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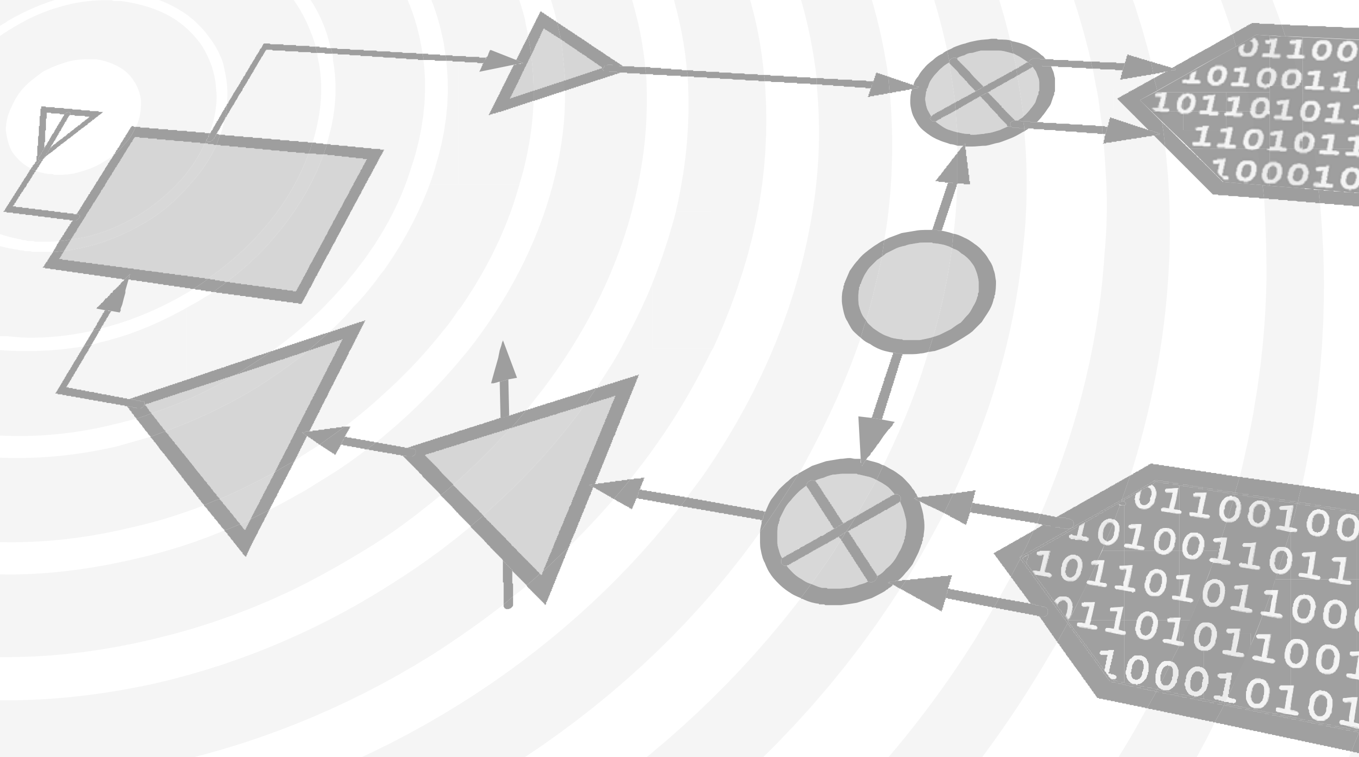

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Hittite's Vector Modulators

General Description

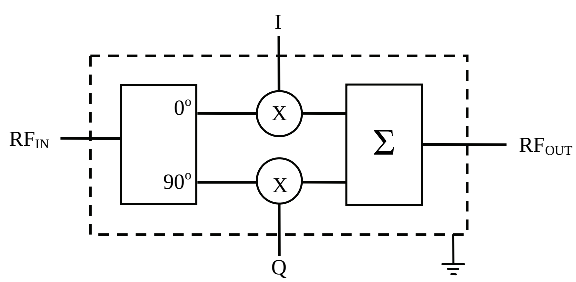
This application note is intended to serve as a supplement to Hittite Microwave's Vector Modulator Datasheets. You will find a full product listing and a link to download the datasheet for each of Hittite's Vector Modulator products at www.hittite.com.

This application note describes how vector modulators operate, and provide details for practical application of the gain control relationships, in terms of it's I and Q control inputs.

Ideal Vector Modulators

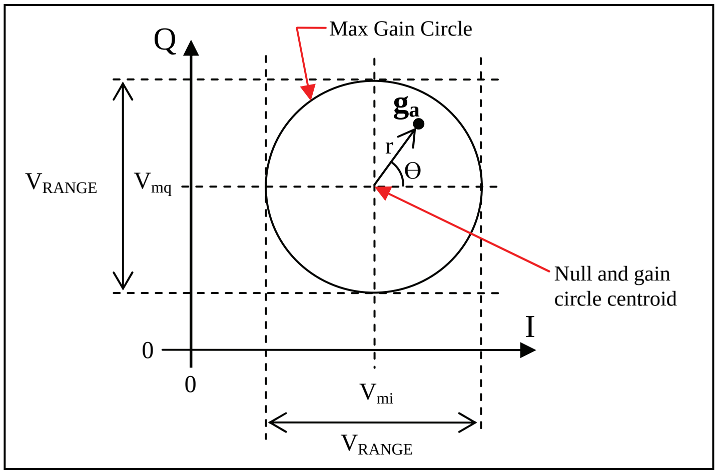
The vector modulator is essentially a device which applies a variable gain and variable phase shift to an arbitrary RF signal, over a finite bandwidth. Two control signals, I and Q, describe a 2-dimensional plane on which gain magnitude and angle can be uniquely defined.

Figure 1: Vector Modulator Block Diagram



The figure above illustrates the functional blocks of any vector modulator. The RF input signal is split into two signals; one in quadrature to the other. Each quadrature component is multiplied with a control signal, and then re-combined. This operation provides gain control described by I and Q over a two-dimensional plane, where gain is a vector quantity.

Figure2: Gain Control Over A Two-Dimensional Plane



Any single point can be described by an I-coordinate, and a Q-coordinate. That unique point, g_a, is a gain setting, which can also be described in polar form: gain magnitude, G, and gain angle, Θ. A vector modulator gain adjustment is bounded on the low-side by the gain null (G=0 ideally) and on the high-side by G_{MAX}.

Hittite's Vector Modulators

The following two relationships describe gain magnitude and gain angle for an *ideal* Vector Modulator, in terms of its control inputs (I & Q):

Gain = |G|, <Θ

$$|G| = G_{MAX} \times 2 \times \sqrt{\left(\frac{I - Vmi}{V_{RANGE}}\right)^2 + \left(\frac{Q - Vmq}{V_{RANGE}}\right)^2} = G_{MAX} \times r\,,\ \angle\theta = \arctan\left[\frac{Q - Vmq}{I - Vmi}\right]$$

Where Vmi and Vmq describe the gain null point for I and Q, respectively,

V_{RANGE} defines the range of I and Q control: that control range is specified on the datasheet,

G_{MAX} is maximum gain, and r describes a circle of variable radius, with maximum radius of r=1.

Observations:

- The gain null (G=0) is located at a coordinate defined by I=Vmi, and Q=Vmq,
- This null point serves as the origin for the gain vector,
- Gain magnitude is constant on concentric circles centered on the null point,
- Gain angle is constant when the (Q-Vmq)/(I-Vmi) ratio is constant,
- The *Ideal Maximum Gain Circle* occurs over a circle with radius, *r* = 1. This circle is centered on the ideal null point: I=Q=1.5V.

Example Calculations:

(let Vmi=Vmq=1.5V, V_{RANGE} =2.0V)

For I=2.5V, Q=1.5V, G = G_{MAX}, Θ = 0^o

For I=1.5V, Q=2.5V, G = G_{MAX}, Θ = 90^o

For I=0.5V, Q=1.5V, G = G_{MAX}, Θ = 180^o

For I=1.5V, Q=0.5V, G = G_{MAX}, Θ = 270^o

For I=2.5V, Q=2.5V, G = G_{MAX} * √2, Θ = 45^o

For I=2.0V, Q=2.0V, G = G_{MAX} / √2, Θ = 45^o

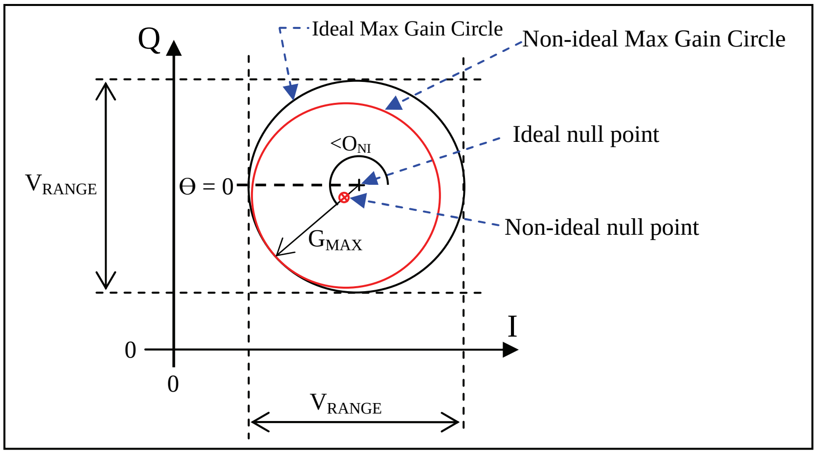
Non-ideal Vector Modulators

Under real world conditions, vector modulators deviate from the ideal model in some respects, however small. In a so-called non-ideal vector modulator, the null point deviates slightly from its ideal location at I=1.5V, Q=1.5V. Hittite's vector modulators are designed to keep that null offset part-to-part variation to less than ±100mV. Also maximum gain will vary slightly from part-to-part (±1dB). For accurate gain control, these small variations should be taken into account.

Let's consider the consequences of these "real world" deviations:

1. The actual null point might be shifted slightly on the I-Q plane: the concentric Gain circles will shift by exactly the same amount, since they are also still centered on the actual null point.
2. A less obvious observation is that the maximum gain circle for the non-ideal vector modulator should be inside of the *Ideal Maximum Gain Circle*. Performance is optimized for operation within the *Ideal Maximum Gain Circle*.
3. A gain angle offset, Φ(*f*), is included in the expression for gain angle to compensate for a constant phase offset, at a specific RF signal frequency.

Figure 3: Non-Ideal Maximum Gain Circle



In figure 3. the null offset is exaggerated to better illustrate the effect on the gain adjustment range.

We define the null offset as:

$O_{NI}(\Delta I, \Delta Q)$ = [(Vmi-1.5V),(Vmq-1.5V)],

Where Vmi and Vmq locate the actual null point, and the ideal null point is located at I=Q=1.5V.

The point at which ideal max gain circle and non-ideal max gain circle coincide will be on a vector at an angle of <Onull originating from I=Q=1.5V.

$<O_{NI}$ = arctan[(Vmq-1.5V)/(Vmi-1.5V)]

We can determine the non-ideal maximum gain, G_{NI}, by calculating the maximum circle radius allowed within the *Ideal Max Gain Circle*, centered on the actual (or non-ideal) null point. Gain for the non-ideal vector modulator is expressed as:

$$|G| = G_{NI} \times 2 \times \sqrt{\left(\frac{I - Vmi}{V_{RANGE}}\right)^2 + \left(\frac{Q - Vmq}{V_{RANGE}}\right)^2} = G_{NI} \times r \quad , \quad \angle\theta = \arctan\left[\frac{(Q - Vmq)}{(I - Vmi)}\right] + \Phi(f)$$

where Φ(*f*) is a constant phase angle, at a specific RF signal frequency, *f*.

Example Calculation:

Actual null point for a DUT has been measured to be at Vmi = 1.49V, and Vmq = 1.41V,

(Refer to the procedure below for "Locating The Null, and Measuring G_{null}")

The control input ranges for I and Q are specified on the datasheet for a vector modulator with no null offset: $O_{NI}(\Delta I, \Delta Q) = 0$.

We read 0.5V ≤ I ≤ 2.5V, and 0.5V ≤ Q ≤ 2.5V off the datasheet and let VR_{MIN} = 0.5V, VR_{MAX} = 2.5V.

We must determine the control input range for the non-deal vector modulator: $O_{NI}(\Delta I, \Delta Q) \neq 0$

$V_{RANGE}/2 = MIN[(Vmi – VR_{MIN}), (Vmq – VR_{MIN}), (VR_{MAX} – Vmi), (VR_{MAX} – Vmq)]$

In this case, the control input range is $V_{RANGE} = 2(Vmq – Q_{MIN}) = 2(1.41 – 0.5) = \boxed{1.820\text{ V}}$,

System Calibration:

Due to part-to-part variations, a system-level calibration is recommended to satisfy gain control accuracy requirements. Measure each of the four following parameters at system-level test, and store these values in non-volatile memory for use as calibration constants:

1. Vmi and Vmq: refer to the procedure for "Locating the Null, and Measuring G_{null}"
2. Maximum gain, G_{NI}: refer to the procedure for "Measuring Maximum Gain, G_{NI}:"
3. and gain angle offset, Φ: refer to the procedure for "Measuring Gain Angle Offset, Φ"

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Some creative test methodology and clever algebra can provide alternate, more efficient methods for finding each of these four parameters: Vmi, Vmq, Φ, and $G_{MAX.}$

Locating the Null, and Measuring G_{null}:

1. With Q held constant at 1.5V, sweep I from 1.4V to 1.6 V, and note at what voltage the gain is at a minimum. This is Vmq.

2. With I held constant at the voltage found in step 1, sweep Q from 1.4 V to 1.6V, and again note at what voltage the gain is at a minimum. This is Vmi.

3. The Loss at this null point (I=Vmi, Q=Vmq) corresponds to $G_{null} = G_{MIN}$.

Measuring Maximum Gain, G_{NI}:

Measure Maximum Gain, G_{NI}, at the largest radius defined by control input range. The gain measured at each of these points should be equal (±1dB). If so, the measured gain is at maximum, G_{NI}. ***If the gain measures differently on the same radius, the actual null point is offset.*** Use the procedure described under "Locating the Null, and Measuring G_{null}" to locate the actual null point, and then re-measure the gain with *r=1*.

For example:

If the control input range for I and Q is specified as 0.5V to 2.5V,

and the null point is at Vmi=Vmq=1.5V,

then V_{RANGE} = 2*MIN[(Vmi – VR_{MIN}), (Vmq – VR_{MIN}), (VR_{MAX} – Vmi), (VR_{MAX} – Vmq)] = $\boxed{2.0V}$

Measure the gain at several points on a circle with *r*=1. If the gain measures the same, this is the maximum gain, G_{NI}.

$$|G| = G_{NI} \times 2 \times \sqrt{\left(\frac{I-1.5}{2.0}\right)^2 + \left(\frac{Q-1.5}{2.0}\right)^2} = G_{NI} \times r$$

Measuring Gain Angle Offset, Φ:

Measure the gain angle offset by first setting the I and Q control inputs for any gain. Measure the phase shift of the RF output signal with respect to the input RF signal. The difference between the calculated gain angle and the measured phase shift is the gain angle offset, Φ. Keep in mind that the tan(Θ) function is periodic every 180^o.

Example Calculation:

If we set I = 1.0V, and Q = 1.0V,

Ideally we would expect gain angle = Θ = arctan([1.0V – 1.5V)/(1.0V – 1.5V)] = $\boxed{45^o}$, for Vmi=Vmq=1.5V,

We measure phase difference between RFout and RFin as 102^o.

The gain angle offset = Φ = $102^o – 45^o$= $\boxed{57^o}$

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A Real World Example using Hittite's HMC500LP3 Vector Modulator:

Note: The following concepts and methods are exactly the same for all other Hittite Vector Modulators.

1. Initial gain magnitude and gain angles measurements assuming an ideal vector modulator:

   Vmi = Vmq = 1.5V, and V_{RANGE} = 2.0V.

   Measurements are performed on the HMC500LP3 evaluation board (refer to HMC500LP3 datasheet).

Table 1: Initial Gain Magnitude measurements assuming Vmi=Vmq=1.5V

Gain Magnitude [dB] Measured Assuming $O_{NI}(\Delta I, \Delta Q)=0$

Q \ I	0.500V	1.00V	Vmi= 1.500V	2.00V	2.500V
0.50V	-8.0	-10.0	**-10.7**	-9.42	-7.6
1.00V	-10.5	**-15.4**	**-18.3**	**-13.6**	-9.9
Vmq=1.50V	**-11.0**	**-18.0**	**-29.3**	**-15.5**	**-10.6**
2.00V	-9.4	**-12.9**	**-14.3**	**-12.0**	-9.14
2.50V	-7.16	-9.0	**-9.6**	-8.7	-7.1

Table 2: Initial Gain Angle measurements assuming Vmi=Vmq=1.5V

Gain Angle [degrees] Measured Assuming $O_{NI}(\Delta I, \Delta Q)=0$

Q \ I	0.500V	1.00V	Vmi= 1.500V	2.00V	2.500V
0.50V	104	125	**151**	-182	-167
1.00V	81	**102**	**157**	**-158**	-144
Vmq=1.50V	**51**	**44**	**-61**	**-113**	**-117**
2.00V	23	**0**	**-37**	**-74**	-89
2.50V	8	-12	**-34**	-58	-73

For r = 1.0, the measured gains are: -10.7dB, -10.6dB, -9.6dB, and -11.0dB

For r = √2, the measured gains are: -15.4dB, -13.6dB, -12.0db, and -12.9dB

Where r = SQRT[$(I-1.5)^2+(Q-1.5)^2$], and V_{RANGE} = 2.0V

2. Gain magnitudes measured on the same gain circle have differences slightly greater than ±1dB. The actual null point must be slightly offset from I=Q=1.5V. Using the procedures described above, we now measure the four calibration parameters: Vmi, Vmq, G_{NI}, and Φ.

Vmi measures 1.423V	Vmq measures 1.389V	Gnull measures -63.2dB

So then the control voltage range is:

$$V_{RANGE} = 2{*}MIN[(Vmi - VR_{MIN}), (Vmq - VR_{MIN}), (VR_{MAX} - Vmi), (VR_{MAX} - Vmq)]$$

$$= 2{*}MIN[(1.423 - 0.5), (1.389 - 0.5), (2.5 - 1.423), (2.5 - 1.389)] = 2{*}(1.389 - 0.5) = \boxed{1.778\ V}$$

3. We now re-measure the gain magnitude and gain angle at various points on the I/Q plane, using the actual null point:

Gain Magnitude |G|, [dB] Re-measured

Table 3: Re-measured gain magnitude using actual null point

Q \ I	0.534V	0.923V	Vmi= 1.423V	1.923V	2.312V
0.500V	-8.2	-9.8	**-10.8**	-9.8	-8.3
0.889V	-10.2	**-13.3**	**-15.7**	**-13.4**	-10.4
Vmq=1.389V	**-11.5**	**-16.7**	**-63.2**	**-17.0**	**-11.8**
1.889V	-10.2	**-13.5**	**-16.5**	**-13.9**	-10.7
2.278V	-8.3	-10.2	**-11.4**	-10.4	-8.7

Gain Angle ϴ, [degrees] Re-measured

Table 4: Re-measured gain angles using actual null point

Q \ I	0.534V	0.923V	Vmi= 1.423V	1.923V	2.312V
0.500V	105	120	**148**	-187	-171
0.889V	88	**105**	**148**	**-172**	-156
Vmq=1.389V	**57**	**57**	**-135**	**-123**	**-123**
1.889V	28	**12**	**-31**	**-75**	-92
2.278V	12	-4	**-32**	-59	-76

We can see that the gain at four point on *r* = 1 measures: -10.8dB, -11.5dB, -11.4dB, and -11.8dB

For maximum gain we could average these four measurements for G_{NI} = $\boxed{\text{-11.4dB or 0.0731}}$

Also we can

4. Now incorporating these calibration parameters into the following gain control relationships:

$$|G| = G_{NI} \times 2 \times \sqrt{\left(\frac{I - Vmi}{V_{RANGE}}\right)^2 + \left(\frac{Q - Vmq}{V_{RANGE}}\right)^2} \quad , \quad \angle\theta = \arctan\left[\frac{(Q - Vmq)}{(I - Vmi)}\right] + \Phi(f)$$

We have:

$$|G| = 0.0731 \times 2 \times \sqrt{\left(\frac{I - 1.423}{1.778}\right)^2 + \left(\frac{Q - 1.389}{1.778}\right)^2} \quad \text{, gain expression [1]}$$

$$\angle\theta = \arctan\left[\frac{(Q - 1.389)}{(I - 1.423)}\right] + \Phi(f) \quad \text{, gain expression [2]}$$

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5. Now if calculate the gain magnitude and gain angle we would expect to see using the gain expressions above:

Gain Magnitude

|G|, [dB]

Calculated using

Gain Expression [1]

Table 5: Calculated Gain Magnitudes using Gain Expression [1]

Q \ I	0.534V	0.923V	Vmi= 1.423V	1.923V	2.312V
0.500V	-8.4	-10.2	**-11.4**	-10.2	-8.4
0.889V	-10.2	**-13.4**	**-16.4**	**-13.4**	-10.2
Vmq=1.389V	**-11.4**	**-16.4**	**null**	**-16.4**	**-11.4**
1.889V	-10.2	**-13.4**	**-16.4**	**-13.4**	-10.2
2.278V	-8.4	-10.2	**-11.4**	-10.2	-8.4

Gain Angle

ϴ, [degrees]

Calculated using

Gain Expression [2]

using Φ(*f*) = 0

Table 6: Calculated Gain Angles using Gain Expression [2], **using Φ(*f*) = 0**

Q \ I	0.534V	0.923V	Vmi= 1.423V	1.923V	2.312V
0.500V	45	61	**90**	-241	-225
0.889V	29	**45**	**90**	**-225**	-209
Vmq=1.389V	**0**	**0**	**null**	**-180**	**-180**
1.889V	-29	**-45**	**-90**	**-135**	-151
2.278V	-45	-61	**-90**	-119	-135

6. We can now determine Φ(*f*): the next table calculates the difference between table 6 and table 4:

Gain Angle

ϴ, [degrees]

Calculated using

Gain Expression [2]

using Φ(*f*) = 0

Table 7: Difference between Measured Gain Angle and Calculated Gain angle (using Gain Expression [2] with Φ(*f*) = 0)

Q \ I	0.534V	0.923V	Vmi= 1.423V	1.923V	2.312V
0.500V	60	60	**58**	54	54
0.889V	59	**60**	**58**	**53**	54
Vmq=1.389V	**57**	**57**	null	**57**	**57**
1.889V	57	**57**	**59**	**60**	58
2.278V	57	57	**58**	60	59

To calculate the gain angle offset, we will average the differences from table 7, for r<1 (not including null).

Φ(*f*) = [average of non-shaded squares in table 7] = 57^o, so the expression for gain angle is:

$$\angle\theta = \arctan\left[\frac{(Q-1.389)}{(I-1.423)}\right] + 57^o$$

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Conclusion: System-Level Calibration Provides Improved Gain Control Accuracy

Defining Gain Magnitude Error as:

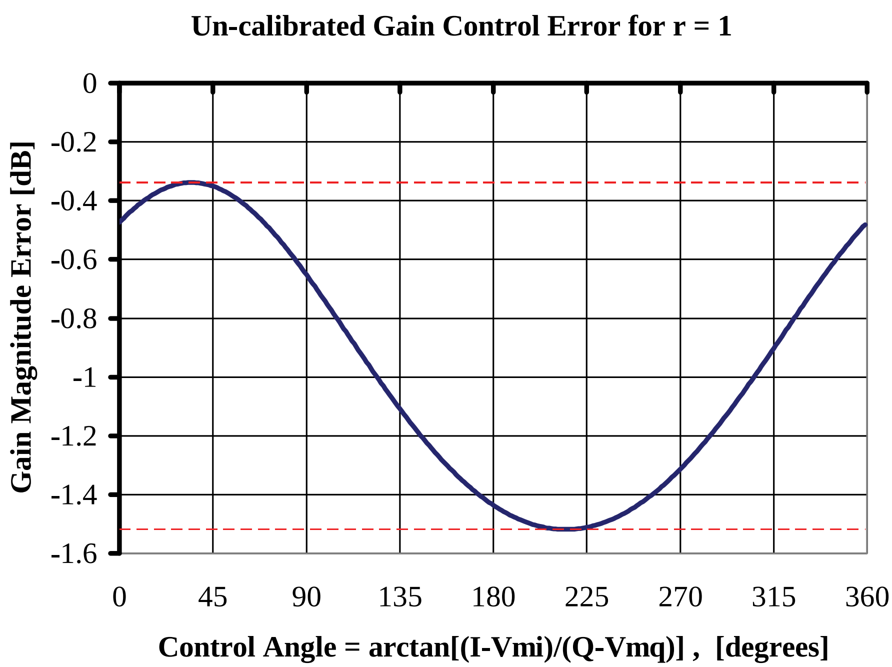
Gain Magnitude Error = [Gain assuming Vmi=Vmq=1.5V] – [Gain using Vmi=1.423V, Vmq=1.389], dB

[Gain assuming Vmi = Vmq = 1.5V, V_{RANGE} = 2.0V] $= 0.912 \times 2 \times \sqrt{\left(\frac{I-1.5}{2.0}\right)^2 + \left(\frac{Q-1.5}{2.0}\right)^2} = G_{MAX} \times r$

Where G_{MAX} = 0.903 or -10.4dB from table 1 = linear average of (-10.7dB, -10.6dB, -9.6dB, -11.0dB)

[Gain using Vmi=1.423V, Vmq=1.389, V_{RANGE} = 1.778V] $= 0.0731 \times 2 \times \sqrt{\left(\frac{I-1.423}{1.778}\right)^2 + \left(\frac{Q-1.389}{1.778}\right)^2} = G_{NI} \times r$

Figure 4: Gain Magnitude Error: Comparing Gain Magnitude With and Without System-Level Calibration



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