Optimization of Quadrature Modulator Performance

Introduction

Quadrature modulators are common building blocks in a communications link. By their nature they are capable of sending virtually any modulation scheme. They can send both analog, such as AM and FM, and digital modulation schemes, such as BPSK, QAM, and QPSK.

A common set of specifications for quadrature modulators is the carrier suppression and sideband suppression. The question often arises as to how they correlate with amplitude and phase error for the same device. This article presents a derivation showing the relationship between these four parameters.

Because the overall performance of the system can be affected by the modulator, its performance is important. Therefore, the need to optimize the carrier suppression and the sideband suppression of a quadrature modulator often arises. For those who may not be experienced with quadrature modulators, this can be a confusing task. This article will make this optimization easier to understand and perform.

Discussion

The first question that arises is why optimization is required at all. The primary reason is that there are imbalances in the Gilbert cell mixers and phase error introduced by the phase-shifting network. These imperfections are caused by slight differences in devices on the same die. There are also imbalances and offsets between the in-phase and quadrature signal paths as a result of process variations. These errors are not present in an ideal device, however they cannot be eliminated in practice.

The second question then would be how to compensate the device to optimize the performance. To understand how compensation can be achieved, it is helpful to understand how sideband suppression, carrier suppression, amplitude error and phase error are related.

The block diagram of a typical quadrature modulator is shown in Figure 1.

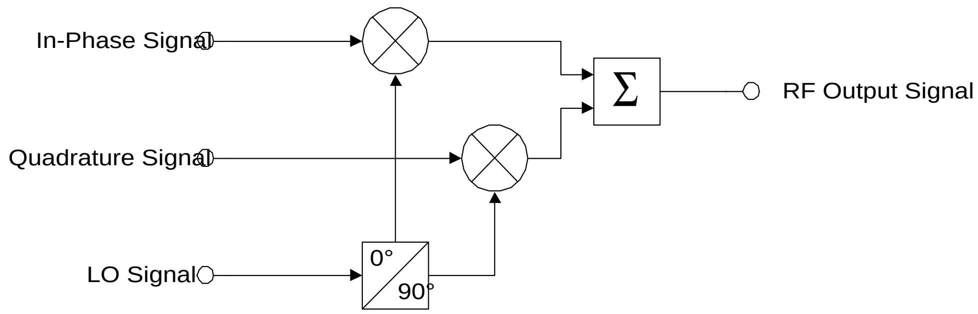

Figure 1. Quadrature Modulator Functional Block Diagram

The circuit multiplies the in-phase signal by the local oscillator and the quadrature signal by a 90° shifted version of the local oscillator. These signals are then summed to form the RF output signal.

Derivation

To begin the derivation, the input signals are defined as follows:

$$I(t) = G\cos(\omega t + \phi) + D$$

$$Q(t) = \cos(\omega t + 90°)$$

Note that this implies that the error injected into the system is due to the in-phase signal. The amplitude G represents the ratio of the amplitudes of the input signals. The phase offset, ϕ, represents the phase error. This is typically a small value representing how far from quadrature the signals are. The DC offset, D, represents the DC offset between the two signals. Ideally there is no offset, but in practice, there is an offset introduced by imbalances in the modulator circuitry. The quadrature signal is, by definition, 90° out of phase with the in-phase signal.

With the signals defined, it is a matter of performing the mathematical analysis that parallels the modulators' functionality. The RF output is given by

$$RF(t) = G\cos(\omega t + \phi)\cos(\omega_c t) + D\cos(\omega_c t) - \sin(\omega_c t)\cos(\omega t + 90°)$$

As can be seen, the carrier can only be present at the output if there is a DC offset between the input signals. Now, rearrange the terms to get the upper sideband and lower sideband terms using the trigonometric identities[1]

$$\sin(\alpha)\cos(\beta) = \frac{1}{2}\sin(\alpha - \beta) + \frac{1}{2}\sin(\alpha + \beta)$$

$$\cos(\alpha)\cos(\beta) = \frac{1}{2}\cos(\alpha - \beta) + \frac{1}{2}\cos(\alpha + \beta)$$

$$USB(t) = \frac{1}{2}G\cos(\omega_c t + \omega t + \phi) - \frac{1}{2}\sin(\omega_c t + \omega t + 90°)$$

$$LSB(t) = \frac{1}{2}G\cos(-\omega_c t + \omega t + \phi) - \frac{1}{2}\sin(\omega_c t - \omega t - 90°)$$

These can be rewritten to obtain

$$USB(t) = \frac{1}{2}G\cos(\omega_c t + \omega t + \phi) - \frac{1}{2}\cos(\omega_c t + \omega t)$$

$$LSB(t) = \frac{1}{2}G\cos(\omega t - \omega_c t + \phi) + \frac{1}{2}\cos(\omega_c t - \omega t)$$

Applying the trigonometric identity[1]

$$\cos(\alpha + \beta) = \cos(\alpha)\cos(\beta) - \sin(\alpha)\sin(\beta)$$

with

$$\alpha = \omega_c t + \omega t$$

$$\beta = \phi$$

the final form of the equations is reached

$$USB(t) = \frac{1}{2}G\cos(\omega_c t + \omega t)\cos(\phi) - \frac{1}{2}G\sin(\omega_c t + \omega t)\sin(\phi) - \frac{1}{2}\cos(\omega_c t + \omega t)$$

$$LSB(t) = \frac{1}{2}G\cos(\omega t - \omega_c t)\cos(\phi) - \frac{1}{2}G\sin(\omega t - \omega_c t)\sin(\phi) + \frac{1}{2}\cos(\omega_c t - \omega t)$$

We want these equations in this form is to allow them to be easily converted to envelope-phase form[2] since the sideband suppression is the ratio of the magnitude (envelope) of the upper sideband to the magnitude of the lower sideband. In general, a signal can be represented as the sum of the real and imaginary terms

$$x(t) = x_R(t)\cos(\omega t) - x_I(t)\sin(\omega t)$$

This expression can be rewritten in envelope-phase form as follows

$$x(t) = r(t)\cos[\omega t + \phi(t)]$$

where

$$r(t) = \sqrt{x_R{}^2(t) - x_I{}^2(t)}$$

$$\phi(t) = \operatorname{atan}\left[\frac{x_I(t)}{x_R(t)}\right]$$

The upper sideband and lower sideband envelopes are

$$USB_{env} = \sqrt{\left(\frac{1}{2}G\cos\phi - \frac{1}{2}\right)^2 + \left(-\frac{1}{2}G\sin\phi\right)^2}$$

$$LSB_{env} = \sqrt{\left(\frac{1}{2}G\cos\phi + \frac{1}{2}\right)^2 + \left(-\frac{1}{2}G\sin\phi\right)^2}$$

After expanding these terms we obtain

$$USB_{env} = \sqrt{\frac{1}{4}G^2 - \frac{1}{2}G\cos\phi + \frac{1}{4}}$$

$$LSB_{env} = \sqrt{\frac{1}{4}G^2 + \frac{1}{2}G\cos\phi + \frac{1}{4}}$$

The ratio for sideband suppression is then given by

$$\frac{USB_{env}}{LSB_{env}} = \sqrt{\frac{\frac{1}{4}G^2 - \frac{1}{2}G\cos\phi + \frac{1}{4}}{\frac{1}{4}G^2 + \frac{1}{2}G\cos\phi + \frac{1}{4}}} = \sqrt{\frac{G^2 - 2G\cos\phi + 1}{G^2 + 2G\cos\phi + 1}}$$

Therefore, the lower sideband suppression in dBc (decibels relative to the upper sideband) is given by

$$Suppression(dBc) = 20\log\sqrt{\frac{G^2 - 2G\cos\phi + 1}{G^2 + 2G\cos\phi + 1}} = 10\log\sqrt{\frac{G^2 - 2G\cos\phi + 1}{G^2 + 2G\cos\phi + 1}}$$

This expression can be plotted as a set of suppression contours,[3] with amplitude error and phase error as the axes. To facilitate this, the equation was solved for phase error, ϕ, in terms of amplitude error, G, and sideband suppression, SBS.

$$\phi = \operatorname{acos}\left[\frac{1 - 10^{\frac{SBS}{10}} - G^2 10^{\frac{SBS}{10}} + G^2}{2G10^{\frac{SBS}{10}} + 2G}\right]$$

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TECHNICAL NOTES AND ARTICLES

This equation was used in conjunction with the sideband suppression equation to generate data using a spreadsheet program. This data was plotted and the result is contained in Figure 2.

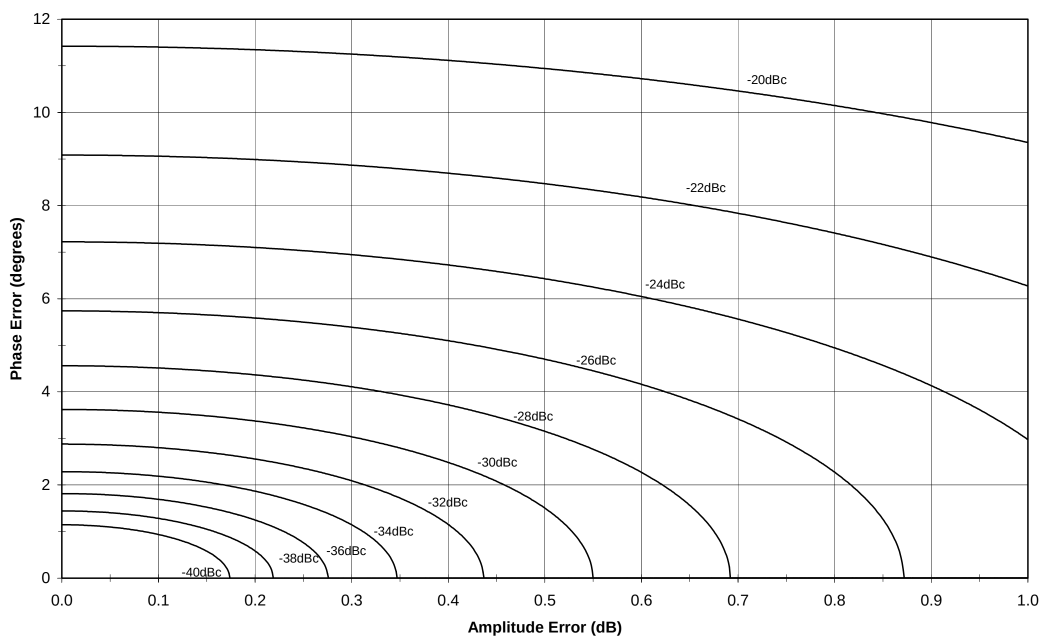

Figure 2. Sideband Suppression vs. Amplitude Error and Phase Error

Since it is often easiest to balance the amplitude error, it is convenient to plot phase error versus sideband suppression assuming the amplitude error has been balanced. Figure 3 is such a plot.

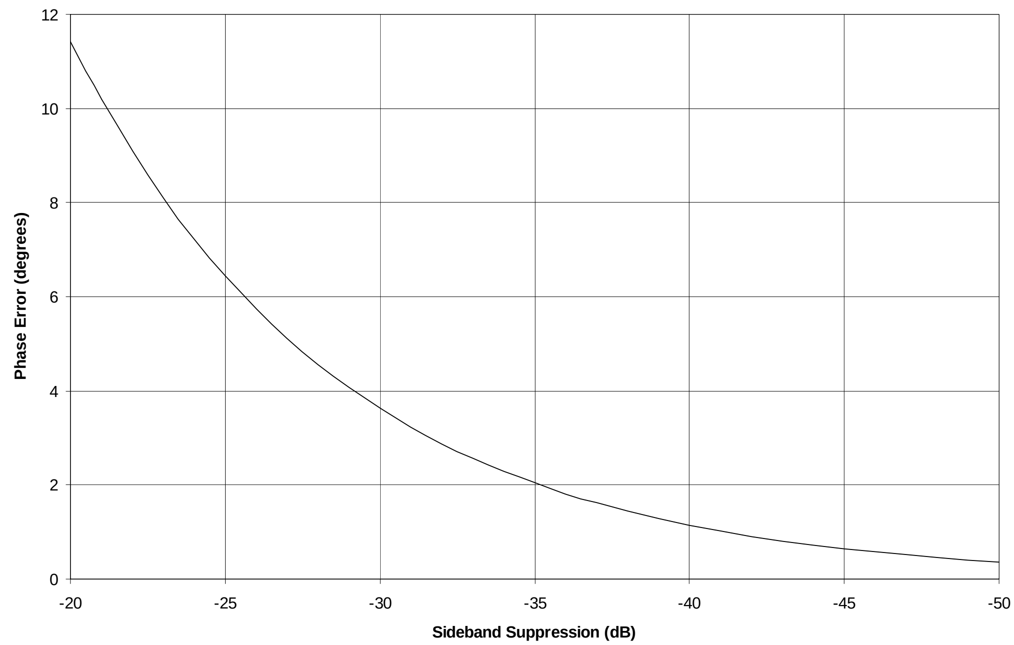

Figure 3. Sideband Suppression vs. Phase Error with no Amplitude Error

Optimization Example

The RF2422, an HBT 2.5GHz direct quadrature modulator, and its fully assembled evaluation board were chosen to demonstrate one way of optimizing performance. The board allows quick testing of the device, requiring two DC connections, a local oscillator input, two baseband inputs (In-Phase and Quadrature), and the RF output. All but the DC inputs are standard SMA style connectors. Refer to the schematic in Figure 4.

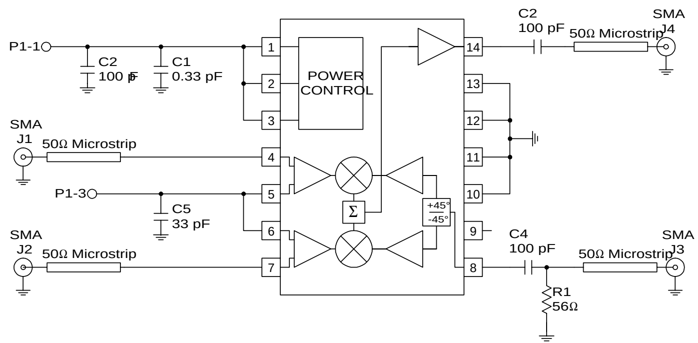

Figure 4. RF2422 Evaluation Board Schematic

Carrier suppression is a function of the DC offset between the in-phase signal and the quadrature signal in the device. This offset can be compensated by altering the DC offset of the input signals. Therefore, to improve the carrier suppression, start by adjusting the DC component of the in-phase signal (which should nominally be equal to V_{REF}), watching the output on the spectrum analyzer. As it is adjusted, there will be a point where the carrier level is minimized. Next, do the same with the DC component of the quadrature signal. Again, there will be a point where the carrier level is minimized. At this point, the carrier suppression has been optimized. The change to each DC level should be no more than about 20mV.

The carrier suppression can also be adjusted by adjusting V_{REF}. This is a course adjustment since V_{REF} is connected to both I_{REF} and Q_{REF} and the degrees of freedom have been reduced. The above procedure could then be used to fine tune the adjustment. Either way, the same results should be obtained.

Sideband suppression is a function of both the amplitude error and the phase error of the device. These errors can be compensated by adjusting the input signals. Therefore, to optimize the sideband suppression, begin by adjusting the amplitude of the in-phase signal. There will be a point when the sideband level is at a minimum. Next, do the same for the quadrature signal. Again, there will be a point when the sideband level is minimized. To optimize further, adjust the phase of the quadrature signal. Again, there will be a point where the sideband level is minimized. At this point, the sideband suppression is optimized. The change in the amplitude should be no more than about 10mV and the change in phase should be no more than about 4°. Table 1 provides a list of the test equipment used.

Signal	Equipment
Local Oscillator	Rohde&Schwarz SMT-03 Signal Generator
V_{CC} and V_{REF}	Hewlett-Packard E3620A Dual Output Power Supply
I and Q Signals	Hewlett-Packard 8904A 4-Channel Multifunction Synthesizer
RF Output	Hewlett-Packard 8593E Spectrum Analyzer

Conclusions

This note has presented the derivation of the relationship that exists between the four primary specifications for a quadrature modulator: carrier suppression, sideband suppression, phase error, and amplitude error. Equations were presented that allow for translation between sideband suppression and phase and amplitude error. These equations were used to generate a plot that allows the designer of a system to quickly see how these specifications interact. It can be seen that good sideband suppression is the combination of both little phase error and little amplitude error.

It is often desirable to optimize the carrier suppression and the sideband suppression of quadrature modulators. This article presented a simple and straight-forward method of performing this optimization. This method is suitable for other similar devices and has been used to increase their performance.

An example of the outlined optimization method was used to improve the performance of an RF2422. For an RF2422 evaluation board, a carrier suppression of 44.1dB and a sideband suppression of 54.5dB were achieved. This is roughly a 15dB to 20dB improvement over an uncompensated board. Comparable improvements have been attained with other quadrature modulators.

References

1. M. Spiegel, Mathematical Handbook of Formulas and Tables, McGraw-Hill Book Company, 1968.
2. R. E. Ziemer, Introduction to Digital Communication, Macmillan Publishing Company, 1992.
3. W. Djen, Application Note AN1892, Philips Semiconductors, December 1994.