

The impact of a balun on the second harmonic of an RF DAC

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Introduction

A radio-frequency (RF) balun is a necessary component for the output-matching network of an RF digital-to-analog converter (DAC), which is used to convert signals from differential to single-ended. Some of the key parameters to consider when selecting a balun to match an RF DAC are insertion loss, return loss, and magnitude and phase imbalance. Insertion loss is a guide to the bandwidth capability of the balun. Return loss, also useful, allows the termination to be designed to match the balun's response at a particular frequency or band of frequencies.

Designers usually understand the insertion- and return-loss effects on RF DAC performance and know how to choose the best device. But the magnitude and phase imbalance are often overlooked because their effects on RF DAC performance are not always obvious. For example, a low-temperature co-fired ceramics (LTCC) balun may be chosen if the decision is between it and a winding balun because the LTCC balun has a small size and a stable assembly. However, an LTCC balun has very bad magnitude and phase imbalance.

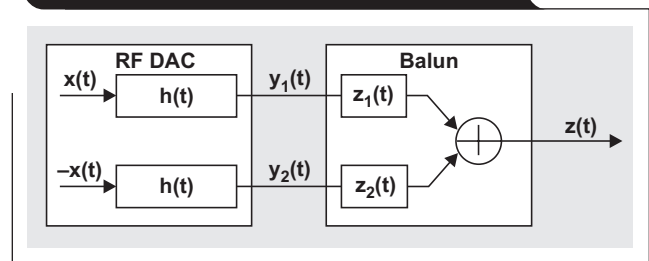
It's important to know the quantifiable impact of a balun's magnitude and phase imbalance on an RF DAC's performance in order to make proper trade-offs against the balun's package and performance for an RF design. The focus of this article is on magnitude and phase imbalance and how they affect an RF DAC's second-harmonic (HD2) performance.

Theoretical analysis

Despite a wide bandwidth rating, coupling between the balun's differential primary and single-ended secondary, although linear, introduces magnitude and phase imbalances. When applied to a converter or any other differential-output devices, these imbalances worsen even-order cancellation of the converted, or processed, signal. Although these imbalances are usually negligible at low frequencies, the added distortion in high-speed data converters becomes significant, especially for an RF DAC.

The starting point is a review of how the magnitude and phase imbalance of a balun affects the HD2 cancellation of an RF DAC. Figure 1 shows a model of an RF DAC with an external balun. An RF DAC will distort the differential input signal, $x(t)$, to become the output signal, $y(t)$, and $y(t)$ will be taken as the input signal of the balun. Adding $y(t)$ to the magnitude and phase imbalance information of the balun becomes $z_1(t)$ and $z_2(t)$. Finally, $z_1(t)$ plus $z_2(t)$ becomes the single-ended output signal, $z(t)$.

Figure 1. Simplified block diagram of an RF DAC with a balun



The RF DAC can be modeled as a symmetrical third-order transfer function. Then its transfer function $h(t)$ can be expressed by Equation 1.

$$h(t) = a_0 + a_1x(t) + a_2x(t)^2 + a_3x(t)^3 \tag{1}$$

Then the $x(t)$ input signal will become $y(t)$ after the RF DAC and can be expressed with Equation 2.

$$y_1(t) = h[x(t)] = a_0 + a_1x(t) + a_2x(t)^2 + a_3x(t)^3 \text{ and} \tag{2}$$

$$y_2(t) = h[-x(t)] = a_0 - a_1x(t) + a_2x(t)^2 - a_3x(t)^3$$

Best case: Balun has no imbalance

If the Balun has no imbalance, then $z_1(t)$ and $z_2(t)$ are perfectly balanced, they have the same magnitude ($k_1 = k_2 = k$) and are exactly 180 degrees out of phase. This can be expressed with Equation 3.

$$z_1(t) = ky_1(t) \text{ and} \tag{3}$$

$$z_2(t) = -ky_2(t)$$

The balun will transform the $z_1(t)$ and $z_2(t)$ differential signal to single-end signal, $z(t)$, and Equation 4 can be used to calculate $z(t)$.

$$z(t) = z_1(t) + z_2(t) = 2ka_1x(t) + 2ka_3x(t)^3 \tag{4}$$

Equation 4 shows the familiar result for a differential circuit: even harmonics cancel while odd harmonics do not.

Balun with magnitude imbalance

Suppose the balun has magnitude imbalance, but no phase imbalance. In this case, $k_1 \neq k_2$. This can be expressed by Equation 5.

$$z_1(t) = k_1y_1(t) \text{ and} \tag{5}$$

$$z_2(t) = -k_2y_2(t)$$

Through the balun, $z(t)$ can be expressed by Equation 6.

$$\begin{aligned} z(t) &= z_1(t) + z_2(t) \\ &= (k_1 - k_2) \times a_0 + (k_1 - k_2) \times a_1 x(t) \\ &\quad + (k_1 - k_2) \times a_2 x(t)^2 + (k_1 - k_2) \times a_3 x(t)^3 \end{aligned} \quad (6)$$

Equation 6 shows that the HD2 is directly proportional to the difference of the magnitude terms, k_1 and k_2 .

Therefore, $HD2 \propto (k_1 - k_2)$

In a real application, sinusoidal frequencies are usually used to evaluate the HD2. If $x(t) = \sin(\omega t)$, then Equation 6 yields Equation 7.

$$\begin{aligned} z(t) &= z_1(t) + z_2(t) \\ &= (k_1 - k_2) \times a_0 + (k_1 - k_2) \times a_1 \sin(\omega t) \\ &\quad + (k_1 - k_2) \times a_2 \sin^2(\omega t) + (k_1 - k_2) \times a_3 \sin^3(\omega t) \end{aligned} \quad (7)$$

Applying the trigonometric power identities:

$$\sin^2(\omega t) = \frac{1 - \cos(2\omega t)}{2} \quad \text{and}$$

$$\sin^3(\omega t) = \frac{3\sin(\omega t) - \sin(3\omega t)}{4}$$

Then take out the HD2 results in Equation 7 to yield Equation 8.

$$z(2\omega t) = (k_1 - k_2) \times a_2 \cos(2\omega t) \quad (8)$$

Phase imbalance

If the balun generates a phase imbalance, ϕ , between the two input signals, and there is no magnitude imbalance, then $k_1 = k_2$ and $\phi \neq 0$. A balun with phase imbalance will have different delay for $z_1(t)$ and $z_2(t)$. When the output signal of the RF DAC passes through the balun, the balun will produce a fixed signal delay and generate a related phase. Suppose for the fundamental signal, the phase is ϕ . Then for the HD2, the phase is 2ϕ ; for the third harmonic (HD3), the phase is 3ϕ . After the balun, a single-end signal can be expressed as Equation 9.

$$\begin{aligned} z(t) &= z_1(t) + z_2(t) \\ &= k_1 a_1 x(t) (1 - e^{j\phi}) + k_1 a_2 x(t)^2 (1 - e^{j2\phi}) \\ &\quad + k_1 a_3 x(t)^3 (1 - e^{j3\phi}) \end{aligned} \quad (9)$$

Equation 9 shows that the second-harmonic amplitude is proportionate to the magnitude term, k_1 . Therefore,

$$HD2 \propto k_1$$

Sinusoidal frequencies are usually used to evaluate the HD2, so letting $x(t) = \sin(\omega t)$, according to Equation 2, the result is by Equation 10.

$$z_1(t) = k_1 a_0 + k_1 a_1 \sin(\omega t) + k_1 a_2 \sin^2(\omega t) + k_1 a_3 \sin^3(\omega t) \quad (10)$$

Applying the trigonometric power identities:

$$\sin^2(\omega t) = \frac{1 - \cos(2\omega t)}{2} \quad \text{and}$$

$$\sin^3(\omega t) = \frac{3\sin(\omega t) - \sin(3\omega t)}{4}$$

For 2ω and $3\omega t$, phases 2ϕ and 3ϕ are added, which results in $z_2(t)$, as shown in Equation 11.

$$\begin{aligned} z_2(t) &= k_1 a_0 + k_1 a_1 \sin(\omega t + \phi) + k_1 a_2 \frac{1 - \cos(2\omega t + 2\phi)}{2} \\ &\quad + k_1 a_3 \frac{3\sin(\omega t + \phi) - \sin(3\omega t + 3\phi)}{4} \end{aligned} \quad (11)$$

So, the $z(t)$ single-end signal will be $z_1(t) + z_2(t)$. The removal of $2\omega t$ from the equation yields Equation 12.

$$z(2\omega t) = -k_1 a_2 \sin(\phi) \times \sin(2\omega t + \phi) \quad (12)$$

Therefore, $HD2 \propto k_1$

Observations

A comparison of Equations 8 and 12 indicates that the HD2 amplitude is more sensitive to the phase imbalance than to the magnitude imbalance. For phase imbalance, the second harmonic is proportional to k_1 , while for magnitude imbalance, HD2 is proportional to the difference between k_1 and k_2 . Because k_1 and k_2 are approximately equal, this difference is small.

To test the validity of these calculations, Appendix A shows the MATLAB code that was written for the model described in this article to quantify and illustrate the impact of balun amplitude and phase imbalance on HD2 cancellation of an RF DAC. The model includes additive white Gaussian noise.

The converter distortion coefficient, a_2 , decided the HD2 level such as power or amplitude. For a data converter, the HD2 power is usually compared with the signal power to get dBc units in frequency domain to explain the HD2 level. Because the HD2 level is just a small portion of signal power, a_2 has the range of $0 < a_2 < 1$.

Figure 2 shows RF-DAC HD2 performance with a different HD2 coefficient, a_2 , and with certain phase and amplitude imbalance balun. For Figure 2, the frequency is 2.6 GHz, the balun's amplitude is 0.4 dB and the phase imbalance is 10.8 degrees. According to the DAC38RF83 data sheet, the HD2 is 54 dBc at a 0 dBFS output with 2.6 GHz frequency. As shown in Figure 3, the HD2 a_2 coefficient of the RFDAC38RF83 is 0.01, which means $a_2 = 0.01$.

Figure 3 illustrates the $z_1(t)$ and $z_2(t)$ behavior with the phase and amplitude imbalance. Note that $z(t)$ is not zero, which means the balun cannot cancel the HD2 of the RF DAC.

Figure 4 shows the HD2 plots for the DAC38RF83 RF DAC at 2.6-GHz with only phase or only amplitude imbalance

Figure 2. RF-DAC HD2 at different HD2 coefficients

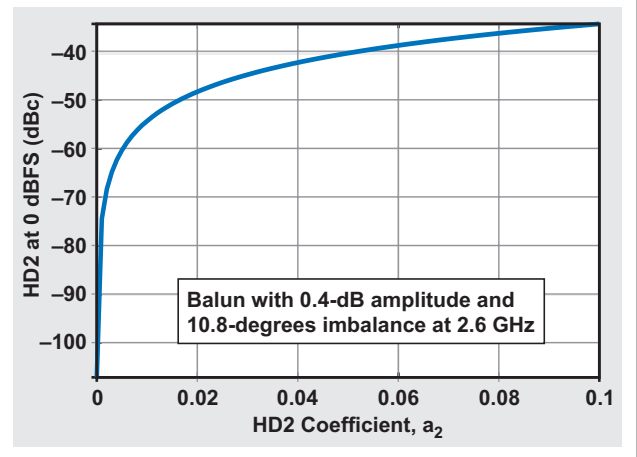


Figure 3. The balun output with only amplitude and only phase imbalance

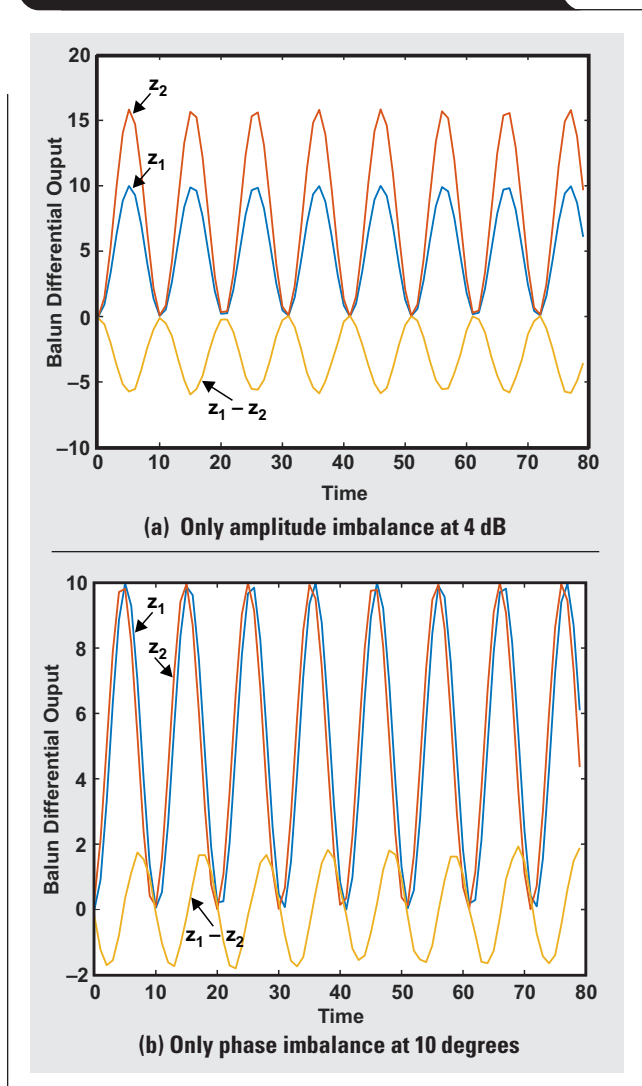


Figure 4. HD2 plots for DAC38RF83 RF DAC at 2.6-GHz output

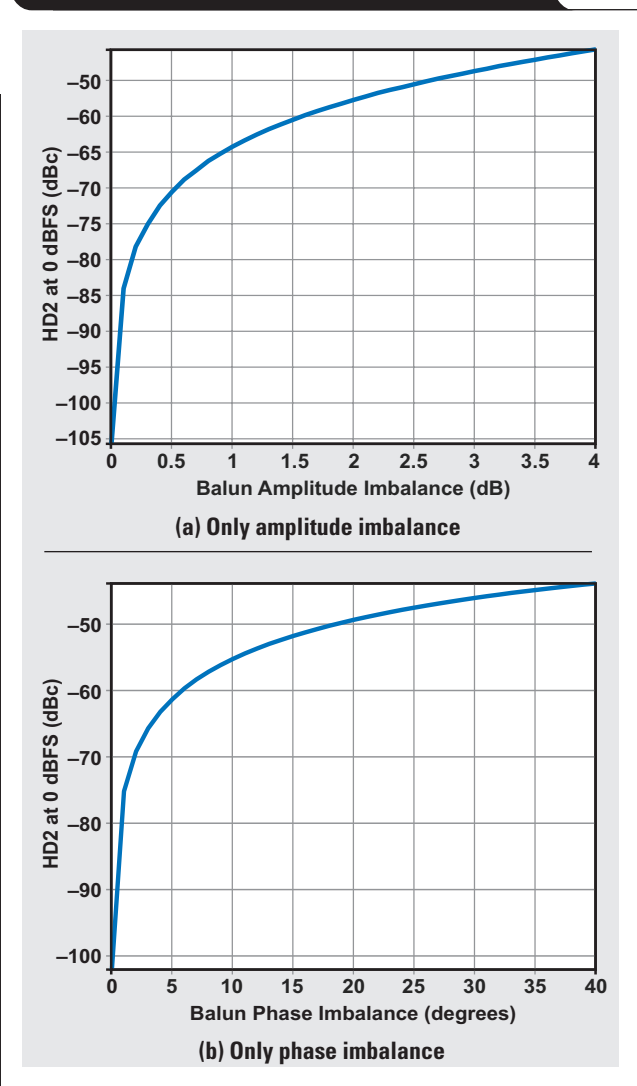


Figure 5 shows the HD2 plots at various balun amplitude and phase imbalance for the DAC38RF83 RF DAC at 2.6 GHz.

Conclusion

This article provided theoretical equations that illustrated how balun amplitude and phase imbalance impact the HD2 of an RF DAC.

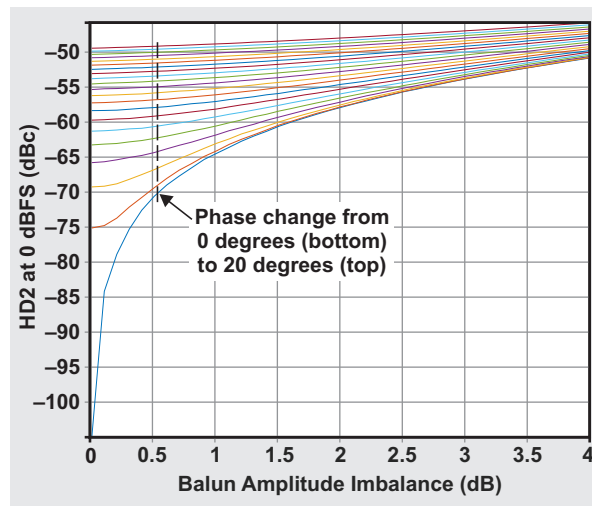
Equations 8 and 12 showed that HD2 is more severely affected by phase imbalance than magnitude imbalance. The Texas Instruments DAC38RF83 RF DAC, which is popular in wireless infrastructure applications, further illustrates this effect.

Using a 2.6-GHz frequency output and the MATLAB® code in Appendix A below, the quantitative impact on HD2 can be determined for other frequency bands. Once the quantitative impact is known, the best balun can be chosen and the trade-offs for various balun package types can be examined for optimum performance.

Related Web sites

Product information:
DAC38RF83

Figure 5. DAC38RF83 RF-DAC HD2 plots at various amplitude and phase imbalance



Appendix A

MATLAB® code used in this article:

```
% Matlab code to study the effect of phase and
% magnitude imbalance of input
% signals on the output
% April 24, 2018
clear all; close all;
% Error terms that can be set by the user
magnErrdB = 0:0.1:4; %in dB
% magnErrdB = 4; %in dB
phaseErr = 0:1:20; %in degrees
sd_noise = 100e-6; %std dev of noise
% Convert dB magnErr to voltage level
magnErr = 10.^(magnErrdB/20);
% Coefficients
a0=0; %dc offset
% Coefficients of 2ndharmonics
a2=0.01;% DAC38RF83 HD2 is 54dBc at 9G for 2.6G
% a1=0.89;
% a2=0.01;
% a3=0.0007;
%input freq - does not affect calculations
fin = 100;
t = 0:1:2047;
%Input signals
k1=1;
k2=k1*magnErr;
%Each differential signal multiplied by the DAC
for j=1:length(phaseErr);
for i=1:length(magnErrdB);
y1 = 0.5*k1*a2*(1-cos((t/2048)*2*pi*2*fin));
y2 = 0.5*k2(i)*a2*(1-cos((t/2048)*2*pi*2*fin+2*(
pi/180)*phaseErr(j)));
%Output only amplitude error

z1=y1;
z2=y2;
% z = z1;
```

```
z = z1-z2;
noise = sd_noise*randn(1,length(z));
z = z + noise;
% figure;
% plot(t(1:80),1000*z1(1:80),t(1:80),1000*z2(1
:80),t(1:80),1000*z(1:80));
% title('Only Balun Amplitude unblance@4dB ');
% xlabel('Time');
% ylabel('Balun differential output ');
%Take the FFT
fft_y = fft(z/1024, 2048);% magnitu/1024 equal
to time domain
Pyy = 10*log10(fft_y.*conj(fft_y));
freq_axis = 0:1:1023;
% figure;
% plot(freq_axis, Pyy(1:1024));
% title('Frequency of the RFDAC output');
% xlabel('Frequency (Hz)');
% axis tight;
% Print fundamental and 2nd, 3rd harmonics
f = Pyy(101);
h2(j,i) = Pyy(201);
if i>=2
hd2_deta_A(j,i)=h2(j,i)-h2(j,i-1);
end
end
end
figure;
grid on;
plot(magnErrdB,h2);
title('Balun Phase and Amplitude imbalance
@2.6G ');
xlabel('Balun amplitude imbalance (dB)');
ylabel('HD2@0dBfs (dBc)');
axis tight;
grid on;
```

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