

Ultrapure sinewave generation by combining Josephson systems

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Abstract—The combination of systems exploiting binary-divided and pulse-driven Josephson arrays allows the generation of sinewaves with amplitudes of up to 10 V and very low harmonic distortion (-122 dBc). We present results from the combination of a 1 V binary divided Josephson array employed as a multilevel digital to analogue converter and a pulse driven array that is programmed to cancel the harmonic content present in the stepwise approximated output of the binary array. The synthesized waveform can be locked to a timing reference for ultimate frequency stability. The quantum nature of the Josephson synthesizers guarantees the stability of the amplitude. The unprecedented amplitudes available with this spectral purity open new possibilities for testing of electronic modules and analogue to digital converters

I. Introduction

Low harmonic distortion sinewaves can be generated by using a carefully designed Wien oscillator [1]. Precision electronic circuits like for instance high resolution Analogue to Digital Converters (ADCs) demand spectral purity that requires characterization of components for voltage and temperature coefficients below parts in 10^7 [2]. In order to use these circuits to characterize other electronic devices also demands careful and time consuming characterization of the linearity of their output amplitude. Moreover, the sine wave generated is free running and can only be synchronized to another waveform if it acts as master in the master slave arrangement. For many applications in electrical metrology, a further shortcoming is the impossibility to lock the oscillator to a 10 MHz reference.

Digitally synthesized sources overcome some of these shortcomings and have recently been shown to be capable of very high SFDR (Spurious Free Dynamic Range) at power line frequencies [3]. These digital sources can be clocked from a 10 MHz frequency reference and also increase the flexibility of their synchronization. However, the already mentioned calibration at different output amplitudes and frequencies is still required.

Series arrays of Josephson junctions or voltage standards have been used as fundamentally accurate Digital to Analogue Converters (DAC), as proposed in [4], in AC applications for nearly a decade now [5,6]. Two categories of quantum based voltage standards are utilized for synthesizing AC waveforms. The first one is based on programmable Josephson voltage standards (PJVS) consisting of Josephson arrays that are typically divided in segments of binary order. Fast bias electronics allow rapidly switching these segments on and off to synthesize stepwise approximated waveforms. Josephson arrays for 10-V amplitudes are available [7], but the time between quantum defined voltages varies with a number of parameters. On the other hand, Josephson arbitrary waveform synthesizers (JAWS) are able to generate spectrally pure waveforms by driving Josephson arrays with pulses less than 100 ps wide. On-chip voltages are truly quantized, but voltage amplitudes are still limited below the 1-V level [8]. Increasing the amplitude from JAWS is very difficult due to the wide-band requirement imposed by the faithful transmission of these short pulses.

Numerous applications have been developed with these two Josephson systems [9], but their use as a quantum synthesizer has been limited.

In this paper, we present experimental data for the combination first suggested in [10] in order to synthesize a spectrally pure sinusoidal wave with amplitudes so far only at the reach of PJVS.

II. Experimental setup

The schematic setup for the evaluation of the PJVS + JAWS approach is shown in Fig. 1. The PJVS is depicted at the top of Fig. 1 and can be understood as a multi-bit quantum accurate DAC. For these initial measurements, we used a series array with 8192 Josephson junctions irradiated with 70 GHz microwaves, resulting in a peak amplitude of 1.18 V. This array is divided into 13 segments that can be individually biased to the $n = -1, 0$ or $+1$ Shapiro steps. Therefore, the PJVS can be considered a 14-Bit DAC with quantum accuracy. As such, its output

is free from noise and drift. However, the transitions between the fundamentally accurate levels at the output depend on a number of factors like microwave power used or the exact values of the biasing currents.

The JAWS uses a Josephson array operated at a clock frequency of 5 GHz. The maximum amplitude of 47 mV is defined by the 4795 junctions, the maximum pulse repetition rate at this clock frequency and a “code amplitude factor” of 95 % (peak amplitude of the waveform / maximum amplitude of the array), required for quantised operation at all amplitudes generated. For the analogy with widespread electronic components, the JAWS can be

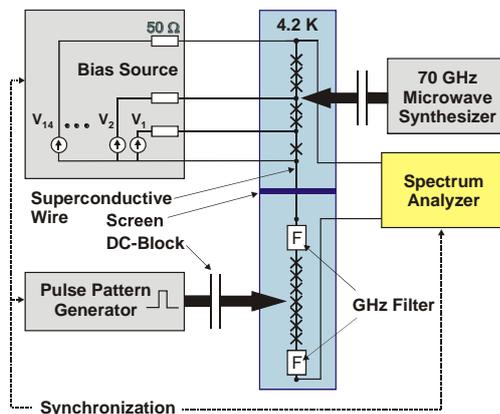


Figure 1. Schematic diagram for the combination of the PJVS and the JAWS.

thought of as an ideal 3-level quantum DAC ($n = -1, 0$ or $+1$) driven at 15 GHz as part of a sigma-delta modulated DAC. As with the PJVS, the JAWS is also free from drift or noise.

In order to accomplish ideal addition of these quantum defined voltages, the arrays are placed into a single cryoprobe back to back. The short distance between the two arrays, less than 5 cm, results in reflections from sharp changes in voltage of less than 1 ns or to frequencies above 1 GHz. These reflections therefore become invisible in the audio frequency band of interest for the combined output. A metallic screen prevents microwave radiation from one array reaching the other. The voltage across both arrays is defined as the sum of the voltages across the two arrays and any voltage resulting from current flowing in the connection. A superconducting wire made from NbTi was used and the resistance is hence dominated by the Al bonding wires to approximately 10 mΩ. All instruments in the setup that are tied to “ground” or “earth” potential are electrically isolated from the arrays. The spectrum analyser (NI PXI 5922¹) is operated on batteries. All synchronization signals are optically isolated. Detailed descriptions of the Josephson systems have been published previously in [9-11].

The PJVS generates a stepwise approximated sinewave with the desired amplitude. Without any signal from the JAWS, this waveform can be used to perform an AC linearity calibration of the spectrum analyser used, as introduced in [12]. At first, the signal synthesized by the JAWS corresponds to the difference between an ideal sine wave and the stepwise approximated waveform generated by the PJVS. At this stage, ideal transitions between quantized voltages from the PJVS with zero duration are assumed. In reality, those transitions have a certain duration. When observed at the load, in our case the spectrum analyser, the waveform also includes a degree of ringing after each transition, due to reflections from the high frequency components, among other deviations from the ideal waveforms. The waveform generated in reality is the sum of the waveforms from real PJVS plus ideal JAWS correction. This waveform is measured with the spectrum analyser at a sampling rate of 4 MS/s and is used to modify the waveform generated by the JAWS so that the sum of both actual waveforms corresponds to the ideal sinewave. The resulting spectrum is shown in Figure 2.

¹ Commercial instruments are identified in this paper to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by PTB.

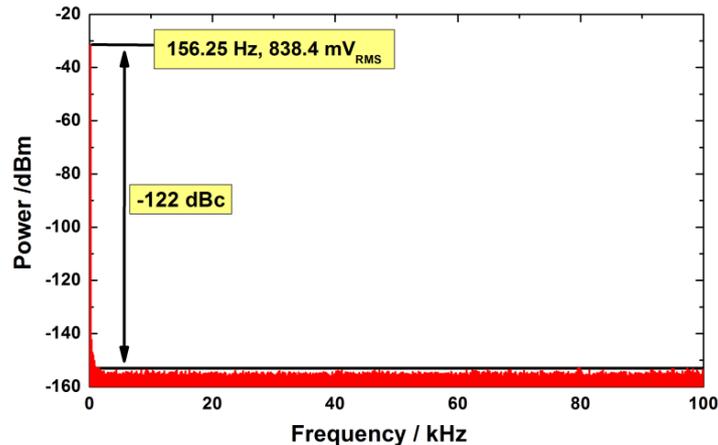


Figure 2. Frequency spectrum of the output of the PJVS+JAWS combination after one iteration.

III. Conclusions

We have demonstrated the low harmonic distortion (-122 dBc) for amplitudes of approximately 1 V that can be achieved by the combination of two Josephson systems. This opens up a new range of applications for these systems as the ultimate tool for the characterization of high resolution electronics. Ongoing work is directed at increasing the amplitudes to 10 V and to the generation of arbitrary waveforms using the principle of operation presented in this extended abstract. In addition, the frequency and amplitude stability of this combined synthesizer is being evaluated.

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