Realization of a Quantum Standard for AC Voltage: Overview of a European Research Project

Oleg A. Chevtchenko, Helko E. van den Brom, Ernest Houtzager, Ralf Behr, Johannes Kohlmann,
Jonathan M. Williams, Theodoor J. B. M. Janssen, Luis Palafox, *Member, IEEE*,
David A. Humphreys, *Senior Member, IEEE*, François Piquemal, S. Djordjevic, O. Monnoye, André Poletaeff,
Rado Lapuh, *Member, IEEE*, Karl-Erik Rydler, and G. Eklund

***Abstract*—The European Josephson arbitrary waveform synthesizer (JAWS) project addresses the lack of instrumentation and knowledge for accurate and traceable measurement and generation of alternating (AC) voltage with arbitrary waveforms. The objective is to develop a standard based on a JAWS, a precise instrument that links the generated voltage to the Josephson effect, which in turn relates voltage to fundamental constants and frequency. The standard aims at synthesized voltages up to 10 mV, frequencies up to 10 kHz and uncertainty smaller than 100 μV/V as a first step. This paper reports on the progress in developing the key components for JAWS.**

***Index Terms*—Calculable filter, delta-sigma modulation, Josephson effect, Josephson junction, pulse drive optoelectronics, series Josephson array, tunneling, voltage measurement, voltage standard, voltage synthesis.**

I. INTRODUCTION

THE MAIN technological objective of the Josephson arbitrary waveform synthesizer (JAWS) project is to build an operational JAWS for generation and calibration of arbitrary waveforms and of root-mean-square values in the regime of low frequency and low voltage signals. To this end, three innovative research objectives are pursued, being the realization of new types of Josephson arrays, dedicated pulse drive electronics for the generation of very fast digital codes and signal processing. The last includes modulation of signals, calculable filtering and a special cryostat with a shorter cryoprobe.

The working principle of JAWS is based on a high-speed digital code that is fed to and transformed by a Josephson array for quantum-based accuracy [1], [2]. This code has to be filtered in a calculable way in order to obtain a useful high precision voltage signal. When the Josephson array is biased with repetitive current pulses at a frequency f, the output voltage is

$$V_n = \Phi_0 \cdot N \cdot n \cdot f \tag{1}$$

where $\Phi_0 = h/2e \approx 2.07 \cdot 10^{-15}$ is a magnetic flux quantum, N is the number of junctions in the array, and n is the Shapiro step number. With N and n fixed, the voltage $V_{\rm n}$ depends only on the frequency f.

A Josephson array typically operates at 4.2 K, while both pulse drive electronics and optional at this stage device under test (DUT) operate at room temperature, as seen in Fig. 1. The digital code to and the synthesized signal from the array have to be delivered with minimum error. For this reason steps are taken in the project to minimize the interface error by optimising a cryostat and a cryoprobe.

Highlights of the JAWS project as compared to other studies [1] are SINIS Josephson series arrays, dedicated (opto)electronics that sends a programmable stream of individual current pulses, calculable filters, and a compact cryostat.

II. JOSEPHSON ARRAYS

The Josephson junction series array biased with a stream of current pulses generates voltage pulses with a time integrated area $\mathrm{m} \cdot \Phi_0$ (m is an integer) and, thus, refers the generated voltage to fundamental constants, see (1). A suitable array consisting of overdamped Josephson junctions is a key component of JAWS.

The challenge is to develop a series array integrated into a broadband microwave transmission line and to eliminate any common-mode voltages, which are associated with the termination impedance for the transmission line. The use of SINIS (Superconductor/Insulator/Normal conductor/Insulator/Superconductor) Josephson junctions appears promising [3]. SINIS junctions are intrinsically shunted junctions and show a tunable characteristic voltage $V_{\rm c}$. A typical characteristic voltage for operation in the JAWS is about 20 μV per junction.

To avoid common mode voltages, lumped arrays are developed [4]. These arrays are directly grounded ($R_1 = 50\,\Omega, R_2 = 0$, see Fig. 1). To assure that the input pulses uniformly operate each junction, the length of the arrays is made short as compared to the wavelength of the clock frequency. The array consists of (up to) 240 SINIS junctions integrated into the center line of a 50 Ω coplanar waveguide transmission line. To increase the output voltage, the array can be operated at higher order Shapiro steps.

Manuscript received July 2, 2004; revised November 2, 2004. This work was supported by the European Union as part of the FP 5 under Contract G6RD-CT 2001-00599.

O. A. Chevtchenko, H. E. van den Brom, and E. Houtzager are with the Department of Electricity and Temperature, NMi Van Swinden Laboratorium, Netherlands Metrology Institute, 2600 AR Delft, The Netherlands (e-mail: ochevtchenko@nmi.nl).

R. Behr and J. Kohlmann are with the Physikalisch—Technische Bundesanstalt, D-38116 Braunschweig, Germany.

J. M. Williams, T. J. B. M. Janssen, L. Palafox, and D. A. Humphreys are with the National Physical Laboratory, Teddington TW11 0LW, U.K.

F. Piquemal, S. Djordjevic, O. Monnoye, and A. Poletaeff are with the BNM-LNE/LAMA, 78197 Trappes, France.

R. Lapuh is with the Slovenian Institute of Quality and Metrology, 1000 Ljubljana, Slovenia.

K.-E. Rydler and G. Eklund are with the SP Swedish National Testing and Research Institute, SE-501 15 Borås, Sweden.

Digital Object Identifier 10.1109/TIM.2004.843078

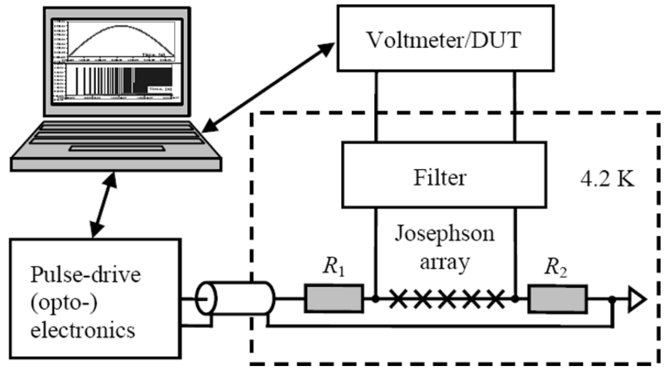

Fig. 1. Layout of the JAWS for lumped Josephson arrays $R_1 = 50\,\Omega, R_2 = 0$ and for distributed Josephson arrays $R_1 = 0, R_2 = 50\,\Omega$.

When operated at a frequency of 5 GHz on the first, second, third, fourth, and fifth Shapiro step, the array generates voltages of about (2, 4, 6, 8, and 10) mV, respectively. In order to achieve the target signal level of 10 mV, longer (distributed) arrays with up to 2000 junctions are also fabricated. In order to assure uniform operation of the junctions, this longer array cannot be directly grounded $(R_1 = 0, R_2 = 50\ \Omega)$, see Fig. 1. Fortunately, there are ways to solve the common mode problem in this case [1], [5]. Different kinds of SINIS arrays were fabricated at PTB using the reliable Nb/Al-Al_2O_3 technology and studied at partner laboratories [3].

III. PULSE DRIVE (OPTO-)ELECTRONICS

Two sets of dedicated electronics have been manufactured for driving JAWS and are described in [6] and [7]. Ultimately, the stream of negative and positive current pulses is needed to drive the array of Josephson junctions in order to generate arbitrary ac waveforms or programmable dc levels [1], [2]. This bipolar pulse stream can be obtained either by combining a digital code with a radio frequency sine wave [1], [6], [7] or by detecting two time-aligned sequences of optical pulses in a balanced pair of photodiodes [2], [6]. In both cases, the contents of a pattern memory are translated into the presence $(\mathrm{memory} = 1)$ or absence (0) of a positive or negative electrical pulse at the output. To retain the JAWS quantum-based accuracy, the pulse parameters must remain within certain boundaries for shape, duration and amplitude [1], [2], [6].

IV. SIGNAL CONDITIONING

Delta-sigma modulation is an efficient technique for high-resolution conversion of low frequency analog signals into stream of two- $(-1, 1)$ [1], [6], [7] or three-level pulses $(-1, 0, 1)$ [2], [6]. The working principle of a first-order delta-sigma modulator is based on an integrator and a feedback loop. The integrator accumulates the difference between the average input and the actual output; eventually the feedback loop will correct for this difference. The transmission of the current pulse stream to and synthesized signal from a Josephson array with minimum error is done via a cryoprobe with coaxial cables, which serves as an interface between the electronics, the array and the DUT.

The demodulation of the synthesized signal is done using a filter. The main objective is to have the filter response calculable. Ideally it should attenuate the modulation residuals completely and at the same time not influence the generated signal. In reality, the influence on the generated signal must be predictable by calculation or by measurement of the filter characteristics. The filter should also minimize the distortion of the input pulses to the Josephson array due to the output cable and the measuring instrument [1]. Various filter schemes have been studied, see results in [8].

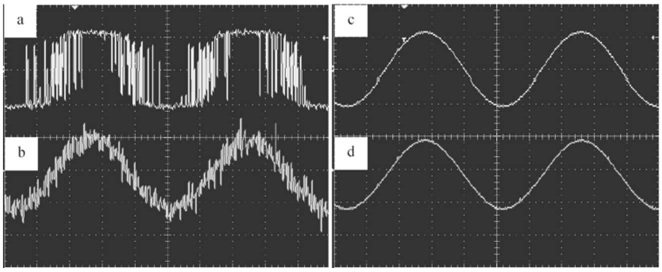

Fig. 2. Synthesis of sinusoidal voltage waveform with 2.1 mV amplitude and 10.4 kHz frequency using JAWS [7]. (a), (c) Measured output signal from the electronics. (b), (d) Voltage response of the Josephson array. (a), (b) Unfiltered and (c), (d) filtered using a simple RC filter with a cutoff frequency around 1 MHz. Vertical axes: voltage on 2 mV/div scale. Horizontal axes: time on 20 μs/div scale.

A dedicated JAWS cryostat has been developed at BNM-LNE (from the concept of a microscope cryostat). It is a continuous helium flow cryostat with a cooling power of 1 W at 4 K and dimensions of about 28 cm × 13 cm × 13 cm. The Josephson array is fixed in a sealed chamber under 20 mbar of helium pressure to ensure thermal contact with the cold plate of the cryostat. The temperature of the array can be monitored at any time using silicon-diode based thermometers. The compact cryostat allows a short cryoprobe (about 15 cm) what reduces the uncertainty in the voltage transmission from the array (down to 1 μV/V at 10 kHz) as well as attenuation and distortion of the code signal to the array.

V. MEASUREMENT AND SIMULATION RESULTS

Various modulation schemes are investigated in order to facilitate the conversion between pulse and waveform [8]. The best results are obtained with a second-order delta-sigma modulator, which shifts modulation and sampling noise to a high frequency region, away from the generated signal frequency [1]. For instance, when using a 10 Gbit/s pulse generator for synthesized signals up to 10 kHz, the noise can be kept below 90 dB up to 30 MHz.

Selected experimental results on the synthesis of sinusoidal and triangular waveform voltages at 10.4 kHz using JAWS are shown in Figs. 2 and 3 (the white square indicates the size of one division). In this case, the electronics combines an RF signal at 10 GHz with the digital code signal [6], [7]. The Josephson array has 100 junctions and it is operated on the first Shapiro step. In these measurements, with no special precautions on filtering one can see a synthesized input and output waveforms both with and without low-pass filtering. The amplitude of the generated waveform after filtering is within a few percent of the expected value of 2.1 mV, Fig. 2(d). More experimental and simulation results for this case are presented in [7], the principle of JAWS was first demonstrated in [1].

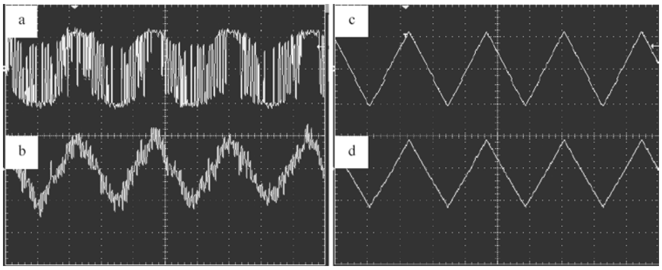

Fig. 3. Synthesis of triangular voltage waveform with 2.1 mV amplitude and 10.4 kHz frequency using JAWS. (a), (c) Measured output signal from the electronics. (b), (d) Voltage response of the Josephson array. (a), (b) Unfiltered and (c), (d) filtered using a simple RC filter with a cutoff frequency around 1 MHz. Vertical axes: voltage on 2 mV/div scale. Horizontal axes: time on 20 ms/div scale.

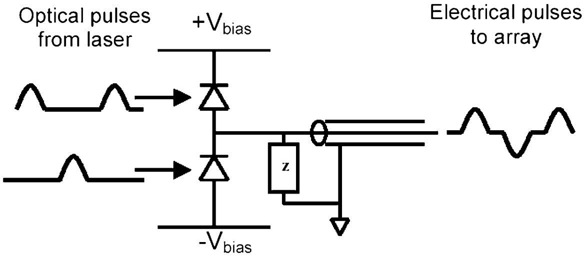

Fig. 4. Schematic diagram coupling of optical pulses to a balanced photodiode to generate bipolar electrical pulses.

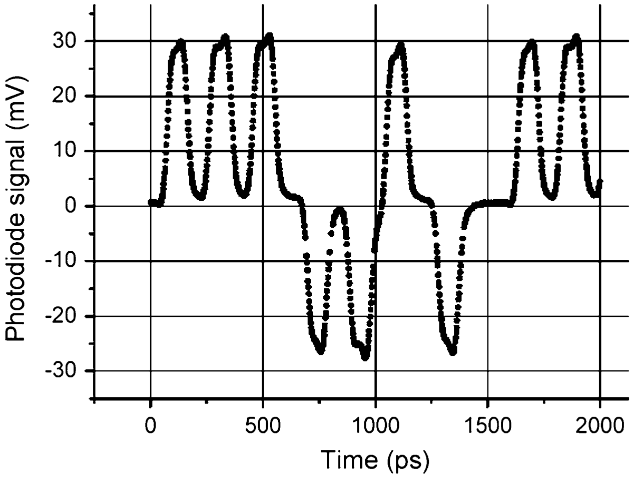

Fig. 5. Bipolar pulse pattern from balanced photodiode.

An initial experiment to bias a lumped array of 100 SINIS junctions with opto-electronically generated pulses has been completed. A schematic diagram of the experimental arrangement is shown in Fig. 4 and illustrates how two optical pulse streams are combined to a bipolar electrical signal using a balanced photodiode. The pulse waveform used for the measurements consisted of four positive pulses and three negative pulses with a pattern repetition frequency of 640 MHz as shown in Fig. 5. The array current-voltage measurement for three conditions of pulse bias is shown in Fig. 6 and demonstrates how a quantized voltage is obtained at zero current bias under pulse bias conditions. The three traces show quantized array voltages at zero current with values of 0.54 mV, −0.40 mV, and 0.14 mV corresponding to the net number of pulses multiplied by the pattern repetition frequency.

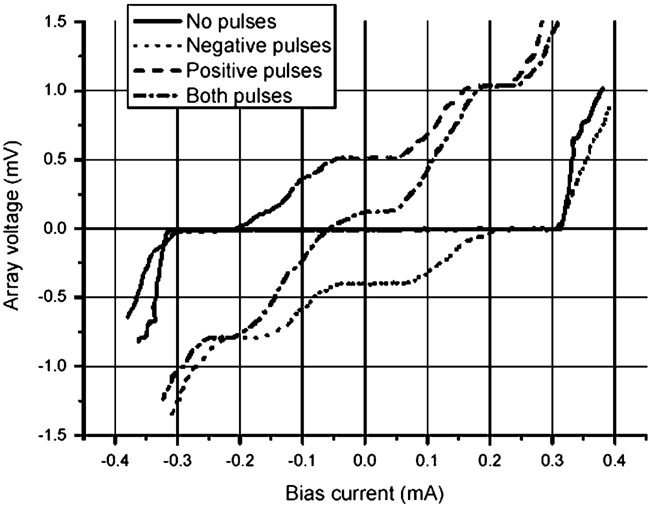

Fig. 6. Array direct current-voltage curves measured under three different pulse bias conditions.

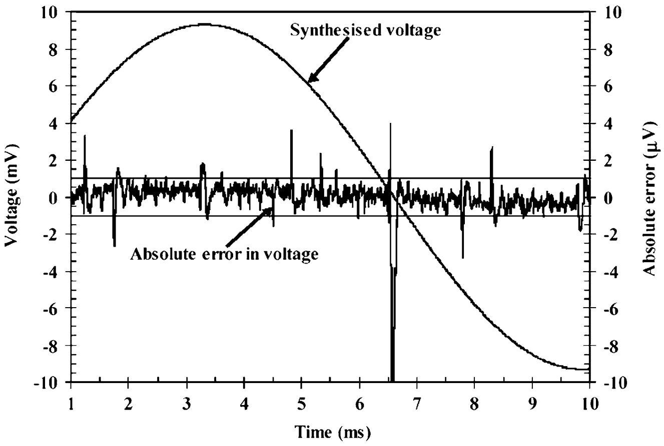

Fig. 7. Simulated synthesis of sinusoidal voltage waveform with 9.3 mV amplitude and 76 kHz frequency using JAWS. The smooth line shows the simulated synthesized with JAWS output voltage (after the filter) versus time. The uneven line shows the absolute error in voltage versus time (right axis).

Results using a numerical model of the complete JAWS circuit (see Fig. 1 and [7]) are shown in Fig. 7. In the example, a sinusoidal waveform with 9.3 mV amplitude and 76 kHz frequency is synthesized with JAWS. The pulse-drive optoelectronics has a return-to-zero data rate of 5 Gbit/s. The first-order delta-sigma representation of the synthesized sine wave consisted of 65 536 points corresponding to a frequency f_0 of about 76.3 kHz. A prefactor equal to 0.9 (of the voltage amplitude value) is used when generating the delta-sigma code in order to avoid long trains of the current pulses. The series Josephson array consists of 1000 junctions and is operated on the first Shapiro step. A simple two-stage $R_{\mathrm{a,b}}C_{\mathrm{a,b}}$ filter with an inductor L in front is used ($R_{\mathrm{a}} = 400\ \Omega; C_{\mathrm{a}} = 100$ pF; $R_{\mathrm{b}} = 100\ \Omega; C_{\mathrm{b}} = 10$ pF, and $L = 10\ \mu$H). The effective resistance of the future DUT (such as a thermal converter, see Fig. 1) is 10 MΩ [8].

The expected voltage in this case is: $V_e = V_{e0}\cdot\sin(2\pi\cdot f_0\cdot t + \varphi_0)$, with amplitude $V_{\mathrm{e0}} = 0.9\cdot V_1 = 9.305\,25$ mV, frequency $f_0 = 76.294$ kHz and phase $\varphi_0 = 0$. However, the filter shifts the phase of the JAWS output voltage by $\varphi_{01} = 0.0216$, see

Fig. 7. The absolute error (defined as the difference between the expected and calculated voltages with the phase corrected by φ_{01}) versus time is also shown in Fig. 7.

The simulation shows that using JAWS with the optoelectronics arbitrary waveform voltages can be synthesized with amplitude of up to about 10 mV and that an error less than the targeted ±100 μV/V should be possible. Further analysis of the data shows that most of the error in Fig. 7 near 6.5 ms comes from imperfections in the delta-sigma code (currently under improvement). More experimental and simulation results when using the pulse-drive optoelectronics are presented in [2], [6], and [9].

VI. CONCLUSION

The European JAWS project aims for the realization of a quantum voltage standard of arbitrary waveforms. The current focus is on testing of four components: new Josephson arrays, dedicated pulse electronics, calculable filters, and compact cryostat with short cryoprobe. The first measurements carried out by the consortium on the JAWS components and on the complete JAWS system are very promising. Further optimization of device parameters and measurement techniques are needed in order to reach the desired accuracy. For more information and current progress of this project, visit: www.jaws-project.nl

REFERENCES

[1] S. P. Benz, C. J. Burroughs, P. D. Dresselhaus, and L. A. Christian, "ac and dc voltages from a Josephson arbitrary waveform synthesizer," *IEEE Trans. Instrum. Meas.*, vol. 50, no. 2, pp. 181–184, Apr. 2001.

[2] J. M. Williams, T. J. B. M. Janssen, L. Palafox, D. A. Humphreys, R. Behr, J. Kohlmann, and F. Muller, "Simulation and measurement of the response of Josephson junctions to optoelectronically generated short pulses," *Supercond. Sci. Technol.*, vol. 17, pp. 815–818, 2004.

[3] J. Kohlmann, R. Behr, F. Müller, D. Hagedoorn, and J. Niemeyer, "SINIS Josephson junction series arrays for operation in the Josephson arbitrary waveform synthesizer," in *Proc. CPEM Conf. Dig.*, 2004, pp. 156–157.

[4] S. P. Benz, P. D. Dresselhaus, and C. J. Burroughs, "Nanotechnology for next generation Josephson voltage standards," *IEEE Trans. Instrum. Meas.*, vol. 50, no. 6, pp. 1513–1518, Dec. 2001.

[5] K.-E. Rydler, V. Tarasso, R. Lapuh, and R. Pajntar, "A method for the dissemination of the ac-voltage of a Josephson arbitrary waveform synthesizer," in *Proc. CPEM Conf. Dig.*, 2004, pp. 162–163.

[6] L. Palafox, E. Houtzager, J. M. Williams, H. E. van den Brom, T. J. B. M. Janssen, and O. A. Chevtchenko, "Pulse drive electronics for Josephson arbitrary waveform synthesis," in *Proc. CPEM Conf. Dig.*, 2004, pp. 160–161.

[7] O. A. Chevtchenko, E. Houtzager, and H. E. van den Brom, "Toward a Josephson arbitrary waveform synthesizer (JAWS): Experiment and simulation," in *Proc. 6th EUCAS Conf. Proc.*, 2004, pp. 2866–2871.

[8] R. Lapuh, R. Pajntar, K.-E. Rydler, V. Tarasso, and J. Stenarsson, "Calculable filter for Josephson arbitrary waveform synthesis," in *Proc. CPEM Conf. Dig.*, 2004, pp. 152–153.

[9] O. Monnoye, S. Djordjevic, P. Cancela, and F. Piquemal, "Generation of constant voltage steps by a Josephson array driven by optoelectronically generated pulses at BNM-LNE," in *Proc. CPEM Conf. Dig.*, 2004, pp. 658–659.