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Development of Josephson junction series arrays for synthesis of AC voltages and arbitrary waveforms

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Abstract. Josephson junctions operated by short pulses make the synthesis of AC and arbitrary waveforms possible. Series arrays of intrinsically shunted SINIS and SNS Josephson junctions were developed and characterized for applications in this Josephson arbitrary waveform synthesizer (S: Superconductor, I: Insulator, N: Normal conductor). First measurements under pulse irradiation are presented.

1. Introduction
Josephson junction series arrays are world-wide used for precision measurements and as primary DC voltage standards [1, 2]. The increasing interest in highly precise AC voltages has stimulated different attempts to develop measurement tools on the basis of Josephson arrays for these kinds of applications. A fundamental approach to AC and arbitrary waveform synthesis suggested and demonstrated by S. Benz et al. is based on overdamped Josephson junctions operated by a train of short pulses instead of continuous microwaves [3, 4]. This train of pulses controls the number of flux quanta \( \Phi_0 = h/2e \approx 2.07 \, \mu \text{V/GHz} \) transferred through the Josephson junctions at any time, i.e. output voltage:

\[
U(t) = n \cdot \Phi_0 \cdot f_p(t)
\]

where \( n \) is the number of flux quanta transferred through the junction by each pulse, \( h \) the Planck’s constant, \( e \) the elementary charge, and \( f_p(t) \) the pulse repetition frequency at the time \( t \).

While first measurements of unipolar voltages were demonstrated using unipolar pulses [3, 5], a Josephson arbitrary waveform synthesizer (JAWS) should generate bipolar voltages. The bipolar pulses needed for this can be generated by superposition of a fast digital code of a commercial high-speed code generator and a sine wave with a frequency of about 10 GHz [4, 6]. J.M. Williams et al. suggested an alternative method using photodiodes operated by short optical pulses and demonstrated first measurements using unipolar pulses [7]. For the generation of bipolar pulses balanced photodiodes, one for each polarity of pulses, were proposed.

The overdamped Josephson junctions needed for the operation within the JAWS were realized by intrinsically shunted SNS or SINIS junctions (S: Superconductor, N: Normal conductor, I: Insulator). The junctions were integrated into a 50-Ω coplanar waveguide transmission line [3, 8] or into a coplanar stripline [9]. This paper briefly describes the development of SINIS and SNS junction series arrays for the JAWS performed within the framework of the EU-funded joint project JAWS, cf. [10].

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1385
2. Design and fabrication

The arrays for the JAWS initially aim at voltages of up to 10 mV for generating waveforms in the kHz range. Assuming a maximum pulse repetition frequency of 5 GHz, series arrays consisting of at least 1000 junctions are needed to reach this amplitude. Furthermore, broadband coupling of the pulses from DC to a multiple of the maximum pulse repetition frequency is required to preserve the pulse characteristics. The high-frequency components are important to assure accordingly short rise and fall times of the pulses. As the resistive load at the end of typical Josephson arrays generates common mode voltages, modified arrays or an adapted operation (e.g. AC coupling, cf. [11]) are needed.

The simplest case is when the array of Josephson junctions can be treated as lumped element at high frequencies as suggested by S. Benz et al [12]. The length of the array must be short compared to the wavelength $\lambda$ of the highest significant frequency, typically $\lambda/8$ ($\lambda \approx 12$ mm for a frequency of 10 GHz within a coplanar waveguide transmission line on a Si wafer). For a given junction size, the number of junctions and therefore the output voltage is limited. Common mode voltages are avoided, as lumped arrays are directly grounded at the end. Lumped arrays can directly be irradiated with pulses, and their operation is therefore rather simple.

SINIS junction series arrays were developed for first investigations at PTB [8] and fabricated using the reliable Nb/Al-Al2O3 technology [13]. SINIS arrays offer the advantage of homogeneous critical currents, also in the range below 1 mA, mainly determined by two uniform thermal oxidation processes. These low critical currents fit the optoelectronic measurement set-up developed at NPL very well, as has been demonstrated by first measurements [7]. Nevertheless the rather large junction size of typically 8 µm x 50 µm cannot be reduced significantly due to the moderate critical current densities of SINIS junctions (typically about 100 A/cm²).

Therefore the development of SNS junctions and series arrays was started at PTB [14]. The large critical current densities of more than 100 kA/cm² make junction dimensions below 1 µm possible. Lumped arrays of up to 1000 SNS junctions, producing output voltages of up to 10 mV for 5 GHz pulse repetition frequency, can now be realized. A new process was developed for the fabrication of these arrays [14]. This process combines e-beam lithography and chemical-mechanical polishing (CMP). The SNS trilayers consist of Nb/Hf50wt%Ti50wt%/Nb.

Figure 1 shows the design of 512 SNS junction array as an example. The junctions are integrated into the central line of a 50-Ω coplanar waveguide transmission line (CPW). The length of the series array is 1.5 mm corresponding to $\lambda/8$ for a frequency of 10 GHz. Different designs were developed, varying e.g. the number of junctions, the junction area ranging from 0.7 µm x 0.7 µm to 2 µm x 2 µm, and the filters in the output lines.
Figure 2. Unipolar pulse operation of a lumped array consisting of 100 SINIS junctions. The average voltage is measured as a function of the height of the pulses delivered by a commercial PPG. The pulse repetition frequency is 5 GHz resulting in a voltage of the 1st step of 1 mV. Higher-order steps at multiples of 1 mV are also generated.

Figure 3. Scheme for the experimental set-up of parallel operation of several lumped Josephson arrays by balanced photodiodes in order to increase the output voltage.

3. Results and discussion
The arrays are investigated by DC measurements and under continuous microwave irradiation as a first characterization. Measurements are performed at different frequencies in the range from 5 GHz to 20 GHz as a broadband response of the array is required for pulse operation. Arrays showing a low dependence on the microwave frequency are further investigated under pulse operation using the optoelectronical measurement set-up developed and operated at NPL, UK [7], or a commercial pulse pattern generator (PPG) allowing pulse repetition frequencies of up to 6.25 GHz. Fig. 2 shows an array of 100 SINIS junctions under pulse operation using the commercial PPG. A pulse repetition frequency of 5 GHz results in an output voltage of 1 mV for the 1st step of constant voltage. Besides the first step, higher-order steps are also generated when each pulse transfers two, three, four, or more flux quanta through every junction.

Benz and Hamilton showed by simulations [3] that wide steps of constant voltage can be generated under pulse operation for arrays showing a normalized inverse pulse width of about 1 ( being the pulse width and being the characteristic frequency). For Gaussian pulses, as those from the optoelectronic set-up at NPL [7], the Full Widths at Half Maximum of 75 ps corresponds to a characteristic frequency of about 6.5 GHz (i.e. to a characteristic voltage of about 13 µV, being the critical current of the junctions and being the normal state resistance). The conditions for the operation of arrays by the PPG appear similar. The characteristic voltage of the SINIS array shown in Figure 2 is about 20 µV (corresponding to a characteristic frequency of 10 GHz), showing good agreement with the pulse shape characteristics of the PPG (rise and fall times below 40 ps).

In conclusion, SINIS and SNS junction series arrays for operation in the JAWS have been developed and successfully tested. For these investigations, the arrays were realized as lumped arrays as the direct irradiation of the pulses results in a rather simple operation of the arrays. The optoelectronical version of the pulse generation offers important advantages (cf. [7]). As the optical
connection provides electrical isolation between pulse generator and array, the output voltage can be increased by parallel operation of several Josephson junction series arrays, each operated by a separate balanced photodiode pair. Fig. 3 shows a scheme of the experimental set-up. An output voltage of more than 100 mV should be possible by a single lumped array using thousands of sub-µm SNS junctions integrated into a coplanar stripline (CPS) split into parallel arms [9] and using stacked junctions [15]. Voltages of more than 1 V seem within reach in some years when operating about 10 of these arrays in parallel.

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