Sinusoidal Signal Generation for Production Testing and BIST Applications

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***Abstract*— A novel technique to generate spectrally pure sinusoidal signals is proposed. The technique provides a dramatic improvement in spectral performance compared to the existing state of the art. With the proposed approach, spectral performance is inherently robust to variation in operating frequency and spectral characterization is programmable over frequencies. A circuit using extremely low cost operational amplifiers and 5 % accurate passive components has been built that can generate a sine wave with THD of lesser than -100dB at frequency, f=2.737 KHz .**

I. INTRODUCTION

Rapid advances in the field of high speed communications, medical electronics, consumer electronics, avionics, etc. are demanding high performance Analog-Mixed Signal (AMS) circuits in large volume. Testing of AMS circuits is becoming a major contributor to the overall cost of these circuits. High quality stimuli along with well controlled test environment are mandatory to carry out testing of AMS circuits. Expensive equipments like the Automated Test Equipments (ATEs) are widely used to carry out such testing [2]. The high volume nature of the circuits makes even a millisecond on these ATEs expensive. An alternative to this method is to move some of the tester functions off the tester. This can be done by moving some of the function onto the device interface boards (DIB). Another alternative is to move the functionality onto the same chip that is to be tested. This methodology is referred to as Built-in-Self-Test or a design-for-test (DFT) methodology. Built-in-Test also enables testing of complex system-on-chips in which high performance analog, digital and RF blocks are integrated. The focus of this work is a technique to generate practical low-cost sinusoidal signal generators for both production testing and BIST solutions.

Spectral analysis is an integral part of testing AMS circuits like Analog to Digital Converters (ADCs) and Digital to Analog Converters (DACs). The sine wave used to excite the Device under Test (DUT) has to be spectrally more pure than the DUT [1]. A 15-bit ADC would require a sinusoidal signal with a Total Harmonic Distortion (THD) of at least 100dB at a voltage swing that covers the entire input range of ADC. Spectrally pure sine waves are also critical in testing static characteristics of data converters like Integral-nonlinearity (INL) and Differential non-linearity (DNL) using the conventional histogram method[1]-[4]. Generating low THD sine waves over a wide range of frequencies with large signal swings is hard to accomplish even with precision components. Sine wave generation for high performance parts is a challenge requiring novel designs [8].It can also be observed that the literature lacks practical techniques to generate spectrally pure sine waves for on-chip applications at reasonable signal swings [9], [10], [11]. In section II we describe a conventional sine wave oscillator. In section III we propose using a phase shift oscillator with a harmonic cancellation scheme that has the potential to produce sine waves with very high spectral purity. In section IV we present implementation of the method and experimental results, and in section V we conclude the paper.

II. SINE WAVE GENERATORS

Conventional approach to generate sinusoidal signals is described in Fig.1. The Oscillator Block is generally comprised of an amplifier with non-linear gain control and a linear frequency selective network. The frequency selective network is often passive but can include amplifiers as well. If the frequency selective network is a second-order series/parallel RC network, this becomes the Wien Bridge oscillator. If the frequency selective network is set up as a set of delay stages, it is often termed a phase-shift oscillator [6], [7]. Much of the effort on improving the spectral performance is on controlling the pole locations of the loop gain. Generally, spectral performance is improved as poles move closer to the imaginary axis because of inherent nonlinearities.

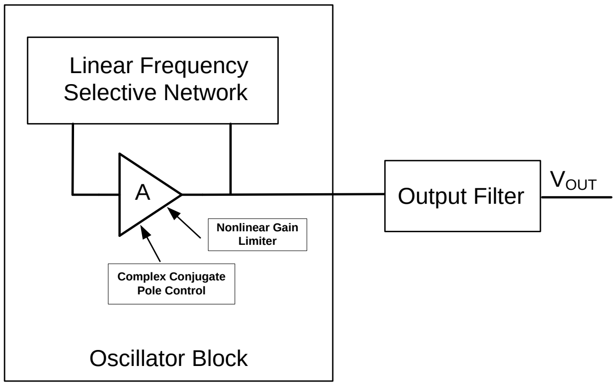

Fig. 1: Conventional approach to generate sine wave

But the movement of the poles closer to the imaginary axis generally results in a decrease in the magnitude of the output voltage. A significant effort is also focused on managing the nonlinearity of the gain function [5], [6], [8]. An abrupt saturation of the amplifier that reduces the gain at higher amplitudes generally results in significant distortion whereas more gradual gain reduction with signal amplitude generally improves spectral purity [5]. The bandpass-based oscillator structures [5], [9], [11] rely on the value of ‘Q’ to obtain spectrally pure signals. The Output Filter is used to attenuate harmonics that appear at the output of the Oscillator Block.

III. PROPOSED METHOD

A method to generate pure sine waves using phase-shift ring oscillators is proposed. The method can help build highly pure, low cost sinusoidal signal generators on Device Interface Board (DIB) thus reducing the test cost.

Consider the k-stage phase-shift ring oscillator shown in Fig. 2. T(s) in each block represents the transfer function of an inverter stage. If the stages are identical, it follows that the outputs are all time-delayed versions of the output X_{01}. This can be mathematically expressed as

$$X_{0i}(t) = X_{01}\left(t - (i-1)\frac{T}{k} \right) \qquad (1)$$

where, k : Number of stages

T: Period of oscillation

X_{0i} : ith stage output

The output waveforms invariably are all plagued by distortion. This can be represented by expressing the outputs in a Fourier series. It thus follows that if X_{01} is expressed as:

$$X_{01}(t) = A_0 + \sum_{n=1}^{\infty} A_n \sin\left(n\omega\ t + \theta_n \right) \qquad (2)$$

where, A_n: Amplitude of the nth harmonic

θ_n : Phase of the nth harmonic

Making the substitution $\omega = 2\pi/T$ in (2) and $X_{01}(t)$ in (1), we have $X_{0i}(t)$ given by (3)

$$X_{0i}(t) = A_0 + \sum_{n=1}^{\infty} A_n \sin\left(n\omega t - \frac{[i-1]n}{k} 2\pi + \theta_n \right) \qquad (3)$$

Consider a 3-stage ring oscillator where k=3, and the output of each stage, X_{01}, X_{02} and X_{03}, can be represented as:

$$X_{0i}(t) = A_0 + \sum_{n=1}^{\infty} A_n \sin\left(n\omega t - \frac{[i-1]n}{3} 2\pi + \theta_n \right) \qquad (4)$$

An important observation is that when n is a multiple of 3, the nth harmonic components at all the three outputs is identical. This observation is used to eliminate the harmonics that are multiples of 3. Consider the sum of all three outputs:

$$Y(t) = X_{01}(t) + X_{02}(t) + X_{03}(t) = \sum_{i=1}^{3} X_{0i}(t) \qquad (5)$$

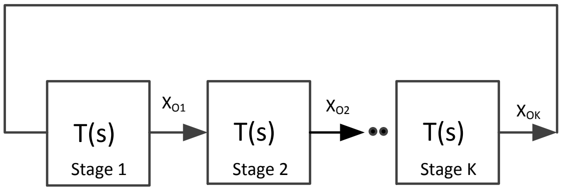

Fig. 2: A k-stage ring oscillator

$$Y(t) = 3A_0 + \sum_{i=1}^{3} \left[\sum_{n=1}^{\infty} A_n \sin\left(n\omega t - \frac{in}{3} 2\pi + \theta_n \right) \right] \qquad (6)$$

(6) can be simplified to yield:

$$Y(t) = 3A_0 + 3\sum_{j=1}^{\infty} A_{3j} \sin(3j\omega t + \theta_{3j}) \qquad (7)$$

It can be observed the fundamental is absent in Y(t) as are the second, fourth and all harmonics that are not multiples of 3. The third harmonic and its multiples, represented by 3j in (7), are scaled by a factor 3 in Y(t). Scaling (7) by a factor 1/3 and subtracting the result from (2) yields:

$$\begin{aligned} F(t) &= X_{o1}(t) - \frac{1}{3}Y(t) \\ &= \left(A_0 + \sum_{n=1}^{\infty} A_n \sin\left(n\omega\ t + \theta_n \right) \right) \\ &\quad - \left(A_0 + \sum_{j=1}^{\infty} A_{3j} \sin(3j\omega t + \theta_{3j}) \right) \\ &= \sum_{n=1, n\neq 3j}^{\infty} A_n \sin\left(n\omega\ t + \theta_n \right) \qquad (8) \end{aligned}$$

It can be seen in (8) that all harmonics that are multiples of 3 have been eliminated from the initial $X_{01}(t)$. In a fully differential scheme, even order harmonics are absent and all the harmonics that are multiples of three can be eliminated using the proposed method. A signal with the fifth harmonic as the significant harmonic is obtained. The fifth harmonic is generally at a much lower level than the lower order harmonics thus significantly improving the spectral purity of the signal.

This method can be readily extended to remove the fifth harmonic and the seventh harmonic and any other harmonics of interest. With this approach, the harmonics are removed by summation. It can also be noted that the weights are all independent of frequency so the summing/differencing circuit will provide the harmonic cancellation independent of the magnitude of distortion that is present. The weighting factor of 1/3 in the above example is actually the reciprocal of the number of stages used in the oscillator and independent of the frequency of operation or the magnitude or type of distortion in the oscillator.

IV. CIRCUIT IMPLEMENTATION AND EXPERIMENTAL RESULTS

The proposed method is implemented using discrete components on breadboard. The results presented are for a discrete implementation but the results can be easily extended to a fully integrated implementation.

The block diagram of a three stage phase shift oscillator, that forms the core of the oscillator scheme, is shown in Fig. 3.

Each stage is an integrator. It is implemented with the low cost LM356Ns operational amplifiers, resistors, capacitors and IN4001 diodes. The diodes along with resistors R_T and R_M provide amplitude stabilization function [5]. The ratio R_F/R_{IN} is set to slightly greater than the critical value of 2 [7]. The frequency of oscillation is set by R_F and C_F.

The summation and subtraction of the signals from (8) is:

$$\begin{aligned} F(t) &= X_{o1}(t) - \frac{1}{3}Y(t) \\ &= \frac{2}{3}X_{o1}(t) - \frac{1}{3}X_{o2}(t) - \frac{1}{3}X_{o3}(t) \end{aligned} \tag{9}$$

This is implemented using the scheme shown in Fig 4. Fig.4 shows the harmonic cancellation scheme. Buffers are used to mitigate any interaction of the cancellation scheme with the oscillator's operation. A single opamp that follows the buffers implements the operation in (9) with an amplification of 3. A third order filter is used to demonstrate the effectiveness of using filter after the cancellation scheme. The output spectrum of the oscillator was analyzed using Audio Precision SYS-2722. The data acquired using this system was analyzed using [12]. It is important to note that the components used in the design were randomly picked from a lot with 5% precision components. The FFT spectrum of the one of oscillator's output V1 (Fig.3) is as shown in Fig.5.The FFT spectrum of output VO (Fig.4) after third harmonic cancellation is as shown in Fig.6.

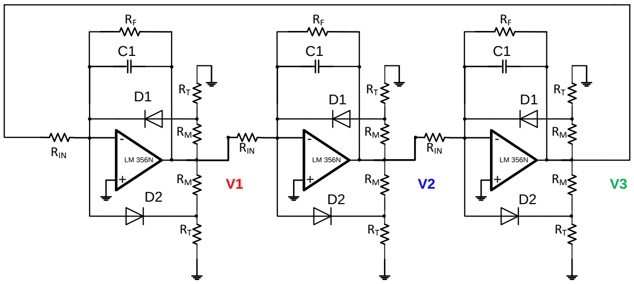

Fig 3: Three Stage Phase shift Oscillator

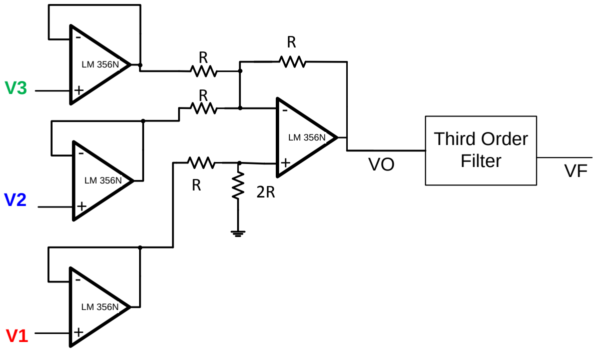

Fig 4: Third Harmonic Cancellation Block + Filter

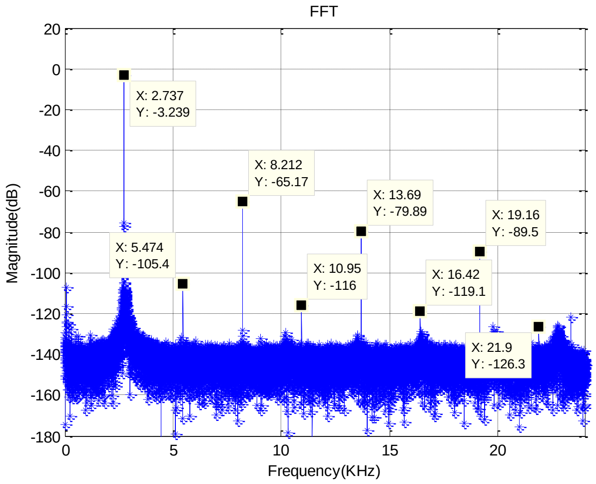

Fig 5: FFT Spectrum of Oscillator's output, V1

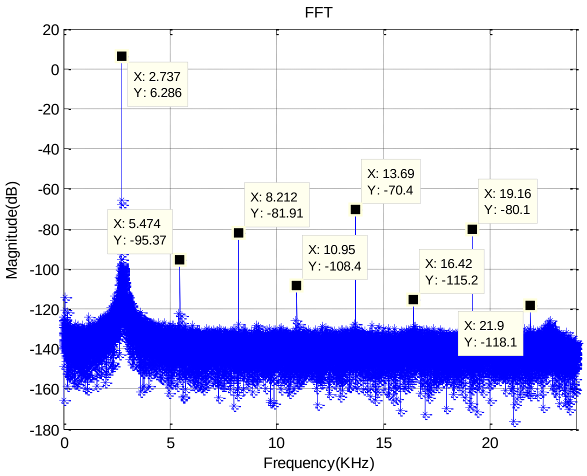

Fig 6: FFT Spectrum of Oscillator's output, VO

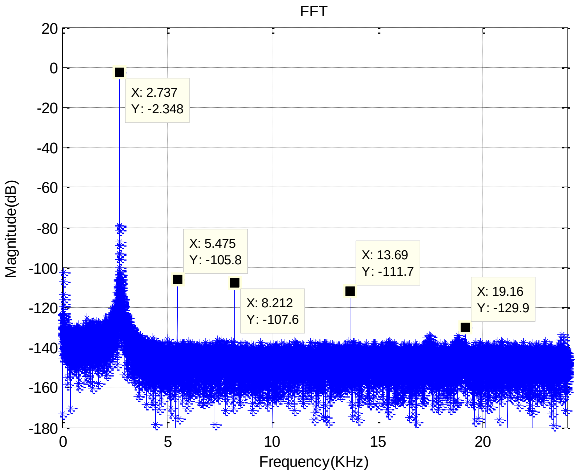

Fig 7: FFT Spectrum of Filter's output, VF

Table 1: Conventional Filtering vs. Proposed method with Filtering

	V1(dB)	V1+ITF (dB)	VF(dB)
f=2.737 KHz	-3.24	-12.27	-2.348
2f=5.474 KHz	-105	-126.34	-105.8
3f=8.212 KHz	-65.2	-95.17	-107.6
4f=10.948 KHz	-116	-152	NF
5f=13.685KHz	-79.9	-122	-111.7
6f=16.422 KHz	-119	-166	NF
7f=19.159 KHz	-89.5	-140	-129.9
8f=21.896 KHz	-122	-175	NF

*NF: Noise Floor

Comparing Fig.5 with Fig.6 it can be observed all the frequency components rise by approximately 9dB but for the third harmonic @ f=8.212 KHz which drops by a dramatic 26dB.The spectrum is now dominated by the 5th Harmonic. A first order passive filter followed by a low pass ,second order , Sallen-key filter with 3-db frequencies at the oscillator's frequency of f=2.737 KHz is designed. The FFT Spectrum after filtering of the signal VF is as shown in Fig 7.The spectrum is of an ultra pure sine wave with a Spurious Free Dynamic Range (SFDR) of 103.5dB. If the signal V1 is filtered using an ideal, third order filter (ITF) with a cutoff frequency at f=2.737 KHz, then the various harmonics would be attenuated as shown in the third column of Table1. This is compared with the spectrum of VF in column 4. It can be concluded that with the proposed method, the third harmonic can be attenuated further thus attaining over 100dB spectral purity. The spectrum of VF is dominated by the second harmonic. It was observed that the second harmonic is that of the LM356N used in the Sallen-Key filter. Using a filter does limit the frequency independence of the scheme. Although the proposed method is frequency independent, the fundamental's amplitude changes with the frequency. But the change is small in comparison with the attenuation provided by the filter to the harmonics. Hence using a filter makes the proposed method more effective.

V. CONCLUSION

In conclusion a practical method to generate ultra pure sine waves has been proposed. The method has been experimentally verified using low cost and imprecise components, and is robust to mismatch in the components. The method can make on-chip testing of AMS circuits more feasible.

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