Bipolar Pulse-Drive Electronics for a Josephson Arbitrary Waveform Synthesizer

Helko E. van den Brom, Ernest Houtzager, Bernd E. R. Brinkmeier, and Oleg A. Chevtchenko

***Abstract*—A Josephson arbitrary waveform synthesizer (JAWS) has been developed in order to generate quantum-based ac voltage signals. The key component of this JAWS is a modified commercial 30-Gb/s pattern generator that can generate ternary patterns (containing the values +1, 0, and −1, resulting in bipolar pulses). The new pulse-drive electronics have been successfully tested by driving Josephson arrays with bipolar current pulses from 1 to 30 Gb/s in order to study their current–voltage characteristics and the spectra of the JAWS signals.**

***Index Terms*—AC Josephson voltage standard, Josephson junction array, metrology, pulse-driven Josephson junction, pulse pattern generator.**

I. Introduction

An ELEGANT way of generating quantum-based ac waveforms is by means of driving a Josephson array with individually programmable current pulses. The array transforms the current pulses into voltage pulses with well-defined quantum-based accuracy. The desired waveform to be generated is decoded from the pulse pattern by low-pass filtering. This type of Josephson arbitrary waveform synthesizer (JAWS) is most suitable in generating signals in the frequency range from a few hundred hertz to 1 MHz. The output level V depends on the amount of Josephson junctions, the clock frequency f, and the Shapiro step number n by the relation $V = n \cdot (h/2e) \cdot f$, where h is Planck's constant, and e is the electron charge.

In order to obtain a bipolar waveform using the JAWS mechanism, a three-level code is necessary: The bit stream should contain positive as well as negative pulses, both returning to zero, in order to excite both the $n = +1$ and $n = -1$ plateaus. So far, commercially available pattern generators have two-level outputs, usually with one of the two levels at ground potential.

An effective three-level code has been obtained by means of a two-level code in combination with an RF sine wave [1]–[3] or with a balanced pair of photodiodes [3]–[5]. Both methods are time consuming due to the number of parameters to tune, and consequently, they are expensive. Instead, an existing pattern generator has been modified such that it generates the desired pattern with no further adjustments [6].

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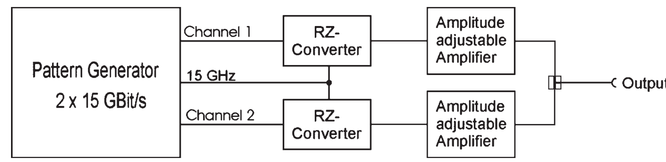

Fig. 1. Block diagram of the data output of the pattern generator modified to drive a Josephson array when used in a JAWS. The two outputs are first converted from NRZ to RZ, amplified with equal magnitude but opposite sign, and then combined.

This paper describes the design of the bipolar pulse-drive electronics and its operation principle. Furthermore, it illustrates the use of the electronics by performing an alternative type of I–V characteristics that is more appropriate in testing pulse-driven Josephson arrays. The measurement results obtained with a complete JAWS based on this pulse-drive electronics are presented elsewhere [7], [8].

II. Pulse-Drive Electronics

A. Modified Pattern Generator

The pattern that is necessary in driving a JAWS is ternary in the sense that each pulse is individually programmable and can take any of the three values: +1, 0, and −1, where zero means no pulse, and the amplitude of the +1 and −1 pulses is adjustable. The pattern generator modified for this purpose is a SYMPULS BMG 30G–64M. It has two differential outputs, with a continuous tunable bit rate from 1 Gb/s to 30 Gb/s. A user-programmable 64-Mb pattern can be loaded to the pattern generator memory via general purpose interface bus (GPIB) or universal serial bus (USB) interfaces. The latest technology, based on integrated circuits in SiGe, InP, and GaAs, as well as application-specific integrated circuits using emitter coupled logic (ECL-ASICs), was used to obtain high speed and high reliability. It is delivered as a compact desktop design with a low power consumption, with dimensions of 47 cm × 13 cm × 44 cm and a weight of 8 kg. The modifications for JAWS operation, as described in the succeeding discussions, are available as options: adjustable output amplitude and ternary output code [9].

Usually, the output of a pattern generator is non-return-to-zero (NRZ), which means that, after programming a bit to one, it does not automatically return to zero. Hence, in order to let the pattern generator generate pulses, each second bit should be a zero. This effectively means that the maximum repetition rate of the pulses is reduced by a factor of two. For our JAWS, the SYMPULS BMG 30G–64M pattern generator was modified by adding an RZ converter to each of the two outputs.

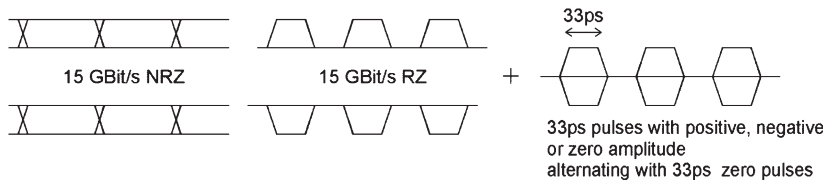

Fig. 2. Schematic conversion of two streams of NRZ pulses into one stream of RZ pulses with positive, negative, or zero amplitude on demand.

As a result, when operated, for example, at its maximum clock frequency of 15 GHz, each pulse is only 33 ps long.

A second important modification is the addition of an amplifier with a variable and stable gain to each of the two outputs (see Fig. 1). As a result, each pulse obtains a well-defined amplitude. The two amplifiers have nominally identical gain and opposite polarity, such that one generates positive pulses, whereas the other one generates negative pulses.

Finally, the two outputs are synchronized and added. When programmed such that channels 1 and 2 do not simultaneously generate a pulse, the two outputs do not influence each other. The two synchronized bit streams combined at the data output then form the required bipolar stream of pulses containing the three-level code (see Fig. 2).

B. Generated Code

Delta–sigma modulation is an efficient technique in representing low-frequency signals with high resolution. A high signal-to-noise ratio in the frequency band of interest is ensured by the combination of an integrator in the modulator, which concentrates the quantization noise power on the higher end of the frequency spectrum, and by subsequent low-pass filtering.

By using a delta–sigma modulation technique, the desired waveform is encoded into a binary file. The file, which is loaded into the pattern generator memory, results in a repeating JAWS drive pattern with a maximum of 33 554 432 individual pulses (with an amplitude adjustable between 400 mV and 600 mV) at the output. Note that, because the pattern is repetitive, the memory can only contain an integer number of waveforms, which puts constraints on the frequencies of the signals to be generated. An improved version of the BMG 30G–64M has a variable pattern length of $128 \cdot m$ pulses $(m = 2, 3, \ldots, 2^{18})$.

Errors in the code will contribute to errors in the output signal of the JAWS. In order to check for such errors, the output of the pattern generator can be visualized on a sampling oscilloscope. For instance, when a sinusoidal signal with a frequency of 447 Hz is synthesized with 33-ps-long pulses, the time scale spans almost seven orders of magnitude, which makes the check a daunting task. Therefore, the delta–sigma algorithm generating the code has been tested only for waveforms consisting of a very limited number of bits.

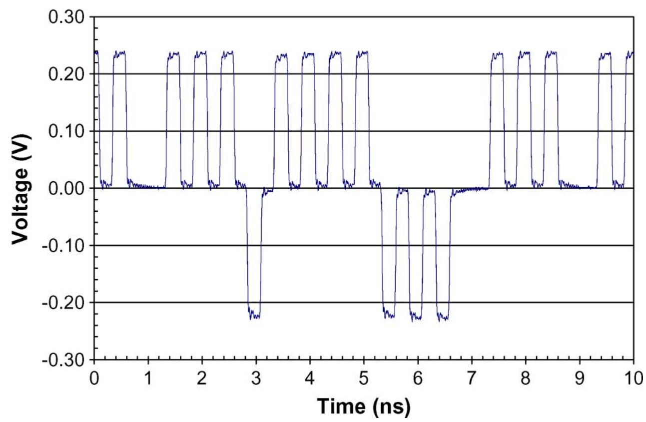

Fig. 3. Measured individually programmable pulses from the electronics operated at 4 Gb/s and loaded with 50 Ω. A fragment 110111-11111-1-1-10111011 is shown.

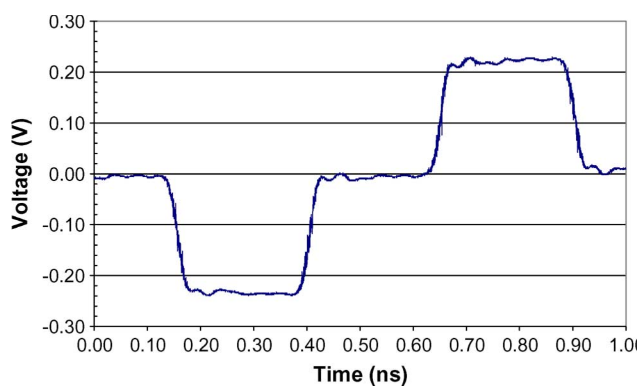

Fig. 4. Smaller fragment of the pattern shown in Fig. 3, showing that the rise time of the pulses is smaller than 50 ps (due to the sampling oscilloscope).

III. Results

A. Pattern Generator Output

An example of a generated pulse pattern, as measured using a 20-GHz sampling oscilloscope, is shown in Fig. 3. The pattern generator is clocked at 4 GHz and loaded with 50 Ω. As shown in the figure, the modified generator output produces bipolar pulses of equal amplitude and duration, as well as zero pulses. Fig. 4 shows two individual RZ pulses in the same pattern. The rise time of the pulses appears to be shorter than 50 ps, which is the limitation of the sampling oscilloscope. The amplitude-adjustable amplifier ensures that all generated pulses have the same well-defined amplitude. However, the limited bandwidth of the transmission lines and the sampling oscilloscope cause a decrease in the amplitude of the first individual pulse after a transition from one polarity to the other.

When carefully measuring the output of the pattern generator, the amplitude of the positive and negative pulses turned out to be slightly nonlinear with respect to their setting. Furthermore, a small difference between positive and negative amplitudes was observed.

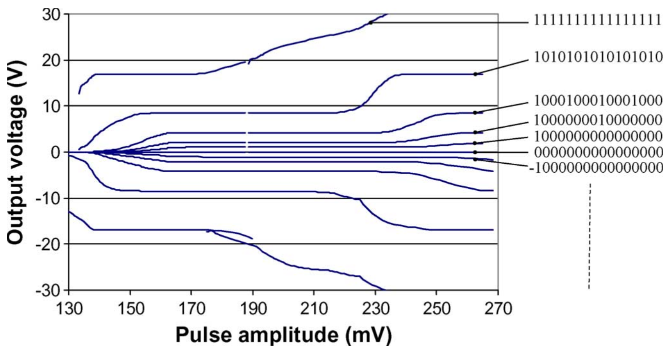

Fig. 5. Measured characteristics of the Josephson output voltage as a function of the pulse amplitude for different codes. Measurements were performed using a 1024 junction SNS array from PTB. The pattern generator was clocked at 8 GHz.

B. Alternative I–V Curves

Conventional I–V characteristics of Josephson arrays are made by applying an RF signal with a fixed amplitude, by adding a tunable dc bias current, and by measuring the dc voltage as a function of the bias current. For the pulse-drive mechanism, however, it is more relevant to study the effect of changing the pulse amplitude because, in this mechanism, no extra dc offset is added. Note that pulses that return to zero contain a dc component so that changing the amplitude of the pulses implies changing not only the RF part but also the dc component.

We measured the output voltage as a function of the pulse amplitude of an superconductor–normal metal–superconductor (SNS) Josephson array from Physikalisch-Technische Bundesanstalt (PTB) consisting of 1024 junctions. Different 16-bit repetitive codes were sent to the pattern generator clocked at 8 GHz, such as 1111..., 1010..., 1000..., etc., and similarly for negative codes. Since the amplitude of the pulses can only be varied between 400 mV and 600 mV, different attenuators were necessary in order to obtain a larger variation in pulse amplitude. For this array, attenuators of 3 dB and 6 dB were used in order to reduce the output of the generator to a factor of 1.4 and 2, respectively.

The results of these measurements are presented as alternative I–V curves in Fig. 5, in which the actual measured values for the pulse amplitude have been used on the horizontal axis. The previously mentioned difference between the positive and negative amplitude behaviors causes the curves to attenuate by 3 dB and 6 dB, where the negative codes partially overlap, whereas the positive codes do not. As shown in the figure, there is a wide range of amplitude values for which all codes, except for 1111... and its inverse, show an output voltage that is independent of pulse amplitude. When generating a long delta–sigma code for a sine wave, one virtually switches from one short code to the next, and the JAWS output virtually switches from the corresponding voltage level in the alternative I–V curve to the next. Hence, the margins of the pulse amplitudes observed in Fig. 5 suggest that, when generating delta–sigma codes for a sine wave, a long series of ones should be avoided in order to obtain a proper quantum-based output voltage. This can be done, for example, by generating a code with half the output amplitude (i.e., after each bit an extra zero is inserted). Another way to align the plateaus is to add a parallel resistor in order to compensate for the offset voltage of the pulses [7], [8].

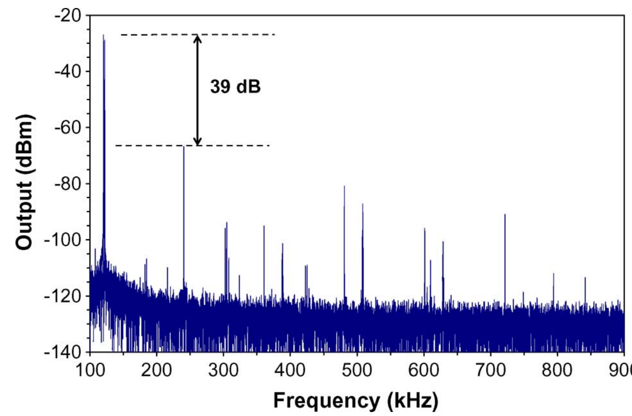

Fig. 6. Frequency spectrum of a code for a sine wave of 122 kHz, as directly measured at the output of the pulse generator. Feeding this code to a Josephson array results in setting the amplitude of the intended 122 kHz sine to a calculable value and suppression of the higher harmonics, making the signal "clean."

Apart from being shifted to the left, the plateau for the 1111... code is less well pronounced than for the other codes. A possible explanation is the limited bandwidth of the whole setup, including cable, chip layout, and connection between the chip and the cable. When the highest frequency components are attenuated more than the lower frequency components, the pulses in the 1111... code will have a lower amplitude, whereas for the other codes, only the rise times are elongated without a change of amplitude. This extra attenuation causes the horizontal axis of the 111... curve to be scaled.

C. Spectra of Codes

The measured spectrum of the generated patterns measured directly at the output of the generator shows higher harmonics of around 40 dB below the fundamental (see Fig. 6). The quantization noise of the delta–sigma algorithm at higher frequencies is not shown in the figure. The preliminary results on the spectra of sinusoidal voltages generated with an optimally tuned JAWS, using the modified generator and Josephson arrays from both Institute for Physical High Technology (IPHT) and PTB, show higher harmonics, which are typically 80 dB below the fundamental tone [7]. Measurements using a conventional binary output pattern generator show similar spectra, but the output voltage of the JAWS is only unipolar (i.e., it has a dc offset), whereas in the case of our modified generator, it is bipolar [8]. This proves that our modified electronics are quite suitable for use as part of a JAWS, allowing for excellent results.

IV. Conclusion

By modifying an existing commercially available 30-Gb/s pulse pattern generator, dedicated electronics has been developed in order to drive a Josephson array with bipolar current pulses for application in a JAWS. The generated patterns are ternary in the sense that each pulse is individually programmable and can take any of the three values: $+1$, 0, and -1, where zero means no pulse, and the amplitude of the $+1$ and -1 pulses is adjustable.

The I–V curves on Josephson arrays, obtained by varying the pulse amplitude when sending a fixed code, show that a promising and cost-effective solution has been found. Preliminary results on the spectra of the output of a JAWS based on these electronics show suppression of higher harmonics better than 80 dB below the fundamental, which confirms the strength of the new pulse-drive electronics.

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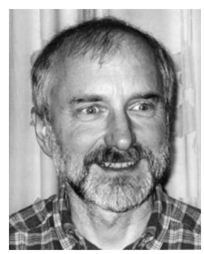

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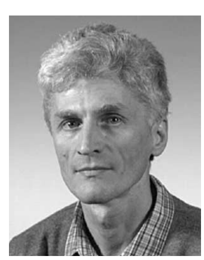

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