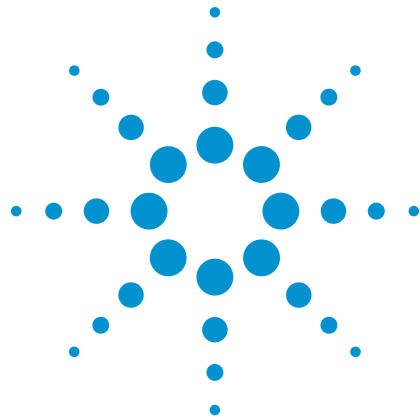


# Agilent I/Q Modulation Considerations for PSG Vector Signal Generators

Application Note



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## I/Q Modulator Operation

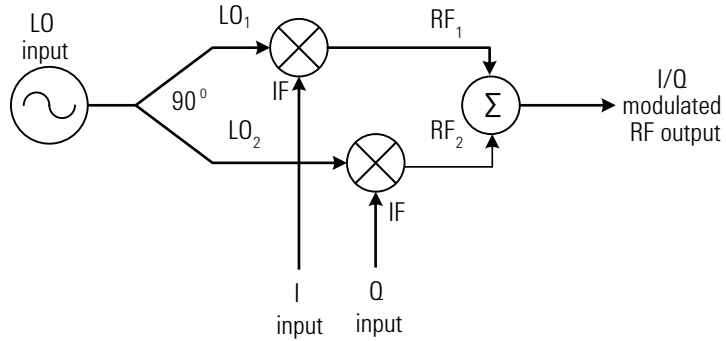


Figure 1. I/Q modulator block diagram

First, consider an ideal I/Q modulator. As shown in Figure 1 above, a CW signal (at the carrier frequency) is fed into a quadrature power splitter, producing two signals which differ in phase by 90 degrees. This phase relationship is called “quadrature.” These signals are fed to the LO ports of two identical mixers. The IF ports (or low-frequency/DC ports) of these mixers are fed by the I and Q inputs respectively. These I/Q signals are referred to as “baseband” signals. The RF outputs of the two mixers are summed together, with, ideally, no phase shift between them. The resulting output from this structure is an I/Q modulated signal at the same carrier frequency as the LO.

To produce an RF signal which is a double-sideband suppressed carrier (DSBSC), a baseband signal can be applied to I, and nothing applied to Q (Or vice versa). For example, assume the LO signals are described by  $LO_1 = \sin(\omega_c t)$  and  $LO_2 = \cos(\omega_c t)$ ,  $I = A \sin(\omega_m t)$ , and  $Q = 0$ . Since the mixers are assumed to be ideal linear multipliers, the mixer outputs will be:

$$RF_1 = \sin(\omega_c t) * A \sin(\omega_m t) = A/2 * \cos((\omega_c - \omega_m)t) - A/2 * \cos((\omega_c + \omega_m)t)$$

$$\text{And } RF_2 = \cos(\omega_c t) * 0 = 0$$

$$\text{The output will be } RF_1 + RF_2 = A/2 * \cos((\omega_c - \omega_m)t) - A/2 * \cos((\omega_c + \omega_m)t) \text{ (DSB)}$$

To produce an RF signal which is a single-sideband suppressed carrier (SSBSC), two baseband signals which differ in phase by 90 degrees are applied to I and Q respectively. For example, assume the LO signals are described by  $LO_1 = \sin(\omega_c t)$  and  $LO_2 = \cos(\omega_c t)$ ,  $I = A \sin(\omega_m t)$ , and  $Q = A \cos(\omega_m t)$ . Since the mixers are assumed to be ideal linear multipliers, the mixer outputs will be:

$$RF_1 = \sin(\omega_c t) * A \sin(\omega_m t) = A/2 * \cos((\omega_c - \omega_m)t) - A/2 * \cos((\omega_c + \omega_m)t)$$

$$\text{And } RF_2 = \cos(\omega_c t) * A \cos(\omega_m t) = A/2 * \cos((\omega_c - \omega_m)t) + A/2 * \cos((\omega_c + \omega_m)t)$$

$$\text{The output will be } RF_1 + RF_2 = A \cos((\omega_c - \omega_m)t) \text{ (Lower sideband)}$$

Here are two ways to generate a single-sideband RF signal using the internal baseband generator in the PSG vector signal generator:

- In the dual Arb mode, select the waveform SINE\_TEST\_WFM. This produces a lower-sideband suppressed carrier signal. The modulating frequency is 500 kHz if a sample clock frequency is 100 MHz; the clock frequency can be reduced for lower modulating frequency.
- In the Custom Real-time mode, set the modulation format to  $(\pi/4)$ DQPSK and data to Fix4. The modulating frequency is 6.25 MHz if the symbol rate is 50 Msymbols/sec; the symbol rate can be reduced for lower modulating frequency.

## I/Q Modulator Imperfections

LO or Carrier feed-through, sometimes called Origin Offset, can be caused by:

- The two mixers not being identically matched and balanced, resulting in LO leakage which is dependent on carrier frequency.
- DC offset at the I and/or Q inputs, resulting in LO leakage which is independent of carrier frequency. The PSG vector signal generator provides adjustable I and Q DC offsets for the internal baseband generator, the standard I/Q inputs, and the optional wideband I/Q inputs.

LO quadrature error results if the two LO signals are not exactly 90 degrees apart. This can be caused by LO splitter phase error, or phase matching imperfections in the mixers. This has the effect of producing an undesired image which does not depend on I/Q modulating frequency. For example, in the SSBSC example above, assume that  $LO_1 = \sin(\omega_c t)$  and  $LO_2 = \cos(\omega_c t + \alpha)$ , where  $\alpha$  is the quadrature error. The mixer outputs will be (see also Figure 2):

$$RF_1 = \sin(\omega_c t) * A \sin(\omega_m t) = A/2 * \cos((\omega_c - \omega_m)t) - A/2 * \cos((\omega_c + \omega_m)t)$$

$$\text{And } RF_2 = \cos(\omega_c t) * A \cos(\omega_m t + \alpha) = A/2 * \cos((\omega_c - \omega_m)t - \alpha) + A/2 * \cos((\omega_c + \omega_m)t + \alpha)$$

The output will be

$$RF_1 + RF_2 = A \cos(\alpha/2) \cos((\omega_c - \omega_m)t - \alpha/2) \text{ (desired lower sideband)}$$

$$-A \sin(\alpha/2) \sin((\omega_c + \omega_m)t + \alpha/2) \text{ (unwanted image)}$$

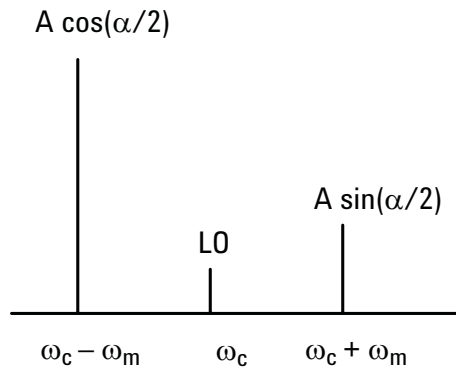


Figure 2. Resulting spectrum of LO feed-through and quadrature error.

Note that a small quadrature error can result in a large image. If the quadrature error is  $\alpha = 1$  degree in the above example, the unwanted image is  $20 * \log[\sin(\alpha/2)/\cos(\alpha/2)] = -41$  dBc. Internal I/Q calibration reduces both of these errors down to typically  $-50$  dBc. This calibration can be done at a spot frequency (DC cal), over a user-defined frequency range, or over the full frequency range. Internal I/Q calibration should be done if the ambient temperature changes more than a few degrees, or every few days.

I/Q mismatch errors also result in unwanted images. These errors are caused by differences between the I and Q signals, due to baseband hardware limitations. These errors can be:

- Amplitude mismatch. For example, in the SSBSC example above, a 0.1 dB difference results in an undesired image level of  $-45$  dBc. The PSG vector signal generator has adjustable I/Q gain balance for the internal baseband generator and standard I/Q inputs, but not the Option 015/016 wideband I/Q inputs.
- Phase mismatch. For example, in the SSBSC example above, a 1 degree difference results in an undesired image level of  $-41$  dBc. Phase mismatch can be adjusted using the internal quadrature adjustment in the PSG vector signal generator.
- Group delay mismatch (skew), which is more predominant at higher modulation rates. For example, in the SSBSC example above, a 1-degree error (resulting in a  $-41$  dBc image) can be caused by a 2.8-nanosecond delay mismatch at a 1 MHz modulating rate, or by only a 5.5-picosecond delay mismatch at a 500 MHz modulating rate. The PSG vector signal generator has adjustable skew correction for the internal baseband generator.

The photos below show the effect of adjusting skew on the spectrum of a multitone signal at 30 GHz. For this example, the baseband signal is 64 tones spaced over 80 MHz, with USB tones turned off.

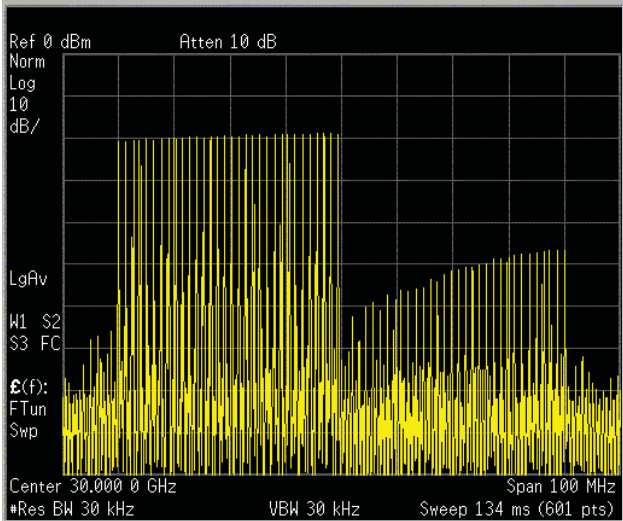


Figure 3. Skew misadjusted 400 picoseconds

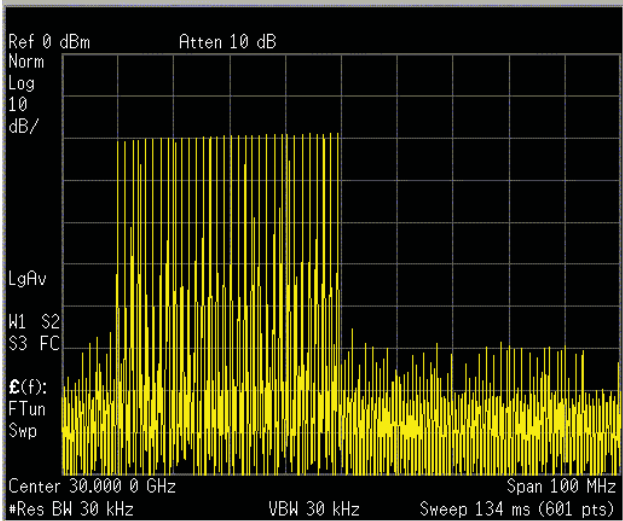


Figure 4. Skew properly adjusted

## A Simplified Block Diagram of the PSG Vector Signal Generator

I/Q baseband signals are processed and fed into the I/Q modulator. The signal from the I/Q modulator (described in the previous section) is amplified, filtered, and delivered to the RF output as shown above. Pulse modulation is added after I/Q modulation. It should be noted that in the PSG vector signal generator there are actually two separate RF chains, one for carrier frequencies below 3.2 GHz and the other above 3.2 GHz. Each RF chain consists of an I/Q modulator, RF gain, ALC and Pulse modulators, output amplification, and filtering. Direct I/Q modulation at the RF carrier frequency is used up to 20 GHz. Above 20 GHz, an upconverter is inserted between the I/Q modulator and the Output section which frequency-translates the I/Q-modulated signal by a factor of 3 (between 20 and 28.5 GHz) or 5 (between 28.5 and 44 GHz).

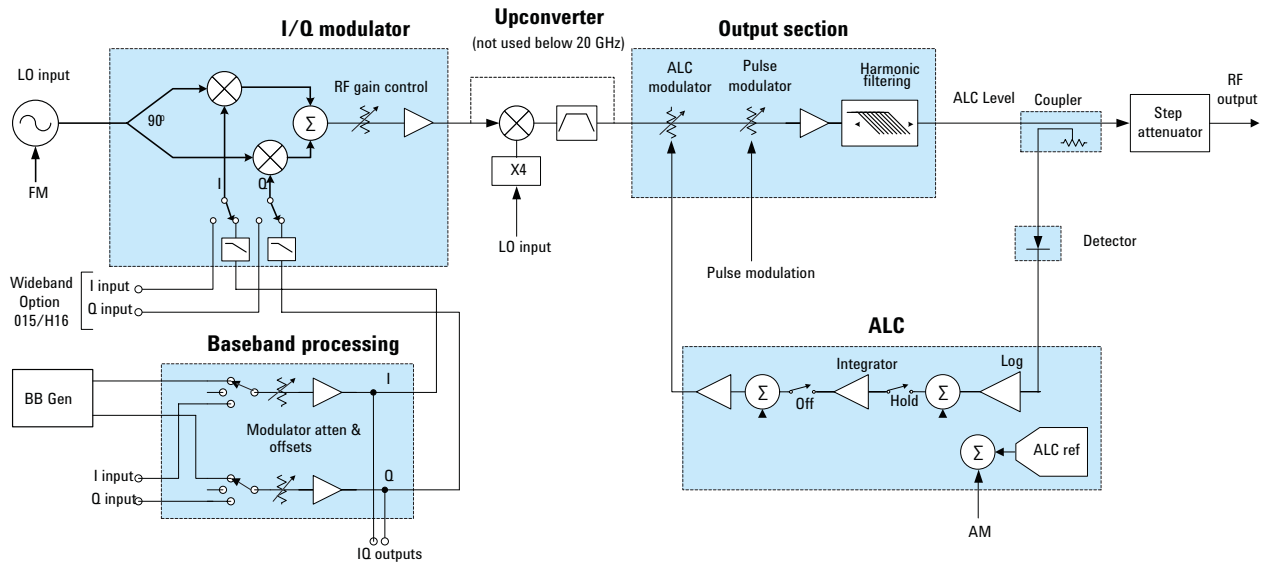


Figure 5. Simplified block diagram of the PSG

## The ALC system: Automatic Level Control

A coupler and detector sense the RF power before the step attenuator. This power level (called the ALC Level) is fed back through the ALC (Automatic Level Control) system to control the ALC modulator. The action of this feedback loop is to adjust the ALC modulator (and hence the gain of the RF path) to whatever value is necessary to achieve the correct ALC level. The step attenuator is normally set automatically (by selecting Atten Hold Off) to deliver the desired RF level (down to -110 dBm), while keeping the ALC level within its most accurate range. For vector operation, the most accurate range is between -6 and -1 dBm (-8 and -1 dBm for 32 GHz and 44 GHz vector models).

There are two methods of controlling the RF level in the PSG: ALC-ON and ALC-OFF with Power Search.

**ALC-ON** is the “normal” mode of level control; the average carrier level is constantly monitored and controlled by the ALC system. Its purpose is to hold output power at its desired level in spite of drift due to temperature and time. ALC loop bandwidth is selectable from 100 Hz to 100 kHz. ALC-ON is used for most CW, AM, FM,  $\theta$ M, and swept applications where the RF level can be accurately controlled by sensing average power. ALC-ON can also be used with I/Q modulation such as the DSB and SSB examples given above, or standard communications formats (PSK, MSK, FSK, QAM), provided the ALC bandwidth is set at least 100 times lower than the symbol rate, to minimize spectral re-growth.

ALC-ON can also be used for certain types of pulsed RF signals. In this mode, the ALC system captures the correct level when the RF is pulsed on; when the RF is pulsed off, the ALC integrator is set to ‘Hold’ mode and the ALC modulator gain does not change. The pulsing can either be through the pulse modulator or the internal baseband generator driving the I/Q modulator. A 10 kHz bandwidth is normally sufficient to capture a repetitive pulse of width greater than 1 micro-second. However, if the signal contains complex modulation during the time the RF is bursted on, the ALC bandwidth may need to be set lower, as described in the last paragraph.

- When using the pulse modulator, the pulse waveform automatically controls the sample/hold ALC integrator.
- When I/Q modulation is used to simulate a pulsed RF signal with the internal baseband generator, the correct sample/hold signal must be routed to the ALC integrator. When using the Dual-Arb mode, this is done by routing one of the marker signals to control the ALC Hold function. As shown in Figure 6, the ALC should sample only during the top portion of the envelope, not during the rise/fall times.
- When I/Q modulation is used with an external baseband generator, its burst or marker signal must be fed to the PSG pulse modulator input.

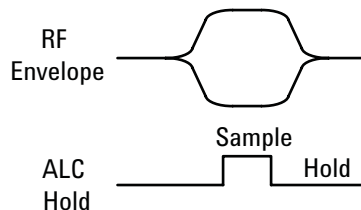


Figure 6. ALC sampling



**ALC-OFF** is used for cases when the RF level cannot be accurately determined by sensing its average level. With ALC off, there is no closed-loop feedback to sense the RF level and correct for errors; Power Search (see page 10) is used to calibrate the RF level when ALC is off. ALC OFF should be used for:

- Non-repetitive pulse modulation.
- Repetitive pulse modulation with pulse widths less than 1 microsecond, since the ALC system cannot capture the correct RF level for narrow pulse widths.
- Applications requiring lowest AM noise (note that AM noise can also be reduced by lowering the ALC bandwidth).
- I/Q modulation when the peaks of the RF signal are much larger than the average value.
- Best spectral re-growth when using I/Q modulation at low symbol rates.
- Some external I/Q modulation applications. With ALC on, the ALC loop acts to hold the signal generator's average output power constant, in spite of variations in the I/Q input power ( $I^2 + Q^2$ ). Rapid variations of ( $I^2 + Q^2$ ) propagate to the output, while slow variations within the ALC bandwidth (normally set to 100 Hz) are removed by the ALC loop. If you do not want this high-pass filtering, use ALC off mode. With ALC off, the I/Q modulation will be DC-coupled and variations in the I/Q input level will directly affect the output RF level.
- Pulse modulation with low symbol rate I/Q modulation. When I/Q modulation is on, ALC bandwidth should be at least 100 times lower than symbol rate, to avoid spectral re-growth. This limits the ability of ALC system to correctly capture the RF level during the pulse width.

## Power Search

Power Search is a calibration routine which is used to set an accurate RF level with ALC off. During a power-search cycle, first the modulation (except for I/Q) is temporarily switched off, then the ALC system is temporarily switched on just long enough to determine (and store) the ALC modulator value which gives the correct RF level, and then the modulation is switched back on. The gain of the RF system is then held constant, so the RF level is accurate even though there is no closed-loop feedback. The power-search cycle at one frequency takes about 10-50 ms.

There are three power search modes:

- **Auto:** The PSG will do a power search any time the user changes RF frequency or amplitude.
- **Manual:** The PSG will only do a power search when the 'Do Power Search' key is pressed.
- **Span:** The PSG will automatically store an array of values over a user-defined set of frequencies. This is useful for applications requiring fast frequency changes.

Since there is no closed-loop feedback control to correct drifts due to time and temperature, power search should be repeated occasionally for best level accuracy. Power Search should be done at the RF power desired, for best level accuracy. If a Power Search is done at one amplitude, the RF level will still be fairly accurate at other power levels, especially below 20 GHz.

**Power Search Reference** is used during I/Q Modulation. There are two choices:

- **Mod:** This is the recommended choice for best power accuracy with I/Q modulation. During the Power Search calibration cycle, the I/Q modulating signal remains on. For this to work properly, the I/Q modulating signal must be steady-state, not pulsed or bursted.
- **Fixed:** During the Power Search calibration cycle, the I/Q modulating signal is replaced by a 0.5V reference to establish a carrier level. This method is not very accurate, but is useful if a steady-state (not pulsed) I/Q signal is not available.

### RF during Power Search

- **Normal:** During the Power Search calibration cycle (10-50ms), the RF level is present on the main output.
- **Minimum:** During the Power Search calibration cycle (10-50ms), the step attenuator is switched to maximum attenuation, minimizing the RF level present on the main output.

## Baseband System

Referring back to the block diagram above (Figure 5), the I/Q baseband signals can come either from the internal baseband generator, from the standard inputs, or from the wideband Option 015/016 inputs. The standard inputs and the internal baseband generator signals can be summed together if necessary to create more complex waveforms. Impairments (or adjustments) can be added to the I/Q signals, to correct for I and Q offsets, I/Q gain balance, and quadrature angle. These signals drive the I/Q modulator either directly or through a 40 MHz low-pass filter. The I/Q Outputs are a replica of the signals driving the I/Q modulator and have their own adjustments of output level, gain balance, DC offsets, and filtering.

The wideband Option 015/016 inputs avoid this baseband processing circuitry and feed directly into the I/Q modulator, which improves baseband frequency response. Impairments (or adjustments) can be added to the wideband I/Q signals to correct for I and Q offsets and quadrature angle, but not gain imbalance. Also, it should be noted that when using the wideband inputs with carrier frequencies below 250 MHz or between 20 and 28.5 GHz, there is a frequency inversion. That is, as the frequency of the signal in the I/Q modulator is increased, the RF output frequency decreases. Therefore, it is necessary to interchange the I and Q baseband signals for proper operation at these carrier frequencies. This is done automatically when the standard (narrowband) inputs or the internal baseband generator is used.

## Signal Levels

With I/Q modulation, proper signal levels are critical to achieve best performance. If at any point in the signal processing path (from baseband input through the RF chain) the signal level becomes too high, the RF output will become distorted. If at any point in the signal processing path (from baseband input through the RF chain) the signal level becomes too low, the RF output will become noisy. This effect is shown in Figure 7, Adjacent Channel Power Rejection (ACPR) vs signal power, which plots the total noise + distortion power in a channel adjacent to the desired signal channel, as a ratio of the desired signal power. At low power levels, the adjacent channel consists mainly of noise, which does not change as the signal power changes, so the ratio of unwanted noise/distortion degrades approx 1 dB for every dB the power of the desired signal is reduced. At high power levels, the adjacent channel consists mainly of distortion products. If the distortion mechanism is third-order, the distortion increases 3 dB for every dB the signal power is increased, so the ratio of distortion to signal power increases 2 dB/dB. As shown in the plot, there is an optimum power range for best ratio of signal to total noise + distortion. In the PSG, the ALC range discussed previously is chosen to coincide with this optimum power range.

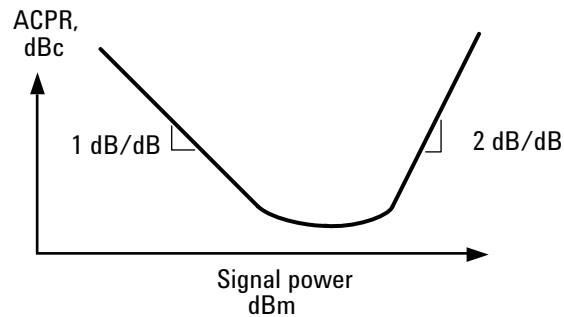


Figure 7. ACPR vs. signal power

## Standard I/Q inputs

The standard (i.e. not wideband Option 015/016) baseband drive levels into the I/Q modulator are adjusted by the “Modulator Atten” in the baseband signal processing section. The optimum I/Q modulator drive level is a trade-off between:

- **If set too Low:** Excessive noise, degraded LO Carrier feed-through, insufficient RF power output
- **If set too High:** Excessive distortion (spectral regrowth or images)

The “Modulator Atten” is normally set to Auto, which gives an I/Q modulator drive level determined by the factory to be “optimum” for most conditions. When using the internal baseband generator, this usually is sufficient to optimize baseband performance. When using the external I/Q inputs, the input level must be set in order for the Auto feature to work properly. To set the input level, press the “Mux” key and the “Config Auto I/Q Atten Settings” soft key; the Ext Input Level can then be set to three choices:

- **Default:** 240 mv RMS
- **Manual:** range 50-1000 mV RMS
- **Meas:** press the “Do External Input Level Measurement” key and the PSG will read the input level

Note that the baseband input level referred to above is actually the RMS sum of the I and Q levels; that is:

$$\text{Input Level (RMS)} = \sqrt{(I_{\text{RMS}}^2 + Q_{\text{RMS}}^2)}$$

The value of the internal RF Gain control (as shown in the block diagram) is factory-determined to allow operation within the normal ALC vernier range (discussed in the ALC section), with the “optimum” I/Q modulator drive level discussed above, and the Step Attenuator Hold off. This adjustment is subject to the trade-offs discussed above, so setting it too high or too low will adversely affect noise, distortion, and RF power output. As the desired RF output power is increased above this normal vernier range, the PSG automatically increases the RF gain and the I/Q modulator drive level, when required to produce the desired RF level.

## Option 015/016 wideband I/Q inputs

The Option 015/016 wideband I/Q inputs have no provision for variable control of I/Q input level or RF Gain. The optimum I/Q input level involves the same tradeoff as discussed above. To have approximately the same I/Q modulator drive level as above, it is recommended to set the wideband I/Q input level within  $\pm 2$  dB of the following:

- **Option 015:**  $\sqrt{(I_{\text{RMS}}^2 + Q_{\text{RMS}}^2)} = 520$  mv RMS OR I and Q each 370 mv RMS
- **Option 016:**  $\sqrt{[(I - I_{\text{bar}})_{\text{RMS}}^2 + (Q - Q_{\text{bar}})_{\text{RMS}}^2]} = 270$  mv RMS OR (I-Ibar) and (Q-Qbar) each 190 mv RMS

These drive levels may need to be increased if higher RF output power is desired.

## I/Q Frequency Response

To measure I/Q modulated frequency response from baseband input to RF output, a swept RF signal generator is fed into the “I” input of a vector signal generator. This generates a double-sideband suppressed carrier, which is displayed on a spectrum analyzer set to the same center frequency as the vector signal generator, and twice the span frequency of the swept RF generator. For these measurements, the swept RF generator is set to 0 dBm and 50-second sweep. The vector signal generator ALC is turned Off. The spectrum analyzer trace is displayed in “Max Hold” mode.

### Standard I/Q inputs

When the standard (front-panel) “I” input is used, the RF signal generator is set to sweep from 1 to 200 MHz. Here are some measurements of a sample PSG at 0.9, 1.8, and 6 GHz, for  $\pm 200$  MHz from carrier, 1 dB/Division:

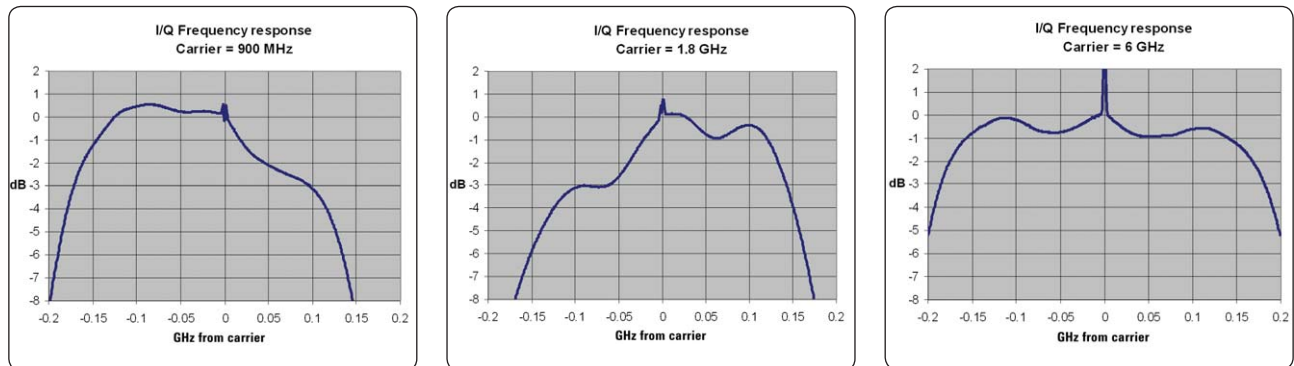


Figure 8. I/Q modulator frequency response measurements of the PSG

These frequency-response plots are a composite of baseband and RF chain flatness. Below 3.2 GHz, the RF chain flatness is significant over this  $\pm 200$  MHz bandwidth, so the I/Q response depends on RF carrier frequency. Above 3.2 GHz, the RF chain is relatively flat over the  $\pm 200$  MHz bandwidth, and so the flatness depends mainly on baseband processing hardware.

Referring to the block diagram of the PSG vector signal generator shown previously (Figure 5), the RF chain consists of amplifiers, gain control, and harmonic filtering. The harmonic filters are switched at certain pre-determined frequencies, resulting in different I/Q frequency response when the carrier is set below or above the switch frequency. The switch frequencies that significantly affect I/Q frequency response over the  $\pm 200$  MHz bandwidth are: 250, 396, 628, 1000, 1500, 2400, and 3200 MHz. Here are some plots taken at some of these frequencies – the blue trace is for carriers at or below the switch point; the green trace is for carrier frequency higher than the switch point:

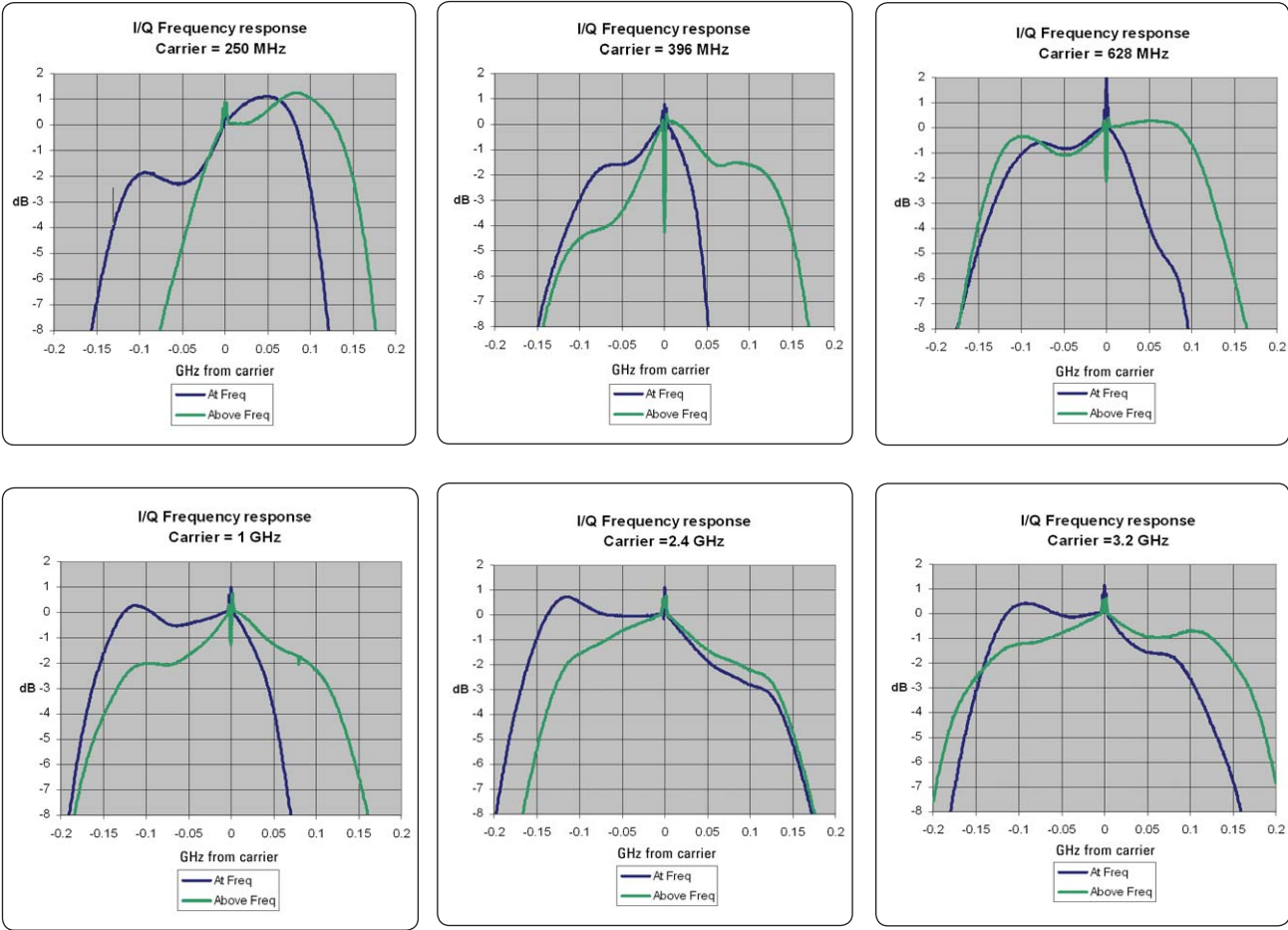


Figure 9. I/Q modulator frequency response measurements of the PSG for various switch frequencies

## Option 015/016 wideband I/Q inputs

When the wideband (rear-panel) "I" input is used, the RF signal generator is set to sweep from 1 to 1000 MHz. Here are some measurements of a sample PSG at 4, 12, and 28 GHz, for  $\pm 1$  GHz from carrier, 1 dB/Division:

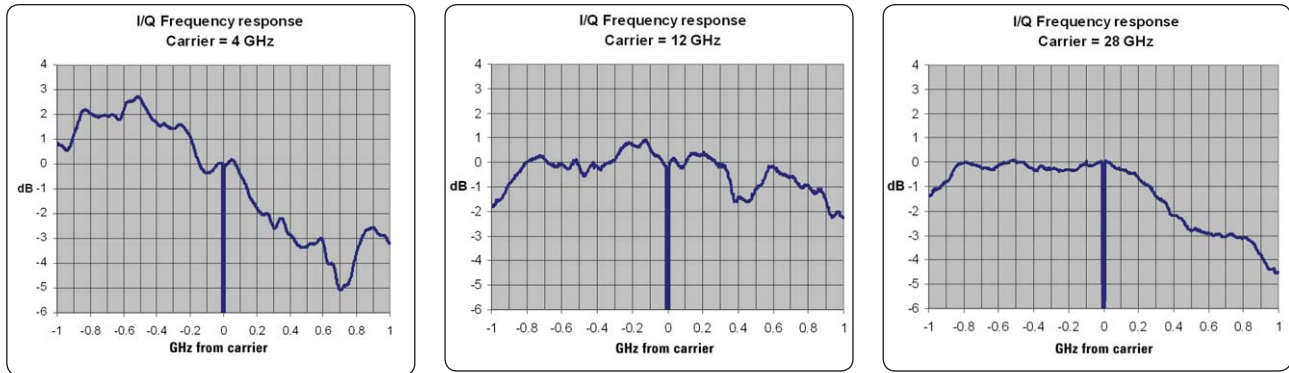


Figure 10. Wideband I/Q modulator frequency response measurements of the PSG

Below 20 GHz, the RF chain consists of amplifiers, gain control, and harmonic filtering. As with the narrowband inputs, the harmonic filters significantly affect I/Q response. The switch frequencies are 5, 8 and 12.8 GHz. Above 20 GHz, the RF chain also includes a mixer and bandpass filters to eliminate undesired mixer responses. These filters are switched at the following frequencies: 20, 24, 28.5, 32, 36, and 40 GHz. Here are plots at six of those frequencies — the blue trace is for carriers at or below the switch point; the green trace is for carrier frequency higher than the switch point:

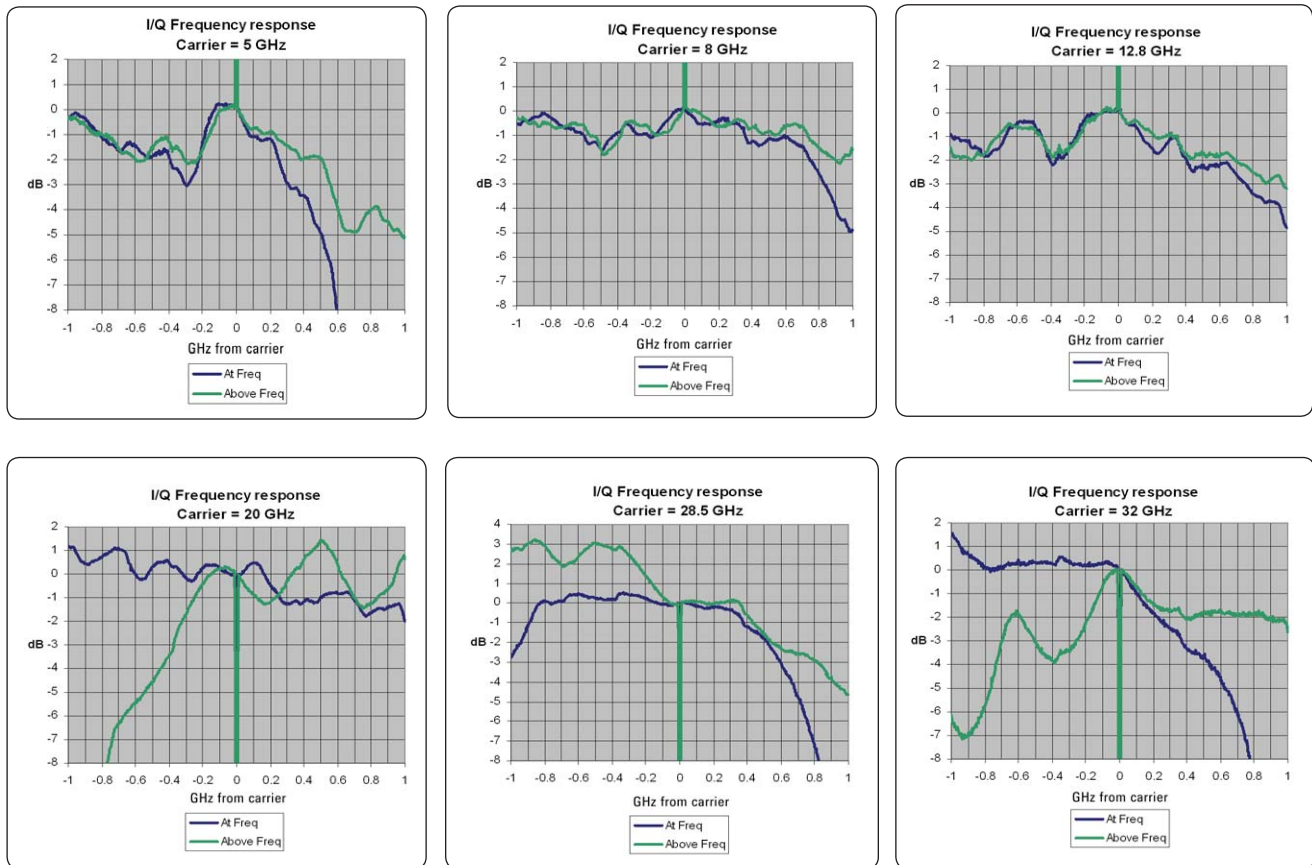


Figure 11. Wideband I/Q modulator frequency response measurements of the PSG for various switch frequencies above 3.2 GHz



Option 016 includes wideband I/Q coverage below 3.2 GHz. Although some of the baseband processing circuitry is bypassed, frequency response is essentially similar to the standard front-panel inputs. As before, harmonic filters significantly affect I/Q response for carrier frequencies close to the switch frequencies, which are 250, 396, 628, 1000, 1500, 2400, and 3200 MHz. Here are plots of wideband response at three switch frequencies:

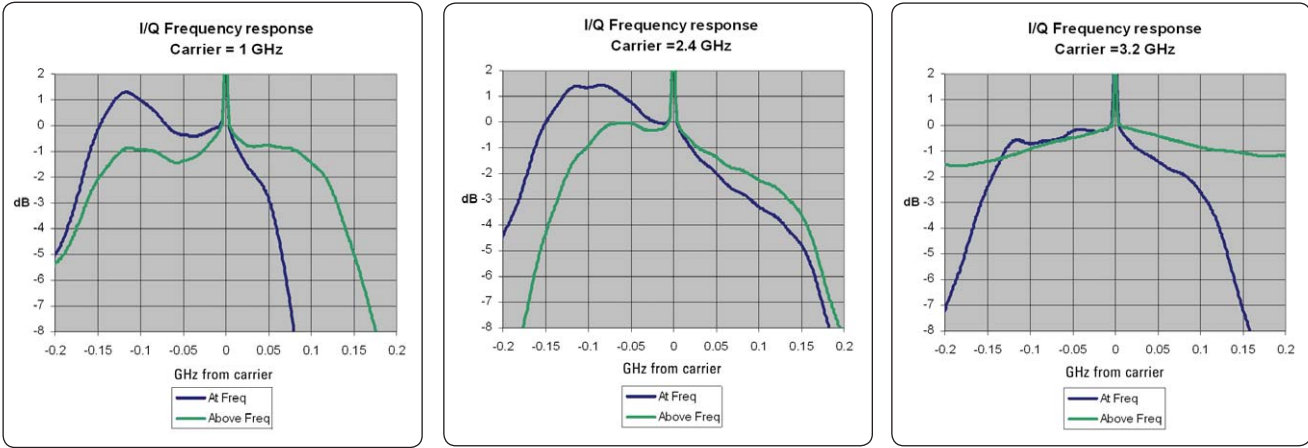


Figure 12. Wideband I/Q modulator frequency response measurements of the PSG for various switch frequencies below 3.2 GHz

## Phase Coherency

If two or more PSG signal generators are set to the same frequency, and are fed from the same 10 MHz reference, their output frequencies will be equal and the phase relationship between the outputs can be adjusted in 0.1-degree increments. However, the outputs are not phase coherent relative to the 10 MHz reference. There will be some long-term phase instability (wandering) with time, due to temperature and noise differences between the synthesizers. In addition, there is no phase repeatability; if the RF output frequency is changed and then changed back, the phase will be arbitrarily different. This is a common limitation of synthesis techniques which employ frequency dividers in their architecture.

Solutions are available which provide phase-coherent outputs between two or more PSG signal generators. Although there is no phase coherence between the outputs and the 10 MHz reference, there is excellent coherence between the outputs themselves. An RF split technique is used, as shown in this conceptual block diagram:

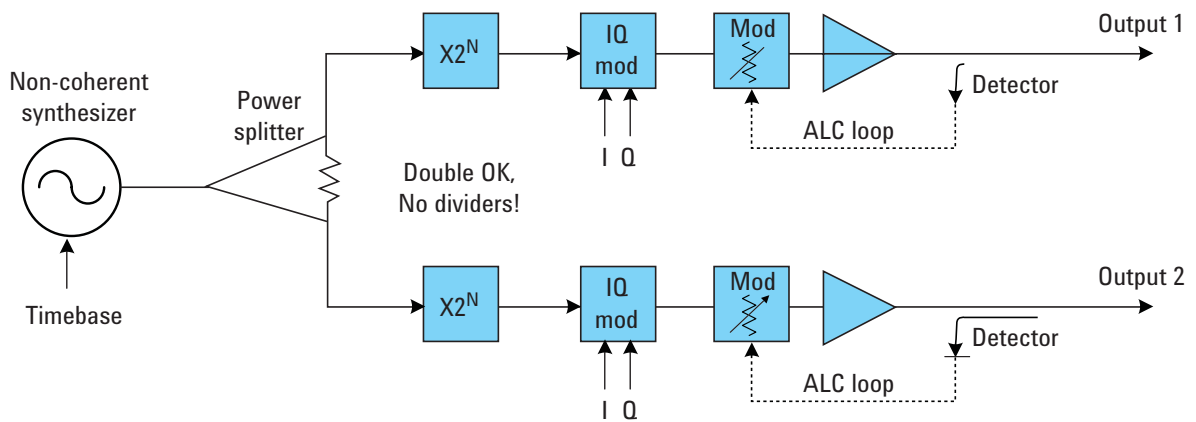


Figure 13. Block diagram demonstrating an RF split technique for phase coherency

The signal from one common synthesizer is split into two or more signals, each driving its own output section, which consist of an I/Q modulator, ALC and pulse modulators, amplification, and filtering. Frequency multipliers can be used if the outputs must be at harmonic multiples of each other, but to maintain phase coherency, no dividers can be inserted between the outputs.

Two PSG signal generators were connected in this way, and the phase difference between the outputs was measured with a network analyzer in the 0.3 to 6 GHz region. As the RF carrier frequency was changed and then changed back, phase repeatability was measured to be within 0.2 degrees. The main source of phase drift was found to be the ALC modulators, which are reflective. As the ALC level on one of the outputs was varied 10 dB, the phase difference changed 10 to 30 degrees Celsius, depending on RF carrier frequency. The ALC modulators are used to maintain a constant level by compensating for gain drift in the rest of the RF chain, and the gain of the total RF chain drifts approximately 1.6 dB for a 10-degree C temperature change. So, to maintain a constant level, the ALC modulator contributes a phase shift of as much as  $30 * 0.16 = 5$  degrees for 10 degree Celsius temperature change, or about 0.5 degrees/degree C. If both signal generators are in the same temperature environment, a 5x reduction in phase drift, or 0.1 degree/degree C, is possible. With this technique, the phase between the outputs can be adjusted with I/Q modulation.



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