# 任意波形発生器を用いた高周波低歪信号生成アルゴリズム

○ 柳田 朋則 * 澁谷 将平 小林 春夫
群馬大学大学院 理工学府 電子情報部門 〒376-8515 群馬県桐生市天神町 1-5-1
Phone: 0277-30-1789 Fax: 0277-30-1707 *E-mail: t161d096@gunma-u.ac.jp

# High-Frequency Low-Distortion Signal Generation with Arbitrary Waveform Generator

○Tomonori Yanagida Shohei Shibuya Haruo Kobayashi
Division of Electronics and Informatics, Graduate School of Science and Technology, Gunma University
1-5-1 Tenjin-cho Kiryu-shi Gunma 376-8515 Japan

**Abstract**
This paper describes algorithms and simulation verification of low-distortion sinusoidal signal generation methods with harmonics and image cancellation using an arbitrary waveform generator (AWG). First, we show low-frequency sinusoidal signal generation methods with HD2 cancellation, HD3 cancellation and HD2 & HD3 cancellation. Next we show high-frequency sinusoidal signal generation algorithms with HD3 image cancellation, HD3 & HD5 images cancellation, and point out that cancellation of even harmonics images (such as HD2 image) is not required because they are far from the signal frequency. With these methods, distortion components close to the signal are suppressed simply by changing the AWG program (or waveform memory contents)—AWG nonlinearity identification is not required—and spurious components, generated far from the signal band, are easy to remove using an analog filter.

**Keyword**: ADC Testing, Low Distortion Signal Generation, Distortion Shaping, Arbitrary Waveform Generator

## I. Introduction

LSI production testing is becoming important in the semiconductor industry, because its testing cost is increasing while its silicon cost per transistor is decreasing [1]. Analog-to-Digital Converters (ADCs) are important key components in mixed-signal SoCs, and here we consider their testing at low cost with high quality.

An AWG consists of a DSP (or waveform memory) and a Digital-to-Analog Converter (DAC). We can use Arbitrary Waveform Generators (AWGs) to generate arbitrary analog waveforms simply by changing the DSP program, and Automatic Test Equipment (ATE) uses AWGs for their flexibility. However, due to AWG nonlinearities, sinusoidal signals generated by AWGs include harmonics that degrade the accuracy of ADC testing when AWGs are used as ADC input signal sources.

This paper reviews our proposed for generating a low-distortion low-frequency and high-frequency signal with harmonics and image suppression simply by changing the AWG program, without AWG nonlinearity identification [2-5]. We also show that for high frequency signal generation (i.e. up to approximately the Nyquist frequency ($f_s/2$) of the DAC in the AWG, where fs is a sampling frequency of the DAC) HD2 image is far from the signal component and its simultaneous HD3 and HD5 suppressions are possible. Its principle, theoretical analysis and simulation results are presented.

## II. Low Distortion Signal Generation for ADC Testing

The AWG generates an analog signal through a DAC whose digital input is provided from DSP (or waveform memory). Hence the nonlinearity of the DAC causes harmonic distortion, and then we propose methods to cancel the DAC nonlinearity effects with the DSP program change as a pre-distortion [2-4], for low-frequency/

### 2.1 Low-Frequency Low-Distortion Sinusoidal Wave Generation Technique.

Eq.1 shows a direct sinusoidal signal generation method with AWG, where $D_{in}$ is a digital input signal to the DAC from DSP inside the AWG.

$$D_{in} = A\sin(2\pi f_{in} nT_s) \qquad (1)$$

Eq.2 shows a low distortion signal generation algorithm with the previously proposed phase switching method using the AWG [3, 4, 5].

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_{in} nT_s + \varphi_0) & n:\text{even} \\ X_1 = A\sin(2\pi f_{in} nT_s - \varphi_1) & n:\text{odd} \end{cases} \qquad (2)$$

$$\varphi_x = \varphi_0 - \varphi_1 = (2m-1)\pi/N. \quad m = 0,1,2,\ldots \qquad (3)$$

Here, $\boldsymbol{n}$ is an integer, and $T_s$ is a sampling period. The DSP output signal $D_{in}$ consists of $X_0$ and $X_1$, and they are interleaved every one clock cycle (Fig.1). Signals having a phase difference $\varphi_x$ reduce the Nth-order harmonics.

We consider here the case that $2^{nd}$ and $3^{rd}$ order distortions are dominant in the DAC and ADC (Fig.2), and we use a simple model as follows:

$$Y(nT_s) = a_1 D_{in} + a_2 D_{in}^2 + a_3 D_{in}^3 \qquad (4)$$

$$Z(nT_s) = b_1 Y + b_2 Y^2 + b_3 Y^3 \qquad (5)$$

Here $Y$ is the AWG output and $Z$ is the output of an ADC under test (Fig.2). Numerical simulation results are shown in Fig.3 and Fig.4 by using Eq.1, Eq.2 and Eq.4 (where $a_1 = 1, a_2 = 1, a_3 = 0$, $f_{in}/f_s = 50/102$, $A = 1$, $\varphi_0 = \pi/4$, $\varphi_1 = -\pi/4$). We see in Fig.4 that the phase-switching signal generation method cancels the power of the 2nd harmonics of the AWG, but it generates a high frequency spurious signals at $f_s/2 - f_{in}$ and $f_s/2 - 2f_{in}$. We call this function as *distortion shaping* [2, 3, 4], because the distortion components move from low to high frequency bands. We can obtain low distortion signals by attenuating the spurious around $f_s/2$ with an analog low pass filter (LPF).

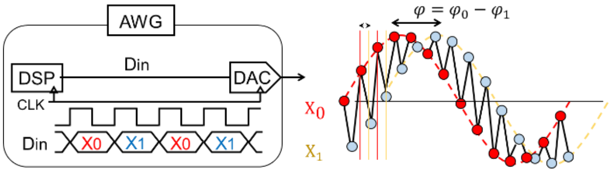


Fig.1 Phase switching signal generation method.

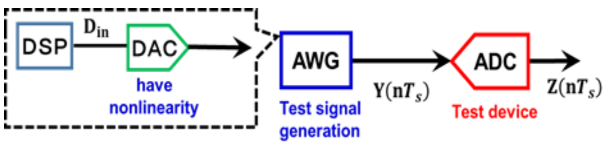


Fig. 2. ADC linearity testing system.

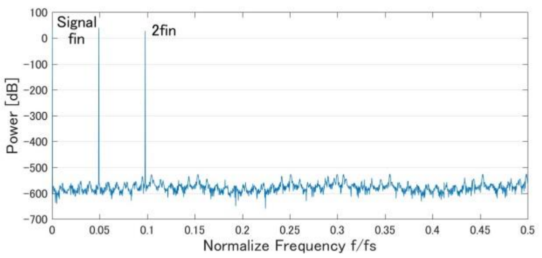


Fig. 3. $Y(nT_s)$ spectrum with the direct low-frequency signal generation method with AWG 2nd-order distortion (using Eq.1).

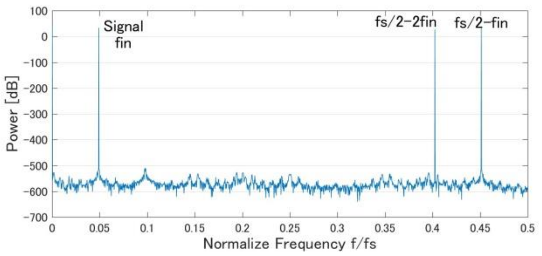


Fig. 4 $Y(nT_s)$ spectrum with the phase-switching low-frequency signal generation method with AWG 2nd-order distortion (using Eqs. 2, 3).

Le us consider the case that $a_1 = 1, a_0 = 0, a_3 = 1$, $f_{in}/f_s = 50/1024$, $A = 1$, $\varphi_0 = \pi/6$, $\varphi_1 = -\pi/6$. Fig. 5 shows the simulation results of the direct method using Eq. (1) and we see that the HD3 appears. Fig. 6 shows the one using Eqs. (2), (3) and we see that HD3 is cancelled but high frequency spurious components appear.

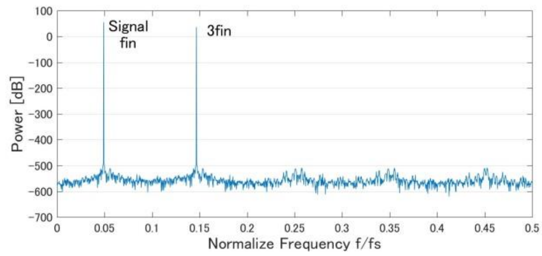


Fig. 5. $Y(nT_s)$ spectrum with the direct low-frequency signal generation method with AWG 3rd-order distortion (using Eq.1).

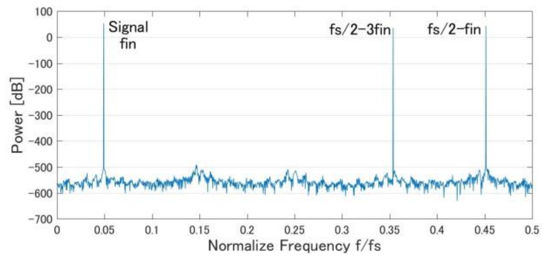


Fig. 6. $Y(nT_s)$ spectrum with the phase-switching low-frequency signal generation method with AWG 3rd-order distortion (using Eqs.2, 3).

2nd and 3rd-order cancellation method uses Eq. (6).

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_{in} nT_s - \varphi_a - \varphi_b) & n = 4k \\ X_1 = A\sin(2\pi f_{in} nT_s - \varphi_a + \varphi_b) & n = 4k+1 \\ X_2 = A\sin(2\pi f_{in} nT_s + \varphi_a - \varphi_b) & n = 4k+2 \\ X_3 = A\sin(2\pi f_{in} nT_s + \varphi_a + \varphi_b) & n = 4k+3 \end{cases} \qquad (6)$$

Numerical simulation results with Eq. 6 are shown in Fig. 8 (where $a_1 = 0.01, a_2 = 0.3, a_3 = 0.4$, $f_{in}/f_s = 20/1024$, $A = 1, \varphi_a = \pi/4$, $\varphi_b = \pi/6$)

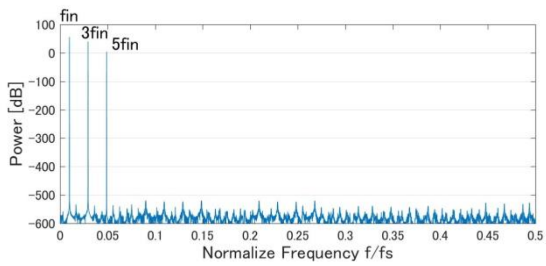


Fig. 7. $Y(nT_s)$ spectrum with the direct low-frequency signal generation method with AWG 2nd and 3rd-order distortions. (using Eq.1).

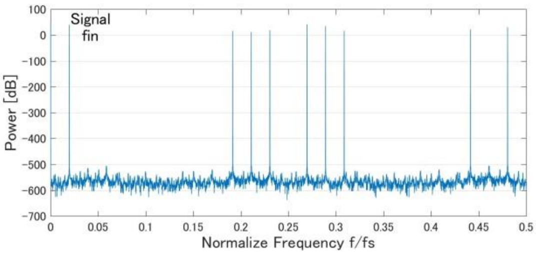


Fig. 8 $Y(nT_s)$ spectrum with the phase-switching low-frequency signal generation method with AWG 2nd and 3rd-order distortions (using Eq. 6).

### 2.2 High-Frequency Low-Distortion Signal Generation Technique

Note that 3rd order harmonics distortion from the AWG is folded back by aliasing when the AWG generates a signal in the vicinity of half the sampling frequency (Fig.9). In the previous section, the conventional phase switching technique is described as limited to the use of only the low frequency signal generation.

We show to generate a low distortion signal around the Nyquist frequency, using a phase difference $\varphi_y$:

$$\varphi_y = \varphi_0 - \varphi_1 = 2m\pi/N \qquad (7)$$

Consider the case of 2nd-order cancellation method. For the low-frequency signal generation (Eq.2), $\varphi_x = \pi/2$, and the AWG output sinusoidal signal frequency is $f_{in}$. On the other hand, for the high-frequency signal generation (Eq.8), $\varphi_y = \pi$ and the AWG output sinusoidal signal frequency is $f_{out} = f_s/2 - f_{in}$ (Fig.10). Numerical simulation results with Eq. 7 are shown in Fig.10(where $a_1 = 1, a_2 = 1, a_3 = 0, f_{in}/f_s = 50/1024$, $A = 1, \varphi_0 = \pi/2$, $\varphi_1 = -\pi/2$). We see that compared to the low-frequency signal generation algorithm, the high-frequency signal generation method generates a high frequency signal of $f_{out} = f_s/2 - f_{in}$ and there are no HD2 image components close to this signal frequency in Fig. 10 even without phase switching (in other words, we do not need HD2 image cancellation for high frequency generation.)

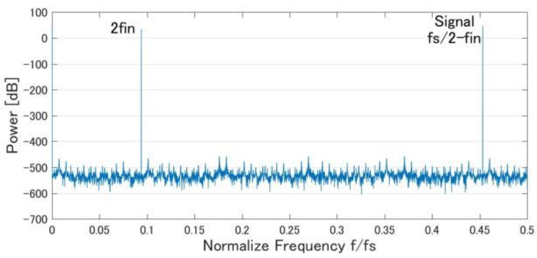


Fig. 9. $Y(nT_s)$ spectrum with the direct high -frequency signal generation method with AWG 2nd-order distortion (using Eq.1).

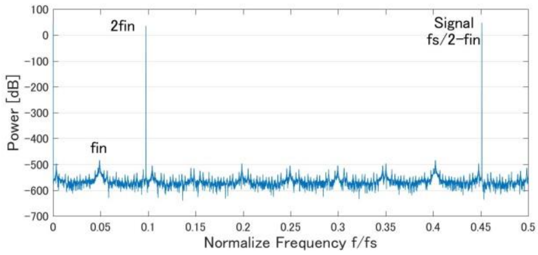


Fig. 10. $Y(nT_s)$ spectrum with the phase-switching high-frequency signal generation method with AWG 2nd-order distortion (using Eqs. 2, 3, 7).

In case of 3rd-order cancellation method, numerical simulation results with Eq. 7 are shown in Fig.12 (where $a_1 = 1, a_2 = 0, a_3 = 1, f_{in}/f_s = 50/1024$, $A = 1, \varphi_0 = \pi/3$, $\varphi_1 = -\pi/3$)

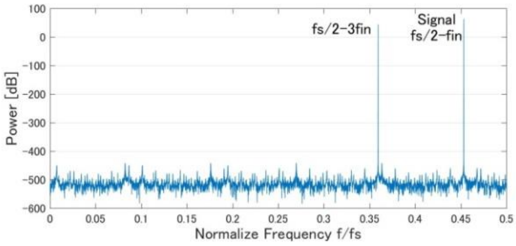


Fig. 11. $Y(nT_s)$ spectrum with the direct low-frequency signal generation method with AWG 3rd-order distortion (using Eq.1).

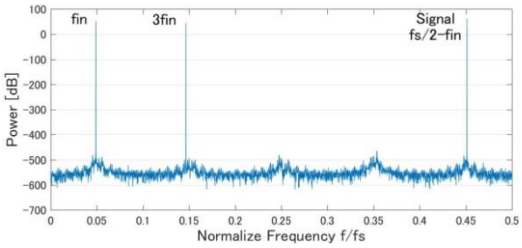


Fig. 12. $Y(nT_s)$ spectrum with the phase-switching high-frequency signal generation method with AWG 3rd -order distortion (using Eqs. 2, 3, 7).

Now we consider the case that the DAC has 3rd and 5th order distortions and we consider to cancel their effects to generate a high frequency sine signal. Let

$$\varphi_a = \frac{\pi}{6}, \quad \varphi_b = \frac{\pi}{5}$$

$$f_{in}/f_s = 20/1024$$

$$A = 1, a_1 = 1, a_3 = 0.3, a_5 = 0.3$$

in eq. (6) and we have the simulation results in Fig. 11; we see that the spurious components at the vicinity of the signal component (fs/2 – fin) are removed.

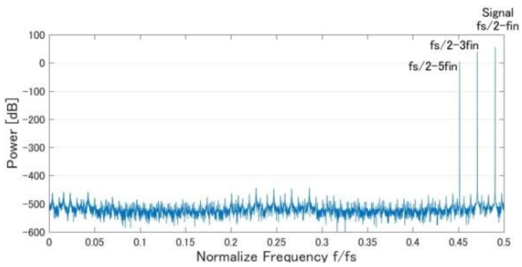


Fig. 13. $Y(nT_s)$ spectrum with the direct high-frequency signal generation method with AWG 3rd and 5th order distortions. (using Eq.1).

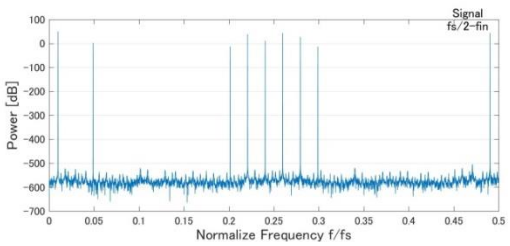


Fig. 14. $Y(nT_s)$ spectrum with the phase-switching high-frequency signal generation method with 3rd and 5th order distortions (using Eqs. 2, 3, 6).

### 2.3 Unified Principle of Low-Frequency and High-Frequency Low-Distortion Signal Generation Methods

We consider here the unified principle of both the low-frequency and high-frequency low-distortion signal generation methods with the phase switching technique. Third-order harmonic component is generated by inputting a sinusoidal signal to the system that having 3rd order nonlinearity. Since the phase switching method interleaves two signals having the same amplitude and frequency but different phases for each clock $T_s$ ($T_s \equiv 1/f_s$), an image signal is also generated around $f_s/2$, and then four frequency components are produced; fundamental component $f_{in}$, its 3rd order distortion component $3f_{in}$, image signal $f_s/2 - f_{in}$, and 3rd order image signal $f_s/2 - 3f_{in}$ (Fig.11). The 3rd harmonic components of the two input signals are cancelled with the reverse phase ($\varphi_x$), and also the 3rd order image signals of the two input signals are cancelled with the same phase ($\varphi_y$) (Fig.12).

## III. Conclusion

We have reviewed our proposed low-distortion low-frequency and high-frequency sinusoidal signal generation algorithms with an AWG using the phase switching technique. It does not need the AWG nonlinearity identification, but need only a simple analog LPF or HPF. Simulation results show its effectiveness.

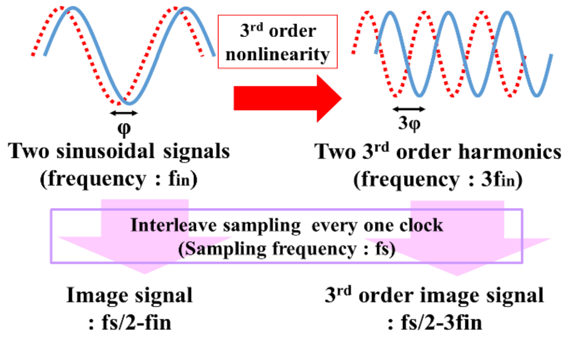


Fig. 15. Frequency components appearing with the phase switching technique.

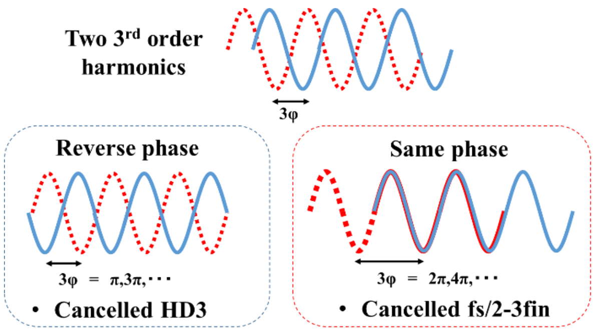


Fig. 16. HD3 components cancellation using the phase difference.

## Acknowledgments

We would like to thank R. Shiota, K. Hatayama, T. Nakatani, K. Asami, F. Abe, Y. Kobayashi for valuable discussions, and STARC for kind support of this project.

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### Appendix: Two tone signal generation

Two-tone signal testing is frequently used in ADC testing for such as communication applications. When the 3rd-order nonlinearity is dominant in the AWG and $f_{out1}$, $f_{out2}$ are used, IMD3 components ($2f_{out1}-f_{out2}$, $2f_{out2}-f_{out1}$) are serious because they are close to the signals ($f_{out1}$, $f_{out2}$) and are difficult to remove with an analog filter. Then we consider to apply the phase switching algorithm. Suppose that the AWG has 3rd-order distortion.

Suppose the following:

$$Y(nT_s) = a_1 D_{in} + a_3 D_{in}^3 \qquad \text{(A1)}$$

For the direct method, we use

$$D_{in} = A\sin(2\pi f_1 nT_s) + B\sin(2\pi f_2 nT_s) \qquad \text{(A2)}$$

Simulation conditions are as follows:

$$f_1/f_s = 30/1024, \qquad f_2/f_s = 40/1024$$

$$A = 1, B = 1, a_1 = 1, a_3 = 1.$$

Then the output spectrum is shown in Fig. A1.

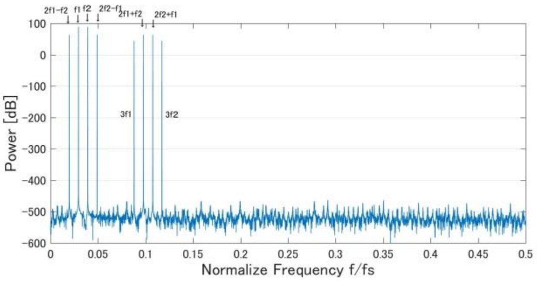


Fig. A1. $Y(nT_s)$ spectrum with the direct low-frequency two-tone signal generation method with AWG 3rd order distortion (using Eq.A2).

On the other hand, let us use the following:

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_1 nT_s + \varphi_0) + A\sin(2\pi f_2 nT_s - \varphi_0) & n: \text{even} \\ X_1 = A\sin(2\pi f_1 nT_s - \varphi_0) + A\sin(2\pi f_2 nT_s + \varphi_0) & n: \text{odd} \end{cases} \qquad \text{(A3)}$$

$$\varphi_0 = \frac{\pi}{6}.$$

Then the output spectrum is shown in Fig. A2 and we see that IMD3 components are cancelled.

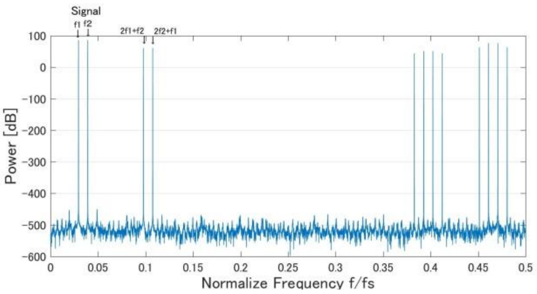


Fig. A2. $Y(nT_s)$ spectrum with the phase-switching low-frequency two-tone signal generation method with AWG 3rd order distortion (using Eq.A3).

Next consider the following:

$$D_{in} = A\sin(2\pi f_1{}' nT_s) + B\sin(2\pi f_2{}' nT_s) \qquad \text{(A4)}$$

$$f_1'/f_s = (f_s/2 - f_1)/f_s = 482/1024,$$

$$f_2'/f_s = (f_s/2 - f_2)/f_s = 472/1024$$

$$A = 1, B = 1, a_1 = 1, a_3 = 1.$$

Then the output spectrum is shown in Fig. A3.

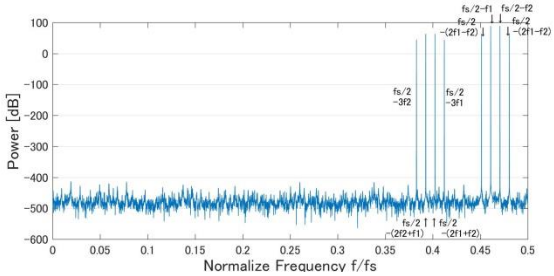


Fig. A3 $Y(nT_s)$ spectrum with the direct low-frequency two-tone signal generation method with AWG 3rdorder distortion (using Eq.A4).

On the other hand, let us consider the high-frequency two-tone phase switching algorithm:

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_1 nT_s + \varphi_0) + A\sin(2\pi f_2 nT_s - \varphi_0) & n: \text{even} \\ X_1 = A\sin(2\pi f_1 nT_s - \varphi_0) + A\sin(2\pi f_2 nT_s + \varphi_0) & n: \text{odd} \end{cases} \qquad \text{(A4)}$$

$$\varphi_0 = \frac{\pi}{3} \qquad \text{(A5)}$$

The output power spectrum is shown in Fig. A3, and we see that the IMD3 components are cancelled.

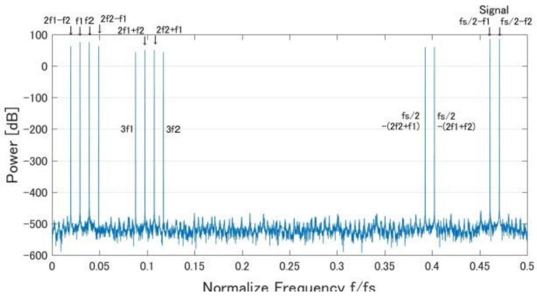


Fig. A4 Spectrum with the phase-switching high-frequency two-tone signal generation method with 3rd order distortions(using Eq.A3)