Nonlinear Behavior of Electronic Components Characterized With Precision Multitones From a Josephson Arbitrary Waveform Synthesizer

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***Abstract*—We have extended the application of quantum-based electrical standards from single frequency calibrations to multi-tone tests that can be used to characterize the nonlinear behavior of electronic components and circuits. Specifically, we have used a Josephson arbitrary waveform synthesizer to generate highly accurate, two-tone waveforms having center frequencies ranging from 10 kHz to 1 MHz. These waveforms have unprecedented spectral purity because they are constructed from perfectly quantized voltage pulses. Using this measurement system, we have characterized the intermodulation distortion properties of a highly linear amplifier used in metrological applications. Additionally, we have shown that these test signals can be upconverted to microwave frequencies, so that they may be used to characterize the nonlinearities of RF and microwave components.**

***Index Terms*—Harmonic distortion, intermodulation distortion, Josephson arrays, signal generators.**

I. Introduction

THE Josephson Arbitrary Waveform Synthesizer (JAWS) is capable of generating multi-tone audio signals with low noise, low distortion, and accurate amplitude and phase [1], [2]. Multi-tone signals are commonly used for characterizing the nonlinearities of electronic devices and components [3]. Typically, these waveforms are generated either by combining the single tones of multiple oscillators with resistive power combiners or by programming a desired time-domain signal with a semiconductor-based arbitrary waveform generator. The first of these techniques combines the noise of multiple sources; a relatively high spectral noise floor will mask the small-amplitude distortion products generated by a system under test. The latter technique pollutes the measurement with distortion components produced within the generator itself. State-of-the-art approaches using sophisticated correction method can dramatically reduce the distortion when generating multitones with either of these traditional methods [4]. Nevertheless, the distortion cannot be completely eliminated. Thus, the inherently low noise and low distortion of a JAWS makes this technology both interesting and ideally suited for characterizing highly linear systems with greater ease and accuracy.

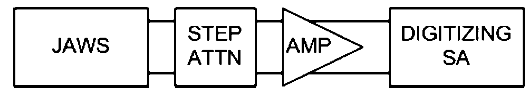

Fig. 1. Block diagram of nonlinear distortion measurement scheme using the Josephson arbitrary waveform synthesizer (JAWS).

The current state-of-the-art performance of a JAWS system enables the characterization of components used for audio (20 Hz to 100 kHz) and ultrasonic applications (extending up to 10 MHz in medical imaging technologies) [1], [2]. However, existing and emerging high-performance communication technologies require the use of frequencies much higher than the JAWS is currently capable of delivering. Ultra wideband (UWB) communication operates in the noise floor of the spectrum spanning 3.1 GHz to 10.6 GHz [5]. U.S. military software radios frequency-hop within the range of 2 MHz to 2 GHz [6]. Similarly, commercially available cognitive radios will most likely borrow bandwidth from the UHF TV band (400 to 800 MHz) and the microwave regime (3 to 10 GHz) [7]. Furthermore, multimode cellular systems require knowledge of distortion introduced by antenna switches and other weakly nonlinear components to accurately decode highly modulated waveforms [8]–[10]. So, JAWS systems could also be used to provide traceability in modulated signal measurements, but in order to take advantage of the low-distortion JAWS waveforms for communication applications, superheterodyning techniques are presently needed to upconvert the quantum-accurate, synthesized waveforms to the RF and microwave bands. However, nonlinearity introduced by the upconversion process is included in this approach.

In this paper, we demonstrate the use of a JAWS for characterizing nonlinearity by performing two-tone intermodulation distortion (IMD) measurements on a pre-amplification stage that is currently used in the NIST Johnson noise thermometry (JNT) experiment [11]. The latest version of this preamplifier, engineered by H. Rogalla, has improved common-mode rejection and has a lower noise figure [12], [13]. The results of our tests have improved our understanding of the nonlinearities present in the quantum-standard-based electronic thermometer and have reduced the uncertainty in its measurements. Additionally, we have upconverted a JAWS two-tone signal with a commercially available broadband mixer and a 10 GHz local oscillator in order to demonstrate the potential use of our system for applications in the microwave frequency regime.

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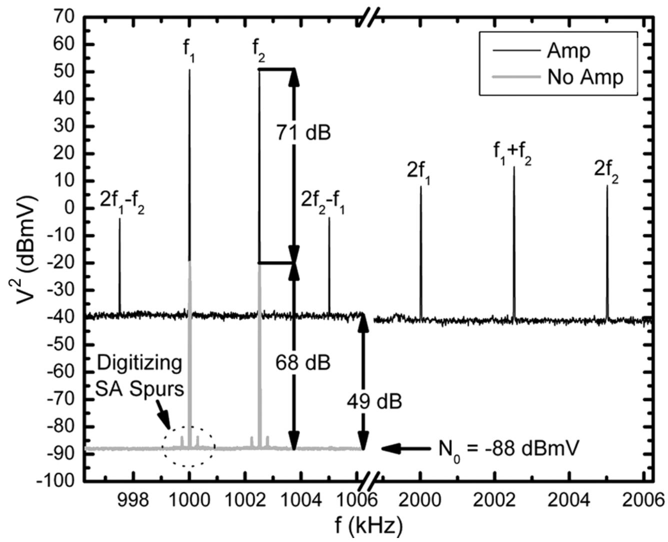

Fig. 2. Two-tone signals and distortion products from JAWS measurements (with and without amplifier). The noise floor measurement of -88 dBmV is limited by the noise of the digitizing SA; the noise floor of -39 dBmV is dominated by that of the amplifier.

II. A Quantum Accurate Synthesizer

A JAWS system [1], [2] is capable of producing bipolar voltage signals—waveforms with both positive and negative voltages. An arbitrary time-dependent voltage waveform is synthesized by implementing a delta-sigma digital-to-analog conversion algorithm. First, the desired waveform is digitized using a two-level delta-sigma modulator algorithm that yields a binary output stream. This routine reduces quantization noise by pushing it out of band, and it appropriately adjusts the binary signal for a bipolar biasing scheme. A two-level periodic code is then loaded into the circulating memory of a semiconductor code generator. A directional coupler allows the Josephson junction (JJ) array to be biased with the combined signal of the code generator's output, clocked at 10 Gbps, and a 15 GHz continuous wave that determines the maximum output voltage. The JJ array responds to this input stream by producing a perfectly quantized output waveform. Finally, a low-pass filter removes the out-of-band digitization harmonics, yielding the desired synthesized waveform.

The JAWS system used in the experiments pertaining to this paper relies on an array of 2560 triple-stacked superconductor/normal-conductor/superconductor (SNS) JJs. Two of these arrays are contained on the surface of a microchip with an area of 1 cm $\times$ 1 cm. Together they can produce a waveform having a total RMS voltage difference of 275 mV [14]. For the measurements described in the following sections, we programmed the JAWS to produce two-tone waveforms with each tone having a magnitude of precisely 100 μV RMS. Each pair of fundamental frequencies, f_1 and f_2, had a separation of $\Delta f = 2.5$ kHz with f_2 being greater than f_1. The frequency values of f_1 included: 10, 30, 100, 300 and 1000 kHz. Fig. 1 shows a diagram of the apparatus used for measuring the nonlinear distortion of the highly linear amplifier. We used a National Instruments PXI-5922 digitizer as a fast Fourier transform (FFT) spectrum analyser (SA). A precision step attenuator (a Pasternack PE7008-2)[1] allowed us to adjust the peak amplitude of the excitation. This method of amplitude variation was more convenient than performing the time-consuming task of reloading different binary streams into the JAWS's code generator.

III. Nonlinear Characterization of a Highly Linear, Audio Preamplifier

Fig. 2 shows a plot of the frequency spectra resulting from the output signal of the JNT preamplifier [12], [13]. The fundamental tones (f_1 and f_2) each have a magnitude of 100 μV RMS and frequencies of 1000 and 1002.5 kHz, respectively. Because the amplifier was driven into its saturation regime, well above its normal operating point of high linearity, there are prevalent spectral lines resulting from second-order harmonic distortion (HD) ($2f_1$ and $2f_2$), second-order IMD $(f_1 + f_2)$, and third-order IMD ($2f_1 - f_2$ and $2f_2 - f_1$). For most communication applications, the third-order IMD products are of greatest interest. For example, in an X-band (8 to 12 GHz) system, the second-order HD and IMD products would be outside of that communication band. In the JNT experiment, all of the mentioned distortion products should be accounted for because they are in-band.

To provide a visual comparison of distorted and undistorted waveforms, Fig. 2 also shows the JAWS two-tone signal without amplification. The magnitudes of the unamplified signal components are 68 dB above a noise floor[2] N_0 of -88 dBmV. There are small spurs present in the neighborhoods of each of these components. They are detection artifacts generated by the digitizer used for data acquisition. We verified that these spurs are not products of the JAWS by attenuating its output signal and observing that the magnitude of the spurs scales differently than that of the two fundamental tones. Amplification increases the fundamental tones by 71 dB, but it increases N_0 by only 49 dB. This measurement indicates that the noise contribution of the "no amplifier" measurement is dominated by that of the measurement equipment—not the JAWS.

By adjusting the magnitude of the two-tone waveform with the precision step attenuator, we determined the nonlinear operating characteristics of the JNT preamplifier with respect to a specified N_0. A plot of the RMS magnitude-magnitude dependence for the second- and third-order IMD products near 300 kHz is shown in Fig. 3. From these data sets, we determined that the preamplifier, in its state that is specific to our measurements, has a spurious-free dynamic range (DR_F) of about 67 dB with a maximum spurious-free input signal $V^2_{IN,max}$ of about -42 dBmV $(V_{IN,max} \approx 8\ \mu V\ RMS)$. However, these values depend on the total N_0 of the entire measurement apparatus and are not characteristic of the amplifier itself. In the

[1]The commercial instruments are identified in this paper only in order to adequately specify the experimental procedure. Such identification implies neither recommendation or endorsement by the National Institute of Standards and Technology, nor that the equipment identified is necessarily the best available for the purpose.

[2]Because our voltage amplifier had an input impedance much greater than 50 Ω, units of dBmV were used rather than dbm. $V^2\{dBmV\} = 20 \cdot \log_{10}[V/1\ mV\ RMS]$. Referencing our signals with respect to 1 mV RMS provided a useful scale.

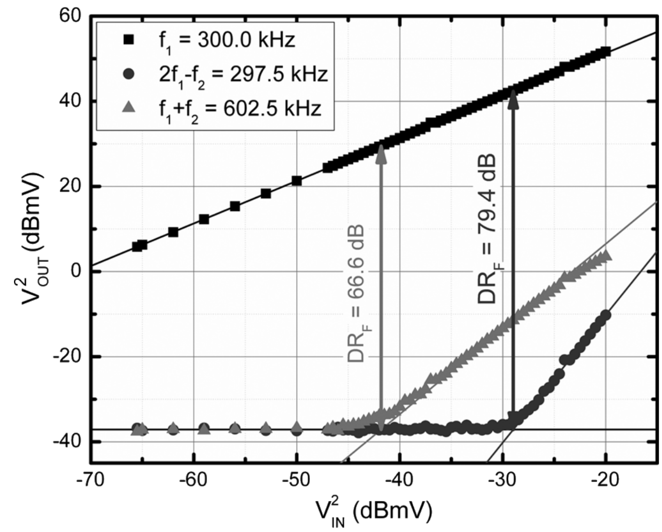

Fig. 3. Output magnitude of the fundamental tone (f_1) and second- $(f_1 + f_2)$ and third-order $(2f_1 - f_2)$ IMD products versus input signal magnitude.

JNT experiments, the measured value of N_0 decreases as a function of the cross-correlation integration time [11]. So, the amplifier should be described in terms of N_0-independent parameters such as the small-signal gain (G) and the extrapolated second- and third-order IMD intercept points (IPs).

We fit the data sets of Fig. 3 to their expected models in order to extract the N_0-independent parameters. First, we numerically calculate the derivatives of the second- $(f_1 + f_2)$ and third-order $(2f_1 - f_2)$ IMD data sets. We then use the data having slopes equal to 2 and 3 dB/dB to determine the dependent-variable-axis intercepts for the respective linear curves. The value of N_0 is determined by averaging the second- and third-order IMD data points corresponding to V_{IN}^2 less than -50 dBmV. Similarly, the offset of the fundamental frequency (f_1) data is extracted by fitting its points, having V_{IN}^2 less than -50 dBmV, to a linear curve with a slope of 1 dB/dB. This parameter is the G (in units of dB) of the preamplifier. In the region where relatively large input signals drive the preamplifier into saturation, the data points deviate from the linear curves. Such large signal compression (or expansion), occurs when the input signal influences the DC biasing of the preamplifier [3].

Analyses of two-tone IMD measurements were performed for frequencies near 10, 30, 100, 300 and 1000 kHz. Fig. 4 shows a plot of the extracted G and IMD IPs for each frequency. By graphical analysis, the DR_F for a specified N_0 can be calculated from these parameters [15]. (1) and (2) indicate DR_F for second- and third-order IPs (IP2 and IP3), respectively (units of variables are expressed in dB and dBmV):

$$DR_F = \frac{IP2 - N_0}{2}; \tag{1}$$

$$DR_F = \frac{2}{3} \cdot (IP3 - N_0). \tag{2}$$

Likewise, the expressions for $V_{IN,\max}^2$ corresponding to IP2 and IP3 are respectively shown in (3) and (4):

$$V_{IN,\max}^2 = \frac{N_0 + IP2}{2} - G; \tag{3}$$

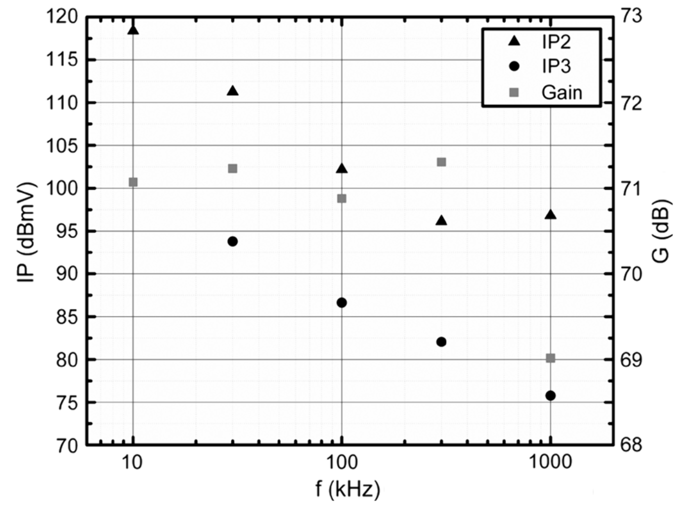

Fig. 4. Small-signal gain and IMD intercept points versus frequency.

$$V_{IN,\max}^2 = \frac{N_0 + 2 \cdot IP3}{3} - G. \tag{4}$$

In Fig. 4, there is a missing data point corresponding to the IP3 measurement at 10 kHz. It was not possible to extract this information because the 100 μV RMS two-tone signal generated by the JAWS was not large enough to induce measurable distortion at that frequency. However, for the JNT experiment, the second-order IMD products are in-band. Since this distortion rises above the noise floor at a lower $V_{IN,\max}$ than that due to third-order IMD, it is necessary to extract only IP2. Our extracted IP values ranged between 75 dBmV and 120 dBmV; low-noise amplifiers (used for TV applications, for example) having IP values in this range are referred to as "highly linear" [16].

Initially, we attempted to perform these measurements using the traditional method of resistively combining the single tones of two commercially available signal sources (Agilent 33220A). The measured values of N_0 ranged from -29 dBmV (at 10 kHz) to -1 dBmV (at 1000 kHz). Unfortunately, the noise floors were unmanageably high, which made it impossible to find a constant linear slope (corresponding to small signal behavior) for extracting the IPs. Although the main advantage of using a JAWS system for distortion measurements is the ability to directly synthesize arbitrary waveforms with perfect linearity and accuracy, another important advantage that it offers over conventional methods of generating multi-tone signals is its inherently low level of generated noise.

IV. Upconverted Signals for Microwave Regime Characterization

In order to extend the application of the JAWS IMD measurements from the audio to the microwave regime, we experimented with upconverting a two-tone signal having RMS magnitudes of 50 mV and frequencies of 1.0000 MHz and 1.0025 MHz. We used an Agilent 83711B signal generator to generate a 7 dBm, 10 GHz continuous wave. The signal was filtered before entering the local oscillator (LO) port of the broadband

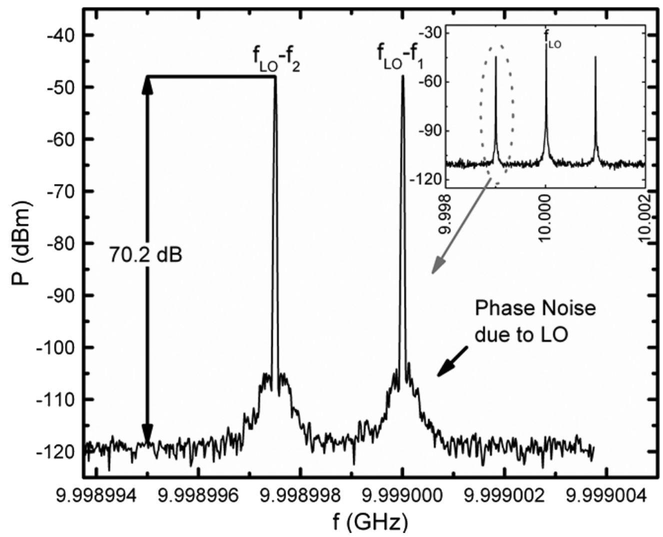

Fig. 5. Upconverted JAWS two-tone signal.

mixer, a Miteq DM0412LW2. The main graph of Fig. 5 displays a "zoomed in" view of the lower upconverted sideband. The inset shows a broader view featuring the LO signal and both of its sidebands. The upconverted tones ($f_{LO} - f_2$ and $f_{LO} - f_1$) are over 70 dB above the frequencies where their IMD products would appear. However, these tones have acquired a significant contribution of phase noise from the LO. Additionally, the noise floor level is higher in the neighborhood of f_{LO} than it is elsewhere.

Within the next two years, improved pulse-generator electronics should render the JAWS system capable of delivering signals with RMS amplitudes as high as 1 V. Research is being done to extend its output frequency range above 10 MHz. The increased magnitude will allow for the characterization of communication components designed for operating with higher dynamic range or higher input power. The increase in frequency will allow for the upconverted sidebands to be pushed further away from the increased noise floor located in the vicinity of f_{LO}. Additionally, novel cancellation techniques that could reduce the influence of the LO phase noise on the measurement are being explored.

V. Conclusion

Quantum-accurate waveform synthesis provides unmatched and unprecedented spectral purity for multi-tone waveforms. The spectral purity of the JAWS system provides a means of characterizing distortion in highly linear audio-frequency electronics. Finding and removing sources of nonlinearity has been important for reducing uncertainties and improving the overall performance of the JNT system. We measured the nonlinear parameters of a highly linear, audio preamplifier used in the JNT system as a means of demonstrating the utility of our system. Previous attempts to perform these measurements using traditional methods had an unmanageable noise floor.

Because there is a growing need to improve the quality of broadband and agile communication systems, we proposed the use of upconverting perfect JAWS audio multitones to the RF and microwave regimes. This measurement technique may improve the ease and accuracy of characterizing nonlinearity in highly linear systems, components and devices (including on-chip ohmic contacts that generate small, but finite, distortion products). Using a mixer and a LO, we generated two-tone waveforms with spectral magnitudes that were over 70 dB above the local noise floor. Current research offers a promising outlook for improving the spurious-free dynamic range of upconverted multi-tone signals.

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