Josephson Series Arrays for Programmable 10-V SINIS Josephson Voltage Standards and for Josephson Arbitrary Waveform Synthesizers Based on SNS Junctions

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***Abstract*—Programmable Josephson voltage standards for output voltages up to 10 V have been realized. Binary-divided series arrays consisting of 69 632 overdamped SINIS Josephson junctions have been fabricated using reliable Nb-Al/Al_2O_3 technology (S : Superconductor, I : Insulator, N : Normal metal). Series arrays of about 1000 SNS Josephson junctions were realized as lumped arrays for applications in the Josephson Arbitrary Waveform Synthesizer (JAWS). We suggest a novel scheme for combining the higher voltages generated by the binary-divided arrays with the frequency spectral characteristics of the JAWS, in order to optimize the frequency spectrum of the generated ac voltages.**

***Index Terms*—Josephson Arbitrary Waveform Synthesizer (JAWS), programmable Josephson voltage standards, SINIS and SNS Josephson junctions.**

I. INTRODUCTION

SERIES ARRAYS of underdamped Josephson junctions are successfully used for precision measurements and as primary dc voltage standards in many laboratories around the world [1], [2]. An increasing demand for highly precise ac voltages has stimulated several research programs to develop measurement tools based on Josephson junction series arrays to meet this requirement. Series arrays of the overdamped Josephson junctions, where the number of junctions per segment follows a binary sequence, were suggested and investigated especially for applications at frequencies below about 1 kHz [3], [4]. These arrays are operated by sinusoidal microwaves. A more fundamental approach is based on the overdamped Josephson junctions operated by a train of short pulses [5], [6]. This train of pulses controls the number of flux quanta $\Phi_0 = h/2e \approx 2.07$ μV/GHz transferred through the Josephson junctions at any time, i.e., the output voltage $U(t)$ follows $U(t) = n \cdot \Phi_0 \cdot f_p(t)$, where n denotes the number of flux quanta transferred through the junction by each pulse, h is Planck's constant, e is the elementary charge, and $f_p(t)$ is the pulse repetition frequency at time t.

Both approaches to establish an ac voltage standard have advantages and limitations. Binary-divided arrays are available for output voltages of 1 V or even 10 V [7], [8]. The biasing electronics presently limit the frequencies of the generated ac voltages to about 1 kHz [4]. As the array is operated as a multibit digital-to-analog (D/A) converter, the spectrum exhibits harmonics in addition to the fundamental frequency, depending on the details of the signal generation. The largest harmonics (about 60 dB below the fundamental) appear at frequencies of $(N-1) \cdot f$ and $(N+1) \cdot f$, where f is the frequency of the generated ac voltage and N is the number of samples used for the digital synthesis. On the other hand, pulse-driven arrays of the Josephson Arbitrary Waveform Synthesizer (JAWS) enable spectrally pure waveforms with harmonics suppressed by at least 100 dBc to be generated [6]. Voltages of about 250 mV (zero to peak) were realized [6]; however, a generation of voltages of 1 V or more seems to be very challenging because of the complex pulse operation among other reasons. To ensure a quantized response from the array, the pulse shape must fulfill strict requirements; a low attenuation and a low dispersion transmission line must also be used to connect the array to the pulse generator.

Increasing the output voltage delivered by binary arrays of 14-bit resolution from the currently available 1- to 10-V output would significantly expand their field of application. The developments of these 10-V arrays based on SINIS Josephson junctions and of SNS junction series arrays for the JAWS are described in this paper (S: Superconductor, I: Insulator, N: Normal metal). Furthermore, a possible combination of both systems for an improved ac voltage source is suggested.

II. 10-V SINIS SERIES ARRAYS

Applications of the available 1-V Josephson waveform synthesizer are at present limited to low frequencies—from dc to about 1 kHz. Besides the calibration of the dc voltage reference standards, ac applications have so far included the measuring of ac waveforms, ac power standards, the characterization of analog-to-digital converters, sigma-delta analog-to-digital signal conversion, and the generation of sine-wave signals with known rms values and uncertainties below $1 \cdot 10^{-7}$ for frequencies below 200 Hz. Furthermore, other applications

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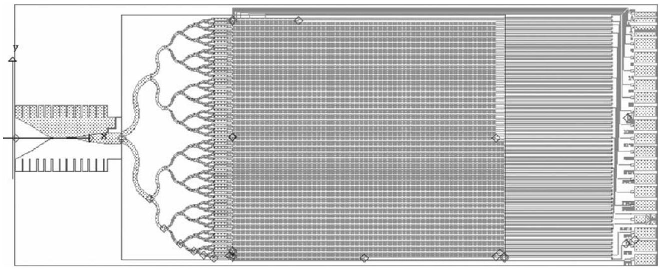

Fig. 1. Design of a 10-V SINIS junction series array with 69 632 junctions integrated into 128 parallel microwave paths. The size of each junction is 12 × 30 μm. The chip size is 10 × 24 mm due to the compact design.

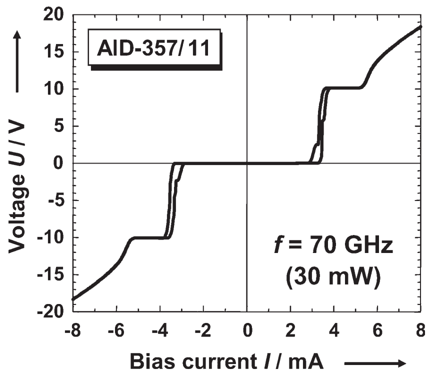

Fig. 2. I–V characteristic of a binary-divided 10-V series array consisting of 69 632 SINIS Josephson junction under a 70-GHz microwave irradiation. A step at the 10-V level is generated. The step width is limited by the available microwave power of about 30 mW at 4.2 K. The whole array is operated by a single bias source.

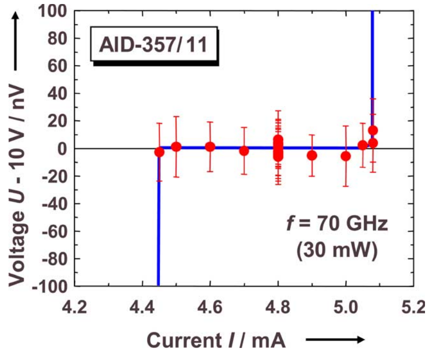

Fig. 3. High-resolution representation of the voltage difference between a binary-divided 10-V SINIS series array and a conventional 10-V SIS Josephson voltage standard. The width of the 10-V step exceeds 625 μA.

that have been performed or proposed with double sine-wave generators, including admittances, in bridges, or dissipation factors, could also benefit from an extension to 10-V amplitude [9]–[11].

The first 10-V SINIS arrays were realized at Physikalisch-Technische Bundesanstalt a few years ago [7]. A step width of about 200 μA and the realization as a 6-bit D/A converter made them suitable for dc applications but not ideal for ac applications, which require wider steps and a higher resolution. To improve the design, the microwave behavior of large SINIS series arrays must be taken into account, i.e., the high attenuation caused by junctions integrated into a low-impedance (5 Ω approximately) microstrip line [12]. The attenuation results in a decrease of the step width with an increasing number of junctions in each of the parallel branches. This behavior was experimentally observed as well as phenomenologically explained initially [13], and more recently by a virtual model [14].

For an optimized 1-V design, this requirement is fulfilled by integrating the 8192 SINIS junctions into 64 parallel microwave branches, each containing 128 junctions [13]. For the new 10-V design, 128 parallel microwave paths were chosen due to the limited microwave power available (typically about 100 mW for 70-GHz Gunn oscillators). As a tenfold increase in the number of junctions is required for generating 10 V compared to 1 V, the number of junctions in each path reaches 562 junctions for the larger segments. The design shown in Fig. 1 contains 69 632 junctions altogether, each having an area of 12 × 30 μm.

Ten-volt SINIS series arrays were fabricated using the reliable Nb/Al-Al_2O_3 technology [15]. They were characterized by dc measurements and under microwave irradiation. A typical current–voltage $(I–V)$ characteristic is shown in Fig. 2. A constant voltage step at the 10-V level is generated under a 70-GHz microwave irradiation. Step widths from 500 to 1000 μA at the 10-V level could be reached for different arrays, which is sufficient for most ac applications. Due to the large critical current density of about 1.1 kA/cm^2, the maximum step width is limited by the available microwave power of about 30 mW at 4.2 K. Investigations of test arrays indicate that the step widths of more than 1 mA should be possible with an adjusted critical current density of about 500 A/cm^2. The constant voltage steps at 10 V were investigated in detail by precision measurements performing a comparison with a 10-V SIS conventional Josephson voltage standard. The 10-V steps of the binary SINIS array are flat with a resolution of better than 5 nV, as shown in Fig. 3, for a 625-μA wide step. An initial direct comparison of the output voltages of a 10-V SIS conventional Josephson voltage standard and a 10-V binary SINIS array was made. The output voltages of both arrays agree well at 10 V : $U_{\mathrm{SIS}} - U_{\mathrm{SINIS}} = (1.8 \pm 0.4)$ nV $(N = 64)$. The small deviation of 1.8 nV $(1.8 \cdot 10^{-10})$ could be due to the higher leakage currents in the test cryoprobe used for the 10-V SINIS array during these measurements.

III. SNS SERIES ARRAYS FOR THE JAWS

The complex pulse operation in the JAWS requires that the microwave behavior of the series arrays be optimized. The generation of bipolar voltages using a pulse-driven array is possible using bipolar drive pulses. These bipolar drive pulses can be realized by superimposing a fast digital code and a sine wave with a frequency of about 10 GHz [6]. Balanced photodiodes operated by short optical pulses can alternatively be used, as suggested in [16]. The simplest case for the operation of the Josephson series arrays in the JAWS is when the array can be treated as a lumped impedance element at high frequencies, in this case $\lambda/8$, where λ is the wavelength. Common mode voltages generated by the resistive termination at the end of typical Josephson arrays can be eliminated by a direct grounding of the lumped array at its end [17], [18]. The overdamped

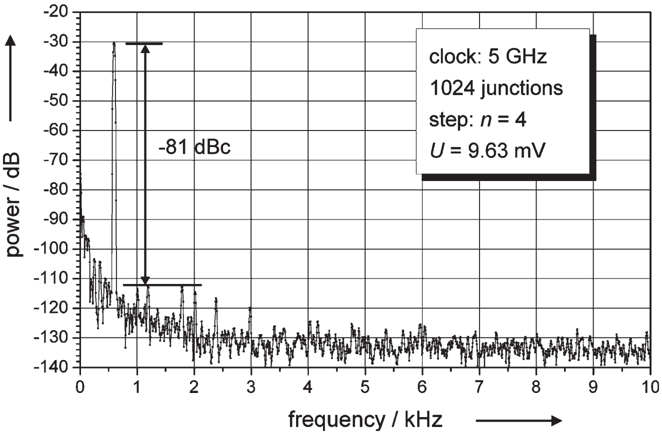

Fig. 4. Frequency spectrum of a 600-Hz synthesized sine wave. The clock frequency of the pulse pattern generator is 5 GHz (i.e., the highest pulse repetition frequency is 2.5 GHz). The array consists of 1024 SNS junctions having a size of 0.8×1.7 μm operated at the fourth step resulting in a voltage of about 10 mV (peak to peak). Higher harmonics are suppressed by more than 80 dBc.

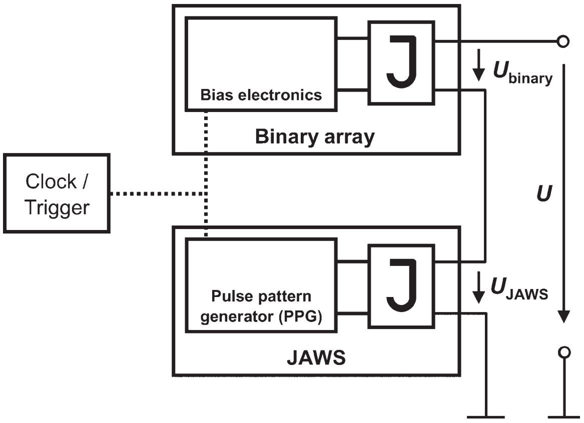

Fig. 5. Scheme of the novel instrument for combining the voltage of 1 or 10 V generated by binary-divided arrays and the frequency spectral characteristics of the JAWS. The spectrum of the JAWS is adjusted to modify the spectrum of signal of the binary-divided array resulting in the output voltage U. "J" represents the Josephson junction series arrays, a 1- or 10-V binary-divided array and a JAWS array, respectively.

Josephson junctions can be fabricated with SNS [5], [6], [19], [20] or SINIS [16], [18] junctions. For SNS junctions, high critical current densities of about 100 kA/cm^2 make junction dimensions below 1 μm possible. A larger number of junctions can therefore be integrated into the limited length of $\lambda/8$.

SNS junctions are integrated into the central line of a 50-Ω coplanar waveguide transmission line. The series arrays are kept shorter than about 1.5 mm, corresponding to $\lambda/8$ for a frequency of 10 GHz. The arrays can therefore be treated as a lumped impedance element. Different designs were developed, e.g., varying the number of junctions from 128 to 2560 and the junction area ranging from 0.2×0.2 μm to 2×2 μm. The filters in the output lines were also varied. The series arrays of the SNS junctions consisting of Nb/HfTi/Nb were fabricated using a new process [21] which combines electron-beam lithography and chemical–mechanical polishing.

The arrays were first characterized by the dc measurements under a continuous microwave irradiation. The arrays showing a small dependence on the microwave frequency were further investigated using a commercial pulse pattern generator. A simple train of pulses at different clock rates is used as a first check for their behavior under pulse operation. Some arrays were then investigated generating sinusoidal ac voltages. Fig. 4 shows the frequency spectrum of a 600-Hz sine wave synthesized in this way. The array consists of 1024 SNS junctions operated on the fourth step, resulting in a peak-to-peak voltage of about 10 mV. Higher harmonics are suppressed by more than 80 dBc, which clearly demonstrates a correct array operation. The transfer of more than one flux quantum per drive pulse through the junctions produces a higher output voltage per junction.

IV. IMPROVED AC JOSEPHSON VOLTAGE SOURCE

Binary-divided 10-V SINIS series arrays have been successfully developed, as well as first SNS series arrays for operation in a JAWS. To take full advantage of these two different Josephson systems, we suggest the combination of a binary-divided array in series with a bipolar pulse-driven JAWS (Fig. 5). The spectrum of the JAWS can be adjusted to modify the spectrum of the 1- or 10-V signal generated by the binary-divided array. By this method, undesired harmonic components are suppressed, or specific ones with known amplitude can be added. It is possible to combine the pure spectrum of the JAWS with the higher amplitudes delivered by the binary-divided series arrays. The generation of ac voltages will be improved by this novel instrument.

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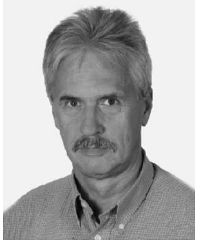

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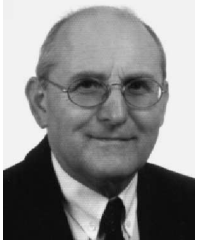

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