TEXAS INSTRUMENTS

Application Report

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LO Harmonic Effects on TRF3705 Sideband Suppression

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ABSTRACT

The LO harmonic effects on I/Q errors and sideband suppression (SBS) in the RF modulator was analyzed in application report SLWA059. This application report further investigated LO harmonic effects when attempting to achieve an increased level of SBS performance. The selectivity requirements for the second- and third-order harmonics are outlined to aid in proper filter design. In the measurement, the baseband I/Q inputs to the TRF3705 modulator were adjusted to minimize the residual sideband leakage floor due to contributions of non-LO harmonic amplitude and phase errors; therefore, the contribution from the LO harmonic components to the sideband can be determined more precisely.

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1 I/Q Mismatch Effects on SBS

The TRF3705 is a high-performance RF modulator for up-converting the in-phase (I) and quadrature-phase (Q) signals to RF signals in the transmit chain. The SBS is one of the major parameters. For zero-IF (ZIF) application, the sideband leakage can distort the modulated signal and degrade the transmitter's error vector magnitude (EVM). The minimum EVM requirement for the most efficient modulation in LTE downlink, OFDM/64QAM, is 8%, corresponding to about 22-dB signal-to-noise ratio (SNR). In real system design, it is typical to minimize RF modulator's sideband leakage so that its impact to the EVM is negligible. For example, if the required EVM for the OFDM/64QAM modulation is 22 dB and the RF modulator SBS is -40 dBc, the sideband leakage degrades the EVM by about 0.068 dB. For a non-ZIF system, the sideband leakage needs to meet the requirements for protection of the base station (BTS) receiver, for co-location, and for co-existence. At the RF modulator output, typically, the requirement is for the unadjusted sideband leakage to be less than -40 dBc and the adjusted sideband leakage to be -60 dBc.

I/Q errors cause sideband leakage. I/Q errors, also called I/Q mismatches, include both the amplitude and the phase mismatches.

The relationship between I/Q mismatches and the sideband rejection can be described as

$$\mathrm{SBS(dBc)} = 10\log_{10}\frac{1 + A^2 - 2A\cos\theta}{1 + A^2 + 2A\cos\theta}$$

where A is the voltage ratio between I and Q amplitudes and θ is the phase difference between I and Q. Figure 1 shows the SBS versus amplitude and phase mismatches. Without amplitude mismatch (i.e., A = 0 dB), θ must be less than 1.146^o to achieve a SBS of better than -40 dBc and 0.36^o for -50 dBc, which reveals that the SBS is very sensitive to the I/Q phase error.

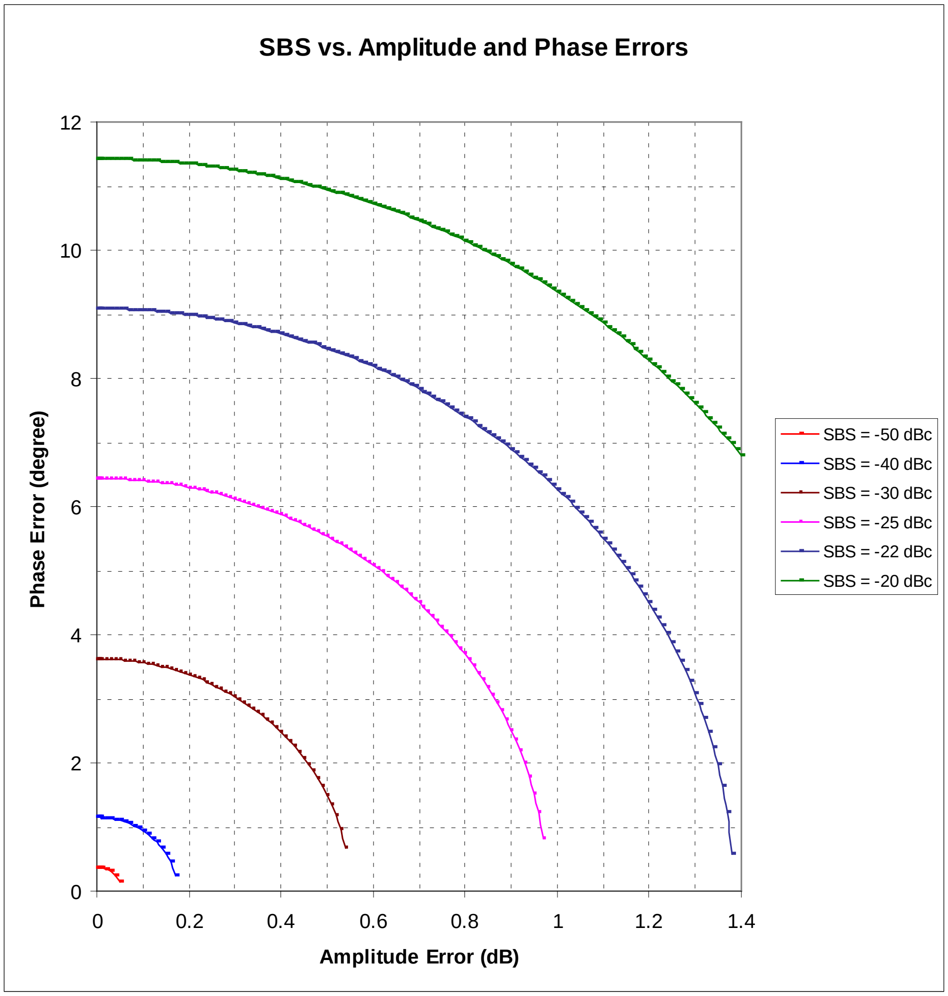


Figure 1. SBS vs. I/Q Amplitude and Phase Mismatches for I/Q Modulator

2 LO Harmonic Effects on SBS

I/Q mismatches result from different sources, such as:

- Phase mismatches from I/Q baseband signals from the DAC,
- Gain and phase error caused by the interface circuitry implemented on the PCB between the DAC and the RF modulator IC (i.e., low-pass filter),
- Gain and phase mismatches inside the RF I/Q modulator, including the input buffer circuitry and I/Q modulator,
- LO gain and phase errors produced in the polyphase bridge as mentioned in application report SLWA059,
- LO harmonic distortion (HD).

The first four sources are obvious contributors to the RF modulator output I/Q mismatch, but the connection from the LO harmonics to I/Q mismatches is unclear. Application report SLWA059 analyzed how the LO harmonics contributed to I/Q mismatches. This work provides more extended discussion and quantitative results for both second harmonic distortion (HD_2) and third harmonic distortion (HD_3) components.

2.1 Phase Error Due to HD_2

Assume that the LO signal, v(t), includes the fundamental, $v_0(t)$ and the second harmonic, HD_2, as expressed in Eq. 1:

$$v(t) = v_0(t) + HD_2 = a_0 \sin(2\pi f_0 t) + a_2 \sin(2 \times 2\pi f_0 t + \phi) \qquad \textit{Eq. 1}$$

where f_0 is the LO frequency, a_0 is the amplitude of the fundamental component, a_2 is the amplitude of the HD_2, and ϕ is the initial phase difference between the fundamental and HD_2 components.

As pointed out in SLWA059, $\phi = 90^o$ produces the maximum phase error and $\phi = 0^o$ produces the minimum phase error between v(t) and the ideal LO signal, $v_0(t)$. Figure 2 is the plot for $v_0(t)$, v(t) with $\phi = 90^o$ and HD_2. The ratio of two amplitudes, $B = 10\log_{10}(a_2/a_0)$, is chosen to be -20 dB. The phase error between v(t) and the ideal LO signal, $v_0(t)$, can be measured by the phase error at the zero crossing as highlighted around $n \times 180^o$, where n = 1, 2, ….

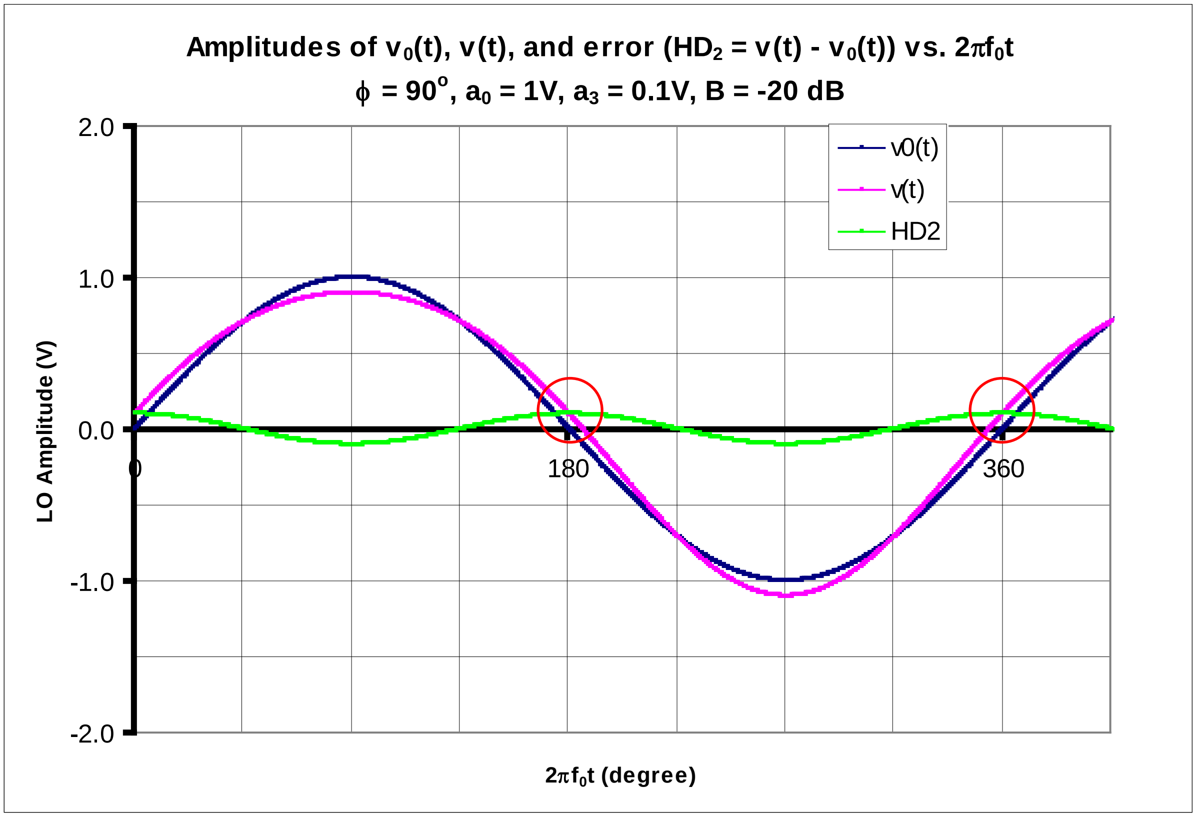


Figure 2. Amplitudes of v(t), v0(t), and HD2 vs. $2\pi f_0 t$

The larger the amplitude of HD_2, the larger the phase error is as shown in Table 1. The data shows that the phase errors have different polarities at 180° and 360° but the same amplitude, which makes the actual impact of HD2 less significant on average than if the phase error has the same polarity. The estimated SBS is also listed based on the calculation in Figure1.

Here the amplitude error is not considered for the reason that TI RF modulators' polyphase bridges include amplitude limiters which remove the amplitude mismatch.

Table 1. Maximum Phase Error Due to HD_2 for Initial Phase $\phi = 90^o$ as Well as Estimated Maximum SBS Based on Data in Figure 1

	max. phase error		Estimated
A (dB)	@180°	@360°	max. SBS
-20	-5.628	5.628	< -26.2
-30	-1.808	1.808	< -36
-40	-0.573	0.573	< -46
-50	-0.182	0.182	< -56
-60	-0.057	0.057	< -66

2.2 Phase Error Due to HD_3

Similarly, assume that the LO signal, v(t), includes the fundamental, $v_0(t)$, and the third harmonic, HD3, as expressed in Eq. 2:

$$v(t) = v_0(t) + HD_3 = a_0 \sin(2\pi f_0 t) + a_3 \sin(3 \times 2\pi f_0 t + \phi) \quad \text{Eq. 2}$$

where a_3 is the amplitude of the HD_3, and ϕ is the initial phase difference between the fundamental and HD_3 components.

Again, $\phi = 90^o$ produces the maximum phase error and $\phi = 0^o$ produces the minimum phase error between v(t) and the ideal LO signal, $v_0(t)$. Figure 3 is the plot for $v_0(t)$, v(t) with $\phi = 90^o$ and HD_3. The ratio of two amplitudes, $B = 10\log_{10}(\mathbf{a_3}/\mathbf{a_0})$, is chosen to be -20 dB.

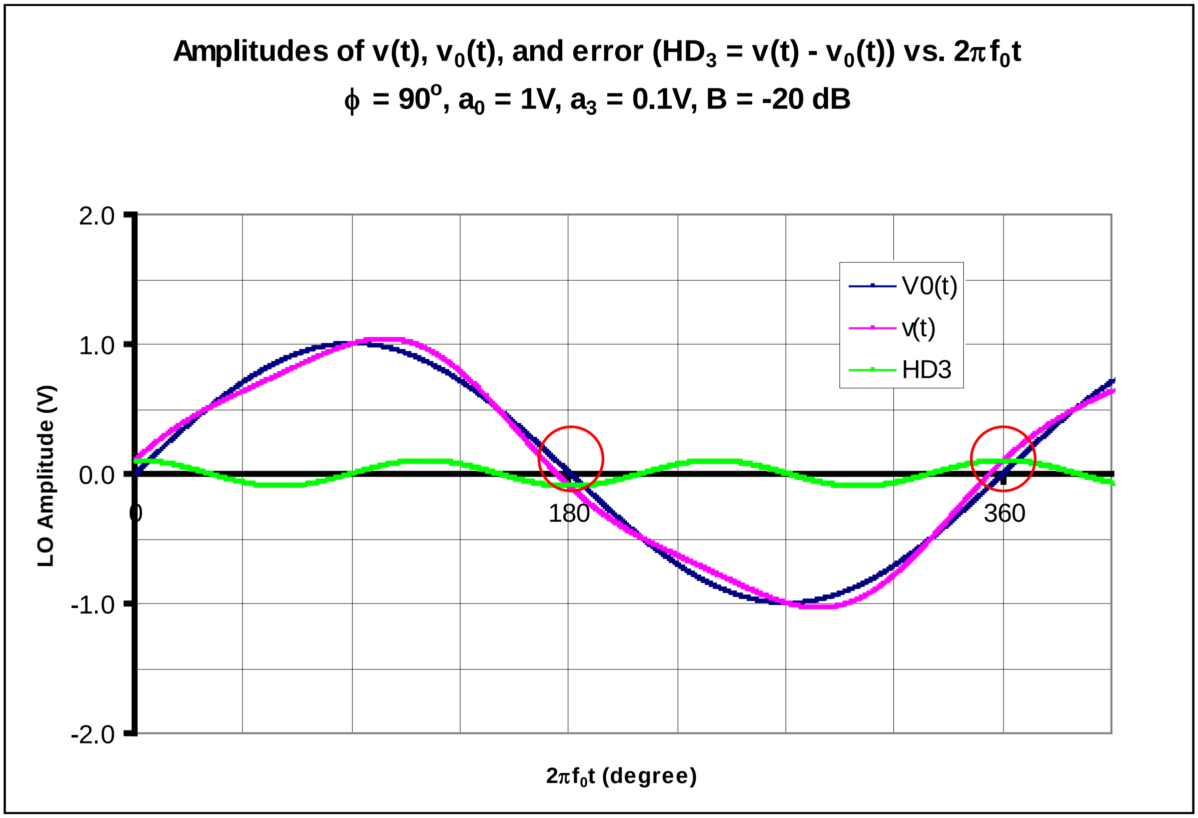


Figure 3. Amplitudes of v(t), v0(t), and HD3 vs. $2\pi f_0 t$

Table 3 shows the maximum phase error due to HD_3 for the initial phase $\phi = 90^o$. It reveals that the phase errors have the same polarity at both 180° and 360° and about the same amplitude. Because of this, one can expect that HD3 makes a more significant impact than HD_2 with the same error amplitude. It is worth to mention that the phase error will be smaller than the maximum phase error given in Table 2 if the initial phase is different from 90°. The estimated SBS also is listed based on the data in Figure 1.

Table 2. Maximum Phase Error Due to HD3 for Initial Phase $\phi = 90^o$ as Well as Estimated Maximum SBS Based on Data in Figure 1

	max. phase error		Estimated max. SBS
A (dB)	@180°	@360°	
-20	5.472	5.544	-26.35
-30	1.800	1.872	-35.9
-40	0.504	0.536	-46.85
-50	0.180	0.200	-55.6
-60	0.061	0.058	-65.9

2.3 Experiments

A test setup similar to the one described in Application Report SLWA059 was used except:

- A low-pass filter (LPF) with a cutoff frequency of 1200 MHz was added to remove harmonic components in the LO fundamental component generation path.
- TRF3705 was adjusted to minimize the sideband leakage before the harmonic component was provided.

Two signal generators with filters separately emulated the fundamental and harmonic components. Two different band-pass filters removed the second and third harmonic components in the HD generation path. The LO frequency was 983 MHz. Figure 4 shows the test setup.

The maximum and minimum SBSs were measured by adjusting the phase of the harmonic component. Note that the phase of the signal generator's output is different even when only the output amplitude level is adjusted; therefore, the output phase of E4438C was readjusted to find the maximum and minimum SBS after its amplitude was changed.

The SBS was measured for the different power levels of HD_2 and HD_3. The results are provided in Figures 5 and 6 and summarized as follows:

1. The measured maximum SBS due to HD_3 was only about 2 dB worse than the theoretical calculation given in Table 2.
2. For the minimum SBS case, SBS should be zero if the initial phase is adjusted to be exactly 0^o. This indicated that there are still some residual amplitude and phase mismatches. For example, it could be due to phase uncertainty from the two generators even though they were synchronized to the same 10-MHz reference signal.
3. The HD_2 impact was much less significant than HD_3, which proved that the different polarity of its phase error at 180° and 360° was the key.

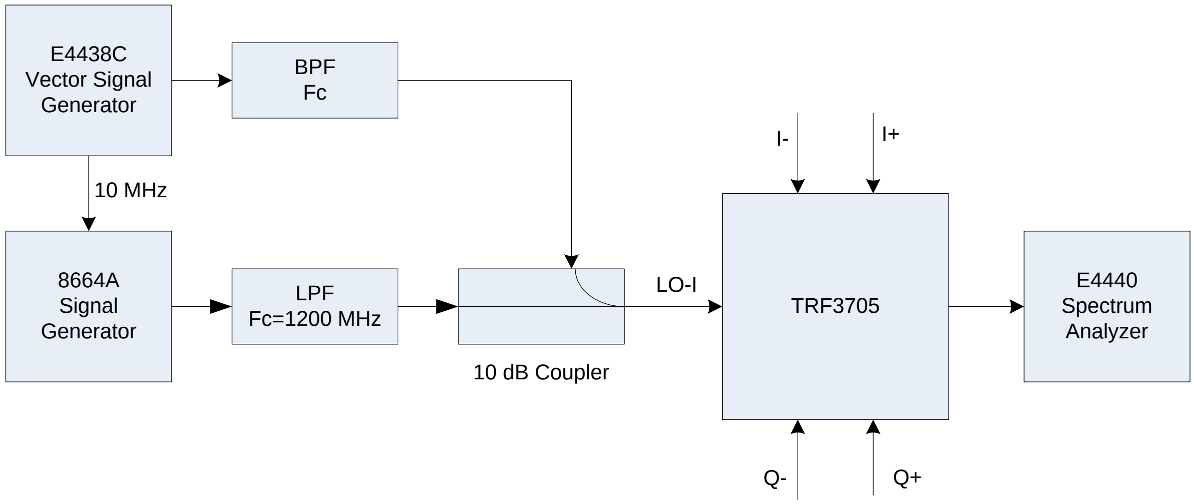


Figure 4. Test Setup

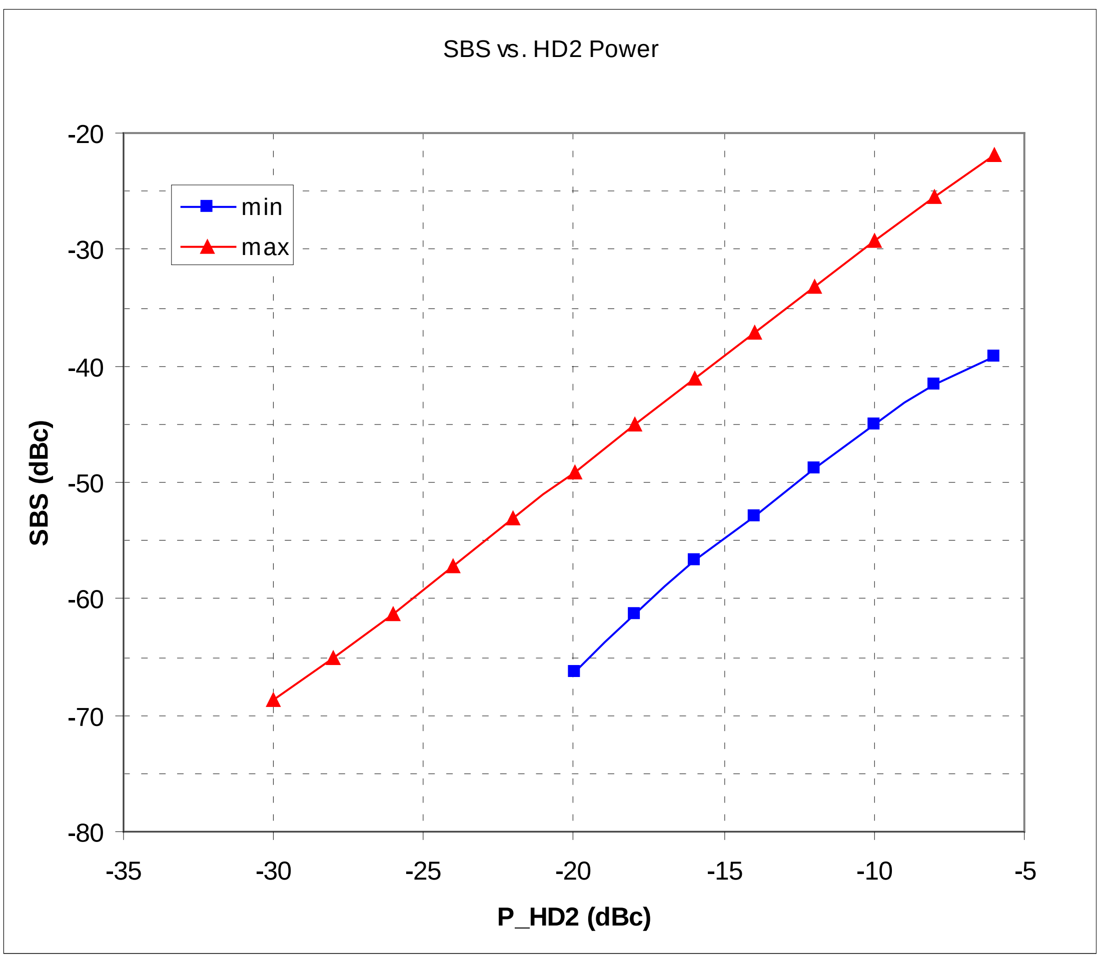


Figure 5. SBS vs. HD2

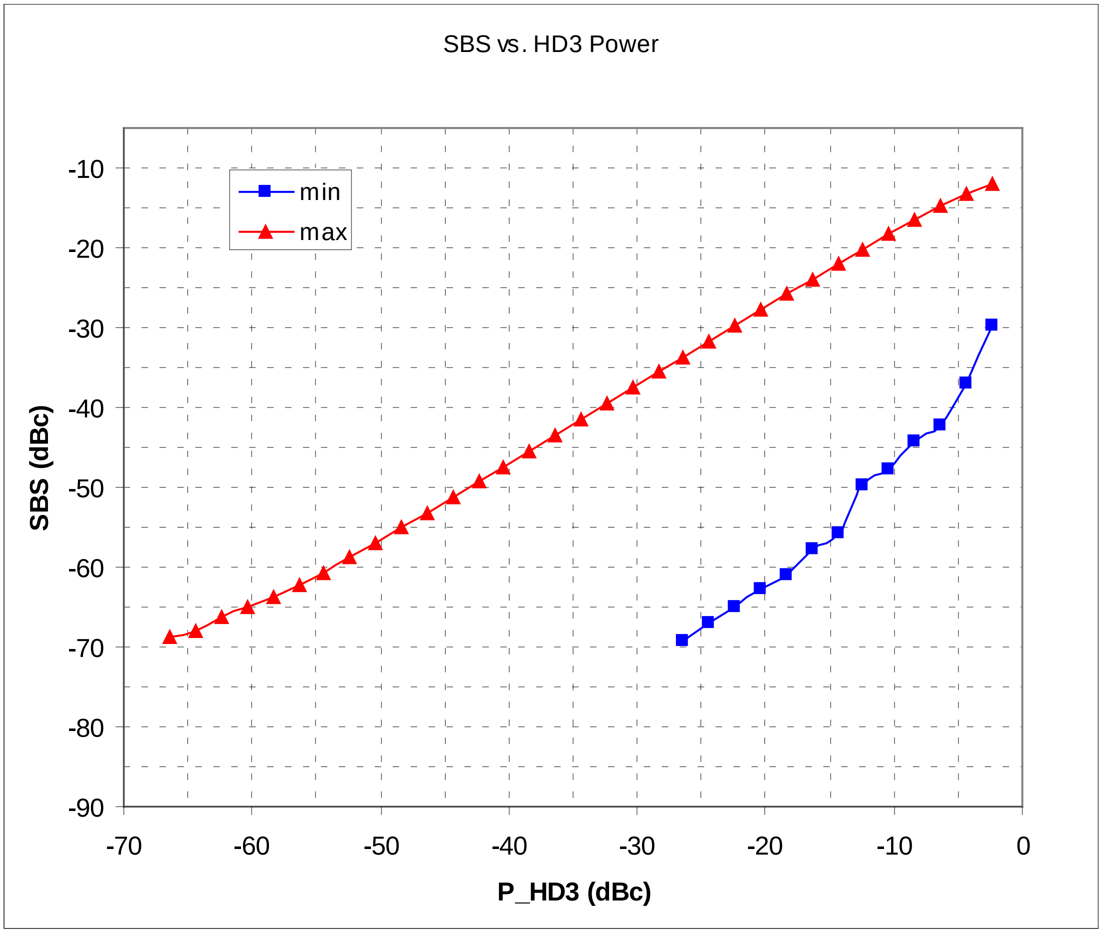


Figure 6. SBS vs. HD3

3 Examples

3.1 Example 1

In a real system, the LO signal is generated by a high-performance RF synthesizer, such as TI's TRF3765 which is a wideband integer-N/fractional-N frequency synthesizer with an integrated, wideband voltage-controlled oscillator (VCO). Usually, this type of RF synthesizer has high harmonic levels. A low-pass filter must be used to suppress its harmonic components to improve the SBS performance.

First, the I/Q phase and amplitude of baseband I/Q inputs to TRF3705 were adjusted to minimize the SBS residual floor when an HP 8664 signal generator was used as the LO source as in Figure 7. Then, the TRF3765 RF output was switched as the LO source. By carefully selecting the fundamental frequency and using a LPF with its cutoff frequency as 2000 MHz, LO signals with different combinations of harmonic components were realized and SBS was measured as shown in Table 3. The estimated maximum and minimum SBSs based on Figures 5 and 6 also were listed. The following are a few observations.

- In Cases 1 and 2, HD_3 component was removed by the LPF with the cutoff frequency f_c = 1200 MHz but HD_2 component was strong. In both cases, the measured SBS fell between the maximum and minimum SBS curves in Figure 5.
- Furthermore, even though the HD_2 in Case 1 was larger than the HD_2 in Case 2, the measured SBS in Case 1 was smaller than the measured SBS in Case 2 due to different relative phase between the fundamental and HD_2 components.
- In Case 3, both HD_2 and HD_3 existed but HD_3 had the dominant impact and the measured SBS fell between the maximum and minimum curves in Figure 6.

In general, the SBS is bounded by the maximum and minimum curves in Figures 5 and 6. The selectivity requirements for the LO filter design must aim for the worst case given by the maximum curves.

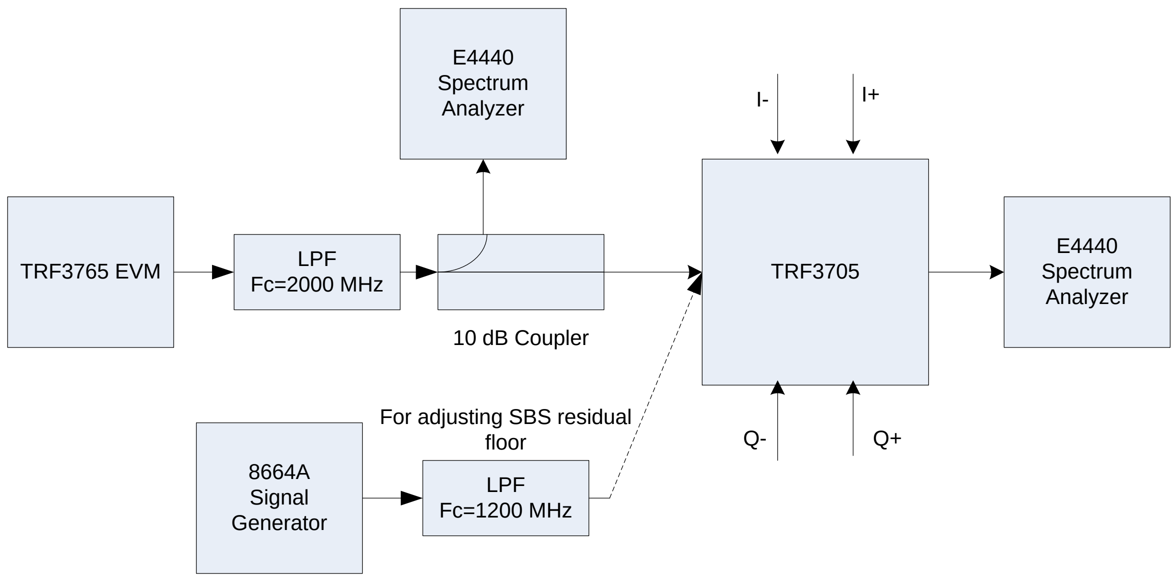


Figure 7. Test Setup Using TRF3765 as LO Source

Table 3. Estimated and Measured SBS Using TI's TRF3765 as LO Source

Case	1	2	3
LO Freq (MHz)	1056.7	1060	725
HD2 amplitude (dBc)	-14.33	-16.8	-18.25
HD3 amplitude (dBc)			-19.2
Measured SBS (dBc)	-49.48	-48.1	-29.1
Estimated max. SBS (dBc) -- HD2	-38	-42	-45.2
Estimated min. SBS (dBc) -- HD2	-54	-57	-61.5
Estimated min. SBS (dBc) -- HD3			-27
Estimated max. SBS (dBc) -- HD3			-62

3.2 Example 2

This example is to design a Chebyshev LPF to reduce the TRF3765 harmonic component levels so that the degradation caused by HD_2 and HD_3 is less than -45 dBc. The typical TRF3765 harmonic distortion levels are shown in Figure 8. At 725 MHz, HD_2 and HD_3 are approximately -22 dBc and -10 dBc. The HD3's contribution is dominant in this case. If a fifth-order Chebyshev LPF filter for 725 MHz is used as shown in Figure 9, the rejection for the HD3 at 2175 MHz is 56 dB, which is more than the needed 31-dB rejection to reduce the -10-dB HD3 component to below -41 dBc for the worst SBS.

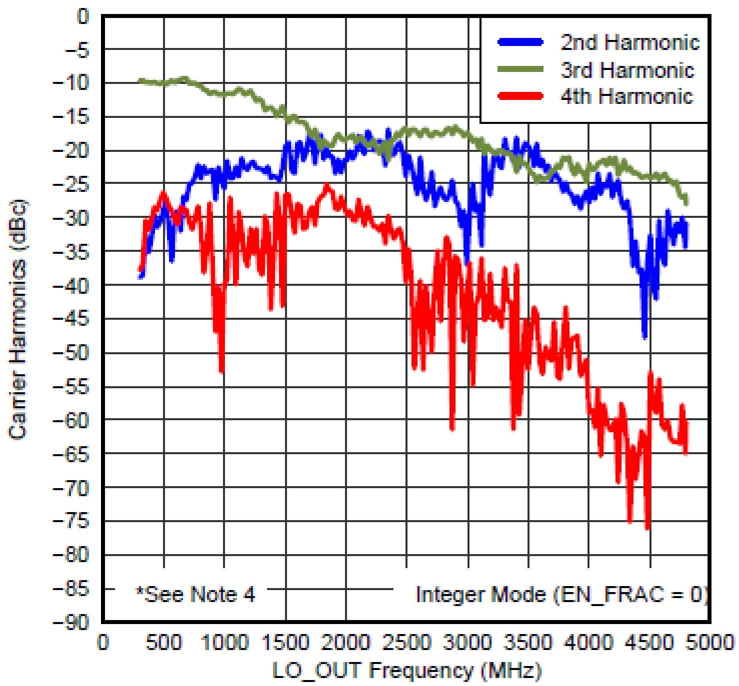
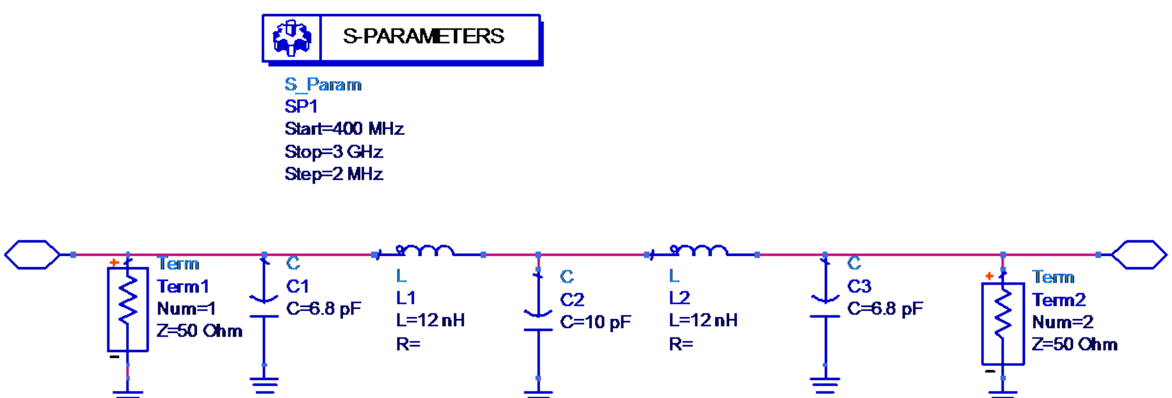


Figure 8. Typical TRF3765 Harmonic Distortion Levels



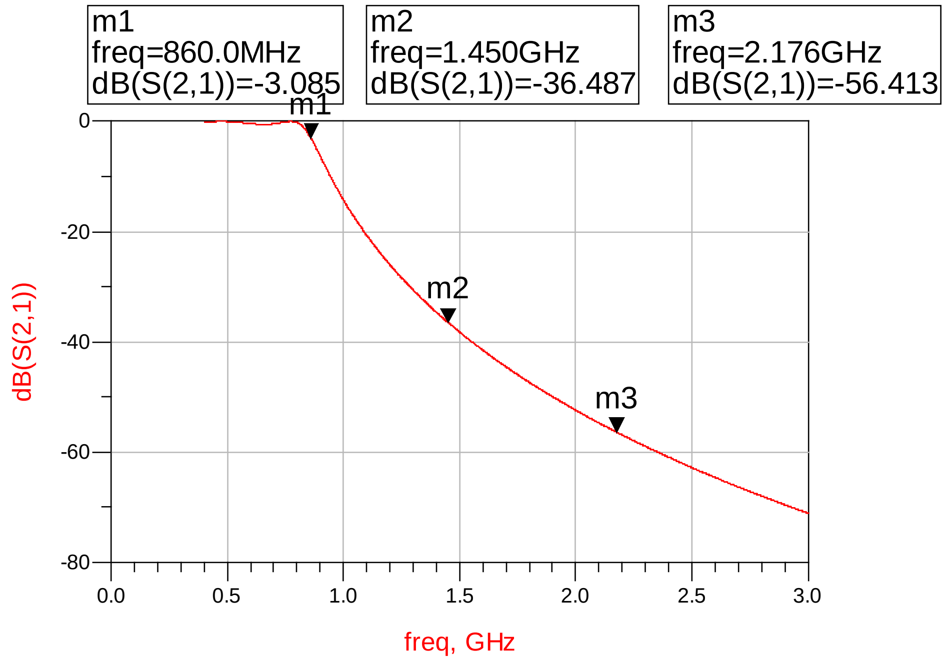


Figure 9. Fifth-Order Chebyshev LPF With Cutoff Frequency = 860 MHz and Its Simulated Frequency Response With 36.5-dB Rejection at 1450 MHz and 56.4-dB Rejection at 2175 MHz.

4 Conclusion

This application report investigates LO harmonic effects when attempting to achieve an increased level of SBS performance. The analysis and measurement provided upper and lower bounds to the degradation caused by LO harmonic components, which defines the selectivity requirements for the proper filter design.

Reference

LO Harmonic Effects on I/Q Balance and SBS in Complex I/Q Modulators application report (SLWA059)