and R_2 is calculated using the equation given in the J2TP bridge [8], i.e.,

$$\frac{R_1 - R_2}{R_2} = \frac{1}{2}\left[2 - \left(\frac{U_2}{U_1} + \frac{U_\mathrm{F}}{U_1} + \frac{U_\mathrm{F}}{U_2}\right) - \left(\frac{U_2'}{U_1'} - \frac{U_\mathrm{R}}{U_1'} - \frac{U_\mathrm{R}}{U_2'}\right)\right] \qquad (3)$$

where $U_i = U_{\mathrm{J}i} - U_{\mathrm{RJ}i}$, and $U_{\mathrm{J}i} = (4/\pi) \cdot (f_i/K_{\mathrm{J-90}}) \cdot 8192$ $(i = 1, 2)$. U_{J1} and U_{J2} represent the amplitude of the

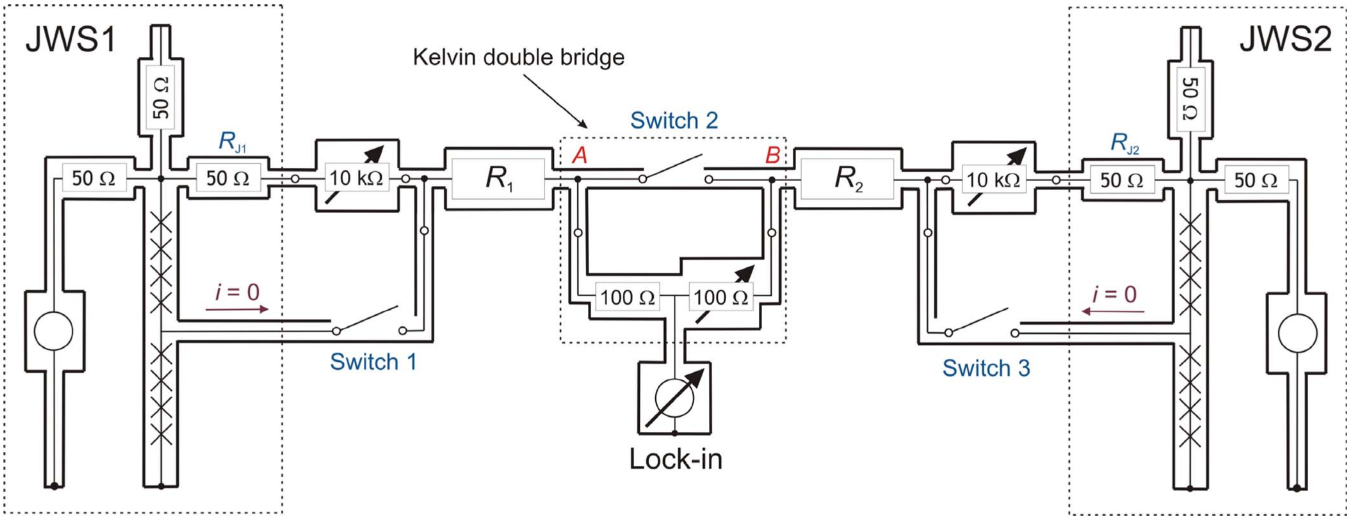

Fig. 5. Schematic of the four-terminal-pair bridge using the lock-in amplifier.

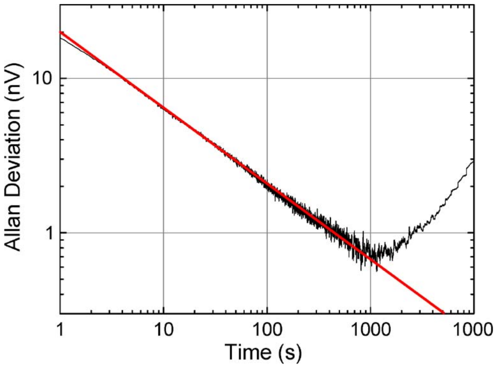

Fig. 6. Allan deviation for measurements made on the four-terminal-pair coaxial setup.

fundamental generated by the Josephson systems 1 and 2, respectively. U_{RJ1} and U_{RJ2} denote the voltages across the 50-Ω resistors connected to the voltage lines for the reflection compensation connection. The unprimed and primed symbols correspond to the *forward* and *reverse* connections, respectively. U_{F} is the lock-in voltage for the *forward* connection, and U_{R} is for the *reverse* connection.

The phase of both systems has to be very precisely aligned for two reasons. Transients between the two Josephson systems are different in terms of ns-resolution and require proper timing. Moreover, the two resistors to be measured, i.e., R_1 and R_2, can have a small but different parallel capacitance, causing a phase shift. For the phase adjustment, we used a computer-controlled delay with 250-ps resolution. At the highest frequencies in the kilohertz range, we added a manual coaxial delay having a resolution of about 10 ps.

Preliminary Allan deviation of this setup shows promising results: Fig. 6 shows 200 000 readings taken every 100 ms. The graph indicates that measurements follow the white noise well into 1000 s (17 min) with an Allan deviation value of less than 1 nV. This is strong proof that the setup is very stable and that it exhibits great potential to achieve measurement accuracies of at least a factor of 10 better than the J2TP bridge, even though manual balancing of the bridge may be unavoidable.

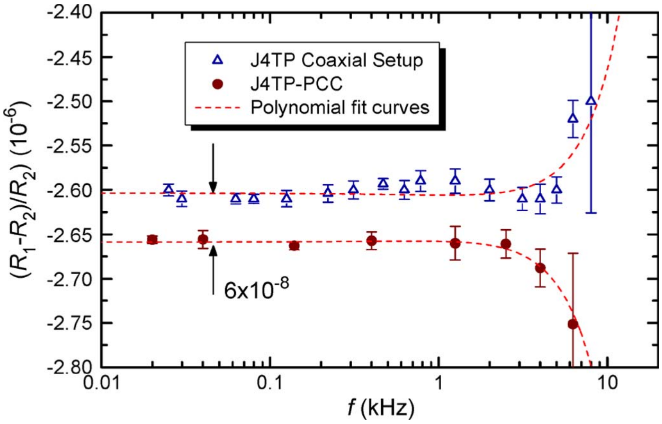

Fig. 7. Preliminary results of the four-terminal-pair coaxial circuit, compared with results of the potential comparison method. Error bars show type-A uncertainty.

B. Results and Discussion

These preliminary results of the four-terminal-pair coaxial circuit shows agreement with the J4TP-PCC setup to about six parts in 10^8 for frequencies below 5 kHz, while it clearly revealed a systematic error within the setup (Fig. 7). The type-A uncertainties at frequencies below 5 kHz are, on average, at 10^{-9} levels $(k = 1)$. The unexpected change in frequency dependence at high frequencies may be due to the strong influence of the transients when balancing the bridge.

Another reason is that, due to the mismatched resistance in the cryoprobe cables, the setup does not have equal and opposite currents flowing through the system. Current equalizers are commonly installed on conventional bridges to achieve equal and opposite current flowing between the inner and outer conductors. However their influence on the transients needs to be evaluated before they can be used in this setup. Hence, this may cause the setup to collect electrical or magnetic interferences from the environment resulting to the systematic error seen in the graph.

One of the challenges faced is that, when opening the switches for balancing, there are large reflections in the system. Transients of the generated waveforms become at least ten times larger and hence contribute large errors when measuring at high frequencies. This probably is the reason for the inconsistency seen in the frequency dependence that is determined by the bridge.

Investigation of the four-terminal-pair coaxial configuration remains with preliminary examinations so far. It has the potential of uncertainties to reach lower than 10^{-9} as soon as the type-B errors are figured out. Further observation will be required, such as the bridge sensitivity, pinpointing the sources of system offsets and minimizing the resistance differences between the outer conductors of the two JWS.

IV. CONCLUSION

For four-terminal-pair Josephson bridges, the potential comparison setup determines the resistance ratios to a few parts in 10^8 in the frequency range below 10 kHz and a factor of 3 better for frequencies below 1 kHz.

The four-terminal-pair coaxial circuit setup has the ability to evaluate the complex impedance of the resistance standards. It shows an agreement with the results from the potential comparison setup to about six parts in 10^8, whereas more investigations have to be made to understand the type-B errors and the deviation between the two different four-terminal setups. The coaxial circuit setup has been shown to be very stable with a type-A uncertainty below 10^{-9} (Fig. 6), so that, once the problems are solved, there is great potential for reaching very good overall uncertainties.

The measurement results in this first application of the four-terminal Josephson bridges show an uncertainty almost as small as that from conventional impedance bridge setups. In addition, impedance measurements can be made at arbitrary frequencies in a wideband range from dc to 10 kHz, compared to conventional bridges with frequencies ranging from 500 Hz to 10 kHz. Furthermore, the four-terminal-pair potential comparison circuit setup will allow semi-automated operation at this level of uncertainty. The measurements presented were made by a predetermined program sweeping through the desired frequency and phase ranges.

In summary, it has been proven that the Josephson impedance bridges are capable of performing impedance ratios measurements almost as accurately as conventional bridges over a wider frequency range. Although the new Josephson impedance bridge technique is still in an early development stage, it has proven its potential for applied and fundamental ac impedance metrology. For instance, the new Josephson bridge technique may provide an independent way of realizing the link between the farad and the ohm, which was shown recently using the ac quantum Hall effect and conventional impedance bridges [10].

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REFERENCES

[1] R. Behr, L. Palafox, G. Ramm, H. Moser, and J. Melcher, "Direct comparison of Josephson waveforms using an AC Quantum Voltmeter," *IEEE Trans. Instrum. Meas.*, vol. 56, no. 2, pp. 235–238, Apr. 2007.

[2] C. A. Hamilton, C. J. Burroughs, S. P. Benz, and J. R. Kinard, "AC Josephson voltage standard: Progress report," *IEEE Trans. Instrum. Meas.*, vol. 46, no. 2, pp. 224–228, Apr. 1997.

[3] W. G. Kürten Ihlenfeld, E. Mohns, R. Behr, J. M. Williams, P. Patel, G. Ramm, and H. Bachmair, "Characterization of a high-resolution analog-to-digital converter with a Josephson ac voltage source," *IEEE Trans. Instrum. Meas.*, vol. 54, no. 2, pp. 649–652, Apr. 2005.

[4] P. Kleinschmidt, P. D. Patel, J. M. Williams, and T. J. B. M. Janssen, "Investigation of binary Josephson arrays for arbitrary waveform synthesis," *Proc. Inst. Elect. Eng.—Sci. Meas. Technol.*, vol. 149, no. 6, pp. 313–316, Nov. 2002.

[5] J. M. Williams, D. Henderson, P. Patel, R. Behr, and L. Palafox, "Achieving sub-100-ns switching of programmable Josephson arrays," *IEEE Trans. Instrum. Meas.*, vol. 56, no. 2, pp. 651–654, Apr. 2007.

[6] F. Müller, R. Behr, R. Wendisch, J. Kohlmann, D. Olaya, P. Dresselhaus, and S. P. Benz, "Arrays with double-stacked NbxSi1-x-barrier junctions for use in programmable Josephson voltage standards driven at 70 GHz," in *Proc. 12th Int. Superconductive Electron. Conf.*, 2009, HF-O4, 3 p.

[7] R. Behr, T. Funck, B. Schumacher, and P. Warnecke, "Measuring resistance standards in terms of the quantized Hall resistance with a dual Josephson voltage standard using SINIS Josephson arrays," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 2, pp. 521–523, Apr. 2003.

[8] J. Lee, J. Schurr, J. Nissilä, L. Palafox, and R. Behr, "The Josephson two-terminal-pair impedance bridge," *Metrologia*, vol. 47, no. 4, pp. 453–459, Aug. 2010.

[9] R. Hanke, "Precise Kelvin double bridge for measuring dissipation factors and capacitances up to 1 F," *IEEE Trans. Instrum. Meas.*, vol. IM-27, no. 4, pp. 434–436, Dec. 1978.

[10] J. Schurr, V. Bürkel, and B. P. Kibble, "Realizing the Farad from two quantum Hall resistances," *Metrologia*, vol. 46, no. 6, pp. 619–628, 2009.

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