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Low-Distortion Waveform Synthesis with Josephson Junction Arrays

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SUMMARY We present measurements of kilohertz and megahertz sine waves synthesized using a Josephson arbitrary waveform synthesizer. A 4.8 kHz sine wave synthesized using an ac-coupled bias technique is shown to have a stable 121 mV peak voltage and harmonic distortion 101 dB below the fundamental (−101 dBc (carrier)). We also present results of our first phase-noise measurement. A 5.0 MHz sine wave was found to have distortion 33 dB lower than the same signal synthesized using a semiconductor digital code generator. The white-noise floor of the Josephson synthesized signal is −132 dBc/Hz and is limited by the noise floor of the preamplifier.

key words: *Josephson juncion, voltage standard, digital synthesis, harmonic distortion, phase noise*

1. Introduction

The Josephson arbitrary waveform synthesizer is capable of synthesizing ac, dc, and arbitrary voltage waveforms with low harmonic distortion and stable, calculable, and reproducible amplitude and phase [1]–[6]. These features are possible because the waveforms are synthesized using the perfectly quantized voltage pulses produced by Josephson junctions. The time-integrated area of every Josephson pulse is precisely equal to the flux quantum, $h/2e$, the ratio of Planck's constant to twice the elementary electron charge. This precision synthesized source will be useful in high-performance audio and radio-frequency (rf) applications, including ac voltage standards and electronic instrument calibration. In this paper we present our highest output voltage to date and our first phase-noise measurement of synthesized sine waves.

Achieving output voltages of at least 100 mV has been one of the major challenges for a practical Josephson synthesizer. Since the output voltage of a single junction is small, series arrays of N junctions are used. The maximum peak output voltage of a series array is $V_p = nNf(h/2e)$, where n is the number of quantized output pulses per input pulse and f is the pulse repetition frequency. Approximately 5×10^{13} pulses per secsond must be produced and controlled to generate a waveform with a 100 mV peak amplitude. Thus, high-voltage output requires both many junctions and a high pulse-repetition frequency. Knowledge of the number of pulses and their position in time is sufficient to precisely synthesize any digital waveform.

The need for higher voltage output led to the development of a bipolar-waveform technique [3]–[5], followed by the ac-coupled bias technique [6]. The bipolar method adds a sine wave to the digital input signal, while the ac-coupled method divides the broadband digital input signal into low- and high-frequency components that are applied to arrays through separate low- and high-speed transmission lines. The ac-coupled technique is particularly useful because it allows the array output to be directly coupled to the spectrum analyzer and enables multiple arrays to be combined in series for higher output voltage [6]. A block diagram of the ac-coupled technique is shown in Fig. 1. The digital code signal V_D is ac-coupled to the array using a 10 MHz high-pass filter (HPF) to remove all signals with frequencies below 10 MHz. However, the low-frequency part of the original digital code signal is necessary for biasing the array. This low-frequency compensation bias current $I_f(t)$ is reapplied to the array through a separate low-speed transmission line.

A digital code that is M bits long is repeatedly cycled through the circulating memory of the code generator. The synthesized waveform thus has a minimum frequency called the pattern-repetition frequency, $f_1 = f_s/M$, where f_s is the clock frequency of the code generator, which is also the sampling frequency of the

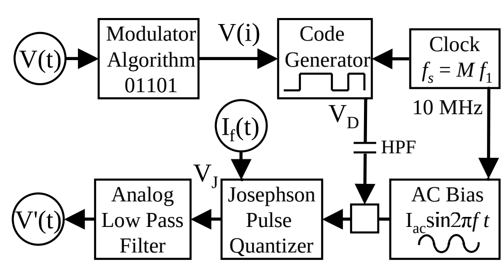

Fig. 1 AC-coupled bias technique for bipolar waveforms of the Josephson synthesizer. High-frequency signals from the digital code generator are ac coupled to the array through a dc blocking capacitor (HPF). Low-frequency compensation bias $I_f(t)$ is applied through separate low-speed bias taps.

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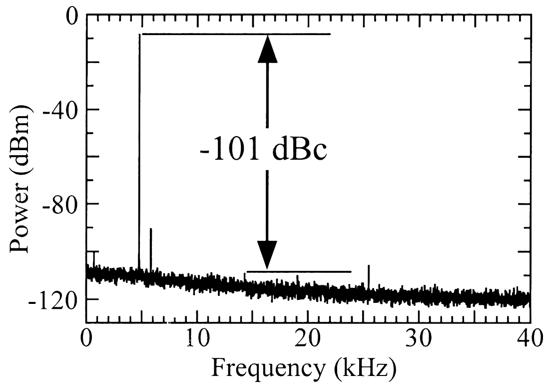

Fig. 2 Measured power spectrum of a 4.8 kHz sine wave signal showing harmonic distortion of 101 dB below the fundamental (−101 dBc). A 1 Hz resolution bandwidth was used.

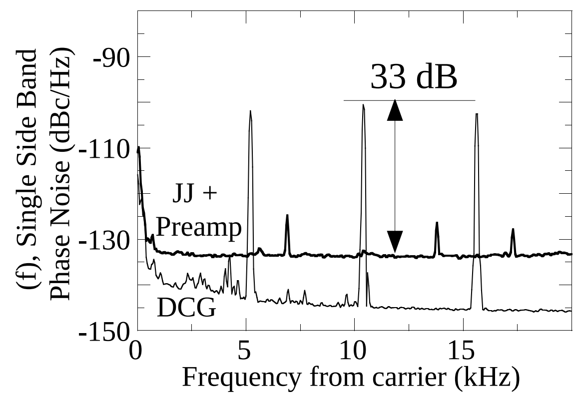

Fig. 3 Single-side-band phase noise of a 5 MHz tone synthesized using (a) a digital code generator (DCG) and (b) a Josephson junction array (JJ).

analog-to-digital conversion of the modulator algorithm [7].

2. Measurements

In order to achieve a large output voltage, we used the ac-coupled bias method and combined the output voltage from two series arrays with 4096 junctions each. The arrays are biased with a 7.5 GHz sine wave. The Nb-PdAu-Nb superconductor-normal metal-superconductor junctions are 2 μm in diameter. The on-chip bias taps to the arrays consist of a series of 2.7 nH square-coil inductors. The arrays have 8.6 mA critical currents and 3.4 mΩ resistances per junction. We synthesized a 4.8 kHz sine wave using a digital code with 1 048 576 bits and a $0.95V_p$ amplitude. These bias conditions yield a 120.8 mV peak amplitude, which corresponds to the measured power of −8.36 dBm.

The power spectrum of the synthesized sine wave is shown in Fig. 2. The harmonic distortion is −101 dBc (carrier), so that all harmonics are more than 100 dB below the fundamental. The harmonic distortion of the digital code generator's output signal for the same waveform is −41 dBc. The 60 dB reduction in distortion of the Josephson array over the semiconductor generator is due to perfect quantization. The 5.8 kHz and 25.5 kHz tones are artifacts of the measurement apparatus; they appear in both spectra and are not harmonics of the pattern-repetition frequency.

Exceeding 100 mV output from this large number of junctions is an important milestone for the Josephson synthesizer. However, synthesis of higher-frequency megahertz signals is also of interest for metrology applications and for demonstrating that perfect quantization improves waveform quality over a broad frequency range. This is of particular interest for a new method of Johnson noise thermometry that uses a Josephson synthesizer to calibrate its correlation electronics over a megahertz frequency range [8].

We synthesized a 5.0 MHz sine wave using the same ac-coupled method described above, but used only one of the 4096-junction arrays. The $0.9V_p$ amplitude yields 57.2 mV, corresponding to a measured power of −14.8 dBm. The digital code is 960 000 bits long, resulting in a 5.2 kHz pattern-repetition frequency.

In order to investigate the spectral purity of this waveform we measured phase noise of both the Josephson array and the code generator output signals with a NIST phase-noise detector and a 5 MHz reference [9], [10]. In order to break ground loops, the Josephson array output was amplified by a unity-gain 100 MHz differential preamplifier with a 50 Ω termination on the input. The digital code generator's amplitude was attenuated so that it was equivalent to the Josephson array output signal amplitude.

Figure 3 shows the single-side-band phase noise as a function of frequency offset from 5 MHz for both the Josephson array and code generator synthesized waveforms. The phase-noise measurement of the code generator's signal shows spurious tones at harmonics of the 5.2 kHz pattern-repetition frequency. These spurs result from the semiconductor generator's distorted output due to intrinsic amplitude and phase noise. The Josephson array's output has an essentially flat power spectral density of 133 dBc/Hz from 1 to 20 kHz with no spurs at the 5.2 kHz pattern-repetition frequency. The white-noise floor and spurious tones at unexpected frequencies are caused by the preamplifier. Nevertheless, the Josephson output signal has pattern-related spurs at least 33 dB below that of the code generator.

3. Conclusion

A lower-noise amplifier is needed to ascertain the true noise floor of the Josephson array. However, the absence of spurs indicates that the Josephson array should have improved phase noise as compared to the digital code generator. This first phase-noise result shows that perfect quantization of the Josephson junctions does provide ideal reproduction of a digital waveform to within our present measurement capabilities.

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Fred L. Walls was born in Portland, OR, on October 29, 1940. He received the B.S., M.S., and Ph.D. degrees in physics from the University of Washington, Seattle, in 1962, 1964, and 1970, respectively. His Ph.D. thesis was on the development of long-term storage and nondestructive detection techniques for electrons stored in Penning traps and the first measurements of the anomalous magnetic (g-2) moment of low energy electrons. From 1970 to 1973 he was a Postdoctoral Fellow at the Joint Institute for Laboratory Astrophysics in Boulder, CO. This work focused on developing techniques for long-term storage and nondestructive detection of fragile atomic ions stored in Penning traps for low energy collision studies. From 1973 to 2000 he was a Staff Member of the Time and Frequency Division of the National Institute of Standards and Technology, formerly the National Bureau of Standards, in Boulder engaged in research and development of ultra-stable clocks, crystal-controlled oscillators with improved short- and long-term stability, low-noise microwave oscillators, frequency synthesis from RF to infrared, low-noise frequency stability measurement systems, and accurate phase and amplitude noise metrology. He has published more than 150 scientific papers and articles. He holds 5 patents for inventions in the fields of frequency standards and metrology. Dr. Walls is a fellow of both the American Physical Society and the IEEE. He is presently chief scientist of Total Frequency of Boulder Colorado.

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Charles J. Burroughs Jr. was born on June 18, 1966. He received the B.S. degree in electrical engineering from the University of Colorado at Boulder in 1988. He worked at the National Institute of Standards and Technology at Boulder first as a student, and since 1988 as a permanent staff member. At NIST, he has worked in the area of superconductive electronics, including the design, fabrication, and testing of Josephson voltage standards, digital-to-analog and analog-to-digital converters. He has 40 publications and 3 patents in the field of superconducting electronics