Measuring Phase and Delay Errors Accurately in I/Q Modulators

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I. INTRODUCTION

This Application Note describes a method to accurately measure internal and external phase and timing errors for a high performance direct I/Q modulator. A direct I/Q modulator, such as the LT5528, translates baseband I and Q signals to RF, and combines them to produce a modulated single sideband signal with (ideally) minimal residual carrier (LO feedthrough) and image signals (undesired sideband). In an ideal I/Q modulator, with perfect 90° phase shift between the I mixer and Q mixer local oscillators (LOI and LOQ), and with no other undesired phase and gain impairments, the modulator output will contain only the desired sideband. In practice, this is very difficult to accomplish. For example, with a requirement of –60dBc image suppression, the residual I-Q phase error is required to be below 0.16°. In practice, there are other sources of phase error, particularly in the baseband signal processing. Examples include baseband skew or other frequency dependent phase shifts in the modulator baseband circuitry; skew errors due to phase or delay mismatched baseband connection paths (e.g., cabling); and phase mismatch between the I and the Q paths in the baseband signal source (e.g., baseband DACs or signal generators.). These phase errors can cause RF output spectra to be shaped like those shown in Figures 1, 2 and 3.

For each plot, the (single) channel is chosen to be at –7.5MHz, –2.5MHz, 2.5MHz and 7.5MHz offset from the RF carrier by choosing the frequency offset function on the baseband generator. As can be seen, the residual sideband spectra are not flat vs RF frequency. Usually, the image rejection calibration is done using one (baseband) frequency, preferably in the center of the desired channel. However, if the uncalibrated residual sideband is not flat

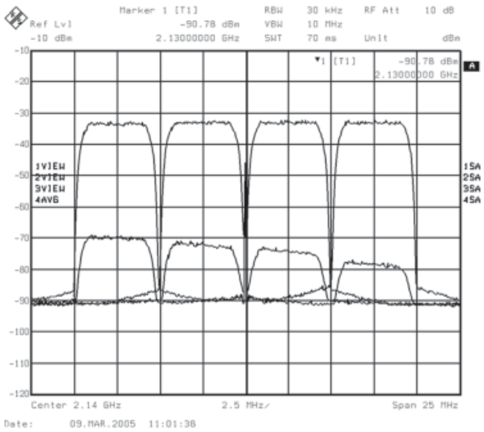

Figure 1. Measurement Compilation of Four One-Channel W-CDMA I/Q Modulator RF Output Spectra Selected to be at –7.5MHz, –2.5MHz, 2.5MHz and 7.5MHz Offset Frequency from the 2.14GHz Carrier Using Baseband I/Q W-CDMA Channel Selection with Uncalibrated Image

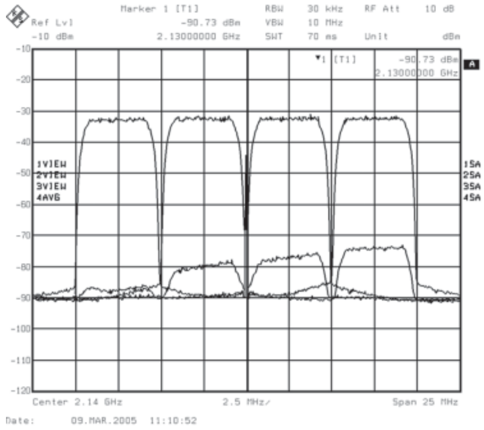

Figure 2. Measurement Compilation of Four One-Channel W-CDMA I/Q Modulator RF Output Spectra Selected to be at –7.5MHz, –2.5MHz, 2.5MHz and 7.5MHz Offset Frequency from the 2.14GHz Carrier Using Baseband I/Q W-CDMA Channel Selection with Uncalibrated Image

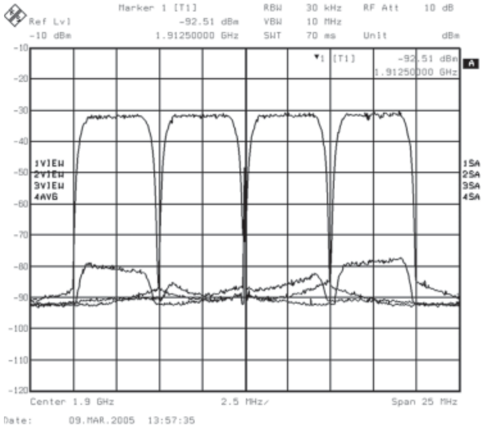

Figure 3. Measurement Compilation of Four One-Channel W-CDMA I/Q Modulator RF Output Spectra Selected to be at –7.5MHz, –2.5MHz, 2.5MHz and 7.5MHz Offset Frequency from the 2.14GHz Carrier Using Baseband I/Q W-CDMA Channel Selection with Uncalibrated Image

versus frequency, it causes the image rejection after calibration to degrade at the edges of the channel. This can be seen in Figure 4 where the image rejection is less than 60dBc and the image channel has a shape in the form of the letter "M". A delay difference between the I and the Q baseband paths can cause the image power to be falling vs RF frequency as in Figure 1, rising as in Figure 2 or to have a "V" shape as in Figure 3. The sign and magnitude of the quadrature phase error in the I/Q modulator, and the sign and magnitude of the I/Q baseband delay difference determine whether the situation is as in Figure 1, 2 or 3.

The residual sideband spectrum of Figure 4 can be improved by adding a compensating delay to the I or Q baseband paths. This is shown in Figure 5.

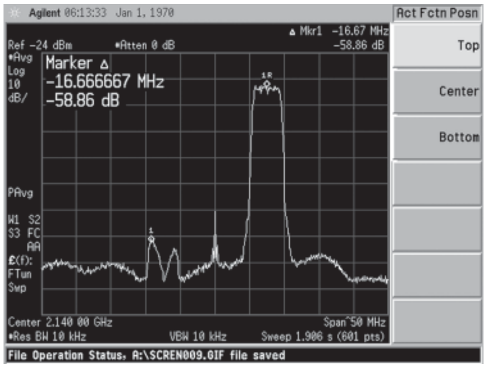

Figure 4. Measurement of a One-Channel W-CDMA Spectrum at the I/Q Modulator Output After Image Nulling at 7.5MHz Baseband Calibration Frequency. The W-CDMA Channel is Located at an Offset of 7.5MHz and the Image is Located at an Offset of –7.5MHz with Respect to the Carrier

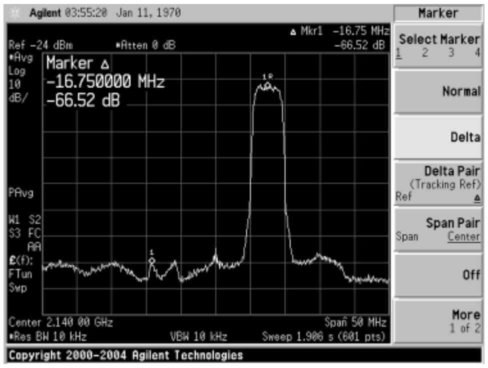

Figure 5. Measurement of a One-Channel W-CDMA Spectrum at the I/Q Modulator Output After Image Nulling at 7.5MHz Baseband Calibration Frequency Using a Baseband I/Q Delay Correction. The W-CDMA Channel is Located at an Offset of 7.5MHz and the Image is Located at an Offset of –7.5MHz with Respect to the Carrier

In order to achieve the best image rejection for a broadband communications channel (such as W-CDMA), it is important to understand what error source(s) causes the image response to be non-flat over frequency. This Application Note provides a measurement method to determine the sources of both RF and baseband phase error, whether it comes from the baseband generator and/or the I/Q modulator. The method consists of three different measurements, each with a slightly different measurement setup. From these measurements, we can determine the quadrature error of the I/Q modulator φ_{LO}, the baseband phase error of the I/Q modulator φ_{MOD}, and the baseband phase error of the baseband signal generator φ_{DGEN}. It is very likely that φ_{DGEN} and φ_{MOD} result from internal skew or time delay errors (τ_{DGEN} and τ_{MOD}, respectively). Therefore, we can write in a more general case for different baseband frequencies (ω_{BB}):

$$\varphi_{DGEN} = \varphi_{DGEN0} + \omega_{BB} \bullet \tau_{DGEN}$$

and

$$\varphi_{MOD} = \varphi_{MOD0} + \omega_{BB} \bullet \tau_{MOD}$$

In the analysis that follows, we disregard amplitude mismatches, because our measurements indicate that phase errors are dominant, and it greatly simplifies the math.

In order to resolve the uncontrolled, systematic phase errors, φ_{LO}, φ_{DGEN} and φ_{MOD}, our technique requires there to be a controllable, adjustable baseband phase offset, φ_{GEN}. This adjustable phase is used to null out the image signal under various measurement conditions. The nulling phases are used to calculate the individual system phase errors.

II. MEASUREMENTS

IIA. First Measurement—Null Out the I/Q Modulator Image Signal with Normal Signal Connections (Figure 6).

A phase error φ_{LO} exists between the quadrature signals LOI and LOQ in the modulator. We try to cancel this with an extra phase shift φ_{GEN1} between the baseband signals I and Q. However, as shown and defined in Figure 6, there can be delay differences between the I and the Q path for both the baseband generator (φ_{DGEN}) and within the I/Q modulator itself (φ_{MOD}). At a particular baseband frequency $\omega_{BB} = 2\pi f_{BB}$, the baseband signals at the modulator's I and Q mixers are given by:

$$I = \cos(\omega_{BB} \bullet t)$$

$$Q = \sin(\omega_{BB} \bullet t + \varphi_{GEN1} + \varphi_{DGEN} + \varphi_{MOD})$$

Note that the placement of the error terms φ_{DGEN}, φ_{MOD} and φ_{LO} in the I or Q paths is arbitrary and does not affect the final conclusions of this analysis.

Here φ_{GEN1} is a controllable phase offset that can be adjusted as needed to compensate for other phase errors in the system.

$$LOI = \cos(\omega_{LO} \bullet t)$$

$$LOQ = \sin(\omega_{LO} \bullet t + \varphi_{LO})$$

$$RF = \cos(\omega_{BB} \bullet t) \bullet \cos(\omega_{LO} \bullet t) + \sin(\omega_{BB} \bullet t + \varphi_{GEN1} + \varphi_{DGEN} + \varphi_{MOD}) \bullet \sin(\omega_{LO} \bullet t + \varphi_{LO})$$

$$\cos(\alpha) \bullet \cos(\beta) = 1/2 \cos(\alpha - \beta) + 1/2 \cos(\alpha + \beta)$$

$$\sin(\alpha) \bullet \sin(\beta) = 1/2 \cos(\alpha - \beta) - 1/2 \cos(\alpha + \beta)$$

$$\begin{aligned} RF = {} & 1/2 \cos[(\omega_{LO} - \omega_{BB})t] + 1/2 \cos[(\omega_{LO} + \omega_{BB}) \bullet t] \\ & + 1/2 \cos[(\omega_{LO} - \omega_{BB})t + \varphi_{LO} - \varphi_{GEN1} - \varphi_{DGEN} - \varphi_{MOD}] \\ & - 1/2 \cos[(\omega_{LO} + \omega_{BB})t + \varphi_{LO} + \varphi_{GEN1} + \varphi_{DGEN} + \varphi_{MOD}] \end{aligned}$$

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

$$\begin{aligned} RF = {} & 1/2 \cos[(\omega_{LO} - \omega_{BB})t] + 1/2 \cos[(\omega_{LO} + \omega_{BB}) \bullet t] \\ & + 1/2 \cos(\varphi_{LO} - \varphi_{GEN1} - \varphi_{DGEN} - \varphi_{MOD}) \\ & \bullet \cos[(\omega_{LO} - \omega_{BB})t] \\ & - 1/2 \sin(\varphi_{LO} - \varphi_{GEN1} - \varphi_{DGEN} - \varphi_{MOD}) \\ & \bullet \sin[(\omega_{LO} - \omega_{BB})t] \\ & - 1/2 \cos(\varphi_{LO} + \varphi_{GEN1} + \varphi_{DGEN} + \varphi_{MOD}) \\ & \bullet \cos[(\omega_{LO} + \omega_{BB})t] \\ & + 1/2 \sin(\varphi_{LO} + \varphi_{GEN1} + \varphi_{DGEN} + \varphi_{MOD}) \\ & \bullet \sin[(\omega_{LO} + \omega_{BB})t] \end{aligned}$$

$$\cos(\varphi) = 1 - \frac{\varphi^2}{2} + \frac{\varphi^4}{24} - \frac{\varphi^6}{720} + \ldots\ldots \approx 1 - \frac{\varphi^2}{2} \approx 1$$

(Small angle approximation)

$$\sin(\varphi) = \varphi - \frac{\varphi^3}{6} + \frac{\varphi^5}{120} - \frac{\varphi^7}{5040} + \ldots\ldots \approx \varphi$$

(Small angle approximation)

$$\begin{aligned} RF = {} & \cos[(\omega_{LO} - \omega_{BB}) \bullet t] - 1/2(\varphi_{LO} - \varphi_{GEN1} - \varphi_{DGEN} \\ & - \varphi_{MOD}) \bullet \sin[(\omega_{LO} - \omega_{BB}) \bullet t] + 1/2(\varphi_{LO} + \varphi_{GEN1} \\ & + \varphi_{DGEN} + \varphi_{MOD}) \bullet \sin[(\omega_{LO} + \omega_{BB})t] \end{aligned}$$

In addition to the desired lower sideband signal at $(\omega_{LO} - \omega_{BB})$ we also see some upper sideband signal at $(\omega_{LO} + \omega_{BB})$.

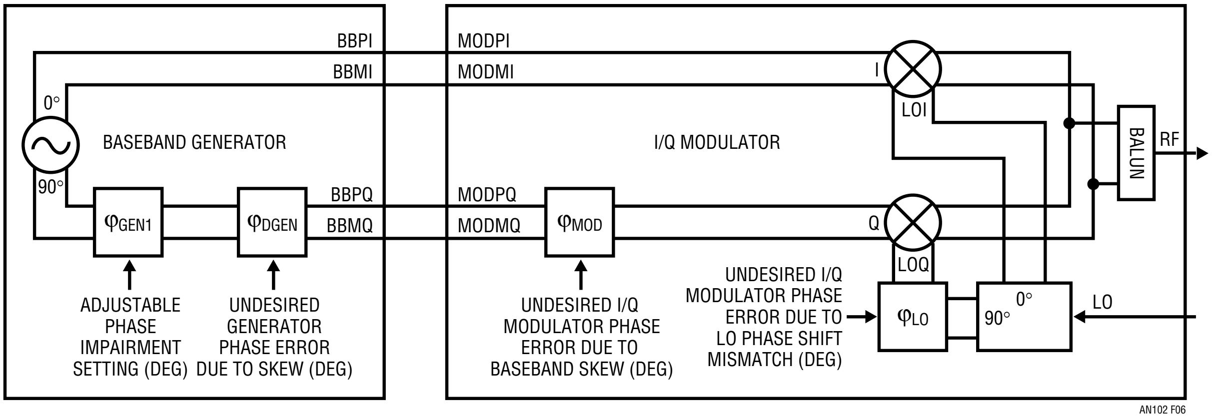

Figure 6. Measurement Setup for Configuration 1

For small phase errors, the upper sideband amplitude is approximately given by:

$$A_{USB} \approx 1/2(\varphi_{LO} + \varphi_{GEN1} + \varphi_{DGEN} + \varphi_{MOD})$$

and the upper sideband suppression is given by:

$$\begin{aligned} R_{SB}\ (dB) &= 20 \bullet \log[1/2(\varphi_{LO} + \varphi_{GEN1} + \varphi_{DGEN1} + \varphi_{MOD})] \\ &= 20 \bullet \log(\varphi_{LO} + \varphi_{GEN1} + \varphi_{DGEN} + \varphi_{MOD}) - 6.02\ (dB) \end{aligned}$$

Note that the phases φ are in radians.

The image term can be minimized by adjusting the generator (impairment) phase setting to:

$$\varphi_{GEN1} = -\varphi_{LO} - \varphi_{DGEN} - \varphi_{MOD}$$

II B. Second Measurement—Null Out the I/Q Modulator Image Signal with Reversed Differential Baseband Signals to the Modulator's Differential I-Channel Inputs (Figure 7).

This configuration differs from that of Figure 6 in that the differential baseband signals to the modulator's I inputs are reversed. In this configuration the image component of the RF output signal is measured and nulled by adjustment of the controllable signal generator phase, φ_{GEN2}. Note that the length of the I signal path is assumed not to change by flipping BBPI and BBMI; the connectors on the baseband generator are just flipped.

$$I = -\cos(\omega_{BB} \bullet t),\ Q = \sin(\omega_{BB} \bullet t + \varphi_{GEN2} + \varphi_{DGEN} + \varphi_{MOD})$$

$$LOI = \cos(\omega_{LO} \bullet t),\ LOQ = \sin(\omega_{LO} \bullet t + \varphi_{LO})$$

$$\begin{aligned} RF = &-\cos(\omega_{BB} \bullet t) \bullet \cos(\omega_{LO} \bullet t) + \sin(\omega_{BB} \bullet t + \varphi_{GEN2} \\ &+ \varphi_{DGEN} + \varphi_{MOD}) \bullet \sin(\omega_{LO} \bullet t + \varphi_{LO}) \end{aligned}$$

Using trigonometric identities, this can be expanded to:

$$\begin{aligned} RF = &-1/2 \cos[(\omega_{LO} - \omega_{BB})t] - 1/2 \cos[(\omega_{LO} + \omega_{BB}) \bullet t] \\ &+ 1/2 \cos(\varphi_{LO} - \varphi_{GEN2} - \varphi_{DGEN} - \varphi_{MOD}) \\ &\bullet \cos[(\omega_{LO} - \omega_{BB})t] \\ &- 1/2 \sin(\varphi_{LO} - \varphi_{GEN2} - \varphi_{DGEN} - \varphi_{MOD}) \\ &\bullet \sin[(\omega_{LO} - \omega_{BB})t] \\ &- 1/2 \cos(\varphi_{LO} + \varphi_{GEN2} + \varphi_{DGEN} + \varphi_{MOD}) \\ &\bullet \cos[(\omega_{LO} + \omega_{BB})t] \\ &+ 1/2 \sin(\varphi_{LO} + \varphi_{GEN2} + \varphi_{DGEN} + \varphi_{MOD}) \\ &\bullet \sin[(\omega_{LO} + \omega_{BB})t] \end{aligned}$$

Again using the small angle approximations, this becomes:

$$\begin{aligned} RF = &-\cos[(\omega_{LO} + \omega_{BB}) \bullet t] - 1/2(\varphi_{LO} - \varphi_{GEN2} - \varphi_{DGEN} \\ &- \varphi_{MOD}) \bullet \sin[(\omega_{LO} - \omega_{BB}) \bullet t] + 1/2(\varphi_{LO} + \varphi_{GEN2} \\ &+ \varphi_{DGEN} + \varphi_{MOD}) \bullet \sin[(\omega_{LO} + \omega_{BB})t] \end{aligned}$$

Now, the desired signal is the upper sideband signal $(\omega_{LO} + \omega_{BB})$, and the image signal is at $(\omega_{LO} - \omega_{BB})$.

For small phase errors, the lower side band amplitude is given by:

$$A_{LSB} \approx 1/2(\varphi_{LO} - \varphi_{GEN2} - \varphi_{DGEN} - \varphi_{MOD})$$

The lower sideband suppression is given by:

$$\begin{aligned} R_{SB}\ (dB) &= 20 \bullet \log[1/2(\varphi_{LO} - \varphi_{GEN2} - \varphi_{DGEN} - \varphi_{MOD})] \\ &= 20 \bullet \log(\varphi_{LO} - \varphi_{GEN2} - \varphi_{DGEN} - \varphi_{MOD}) - 6.02\ (dB) \end{aligned}$$

In this configuration, the image is minimized by adjusting:

$$\varphi_{GEN2} = \varphi_{LO} - \varphi_{DGEN} - \varphi_{MOD}$$

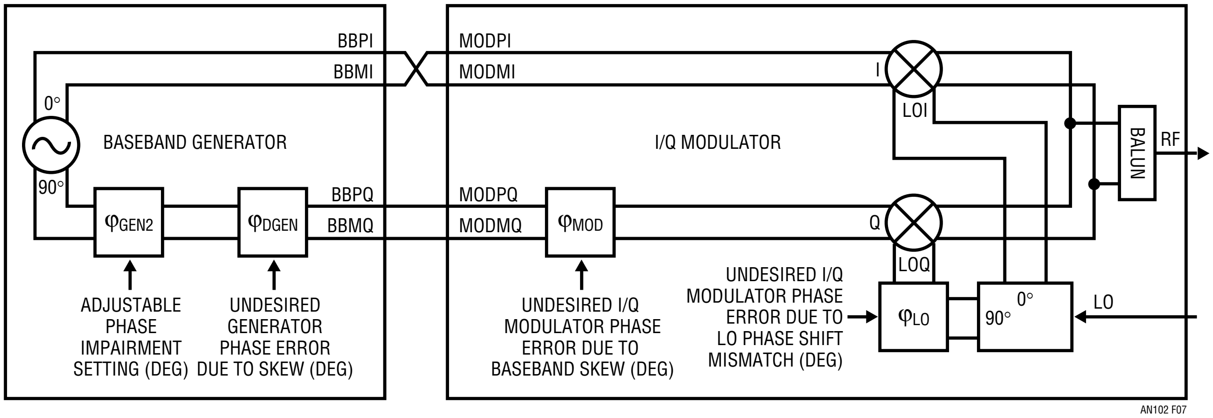

Figure 7. Measurement Setup for Configuration 2

II C. Third Measurement—Null Out the I/Q Modulator Image Signal After Reversing the I and Q Inputs to the Modulator (Figure 8)

This configuration differs from that of Figure 6 in that the I and Q differential inputs are exchanged. Note that the connection lengths in the I and Q path did not change by reversing BBI and BBQ, the connectors on the baseband generator are just flipped.

In this configuration, the image component of the RF output signal is measured and nulled by adjustment of the controllable signal generator phase, φ_{GEN3}.

$Q = \cos(\omega_{BB} \cdot t + \varphi_{MOD})$

$I = \sin(\omega_{BB} \cdot t + \varphi_{GEN3} + \varphi_{DGEN})$

$LOI = \cos(\omega_{LO} \cdot t)$

$LOQ = \sin(\omega_{LO} \cdot t + \varphi_{LO})$

$$RF = \sin(\omega_{BB} \cdot t + \varphi_{GEN3} + \varphi_{DGEN}) \cdot \cos(\omega_{LO} \cdot t) + \cos(\omega_{BB} \cdot t + \varphi_{MOD}) \cdot \sin(\omega_{LO} \cdot t + \varphi_{LO})$$

Using trigonometric identities and small angle approximations, this can be expanded to:

$$RF \approx 1/2(\varphi_{GEN3} + \varphi_{DGEN} + \varphi_{LO} - \varphi_{MOD}) \cdot \cos[(\omega_{LO} - \omega_{BB})t] + 1/2(\varphi_{GEN3} + \varphi_{DGEN} + \varphi_{LO} + \varphi_{MOD}) \cdot \cos[(\omega_{LO} + \omega_{BB})t] + \sin[(\omega_{LO} + \omega_{BB}) \cdot t]$$

Now, the desired signal is the upper sideband frequency component $(\omega_{LO} + \omega_{BB})$ and the image is a lower sideband signal at $(\omega_{LO} - \omega_{BB})$.

For small phase errors, the lower sideband amplitude is given by:

$A_{LSB} \approx 1/2(\varphi_{GEN3} + \varphi_{DGEN} + \varphi_{LO} - \varphi_{MOD})$

The lower sideband suppression is given by:

$$R_{SB}\ (dB) = 20 \cdot \log[1/2(\varphi_{GEN3} + \varphi_{DGEN} + \varphi_{LO} - \varphi_{MOD})] = 20 \cdot \log(\varphi_{GEN3} + \varphi_{DGEN} + \varphi_{LO} - \varphi_{MOD}) - 6.02\ (dB)$$

In this configuration, the image is minimized by adjusting:

$\varphi_{GEN3} = -\varphi_{LO} - \varphi_{DGEN} + \varphi_{MOD}$

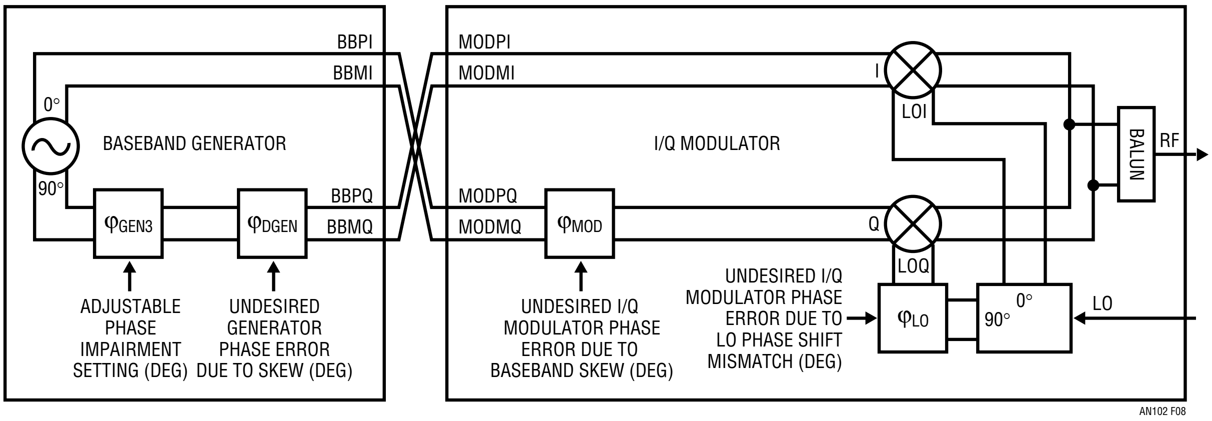

Figure 8. Measurement Setup for Configuration 3

II D. Calculation of Phase Impairments

From II A: $\varphi_{GEN1} = -\varphi_{LO} - \varphi_{DGEN} - \varphi_{MOD}$

II B: $\varphi_{GEN2} = \varphi_{LO} - \varphi_{DGEN} - \varphi_{MOD}$

II C: $\varphi_{GEN3} = -\varphi_{LO} - \varphi_{DGEN} + \varphi_{MOD}$

We can solve these three equations, with three unknowns, to give:

$$\varphi_{LO} = (\varphi_{GEN2} - \varphi_{GEN1})/2 \qquad (1)$$

$$\varphi_{DGEN} = -(\varphi_{GEN2} + \varphi_{GEN3})/2 \qquad (2)$$

$$\varphi_{MOD} = (\varphi_{GEN3} - \varphi_{GEN1})/2 \qquad (3)$$

Note that we can express the phases φ in these equations in radians or degrees.

The equations above hold for an I/Q modulator with an output relationship given by:

$$RF = I \bullet \cos(\omega_{LO} \bullet t) + Q \bullet \sin(\omega_{LO} \bullet t) \qquad (2D\_A)$$

The I/Q modulators provided by Linear Technology will satisfy the above equation.

However, other I/Q modulators may have the following output characteristic:

$$RF = I \bullet \cos(\omega_{LO} \bullet t) - Q \bullet \sin(\omega_{LO} \bullet t) \qquad (2D\_B)$$

There is no international convention on which I/Q modulator equation is the "right" one.

Using an I/Q modulator with the latter relationship will affect the derivations somewhat. In this case, in configuration 1, the desired signal will be then at the *upper* sideband ($\omega_{LO} + \omega_{BB}$) and image nulling will be achieved for:

$$\varphi_{GEN1} = \varphi_{LO} - \varphi_{DGEN} - \varphi_{MOD}$$

In configuration 2, the desired signal will be at the *lower* sideband ($\omega_{LO} - \omega_{BB}$) and image nulling will be achieved for:

$$\varphi_{GEN2} = -\varphi_{LO} - \varphi_{DGEN} - \varphi_{MOD}$$

In configuration 3, the desired signal will be again at the *lower* sideband ($\omega_{LO} - \omega_{BB}$) and image nulling will be achieved for:

$$\varphi_{GEN3} = \varphi_{LO} - \varphi_{DGEN} + \varphi_{MOD}$$

We can again solve these three equations, with three unknowns, to give:

$$\varphi_{LO} = (\varphi_{GEN1} - \varphi_{GEN2})/2 \qquad (4)$$

$$\varphi_{DGEN} = -(\varphi_{GEN2} + \varphi_{GEN3})/2 \qquad (5)$$

$$\varphi_{MOD} = (\varphi_{GEN3} - \varphi_{GEN1})/2 \qquad (6)$$

Note that the sign is different for the φ_{LO} calculation, and the equations for φ_{DGEN} and φ_{MOD} stay the same.

III. APPLYING THE METHOD

For five different LT®5528 boards the image rejection null-vectors for configurations 1, 2 and 3 described in sections II A, II B and II C are measured and logged in Table 1, for baseband frequencies 5MHz and 10MHz. A QPSK signal is programmed into a Rohde & Schwartz AMIQ baseband generator with a bit sequence of 00011011. The symbol rate is 40MHz with oversampling of 2 for the 10MHz baseband frequency, and the symbol rate is 20MHz with an oversampling of 4 for the 5MHz baseband frequency, both resulting in a sample rate of 80MHz. In all cases better than 75dBc image rejection is achieved after nulling.

The quadrature phase error of the LT5528 φ_{LO}, the baseband phase error of the LT5528 φ_{MOD} and the baseband phase error of the generator, φ_{DGEN} can be determined using Equations 1, 2 and 3. The amplitude mismatch results are discarded. The results for the phase errors in degrees are given in Table 2. Also equivalent delays are derived from the phase errors, assuming all phase error is caused by a delay.

Table 1. Image Rejection Null Vectors for Configurations 1, 2 and 3 for 5MHz and 10MHz Baseband Frequency. The Amplitude Adjustment Required for Nulling (Not Shown) is ≤0.35% (Worst Case)

	BASEBAND FREQUENCY = 5MHz			BASEBAND FREQUENCY = 10MHz		
	config1	config2	config3	config1	config2	config3
	φ_{DGEN1}	φ_{DGEN2}	φ_{DGEN3}	φ_{DGEN1}	φ_{DGEN2}	φ_{DGEN3}
UNIT	DEGREE	DEGREE	DEGREE	DEGREE	DEGREE	DEGREE
1	–0.90	1.93	–0.83	–0.48	2.41	–0.41
2	1.13	–0.07	1.24	1.60	0.30	1.74
3	0.32	0.81	0.37	0.73	1.30	0.84
4	0.36	0.74	0.44	0.80	1.20	0.92
5	0.51	0.60	0.62	–0.03	0.10	0.03

Table 2. Phase Error Measurement Results of the LT5528

BOARD	BASEBAND FREQUENCY = 5MHz					BASEBAND FREQUENCY = 10MHz				
	φ_{LO}	φ_{MOD}	τ_{MOD}	φ_{DGEN}	τ_{DGEN}	φ_{LO}	φ_{MOD}	τ_{MOD}	φ_{DGEN}	τ_{DGEN}
UNIT	DEGREE	DEGREE	ps	DEGREE	ps	DEGREE	DEGREE	ps	DEGREE	ps
1	1.415	0.035	19.4	–0.55	306	1.445	0.035	9.7	–1.0	278
2	–0.60	0.055	30.6	–0.585	325	–0.65	0.07	19.4	–1.02	283
3	0.245	0.025	13.9	–0.59	328	0.285	0.055	15.3	–0.785	218
4	0.19	0.04	22.2	–0.59	328	0.20	0.06	16.7	–0.86	239
5	0.045	0.055	30.6	–0.61	339	0.08	0.1	27.8	–1.08	300

IV. CONCLUSION

The method described here is capable of accurately measuring various sources of phase error. The measured quadrature error φ_{LO} using 5MHz and 10MHz baseband frequencies are equal within 0.05 degrees, suggesting quadrature error can be measured quite accurately for relatively high baseband frequencies. It can be seen that the baseband signal generator phase error φ_{DGEN} is dominant in this setup. τ_{DGEN} is about 300ps, compared to the LT5528's baseband delay error τ_{MOD}, which is only about 25ps to 30ps.

A somewhat surprising result is the magnitude of the phase error in the baseband signal source φ_{DGEN}. This baseband signal source phase error may be a dominant error source in a direct I/Q modulation scheme. It should be carefully characterized and compensated. Otherwise, it may limit the extent of image suppression. This is especially important in a broadband application, such as W-CDMA, if the baseband source phase error is a skew (time delay) error, which results in a frequency dependent phase error.

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