Toward a Programmable HTS Josephson Voltage Standard: Recent Results


Abstract—This paper summarizes recent results of our work toward a voltage standard based on a high-temperature superconducting (HTS) Josephson junction array. The concept of a programmable HTS voltage standard and technological aspects of its fabrication are discussed. New circuits providing uniform microwave current distribution along the HTS array are described.

Index Terms—High-temperature superconductors, Josephson arrays, voltage measurements.

I. INTRODUCTION

A NEW type of voltage standard for fast dc measurements was recently demonstrated with niobium Josephson junctions having a nonhysteretic current–voltage characteristic [1]. Such junctions are naturally available in HTS technology, which could make it possible to create similar voltage standards operating at liquid nitrogen temperatures. Of all known HTS Josephson junction types bicrystal junctions are best suited for voltage standard applications [2]–[5].

The many junctions of a programmable array must be biased on a step with the same index \( n \) at a common dc and microwave current. The weakest point of this approach is the need for:

1) narrow spreads of junction critical current \( I_c \) and normal resistance \( R_n \);
2) uniformity of RF current distribution along the array.

Let the spread of the critical current \( \delta I_c = I_{c,\max}/I_{c,\min} \), where \( I_{c,\max} \) and \( I_{c,\min} \) are the maximum and the minimum critical currents and let the spread of the normal resistance \( \delta R \) be defined correspondingly. Unfortunately, \( \delta I_c \) and \( \delta R \) are larger than 2, which makes it difficult to attain synchronization in series arrays.

Here, we summarize the results of our work toward a HTS programmable voltage standard. We focus on an approach to decrease the dependence of external frequency locking upon \( \delta I_c \) and \( \delta R \) in large series arrays. The concept of a converter using two constant voltage steps is presented and technological aspects of operation at liquid nitrogen temperatures are considered. A microwave circuit providing uniform ac power distribution along a series HTS junction array is described.

II. CONCEPT OF A PROGRAMMABLE VOLTAGE STANDARD

In series connected junctions, the amplitude of the microwave induced array current step should be relatively insensitive both to variations of junction parameters and to microwave current amplitude. For a given operating frequency, the design task for a single junction reduces to the selection of optimum values for the critical current, resistance, and step index to maximize the resultant current step amplitude.

A. Bicrystal Junction Design

The spread in normal resistance can be reduced by an external shunt resistance \( R_s \). Previously, we have shown theoretically and experimentally that, when using an additional external shunt resistance, one can tolerate a large spread in critical currents and considerably extend the frequency locking range in series arrays [6]. The first current step with height \( \Delta I_1 \) of the order of the array critical current \( I_{c,\min} \) can then be obtained at optimal microwave power and normalized frequency \( \Omega \equiv f/K_J I_{c,\max} R_s \geq 1 \), where \( K_J = 483.5979 \) GHz/V is the Josephson constant. To determine the maximum admissible spread of critical currents \( \delta I_c \), one has to consider the dependence of current step amplitude on microwave bias \( I_{m,f} \) in the array for \( \Omega > 1 \), which is shown in Fig. 1. From this figure it can be seen that
amplitudes of the zeroth \((n = 0)\) and the first \((n = 1)\) steps are comparable with critical current simultaneously when \(\delta i_{rf} = I_{rf}/I_c\) is in the range of 1.25 to 1.6. Appropriate spread in normalized microwave currents \(\delta i_{rf} = i_{rf,max}/i_{rf,min}\) is \(\delta i_{rf} \leq 1.3\). Here, \(i_{rf,max}\) and \(i_{rf,min}\) are the maximum and the minimum normalized microwave currents in the series array. However, the employment of only the first constant-voltage steps considerably relaxes the requirement for the uniformity of \(\delta i_{rf}\). For example, for \(\Delta I_f \approx I_c\) the admissible value of normalized microwave current is \(\delta i_{rf} \leq 2\) (Fig. 1). Moreover, this value increases up to \(\delta i_{rf} \leq 6\) for \(\Delta I_f \approx 0.5I_c\). With regard to \(\delta i_{rf} = \delta I_f/\delta I_c\), we can expect that with a relatively uniform \(I_{rf}\) distribution \((\delta I_{rf} \leq 2)\) \(\delta I_c\) could be as large as 3. In fact, such a value of \(\delta I_c\) can already be realized in the modern HTS technology. This was confirmed by experiment in shunted bicrystal junction arrays, where only first constant-voltage steps were obtained for \(\delta I_c \leq 3\) [6].

B. Series Array Design

Hamilton et al. [7] demonstrated a programmable voltage standard, based on niobium junction arrays, in which three constant voltage steps \(n = 0, \pm 1\) were used. The array for an \(m\)-bit converter was divided into \(m\) sections containing a binary sequence \((1, 2, 4, 8, \ldots, 2^{m-1})\) of Josephson junctions. The total number of junctions in the array was \(N = 2^{m-1}\). By applying bias currents to the appropriate set of sections, arbitrary voltages with amplitudes not exceeding \(N_f/K_f\) in steps of \(f/K_f\) were obtained.

The utilization of two instead of three quantum steps requires a new slightly different series array circuit design which is shown in Fig. 2 [8]. The \(N = 2^m\) junctions in the array are divided into \(m + 1\) segments (bits). The number of junctions in the first \(m\) segments, including the most significant bit (MSB) of the array corresponds to the binary code \((1, 2, 4, 8, \ldots)\). The last \((m + 1)\) segment consists of only one junction. Zero voltage can be achieved if the MSB is biased oppositely to all the remaining segments. By changing the code of the first bits, one can get any desired voltage in steps of \(2_f/K_f\). The sign of the output voltage is defined by the MSB, and the additional bit has the opposite sign.

III. SHUNTED BICRYSTAL JUNCTION ARRAYS AT LIQUID NITROGEN TEMPERATURES

We have investigated arrays made by meandering Au–YBa2Cu3O7 bilayer strips across the grain boundary (GB) in yttria-stabilized-zirconia (YSZ) bicrystal substrates. To increase the number of junctions in the array, substrates with two parallel grain boundaries were investigated [8]. Microbridges, patterned with a width \(w = 4 \mu m\) across the grain boundaries thus forming Josephson junctions. Arrays of 730 shunted junctions were fabricated. From the measurements of \(I-V\) curves of short subarrays, we estimated that the total spread of critical currents \(\delta I_c\) was not more than 2, which is also typical for bicrystal junction arrays with one grain boundary.

For microwave measurements, samples were mounted in the center of a rectangular reduced-height waveguide section. This section was connected via a matching transition to a standard waveguide. The microwave setup allowed us to carry out the measurements in the frequency band of 15 to 27 GHz. A subarray containing 154 Josephson junctions was synchronized by the external microwave current. As shown in Fig. 3, current steps at voltages of 4.92 mV and at temperatures about 83K were observed. For a frequency of 15.45 GHz, the average shunted resistance was equal to 0.1 \(\Omega\), and the average critical current was \(I_c = 0.15 \text{ mA}\), thus giving a normalized frequency \(\Omega \approx 2\). For these values of \(\Omega\), the height of the first current step should be of the order of \(I_c/2 = 0.13 \text{ mA}\) in the subarray. However, we measured \(\Delta I_f \approx 0.04 \text{ mA}\) (Fig. 3) to be a factor three smaller than \(I_c/2\). As shown below, this could be explained by the inhomogeneous distribution of the microwave current in the subarray.

For the frequency range used, and for a YSZ substrate with a permeability \(\varepsilon \approx 27\), \(\lambda/4 \approx 1.35 \text{ mm}\) where \(\lambda\) is the wavelength. This is to be compared with the length of the subarrays, which is \(\lambda/2.25 \text{ mm}\) for 154 junctions laid out on two grain boundaries. In this case, the microwave current amplitude was likely to change considerably over the subarray length, thereby reducing the step height below \(I_c/2\).

In order to evaluate the influence of thermal noise, another possible factor suppressing the step height, we have performed numerical simulations of current steps in our junctions using...
the resistively shunted junction (RSJ) model and including noise. It was shown that the measured current step height could not be sufficiently reduced in the conditions in which the experiment was performed. Moreover, when the temperature was decreased, i.e., with less noise present, the \( n = 1 \) steps even disappeared. This supports the view that thermal noise is not the reason for step height suppression. Hence, the nonuniformity of the microwave current remains the only plausible cause of the suppression. Future designs must therefore focus on achieving microwave bias uniformity.

IV. NEW MICROWAVE CIRCUIT FOR VOLTAGE STANDARD

In low-temperature standards, a straight-line series array of Josephson junctions is placed in series along either a microstrip line (MSL) [9] or the center conductor of a coplanar wave guide (CPW) [10]. The propagating electromagnetic wave drives the arrays containing up to several thousand junctions. In contrast, the series array of bicrystal junctions is laid out as a meander line. This prevents the uniform distribution of ac current along such an array. To overcome this drawback we decided to place the meander array parallel to the usual superconducting MSL or CPW. This should provide parallel feeding of microwave power to all junctions. Two types of microwaves circuits based on this idea were designed and investigated.

Fig. 4(a) shows schematically a part of the microwave circuit in which a CPW feed line is placed parallel to a meander line with Josephson junctions (between lines 1 and 2). The narrow outer conductor of the CPW line generates a magnetic field used to feed the Josephson array. Each meander contains two superconducting loops, one of which forms a \( \lambda/2 \) resonator with short circuits on both ends. In this resonator the microwave current driving the junctions is induced. The Nb shunt at line 3 is used as a dc block. The \( \lambda/4 \) resonators between lines 2 and 3 transform this microwave short to a microwave open circuit, which is needed to avoid induction of undesired resonances in the second loop of each meander. The decoupling of junctions from each other as well as insensitivity to the connected multiple dc bias leads can be expected.

Fig. 4(b) shows the simulated dependence of the microwave currents on the irradiation frequency of each of eight junctions in a meandered series array placed parallel to the CPW. \( I_{C_{\text{CPW}}} \) is the full microwave current in CPW.

Fig. 5. Second type of microwave circuit. The inset shows the meander line of junctions (1), running along the substrate grain boundary (GB) and being placed parallel to the inner edge of the outer conductor of a CPW feed line (3) (see Section IV).

A second type of new circuit is shown in Fig. 5. A 3 \( \mu \text{m} \) wide meander line containing the Josephson junctions, [(1), see inset], and being connected with \( \lambda/4 \) microstrips (2), is placed in the immediate proximity of the inner edge of a wide outer conductor of the CPW line (3). The microwave currents running through the inner edge generate a magnetic field used to feed the Josephson array. The outer normal metal conductor of the CPW, (4), is insulated from the superconducting layer, and serves as a ground plane for the \( \lambda/4 \) microstrip line. The \( \lambda/4 \) microstrips are used as a dc block. For dc connection, some \( \lambda/4 \) resonators were constructed with band stop filters...
(BSF) (5). This circuit was designed for a drive frequency \( f \approx 25 \text{ GHz} \) and was investigated experimentally.

Circuits consisting of 256 shunted bicrystal Josephson junctions and divided into eight subarrays were manufactured. Such a circuit represents a seven bit digital-to-analog converter. The junction array, the \( \lambda/4 \) microstrips, and the 88 \( \mu\text{m} \) wide central conductor of the 50 \( \Omega \) CPW were made from a Au–YBa\(_2\)Cu\(_3\)O\(_7\) bilayer. Thin films of Au were used for the ground conductors of the CPW. As an insulator a 1 \( \mu\text{m} \) thick SiO film was deposited. In microwave measurements a semirigid coaxial cable coupled the microwaves from room temperature to the microwave probe. BeCu probe tips contacted the Au covered conductors of the CPW on the chip, which was placed in the liquid nitrogen. The CPW was terminated with a 50 \( \Omega \) load.

Short subarrays were used as detectors to evaluate the uniformity of microwave current distribution along the array. The detectors A and B consist of two Josephson junctions, and detector C of eight Josephson junctions (Fig. 5). The distance between detectors A and B was approximately 1.7 mm, and between B and C approximately 2.7 mm. Fig. 6(a) shows the current–voltage characteristics without microwave irradiation for the detectors A, B, and C. Fig. 6(b) shows the \( I-V \) curves for the same detectors measured simultaneously at the same dc bias, microwave power, and the same frequency of 26.54 GHz. These measurements confirm that the investigated microwave circuit provides a high microwave current uniformity along the distance of \( L > \lambda \).

**ACKNOWLEDGMENT**

The authors wish to thank A. I. Braginski for discussions and support. They also wish to thank R. Semerad and W. Prusseit for preparing the YBCO–Au bilayer.

**REFERENCES**


Alexander M. Klushin was born in Gorky, Russia, on January 29, 1946. He received the Dipl.-Radiophys. and Cand. Sci. degree in physics and mathematics from Gorky State University in 1969 and 1985, respectively. He joined the Institute of Electronic Measurement “KVARZ,” Nizhny Novgorod, Russia, in 1969. Since 1993, he has been working as a Guest-Scientist in the Institute of Thin Film and Ion Technology (ISI) at the Research Center, Jülich, Germany. His current research interest is the work with high-Tc Josephson junction arrays for voltage standard. He has authored 44 publications and holds six patents.

Clemens Weber was born in Cologne, Germany, on January 22, 1971. He studied physics at the University of Cologne and received the diploma degree in 1996. Since 1995, he has been working in the field of high-Tc superconductivity (HTS) in the Institute of Thin Film and Ion Technology (ISI), Research Center, Jülich. He investigated ion-implantation techniques for Josephson junction fabrication and now works on metrological applications of HTS-arrays.

Solomon I. Borovitskii was born on September 25, 1921. He received the Cand. Sci. degree in physics and mathematics from Gorky State University, Gorky, Russia, in 1950. His main scientific interests are in cryoelectronics.

Ruslan K. Starodubrovskii graduated from Gorky State University, Gorky, Russia, in 1959. He is a Doctor of Technical Sciences and works as a Section Manager in the Institute of Electronic Measurement “KVARZ,” in Nizhni Novgorod, Russia. His research interests involve creating and developing microwave and mm-wave components, integrated circuits and devices. He holds 20 patents.

Andreas Lauer was born in Duisburg, Germany, on December 15, 1966. He received the Diploma degree from Duisburg University in 1992. He is now with the RF Circuits and Systems Department, Institute of Mobile and Satellite Communication Techniques, Kamp-Lintfort, Germany. His research interests are electromagnetic simulations (FDTD, MOM, etc.), microwave propagation, antennas, waveguides, electromagnetic theory, etc.

Ingo Wolf (M’75–SM’85–F’88) was born in Köslin, Germany, in 1938. He studied electrical engineering at the Technical University of Aachen and received the Dipl.-Ing. degree in 1964. In 1967, he received the doctoral degree, and in 1970, the habilitation degree from the same university. From 1970 to 1974, he was a Lecturer and Associate Professor for high-frequency techniques in Aachen. Since 1974, he has been a Full Professor of electromagnetic field theory at the University of Duisburg, Duisburg, Germany. His main areas of research are in electromagnetic field theory applied to the computer-aided design of MIC’s and MMIC’s, millimeter-wave components and circuits, and the field theory of anisotropic materials. Since 1992, he has been the Director at the Institute of Mobile and Satellite Communication Techniques (IMST), Kamp-Lintfort, Germany, in parallel to his university position. This institute works intensively in the area of mobile communication techniques, microwave and millimeter wave communication techniques, antenna techniques, and electromagnetic compatibility.

Ingo Wolff (M’75–SM’85–F’88) was born in Köslin, Germany, in 1938. He studied electrical engineering at the Technical University of Aachen and received the Dipl.-Ing. degree in 1964. In 1967, he received the doctoral degree, and in 1970, the habilitation degree from the same university. From 1970 to 1974, he was a Lecturer and Associate Professor for high-frequency techniques in Aachen. Since 1974, he has been a Full Professor of electromagnetic field theory at the University of Duisburg, Duisburg, Germany. His main areas of research are in electromagnetic field theory applied to the computer-aided design of MIC’s and MMIC’s, millimeter-wave components and circuits, and the field theory of anisotropic materials. Since 1992, he has been the Director at the Institute of Mobile and Satellite Communication Techniques (IMST), Kamp-Lintfort, Germany, in parallel to his university position. This institute works intensively in the area of mobile communication techniques, microwave and millimeter wave communication techniques, antenna techniques, and electromagnetic compatibility.

Hermann Kohlstedt was born in Eichenberg, Germany, in 1959. He received the diploma degree in physics at the University of Kassel, Germany, in 1986. From 1986 to 1990, he was with the Institute for Radioastronomy with Millimeterwaves (IRAM) in Grenoble, France. He received the doctoral degree in 1989. From 1990 to 1991, he was with the Advantest Company, Sapporo, Japan. Since 1991, he has been a Scientist, Institute of Thin Film and Ion Technology (ISI) at the Research Center, Jülich, Germany. His main areas of research interest are all niobium tunnel junctions for highly integrated Josephson junction circuits, coupling effects in multilayer niobium junctions, and their application for millimeter and submillimeter wave devices.