

# ***LO Harmonic Effects on I/Q Balance and Sideband Suppression in Complex I/Q Modulators***

*Mike Arnold, Randy Class, Francesco Dantoni, Shrinivasan Jaganathan, and Roland Sperlich*

*HPA/HSP*

## **ABSTRACT**

This report describes the effect that high local oscillator (LO) harmonics have on the I/Q balance of a complex (I/Q) modulator. The imbalance that is generated has a direct impact on sideband suppression performance of the I/Q modulator. This application report discusses the theoretical distortion generated by the harmonics, along with measured results showing the effect on sideband suppression in a modulator. It also presents the measured results showing the improvement in sideband suppression that can be obtained by filtering out the LO harmonics before they reach the modulator input.

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## 1 Introduction

Wireless basestation transmit chains increasingly use complex (I/Q) modulation techniques to directly modulate baseband I/Q data onto an RF carrier. Direct modulation eliminates the need for an intermediate IF stage and associated filtering, which reduces transceiver board complexity, size, and cost. The key component in this architecture is the complex (I/Q) modulator, and one of the critical performance parameters is sideband suppression.

In-phase/quadrature (I/Q) modulation does not employ IF filtering – it is the job of the I/Q modulator to provide the bulk of the rejection of the unwanted (or image) sideband. If an I/Q modulator is well balanced, it can provide enough sideband suppression so that no post-modulation filtering is required. This allows for zero-IF operation, where the desired sideband and image are a composite signal both centered at the LO frequency. In cases where the baseband I/Q signal is translated up to an IF frequency, a filter can still be used at the modulator output to provide additional image rejection. The requirements on the filter are greatly reduced because the modulator is already providing much of the needed rejection. From the perspective of input stimulus, the two keys to good sideband suppression for an I/Q modulator are:

1. Balanced I/Q baseband inputs [equal amplitude and quadrature (90°) phase]
2. Quadrature phase balance of the LO signal fed to the mixers of the modulator.

No design is perfect, and a certain amount of imbalance in modulator internal LO and baseband paths is expected. The combined effects of these imbalances can be corrected digitally by controlling the DACs used to generate the baseband I/Q signals. However, to ease system requirements on correction algorithms, it is always desirable to minimize these imbalances in the modulator design so that as little correction as possible is needed. Even if the modulator design provides LO drive to the mixers in perfect quadrature, the balance can still be corrupted if the incoming LO signal contains high harmonic levels.

This application report explains the effects that high LO harmonic levels have on the balance of LO signals fed to the mixers, and the associated effects that can be seen in sideband suppression.

## 2 I/Q Modulator Operation

A simple model of a complex I/Q modulator is shown in [Figure 1](#). Under ideal balanced conditions, the operation of the modulator with single CW tones applied is as follows:

- At the top mixer, a  $\sin(\omega_c t)$  LO signal and  $A\sin(\omega_{bb}t)$  baseband I signal are mixed.
- The output of the top mixer at RF1 consists of two terms:
  - positive  $\frac{1}{2}A\cos((\omega_c - \omega_{bb})t)$  [lower sideband]
  - negative  $\frac{1}{2}A\cos((\omega_c + \omega_{bb})t)$  [upper sideband with 180° shift]
- The LO is shifted by 90° by some mechanism and fed to the bottom mixer.
- At the bottom mixer, a  $\cos(\omega_c t)$  LO signal and  $A\cos(\omega_{bb}t)$  baseband Q signal are mixed.
- The output of the bottom mixer at RF2 consists of two terms:
  - positive  $\frac{1}{2}A\cos((\omega_c - \omega_{bb})t)$  [lower sideband]
  - positive  $\frac{1}{2}A\cos((\omega_c + \omega_{bb})t)$  [upper sideband with 0° shift]
- The outputs of the two mixers are combined at a summing node.
  - The two lower sideband terms add in-phase and produce the desired low-side output  $A\cos((\omega_c - \omega_{bb})t)$ .
  - The two upper sideband terms are out-of-phase and cancel.
- If I and Q inputs are swapped, or the polarity of either I or Q is reversed, the operation is the same, except that the lower sideband terms cancel, and the upper sideband terms add, producing the desired high-side output

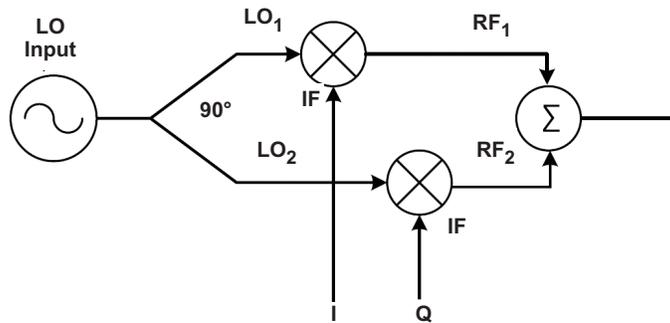


Figure 1. Basic I/Q Modulator Block Diagram

As previously stated, for an ideal modulator the image output completely cancels if I/Q inputs are perfectly balanced and the LO signals fed to the mixers are in perfect quadrature. Imperfections in the I/Q baseband paths can be corrected for by controlling DAC output amplitude and phase. But how is the LO split, and quadrature maintained, especially when this function is integrated on-chip and must operate over a wide range of frequencies? In highly integrated I/Q modulator products such as the Texas Instruments TRF3703-xx and TRF3720, this operation is achieved by using a polyphase bridge.

### 3 The Polyphase Bridge

The polyphase function is shown in Figure 2. For a single-ended system, the LO input is divided into in-phase (0°) and quadrature (90°) components. A differential polyphase circuit also can be implemented that generates four LO components separated by 90°. The 0°/180° pair forms the in-phase differential output, and the 90°/270° pair forms the quadrature differential output.

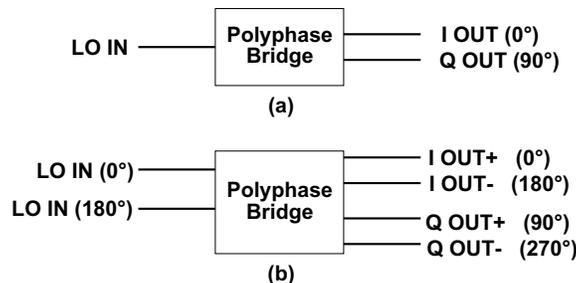
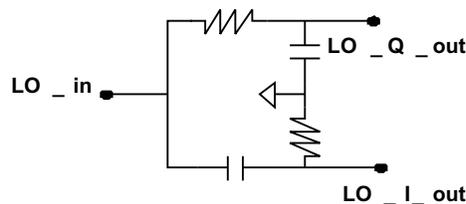


Figure 2. Polyphase Functional Blocks

The circuit of a first-order, single-ended, polyphase bridge is shown in Figure 3. The bridge consists of complementary RC sections that create a low-pass transfer function from input to one output and a high-pass transfer function from input to the other output.



Transfer Functions:

$$LP(f) = \frac{1}{j\omega RC + 1}$$

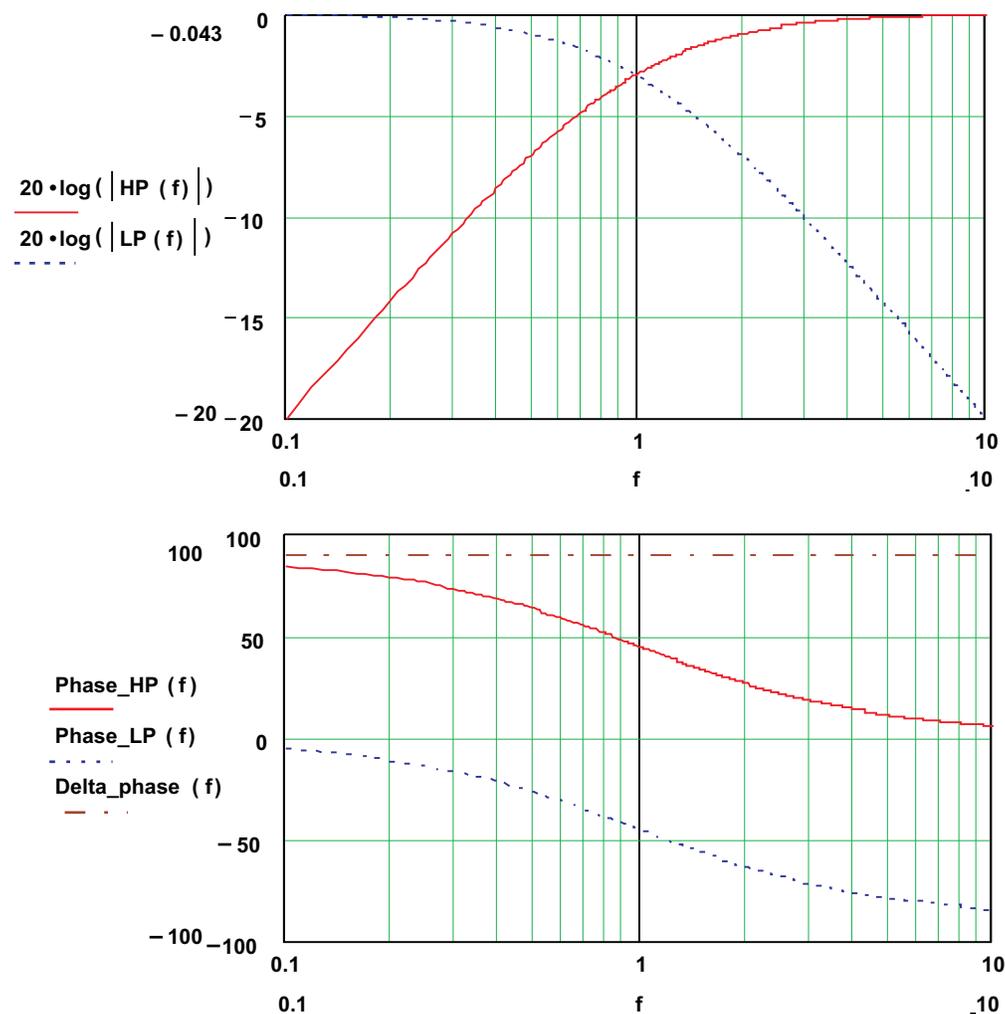
$$HP(f) = \frac{j\omega RC}{j\omega RC + 1}$$

Figure 3. Simple Polyphase Circuit and Transfer Equations

If the R and C values of the two polyphase legs are matched, the amplitude and phase characteristics of the outputs are as depicted in Figure 4. Both legs have the same corner frequency, but more importantly, the phase of one leg tracks the other leg with a 90° shift. The differential phase between legs is the brown dashed line in the phase plot of Figure 4, and the 90° shift can be maintained over a wide frequency range.

The circuit also can be operated above and below the  $f = 1$  crossover frequency in Figure 4 by including limiters at the output of the polyphase circuit as shown in Figure 5. With limiters included at the polyphase output, the sinusoidal outputs of the polyphase are converted to square waves with leading/trailing edges at the zero-crossing locations as shown in Figure 6. If the polyphase is balanced and the input LO is free of harmonic content, the I and Q square waves are in quadrature, and the amplitudes are equal. These signals are the ideal switching waveforms needed to drive the modulator mixers.

Higher-order polyphase circuits usually are employed which provide better amplitude balance over an even wider frequency range. For the purposes of this discussion, the focus is on the simple first-order circuit.



**Figure 4. Amplitude and Phase Characteristics of a Simple Polyphase Circuit**

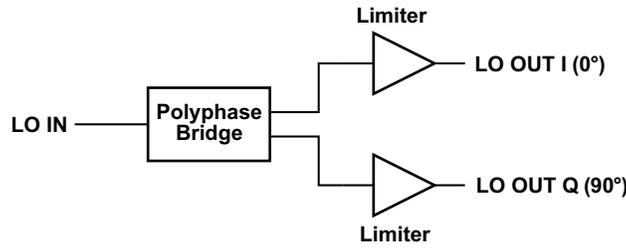


Figure 5. Polyphase-Limiter for Equalized Output Amplitude

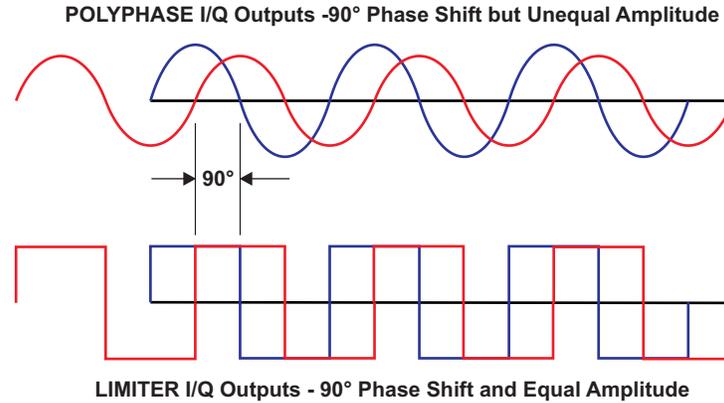


Figure 6. Polyphase and Polyphase+Limiter Waveforms

#### 4 Effect of High LO Harmonics on the I/Q Quadrature Balance of a Polyphase Bridge

The general input and output equations of the polyphase bridge with no harmonics present are as follows:

$$LO\_in = \sin(2\pi ft) \tag{1}$$

$$LO\_in = a_i \sin(2\pi ft + \phi_{LO}) \tag{2}$$

$$LO\_Q = a_Q \sin\left(2\pi ft + \phi_{LO} - \frac{\pi}{2}\right) \tag{3}$$

Depending on the operating frequency, the I and Q output signals may or may not have equal amplitude. Again, this imbalance is removed by the limiters after the polyphase bridge.  $\phi_{LO}$  represents an offset insertion phase common to both the I and Q paths. The important point is that the Q output is shifted by  $\pi/2$ , or 90°, **relative** to the I output.

Now consider the case where a single  $n^{th}$ -harmonic of the LO frequency is present at the polyphase input with an arbitrary phase relative to the LO. In this case, the equations are as follows:

$$LO\_in = \sin(2\pi ft) + b_n \sin(2\pi nft + \phi_n) \tag{4}$$

$$LO\_I = a_i \sin(2\pi ft + \phi_{LO}) + b_i \sin(2\pi nft + \phi_n + \phi_i) \tag{5}$$

$$LO\_Q = a_Q \sin\left(2\pi ft + \phi_{LO} - \frac{\pi}{2}\right) + b_Q \sin(2\pi nft + \phi_n + \phi_Q) \tag{6}$$

The  $b_n$  and  $\phi_n$  terms are the amplitude and phase of the input  $n^{th}$ -harmonic **relative** to the fundamental LO. The  $b_i$  and  $b_Q$  terms are the amplitude of the harmonic that reach the I and Q output, and depend on the loss through each polyphase leg at the  $n^{th}$ -harmonic frequency.  $\phi_i$  and  $\phi_Q$  are the phase shift through each polyphase leg at the  $n^{th}$ -harmonic frequency.

Based on these equations, the I and Q outputs of the polyphase are sinusoidal waveforms superimposed with an  $n^{\text{th}}$ -harmonic sinusoid with some arbitrary amplitude and phase. As can be seen in the following figures, the composite waveforms are distorted, and most importantly, the zero-crossings are shifted causing a quadrature error between I and Q waveforms. The amount of quadrature error depends on the relative phase between the fundamental LO and the  $n^{\text{th}}$ -harmonic. This can be illustrated with two cases.

#### 4.1 Case 1: Minimum Effective Phase Error Case

Consider a simplified case where the LO frequency is at the crossover point  $f = 1$  in Figure 4, with amplitude of 1 V. Also for simplification, set  $\phi_{\text{LO}} = 0$  so that all phases are referenced to 0. The power is split between I and Q outputs, so  $a_I = a_Q = 0.707$  V. Also assume that a third harmonic is present at the input with relative amplitude of  $b_n = 0.1$  V and relative phase shift  $\phi_{n_{\text{min}}}$  such that  $\phi_n + \phi_I = 0$  ( $\phi_n + \phi_Q = -90$ ). From Figure 4, the I path passes the third harmonic ( $f=3$ ) with  $\sim 0.5$ -dB attenuation, so  $b_I \sim 0.1 \times 0.9 \sim 0.09$ . The Q path passes the third harmonic with  $\sim 10$ -dB attenuation, so  $b_Q \sim 0.1 \times 0.32 \sim 0.032$ . For this case, the equations reduce to:

$$\text{LO\_in} = \sin(2\pi ft) + 0.1 \sin(6\pi ft + \phi_{n_{\text{min}}}) \quad (7)$$

$$\text{LO\_I} = 0.707 \sin(2\pi ft) + 0.09 \sin(6\pi ft + 0) \quad (8)$$

$$\text{LO\_Q} = 0.707 \sin\left(2\pi ft - \frac{\pi}{2}\right) + 0.032 \sin\left(6\pi ft - \frac{\pi}{2}\right) \quad (9)$$

Figure 7 shows the I output waveforms. The zero-crossing locations of the composite I output (LO+3LO) have not been affected because the fundamental- and third-harmonic zero-crossing points are coincident. The amplitude of the output has been distorted but the limiters remove this after the polyphase bridge.

Figure 8 shows the Q output waveforms. The results are similar to the I output in that the zero-crossings are coincident, so amplitude is distorted but no change in zero-crossing locations of the composite output occurs.

The overall effect for this case is no phase shift in either the I or Q output.

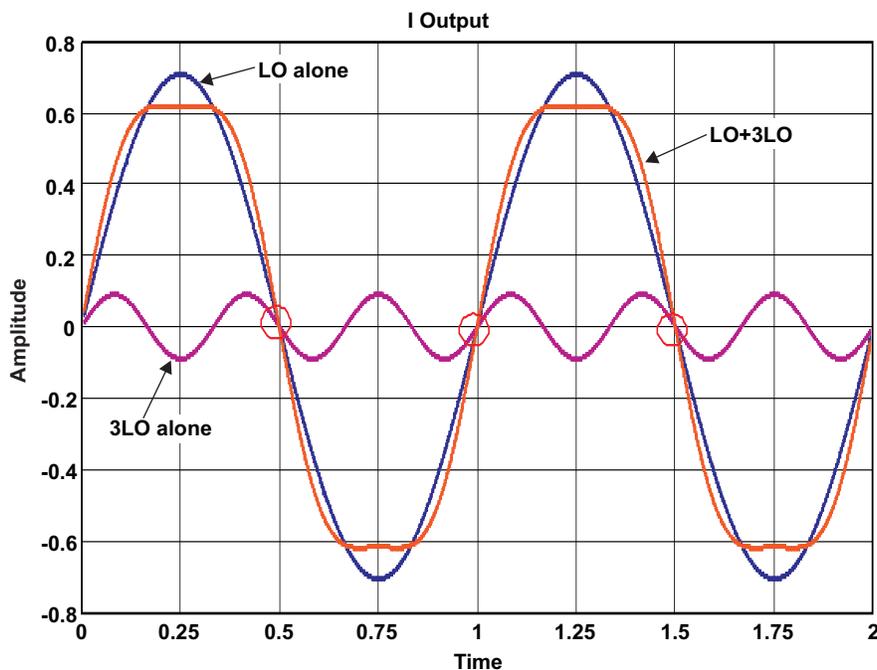


Figure 7. I Output, 0° Relative Input Phase: No Shift

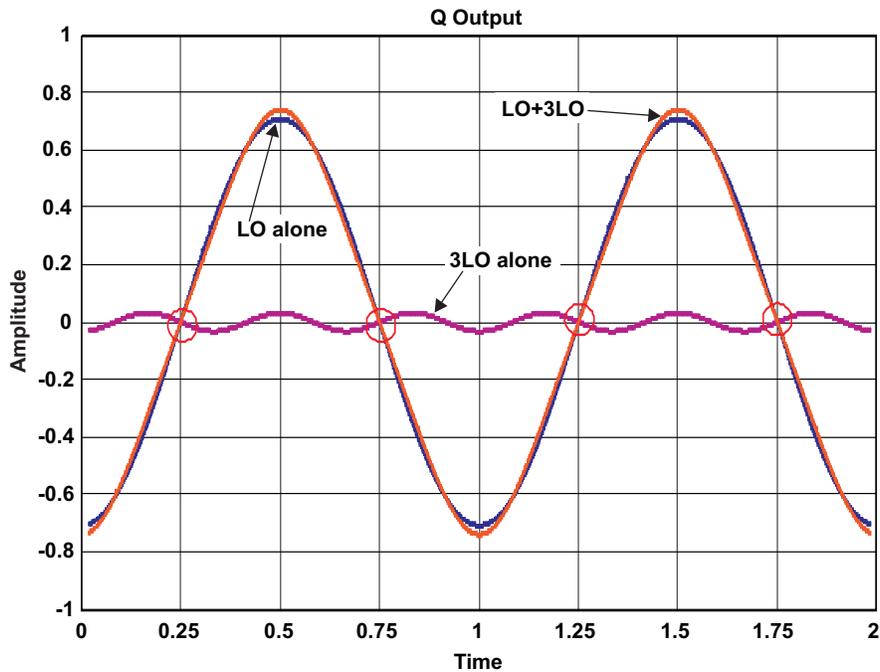


Figure 8. Q output, 0° Relative Input Phase: No Shift

#### 4.2 Case 2: Maximum Effective Phase Error Case

Now consider the case where all conditions are the same as in Case 1 except that the relative phase shift of the third harmonic  $\phi_{n_{\max}}$  is such that  $\phi_n + \phi_l = 90$  ( $\phi_n + \phi_Q = 0$ ). For this case, the equations reduce to:

$$\text{LO}_{\text{in}} = \sin(2\pi ft) + 0.1 \sin(6\pi ft + \phi_n) \quad (10)$$

$$\text{LO}_{\text{I}} = 0.707 \sin(2\pi ft) + 0.09 \sin\left(6\pi ft + \frac{\pi}{2}\right) \quad (11)$$

$$\text{LO}_{\text{Q}} = 0.707 \sin\left(2\pi ft - \frac{\pi}{2}\right) + 0.032 \sin(6\pi ft + 0) \quad (12)$$

Both the I and Q outputs have harmonic components that are out-of-phase with the fundamental tone. This causes a maximum shift in the zero-crossing locations of the composite signal. Figure 9 shows that the I output zero-crossings have been shifted to the left; Figure 10 shows that the Q output zero-crossings have been shifted to the right. Less shift in the Q output occurs because the harmonic voltage is less, but the overall effect is that the relative phase between I and Q zero-crossings has been shifted away from perfect quadrature (90°).

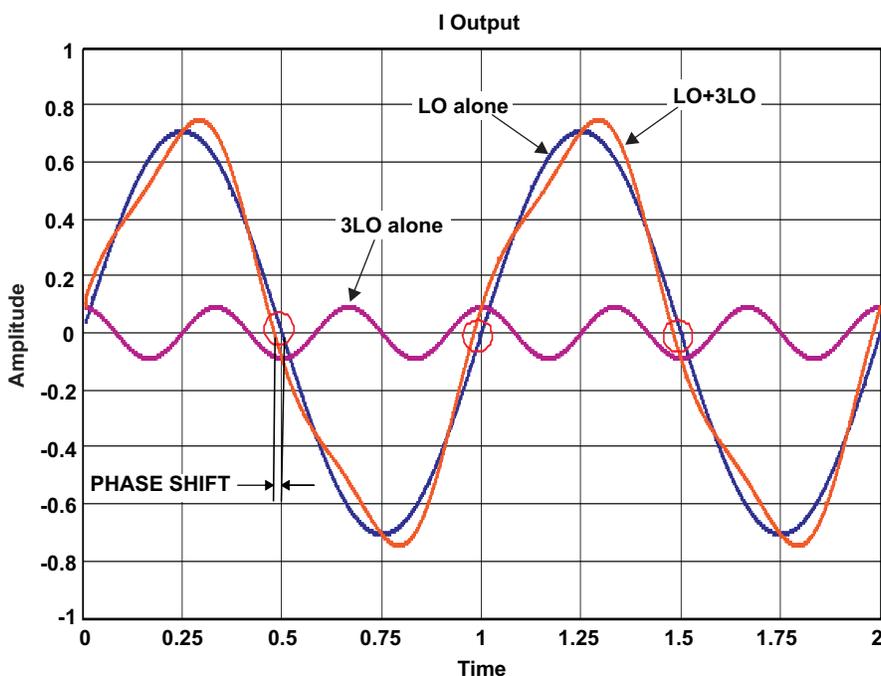


Figure 9. I Output, 90° Relative Input Phase: Large Shift to Left

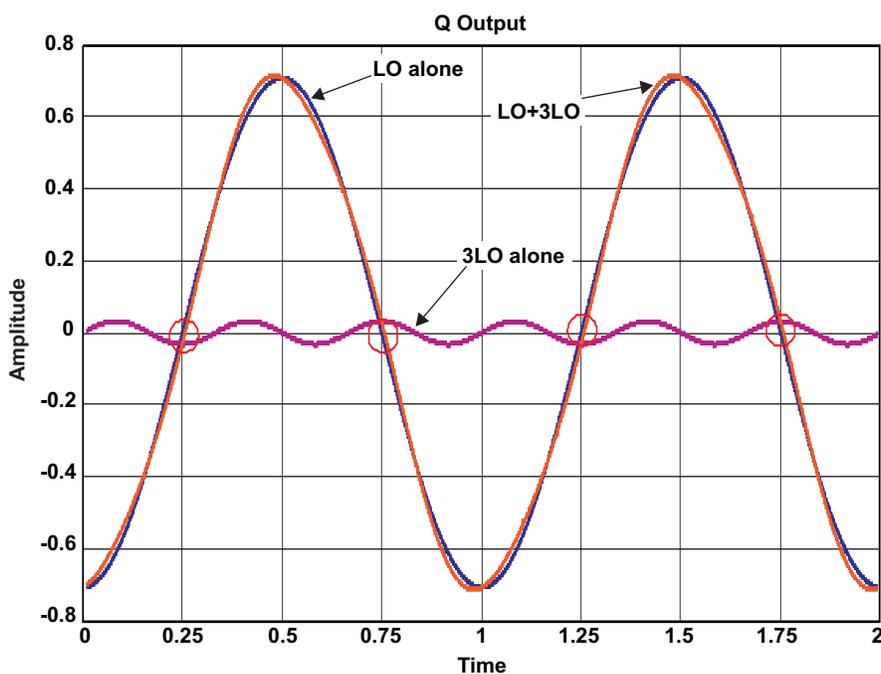


Figure 10. Q Output, 90° Relative Input Phase: Small Shift to Right

The preceding two cases are the extremes for a third-harmonic presence. But what happens in general for an arbitrary relative phase between LO and third harmonic?

The output waveforms can be plotted using the previous equations for a range of LO/harmonic relative phase offsets and harmonic power levels. For each case, the zero-crossing shift of the composite waveform can be found. A profile of the I/Q quadrature error then can be plotted as a function of both LO/harmonic relative phase and harmonic amplitude. This exercise has been performed by simulation of the polyphase-limiter chain of the Texas Instruments TRF3703 with an LO and third-harmonic tone present at the polyphase input. The resulting I/Q quadrature error is shown in Figure 11.

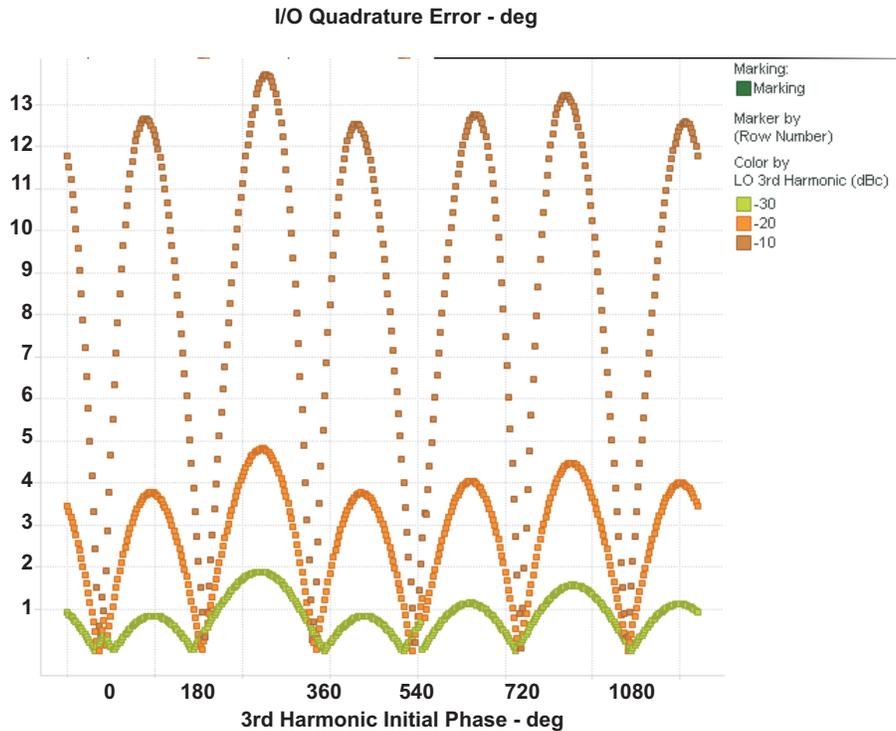


Figure 11. I/Q Quadrature Error vs Third-Harmonic Amplitude and Initial Phase

In Figure 11, the nulls in the plot (where quadrature error is minimized) correspond to initial phase conditions of Case 1, where the harmonic initial phase is 0°, 180°, or any other multiple of 180°. The "peaks" in the plot correspond to the Case 2 condition, where the harmonic initial phase is 90°, 270°, or higher multiples. The three harmonic level conditions plotted show that the quadrature error increases as the harmonic level increases.

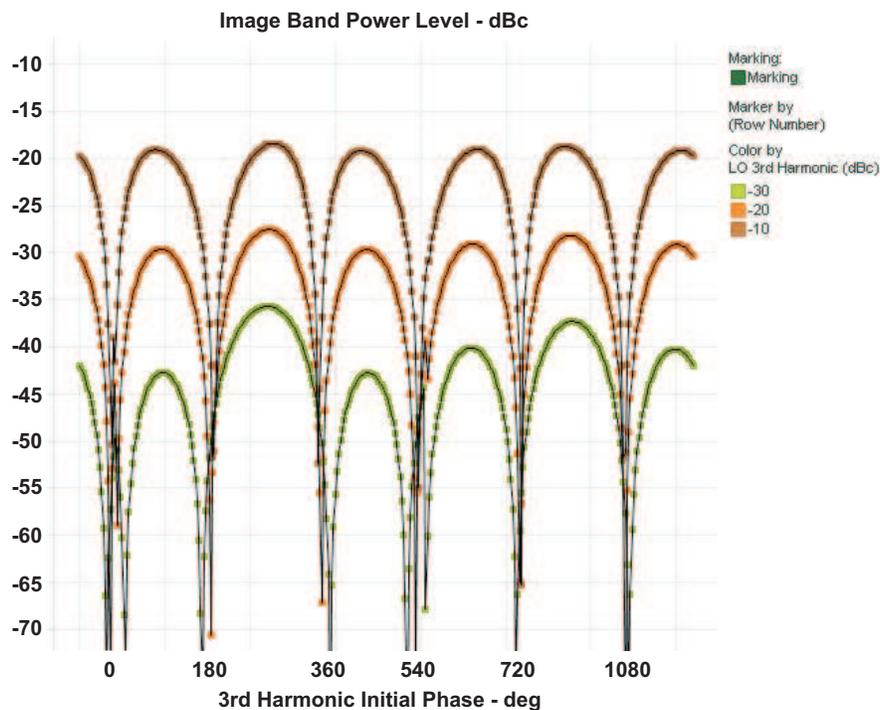
Due to system variance in a real-world application, the phase of the third harmonic relative to the LO fundamental is unknown. The modulator may be operating at or near one of the peak error conditions in Figure 11.

## 5 Relationship Between I/Q Error and Sideband Suppression

The limiter blocks in Figure 5 correct for amplitude imbalance, but not phase imbalance. Therefore, I/Q quadrature error on the LO signals at the polyphase output are passed directly from the output of the polyphase to the mixer LO inputs. Assuming that all other sources of imbalance in the I/Q modulator are negligible, the LO quadrature imbalance by itself generates unwanted image sideband power, and the level of that image power can be calculated using the general conversion equation as follows:

$$\text{Suppression (dBc)} = 20 \log \sqrt{\frac{G^2 - 2G \cos \phi + 1}{G^2 + 2G \cos \phi + 1}} \tag{13}$$

In Equation 13, G represents the voltage ratio between I and Q amplitudes. In this case, assume that I and Q amplitudes are equal, so G = 1. By calculating the image sideband suppression from the values in the I/Q quadrature error plot of Figure 11, the resulting image band suppression level can be plotted as shown in Figure 12.



**Figure 12. Resulting Image Band Levels for Presence of Third Harmonic**

This result shows that the presence of the third harmonic of the LO can present a serious problem. For instance, if a maximum uncorrected image sideband of  $-40$  dBc is required, even a third harmonic at  $-30$  dBc relative to the LO power can cause noncompliance at certain relative phases.

The polyphase design and frequency response, number of harmonics present, harmonic power levels, and harmonic phase relative to the LO play a part in how the I and Q outputs are distorted, and how the relative phase shift between I and Q is disturbed by shifting of the zero-crossing locations. Each particular case has a different effect and can be evaluated using the same procedure as previously outlined.

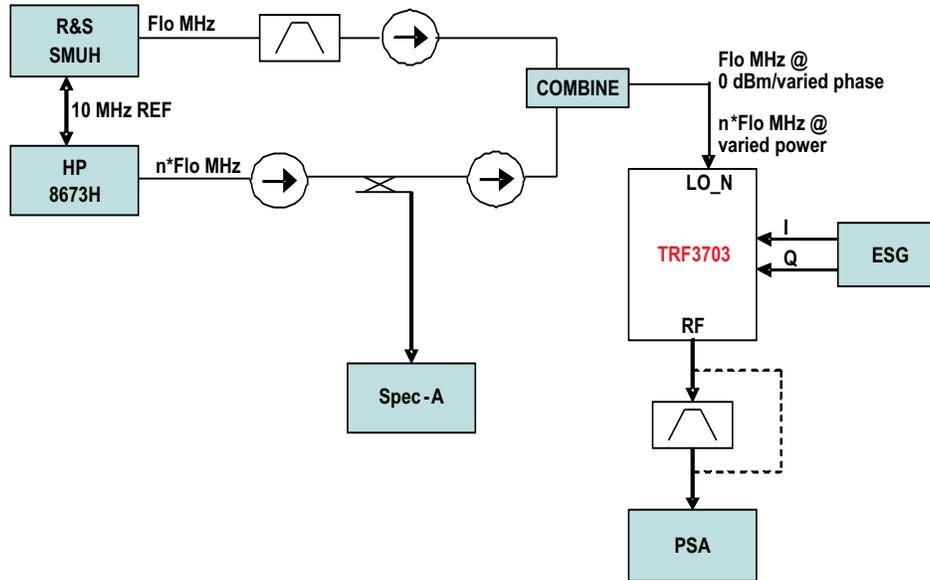
The effects of second- and third-order harmonics have been evaluated, and in general, it was found that the image band power is much more sensitive to the presence of a third harmonic. For either I or Q output, even-order harmonics force the zero-crossing points of the rising and falling edges in different directions, which tend to compensate for one another. Odd-order harmonics shift all edges of one output in one direction, and the other output in the opposite direction. The overall effect is that the worst-case condition for an odd-order harmonic generates a larger effective I/Q phase shift when compared to the even-order worst-case condition. The analysis can be extended to higher order harmonics, or the presence of multiple harmonics, but has not been included in this discussion.

## 6 Measured Effect of LO Harmonics on Sideband Suppression

In a real-world situation, the cases described in this document are complicated by the following:

- Multiple harmonics are present at the LO input of an I/Q modulator with different power levels.
- Biasing and/or tuning at the output of the LO synthesizer presents a different impedance at the fundamental frequency and each harmonic, causing unknown phase shifts.
- Group delay variation across frequency in the LO transmission path between the LO source and I/Q modulator also causes a relative phase shift between fundamental and harmonics.
- All other sources of I/Q imbalance in the modulator circuit are not negligible, and these other error sources add to or subtract from the LO error term depending on the exact operating condition.

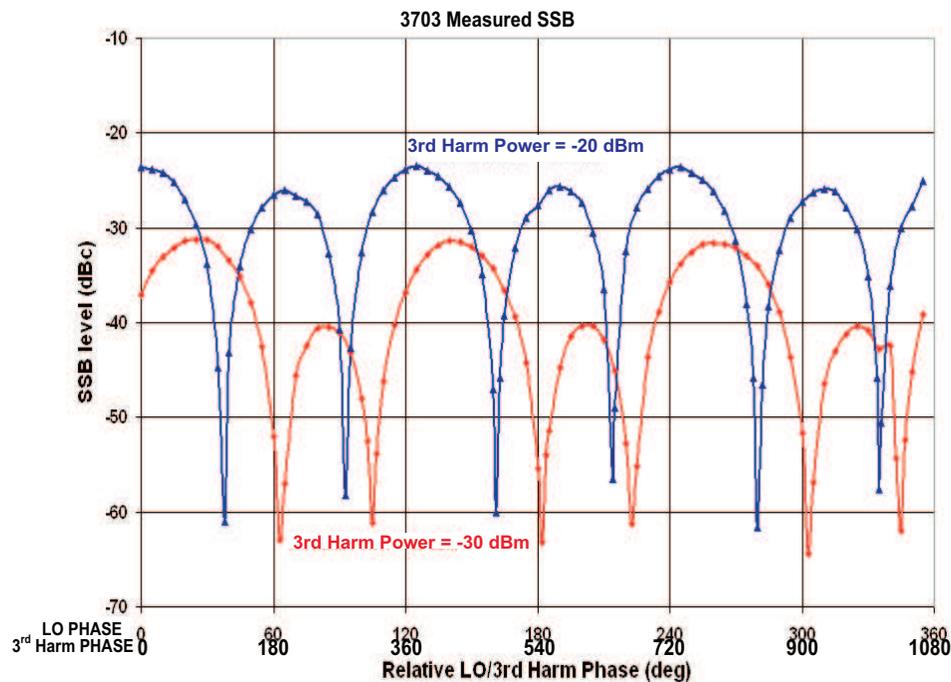
To verify the harmonic effects described, an experimental test was developed where an LO and a single harmonic tone can be generated with precise power and relative phase control. These tones then were used to drive the LO input of a Texas Instruments TRF3703-33 I/Q modulator. The sideband level at the RF output of the TRF3703 was directly measured as the harmonic power and relative phase were varied. The experimental test set-up is shown in [Figure 13](#).



**Figure 13. Test Set-up for Evaluating LO Harmonic Effects**

Two phase-locked sources generate the LO fundamental and the desired harmonic tone ( $n \times F_{lo}$ ). The LO source is well filtered so that its harmonics are well below the test harmonic levels generated by the second source. The LO source has a phase offset function that is used to shift the LO phase relative to the harmonic phase. The harmonic source power level is adjusted to vary the harmonic tone power relative to the LO. The two sources are combined and used to drive the LO port of the TRF3703. A baseband modulator (ESG) provides differential baseband I/Q signals to the TRF3703. The TRF3703 output is monitored on a Spectrum Analyzer.

The image sideband levels were first measured for two third-harmonic power levels as relative phase of the LO was swept from  $0^\circ$  to  $360^\circ$  (or  $0^\circ$  to  $1080^\circ$  with respect to the harmonic). The resulting sideband suppression is shown in [Figure 14](#).



**Figure 14. TRF3703-33 Image Sideband Level in Presence of LO+Third Harmonic**

The sideband suppression follows the same pattern as the simulated case in [Figure 12](#), with the peaks and nulls in sideband suppression spaced  $180^\circ$  apart with respect to the harmonic phase. The patterns shown in [Figure 14](#) are shifted on the x-axis because the absolute starting phase relationship between the LO and harmonic was not experimentally determined for each harmonic power case. The sideband suppression also degrades as harmonic power is increased, as predicted by the plot in [Figure 12](#).

A second test was conducted to determine the sideband level generated over a wide range of harmonic power levels for the worst-case LO/harmonic phase condition. For this test, the harmonic power was adjusted to a desired level and the phase adjustment was varied to maximize the sideband level. This was repeated for several power levels from  $-90$  dBc to  $-10$  dBc. The test was performed for both LO+2nd-harmonic and LO+3rd-harmonic conditions. The results are shown in [Figure 15](#).

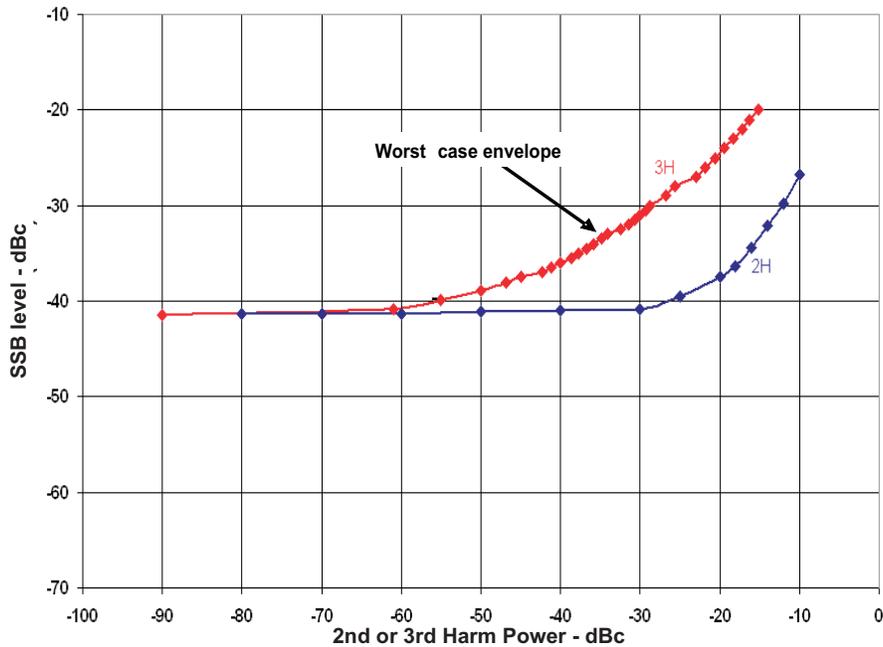


Figure 15. TRF3703-33 Worst-Case Image Sideband Level vs Harmonic Power

At low harmonic levels, the sideband suppression is unaffected and remains at a typical unadjusted level of  $-42$  dBc. As the harmonic power is increased, the sideband suppression can become severely degraded. For instance, the sideband level has degraded 10 dB in the presence of a third-harmonic tone that is  $\sim 30$  dBc down from the LO fundamental. For the second-harmonic case, the sideband degrades 10 dB if the harmonic power is  $\sim 13$  dBc. As explained in Section 5, the sideband levels are more sensitive to the presence of the third harmonic as compared to the second harmonic.

It is clear from these results that if the harmonic content is high enough, and the phase relationship between LO and harmonic happens to be at or near a worst-case condition, the unadjusted image sideband can become unacceptably high.

## 7 Improvement in Sideband Suppression by Employing an LO Filter

VCO/PLL-based synthesizers that are used to generate LO signals on transceiver boards can have high harmonic levels present at their output. Based on the results in the previous section, these harmonic levels may easily be high enough to degrade the sideband suppression performance of the I/Q modulator.

The most straightforward and cost-effective way to correct for this problem is by using a low-pass filter between the synthesizer and I/Q modulator to suppress the second-, third-, and higher order harmonics of the LO. Even a fifth-order LPF using surface-mount components on standard FR4 board construction can provide enough rejection to eliminate the problem.

As an example, the test set-up in Figure 13 was used to generate an LO at 1800 MHz with second harmonic at 3600 MHz and third harmonic at 5400 MHz. A fifth-order filter was designed to pass the LO but provide rejection of the second and third harmonics. The schematic of the filter is shown in Figure 16, and the measured response of the filter is shown in Figure 17.

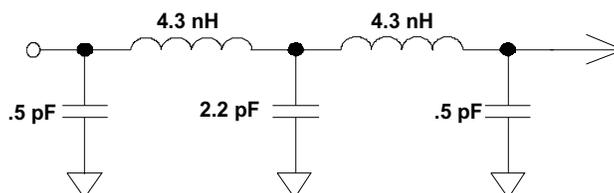
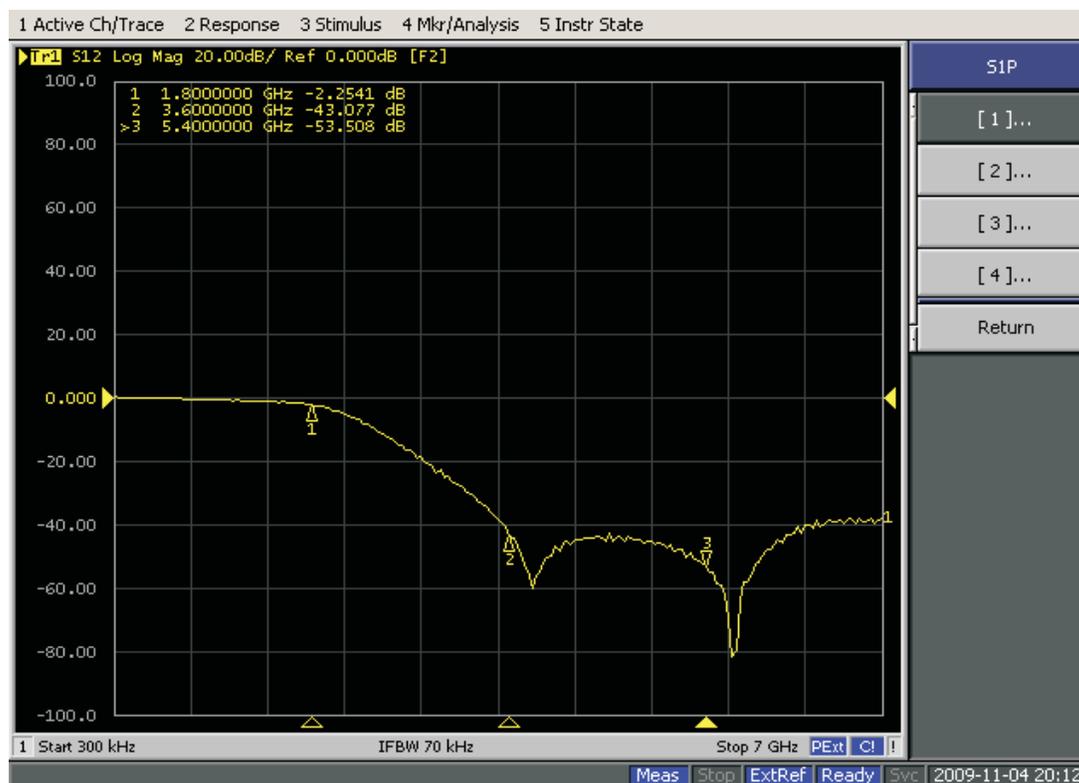


Figure 16. Fifth-Order LPF Filter Schematic



**Figure 17. Fifth-Order LPF Measured Response**

The filter provides 43 dB of rejection at the second harmonic and 53 dB rejection at the third harmonic. The filter rejection is actually much better than what can be calculated using ideal filter components. When implemented on the printed-circuit board, the capacitor parasitics and ground via inductance effectively shift the filter poles to a lower frequency, so the roll-off above the cutoff frequency is much steeper than predicted.

Using this filter, the same test used to generate the plot of [Figure 15](#) was performed again to show the improvement in sideband suppression. The results are shown in [Figure 18](#). Using the filter, the sideband level in the second-harmonic case does not change, even if the second-harmonic power is made equal to the LO power (0 dBc) at the filter input. For the third-harmonic case, the sideband level increases less than 2 dB for equal-power LO and harmonic at the filter input.

This result confirms that filtering the harmonic content of an LO signal nearly eliminates any degradation of sideband suppression that would be seen without the filter.

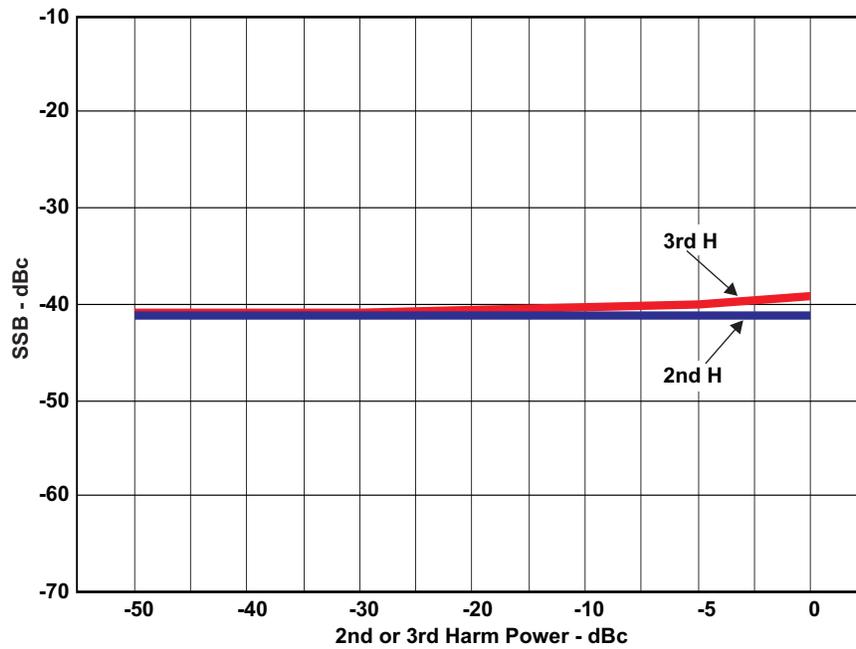


Figure 18. TRF3703-33 Worst-Case Image Sideband Level With LO Filtering

## 8 Summary

Complex I/Q modulators employing polyphase bridge circuits to generate quadrature LO signals can be susceptible to high LO harmonic levels at their input. The high harmonic content causes undesired phase shifts in the I and Q outputs of the polyphase bridge, resulting in high image sideband levels at the modulator output. Fortunately, the effects of LO harmonic content can be eliminated by inclusion of a simple low-pass filter between the LO source and I/Q modulator.

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Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265  
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