AC AND DC VOLTAGE SOURCE USING QUANTIZED PULSES

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Abstract

We have developed an accurate synthesized voltage source for ac and dc metrology, based on the quantized pulses of Josephson junctions. We demonstrated this technique in experiments with arrays of junctions clocked at 6 Gbit/s and synthesized sine waves with millivolt amplitudes at frequencies up to 1 MHz.

Introduction

We present experimental progress toward realizing a quantum mechanically accurate voltage source for ac and dc metrology. We show through simulations that this technique is capable of generating a single-frequency sine wave with a signal-to-noise ratio higher than 100 dB. We experimentally demonstrate that pulse quantization reduces the quantization noise to 75 dB below the fundamental. The final version of this paper will present our latest work toward increasing the experimental signal-to-noise ratio and the output voltage of the synthesized source.

The accuracy of this source is based on the fact that Josephson junctions generate perfectly quantized voltage pulses whose time-integrated area is equal to the unit flux quantum $h/2e$, where h is Planck's constant and e is the elementary charge. Appropriate sequences of these perfectly quantized pulses can be used to generate ac waveforms and dc voltages with quantum mechanical accuracy [1]-[3]. Potential applications of this device include: (1) generation of digitally synthesized ac signals with calculable rms voltages, (2) characterization of D/A and A/D converters, and (3) calibration of dc reference standards and digital voltmeters.

Voltage Pulse Quantization

The heart of the synthesized voltage source is a series array of N junctions distributed along a wide bandwidth transmission line [1]. When a pulse propagates down the line, it induces a quantized voltage pulse with a time-integrated area n/K_J across each junction it passes. Here, n is an integer that corresponds to the number of junction pulses for each input pulse and K_J = 483 597.9 GHz/V is a defined constant that is approximately $2e/h$. A periodic pulse train of frequency f propagating down the line thus generates an average voltage nNf/K_J across the array.

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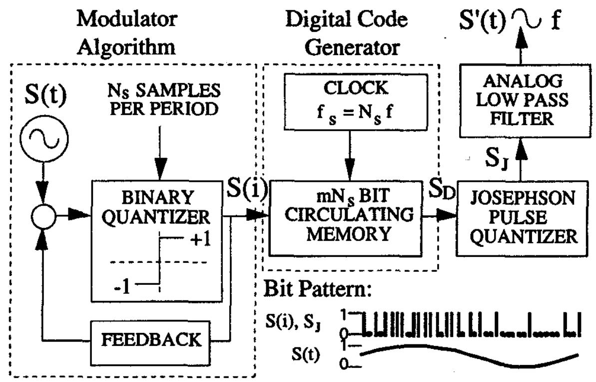

Fig. 1. A block diagram of the synthesized voltage source based on a pulse-driven array of Josephson junctions.

A complex sequence of pulses corresponding to a digital code can be used to generate a desired output waveform [2], [3]. Knowledge of the digital code, the clock frequency, and the number of junctions in the array is sufficient to precisely calculate the output waveform.

Figure 1 is a block diagram of the method used to synthesize a sine wave of frequency f or any other periodic waveform from quantized pulses. The modulator algorithm block is a computer program that digitizes the input waveform and creates a digital code $S(i)$. The digital code generator re-creates the waveform as an output voltage in real time $S_D(t)$ by clocking the memory at the sampling frequency. The Josephson array quantizes the pulses producing the voltage $S_J(t)$. The low pass filter removes unwanted quantization noise from the output spectrum, leaving only the desired waveform $S'(t) \approx S(t)$.

Simulation Results

Fourier spectra of the intermediate waveforms in the synthesized source are shown in Fig. 2 for a synthesized 1MHz offset sine wave having 4 periods and sampled at 2.56 GHz. The spectrum of the "ideal digital code" generated by the modulator algorithm is shown in Fig. 2(a). Points representing the power in each harmonic are connected for clarity. If we could directly generate this perfect digital code, then a pulse quantizer would be unnecessary, because a perfect digital code is quantized by definition. However, the output of real digital code generators have both amplitude and phase noise (σ = 2.5% typical) that degrade the signal as shown in the "real digital code" spectrum for S_D.

The spectra for signals following the pulse quantizer are shown in Fig. 2(b). The spectrum of the "pulse quantized code" is almost identical to the "ideal digital code" spectrum. *Thus, even though the quantizer does nothing to improve time jitter and does not quantize the pulse amplitudes, the fact that the time integral of the pulses is quantized is sufficient to produce a nearly ideal spectrum.* A 3-pole Butterworth filter removes the remaining quantization noise above 5 MHz as shown in the final "filtered output spectrum." In this example, the remaining quantization noise increases the rms value by only 1 part in 10^9.

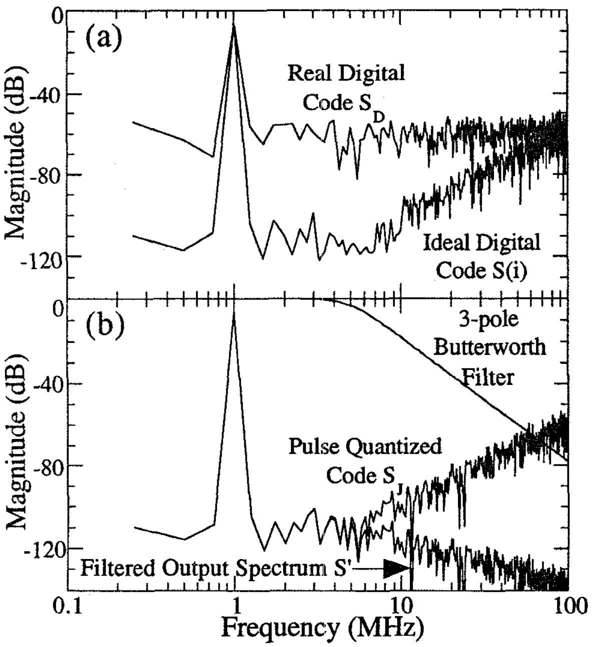

Fig. 2. The simulated Fourier spectra of signals in the synthesized source. (a) Spectra of signals prior to the quantizer. (b) Spectra of pulse quantized output waveforms.

Experimental Results

In order to demonstrate these ideas, we designed and fabricated a circuit consisting of a 7 mm long array of 1000 junctions along the center conductor of a 50 Ω superconducting coplanar stripline [2], [3]. We generated a 256 kbit code for a unipolar 23.4 kHz sine wave using a second-order delta-sigma modulator algorithm with a 6GHz sampling frequency and an oversampling ratio of 256. In the absence of noise or jitter, this ideal code yields harmonics at least 100 dB below the fundamental for all frequencies below 50 MHz.

Figure 3 compares the measured spectra of the digital code generator output and the amplified 4.3 mV (peak to peak) pulse quantized output from the array. The quantization reduces the power of the second harmonic by about 36 dB relative to the fundamental. Similar harmonic reduction is obtained for signal frequencies of 2.34 kHz and 234 kHz.

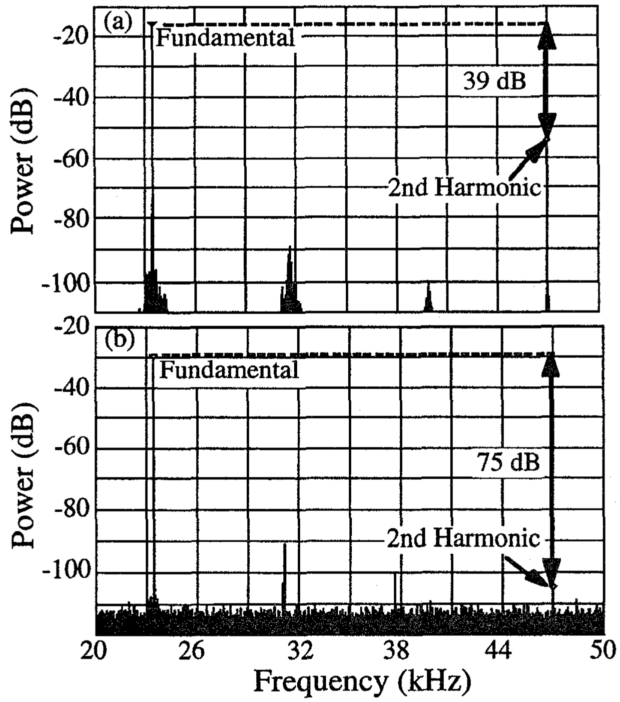

Fig.3. Measured Fourier spectra showing that the quantizing effect of the array improves signal purity. (a) Digital code generator spectrum. (b) Amplified spectrum of pulse-quantized voltage signal. Both spectra are taken with a 1 Hz resolution and video bandwidths. The unlabelled signals are spurious signals within the spectrum analyzer.

This experimental result verifies that the quantizing effect of Josephson junctions will greatly reduce particular types of distortions inherent in the output of conventional digital code generators. However, the 75 dB second harmonic suppression is still 25 dB less than expected from the 100 dB suppression of the ideal digital code. The most probable reason for this discrepancy is direct electromagnetic coupling between the code generator and the spectrum analyzer.

References

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