From August 2005 High Frequency Electronics

Conditioning and Correction of Arbitrary Waveforms— Part 1: Distortion

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This article provides a comprehensive description of the factors that affect the performance of complex signal generators used for testing today's digitally modulated equipment

The fundamental purpose of test equipment is to characterize performance and verify that the device under test functions as expected. Confidence that test results are accurate can only be realized if the test equipment performance is as good or better than the device under test. Minimizing test equipment influences on measurement uncertainty is a big challenge considering the many components that typically comprise a measurement system. The only way to assure an objective test environment that yields accurate results is through comprehensive and precise calibration of the test equipment.

This article addresses methods for minimizing the uncertainty generally attributed to test stimulus of a measurement system. More specifically, we will examine how to obtain the best signal quality for vector modulated signals created using I/Q waveforms. A critical factor that influences the quality of the test signal is the conditioning and calibration of the baseband I/Q waveform.

Driven by the popularity of digital modulation schemes in today's communications systems, vector signal generators have become the instrument of choice to provide real-world test stimuli for modern wireless transceivers and their components. In addition, they can produce easily configurable, pulsed waveforms for radar and electronic warfare (EW) applications. Engineers benefit from the ease with which a wide variety of test signals can be created using wideband arbitrary waveform generators. Virtually any complex modulation scheme is easily achieved using waveform simulation software that is then downloaded to the signal generator for playback. Most vector signal generators are equipped with internal arbitrary I/Q waveform generators and I/Q modulators to support these complex modulation schemes. They provide both baseband and RF or microwave test signals in a single integrated instrument.

At a high level, a vector signal generator is composed of several fundamental blocks as shown in Figure 1—waveform memory, resampling, FIR filters, digital-to-analog converters, analog I/Q filters, I/Q modulator, attenuator, and an automatic level control (ALC) circuit.

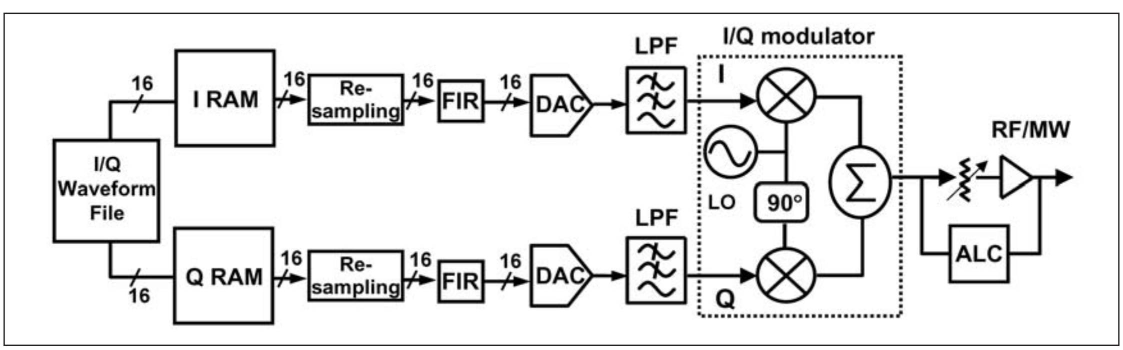

Figure 1 · Vector signal generator block diagram.

To accurately generate repeatable calibrated test stimuli, it is essential to identify the primary sources of error in the signal path and find methods to contend with and/or correct those imperfections. Fortunately, proper conditioning of the waveform can ultimately avoid many additive impairments inherent in the baseband and RF sections of the signal generator hardware.

As indicated by the list below, there are many potential errors encountered when generating vector modulated test signals. These are some common sources of error that can typically be corrected with simple conditioning of the waveform and optimization of the signal generator. The first six of them are discussed in this article, while the remaining six will be discussed in Part 2, which will be published in the September issue of *High Frequency Electronics:*

- Waveform phase discontinuity
- Waveform clipping
- Sampling and filtering
- I/Q path delay and skew
- Carrier feed-through
- Non-linear distortion
- Group delay
- Peak-to-average power ratio
- Level accuracy
- Burst overshoot and droop
- RF amplitude flatness
- Instrument dependent corrections

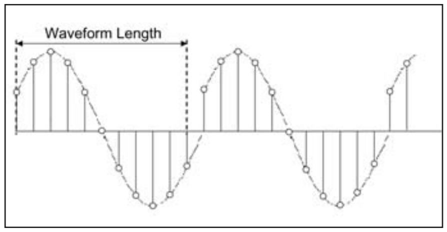

Figure 2 · Sampled sine wave with phase discontinuity.

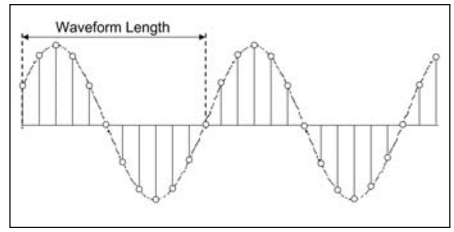

Figure 3 · Sampled sine wave without phase discontinuity.

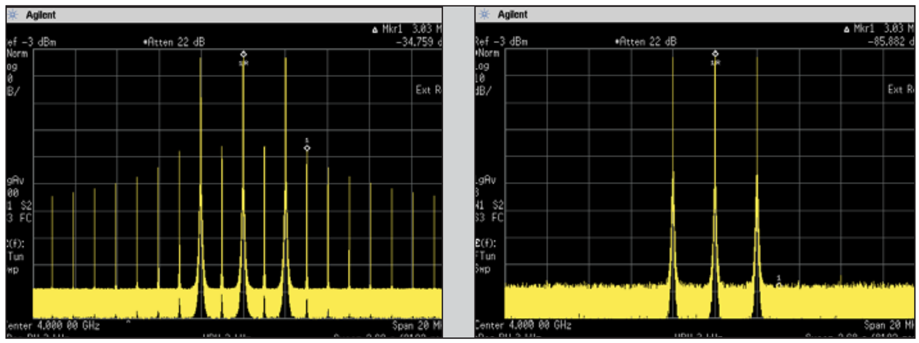

Figure 4 · Waveform spectrum with and without the discontinuity.

Waveform Phase Discontinuity

The most common arbitrary waveform generation use case is to play back a waveform that is finite in length and repeat it continuously. Although often overlooked, a phase discontinuity between the end of a waveform and the beginning of the next repetition can lead to periodic spectral regrowth and distortion.

Consider the sampled sine wave segment shown in Figure 2. Imagine this waveform had been simulated in software or simply captured off the air and sampled. It is an accurate sine wave, however, the waveform does not occupy an entire period (or a multiple) of the sine wave. Thus, when repeatedly played back by an arbitrary waveform generator, a phase discontinuity is introduced at the transition point between the beginning and the end of the waveform.

Abrupt phase changes when the waveform repeats will result in high frequency spectral regrowth. In the case of playing back the sine wave samples, the phase discontinuity produces a noticeable increase in distortion components in addition to the line spectra normally representative of a single sine wave (see Figure 4).

Phase discontinuities for periodic waveforms are easily avoided by simulating an integer number of cycles when creating your waveform segment. Note that if there are N samples in a complete cycle, only the first N–1 samples are to be stored in the waveform segment. Thus, when continuously played back the first and Nth waveform samples are always the same, preserving the periodicity of the waveform as shown in Figure 3.

For TDMA or pulsed periodic waveforms, a phase discontinuity is easily addressed by adding off time at the beginning of the waveform and subtracting an equivalent amount of off time from the end of the waveform. Consequently, no signal is present when the waveform repeats and the issue of phase discontinuity is avoided.

If the period of the waveform exceeds the available waveform playback memory, a periodic phase discontinuity is unavoidable. This may have been a problem in the past, however most newer vector signal generators provide additional waveform playback memory and some even enable waveform streaming directly from a PC hard drive for up to hours of unique, non-repetitive test signal. The discontinuity issue should still be kept in mind when creating long waveform simulations or signal recordings that require waveform repetition that is free of distortion induced by the waveform wrapping.

Waveform Clipping

Arbitrary waveform generators require that the waveform samples be scaled for the digital-to-analog converter (DAC) in either a signed or unsigned format. Figure 5 illustrates an unscaled waveform that exceeds the range of the DAC and will result in a clipped analog waveform. For an n-bit DAC using unsigned integers, the negative full-scale point corresponds to zero and the positive full-scale point corresponds to $2^{(n-1)}$. For a system that uses signed integers, the negative full-scale point is $-2^{(n-1)}$ and the positive full-scale point is $2^{(n-1)}-1$, with zero corresponding to 0.0 volts output.

When creating or manipulating waveform data, care should be taken as to not introduce quantization error when scaling the waveform to within the DAC range. Otherwise the waveform will be distorted during playback, resulting in unwanted high frequency spectral regrowth. To address this, the waveform must be normalized to the maximum DAC range.

In addition to the scaling performed for normalization, it is also generally desirable to include a scaling factor when digitizing the waveform to avoid driving at full-scale (see Figure 6). This minimizes ringing in filters that may cause the DAC to over-range. This is particularly important when generating signals for out-of-channel measurements, because any nonlinearity introduced from driving at full-scale produce out-of-band spectral regrowth from the signal generator, which reduces overall measurement uncertainty.

Unfortunately, waveform scaling also influences the dynamic range of the signal. A rule of thumb approximation is to assign 6 dB dynamic range per bit in the I/Q sample. With this estimate, one would assume a 16-bit DAC could achieve approximately 96 dB dynamic range at baseband. However, if all the bits in the sample are not utilized due to waveform scaling, the dynamic range of the signal is reduced. As a result, it may be necessary to compromise between optimizing dynamic range or distortion performance.

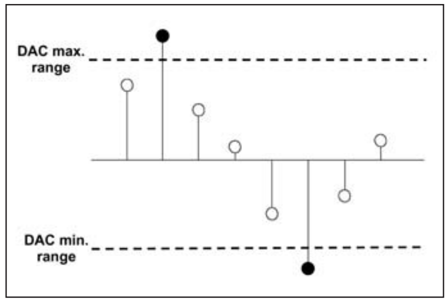

Figure 5 · Waveform samples with clipping.

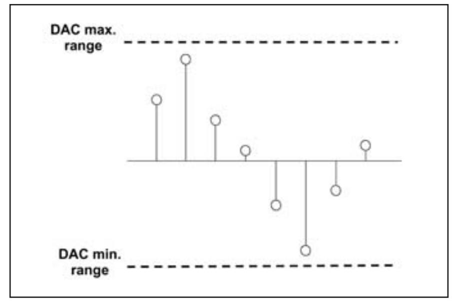

Figure 6 · Sampled waveform with scaling.

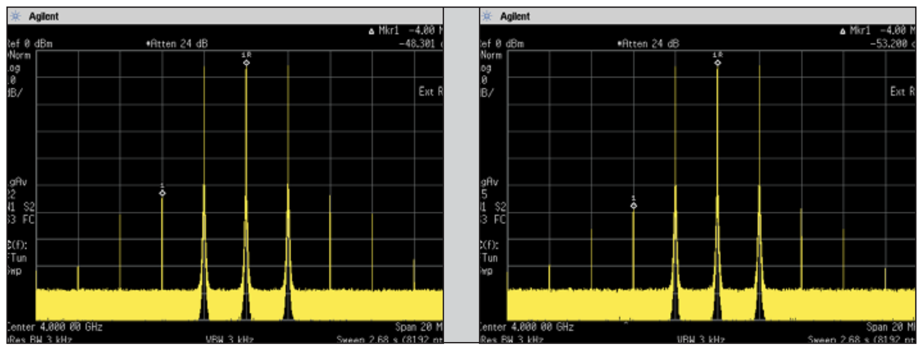

Figure 7 · Effect of waveform scaling on distortion.

Some newer vector signal generators provide run-time waveform scaling so that the tradeoff between distortion performance and dynamic range can be evaluated in real-time. This is a convenient feature, considering that the alternative is to repetitively recalculate and download waveforms with different scale factors and analyze their performance. Figure 7 illustrates that a 5 dB improvement in 3rd order intermodulation distortion (IMD) for a two-tone test stimulus was achieved by changing the waveform scaling from 100% (or full scale) to 70% of full scale. Additional methods to improve IMD performance are discussed later.

Sampling and Filtering

While digital signal processing provides the flexibility to generate nearly any desired test stimulus, it also introduces new sources of error that must be addressed. The effect of waveform sampling in the time domain is the creation of spectral images in the frequency domain. Each frequency image is separated by the sample rate. To remove the sampling images, the DAC output is applied to a reconstruction filter. These low pass filters are intended to pass the baseband signal while rejecting the higher frequency sampling images.

The appropriate reconstruction filter characteristics are a function of two variables: signal bandwidth and sample rate. The reconstruction filter must be broad enough to accurately transmit the entire baseband signal, while the cutoff frequency must be low enough to sufficiently reject the first image appearing at a frequency offset equivalent to the sample rate. In addition, filter side lobes must have enough attenuation to avoid generating out-of-band spurs. The reconstruction filter shown in Figure 8 clearly is not getting the job done.

When designing a waveform, hardware constraints of the baseband generator, such as waveform memory capacity, maximum sample rate, and reconstruction filter characteristics, must be taken into account. Some degree of oversampling is typically applied to the signal in excess of the Nyquist rate. Oversampling is the process of increasing the number of samples per symbol. For example, an oversample ratio of 4 yields four samples per symbol and an increased file size. To maintain the original signal characteristics, a 4× higher sampling rate is required for playback. As shown in Figure 9, this results in increased spacing between the sampling images and relaxes the requirements for the reconstruction filter cutoff frequency.

Oversampling has traditionally been implemented when creating the waveform file (the set of I/Q samples that define the waveform). This is termed software oversampling and the additional sample points expand the size of the file. This can be memory intensive for wideband signals or high multiples of oversampling. Newer vector signal generators are providing hardware oversampling to remove sampling images with a single wideband reconstruction filter. The savvy waveform designer can take advantage of hardware oversampling to conserve waveform memory. In effect, for an equivalent memory depth, a longer time record of unique waveform can be played back if software oversampling is minimized and hardware oversampling is utilized instead. Of course, the original sampled waveform must still meet the Nyquist sampling rate criteria, but the hardware upsampling architecture gives the waveform designer greater flexibility in choosing sample rates, since the constraint of sufficient sampling image rejection is removed.

The example shown in Figure 10 compares the spectra of two different vector signal generator baseband architectures to demonstrate the advantage of hardware oversampling. An I/Q waveform was created to generate a single carrier digitally modulated signal with 614.4 kHz RF bandwidth. A 5× oversample ratio was used resulting in a sample rate equal to 3.072 MSa/s.

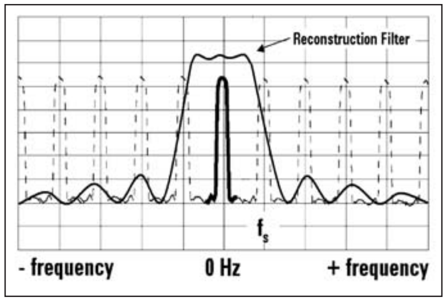

Figure 8 · Example of sampling images and reconstruction filter.

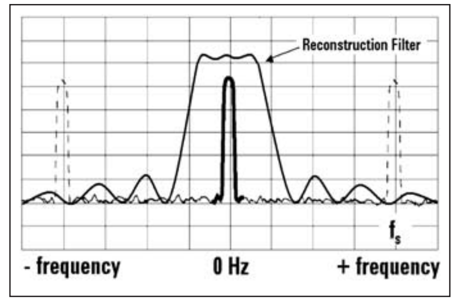

Figure 9 · Sampling images with oversampling.

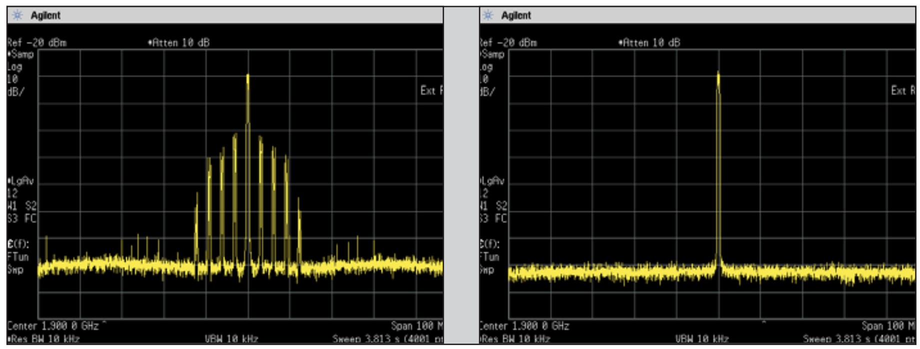

Figure 10 · Waveform spectrum with and without oversampling.

The first measurement is from a vector signal generator equipped with an 8.5 MHz reconstruction filter. Its baseband architecture does not support hardware oversampling, so at the required sample rate, multiple sampling images are passed along with the fundamental. In fact the roll off and side lobes of the reconstruction filter are easily recognized in the spectral domain by viewing the amplitude profile of the sampling images and spurs over the 100 MHz span.

Hardware oversampling DACs are now being used by modern vector signal generators to alleviate the need for multiple reconstruction filters. In the second measurement shown in Figure 10, a vector signal generator, with real-time hardware upsampling implemented during waveform playback, provides an additional 128× oversampling of the waveform. With this technology the first sampling images are effectively pushed out 128× to nearly a 400 MHz frequency offset. This makes the filter roll off and side lobe requirements much less stringent and achievable with a single reconstruction filter. As seen with the measurement in Figure 10, sampling images and spurs are non-existent over the 100 MHz span.

I/Q Path Delay and Skew

Images can also occur in systems that use I/Q modulators and are clearly visible in signals that are non-symmetric with respect to the carrier frequency. These images occur when there is an unequal path delay between the I and Q signals that drive the I/Q modulator. If there is a time delay between the I and Q signals, they are no longer in quadrature and images are introduced. Also, if the magnitude and phase response of the I and Q paths are not matched and/or the I/Q modulator itself exhibits a phase skew such that I and Q are not exactly in quadrature (see Figure 11), images will result.

I/Q images can be improved with slight adjustments to align the path delay between the I and Q signals and/or slight phase adjustments to the I/Q modulator gain and phase skew (see Figure 12); however, I/Q images cannot be completely removed with these methods alone. This is a result of the strong dependence on the mismatch in the magnitude and phase response roll off in the I and Q paths. Fortunately, new solutions utilizing advanced predistortion algorithms have been introduced to minimize images and have proven to be quite successful. Two common predistortion techniques can be used to address I/Q images. The first technique attempts to characterize the I and Q paths and then match the magnitude and phase response through waveform predistortion. The second technique generates a canceling signal 180 degrees out of phase with the image product.

The resulting improved signal quality is useful for many applications, including minimizing uncertainty in multitone and noise power ratio (NPR) distortion test measurements, improving adjacent channel power ratio (ACPR) performance for multicarrier signal generation, and minimizing error vector magnitude (EVM) in digitally modulated test signals.

In the frequency domain, I/Q images are uniquely identified by their "bat wing" amplitude profile from the center frequency to the band edges of the RF modulation bandwidth (see Figure 13). Most vector signal generators give the user the ability to minimize the I/Q path delay and phase skew manually; however, this manual approach is an iterative adjust and measure process that can be time consuming. To address this, some signal generators perform this adjustment automatically as part of their I/Q calibration routine. As shown, these adjustments can typically improve the image rejection by 10 to 20 dB.

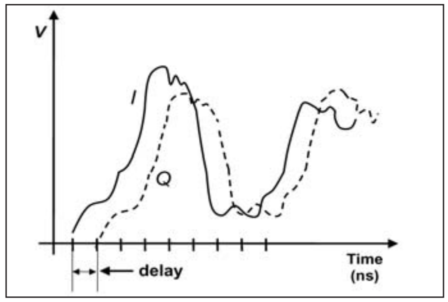

Figure 11 · I and Q mismatch of baseband path.

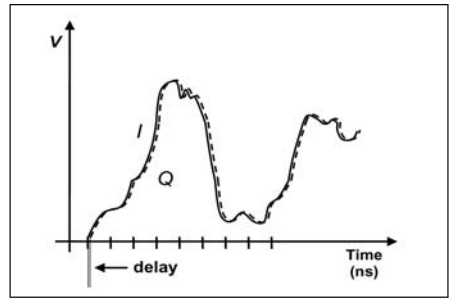

Figure 12 · I and Q paths properly aligned.

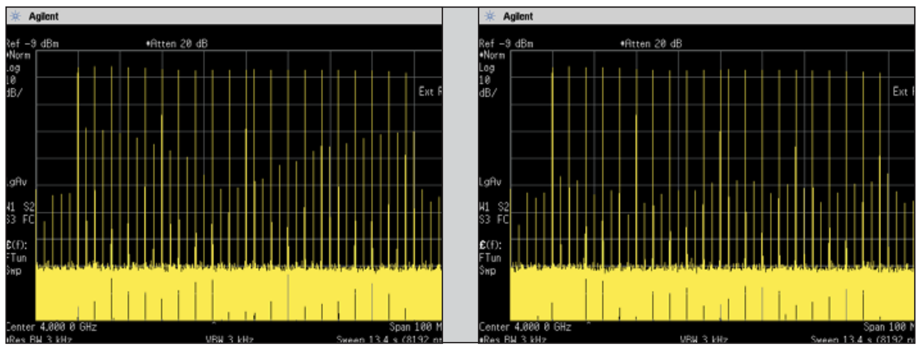

Figure 13 · Effects of I and Q path mismatch on the RF waveform spectrum.

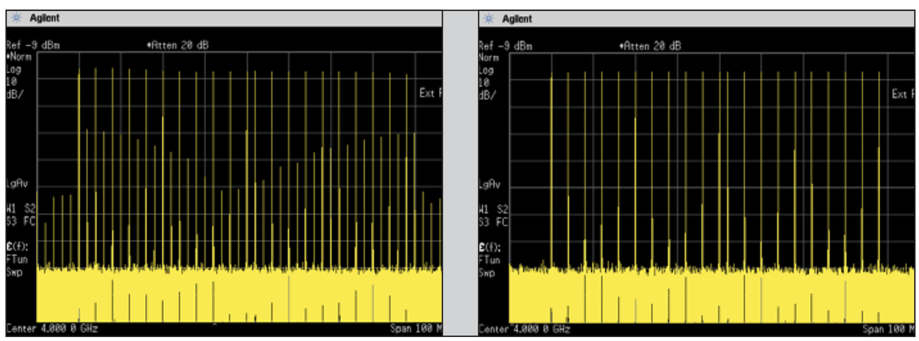

Figure 14 · Effect of predistortion on the RF waveform spectrum.

New advanced predistortion techniques virtually eliminate the I/Q images (see Figure 14). For the same signal, an image rejection improvement of over 50 dB was achieved using a waveform predistortion algorithm that generates a canceling tone at the I/Q image frequency. Due to time, temperature, frequency, and power dependency, the corrections will need to be repeated periodically. How often depends on the stability of the instrument and its operating environment; however, it is clearly worth the effort for measurements that require this level of performance to minimize test uncertainty.

Carrier Feedthrough

Another common problem associated with systems that use I/Q modulators is carrier feedthrough. The carrier signal component is typically visible if a waveform is created with the modulated signal offset from the center (i.e., the carrier) frequency. The carrier feedthrough degrades the out-of-band distortion performance for modulated signals offset from carrier. Otherwise, the carrier feedthrough component is masked inside the modulated signal. This too causes a small level of unwanted in-band distortion and degrades signal quality.

Carrier feedthrough occurs when there is a DC component contributed by the I and/or Q signals that drive the I/Q modulator or by the I/Q modulator itself. Through the I/Q modulator, a DC component multiplies with the local oscillator (i.e., the carrier frequency) and leaks carrier through to the RF output. This can be caused by a DC offset in the I/Q waveform, a DC offset in the I and/or Q path, or an I/Q modulator that is unbalanced for the given operating conditions.

Because I/Q modulator balance is heavily influenced by the frequency of operation, it is difficult to calibrate over the wide range of operating conditions of a vector signal generator. To get an idea of the sensitivity to DC offset, consider a signal generator set to 0 dBm output power. This corresponds to 1 mW into 50 ohms. Using $P = V^2/R$, it can be determined that the output voltage equals 225 mV. At this level, suppressing the carrier feedthrough by 50 dB requires a DC offset voltage less than 0.7 mV.

Carrier feedthrough can be minimized with slight DC offset adjustments to the I and Q paths or by applying predistortion (see Figure 15). Depending on your application, these adjustments can be essential to meet demanding test requirements.

Most vector signal generators give the user the ability to manually adjust the DC offset of the I and Q path to effectively minimize the DC component. Again, this manual approach is an iterative process that can be time consuming. In this example, after DC offset adjustment, the carrier feedthrough was reduced by 11 dB for the two-tone test stimulus. Because I/Q modulators typically drift over time and temperature, the carrier feedthrough will begin to creep back up after the adjustment and need to be corrected again. Some signal generators perform this adjustment automatically as part of a quick I/Q calibration routine.

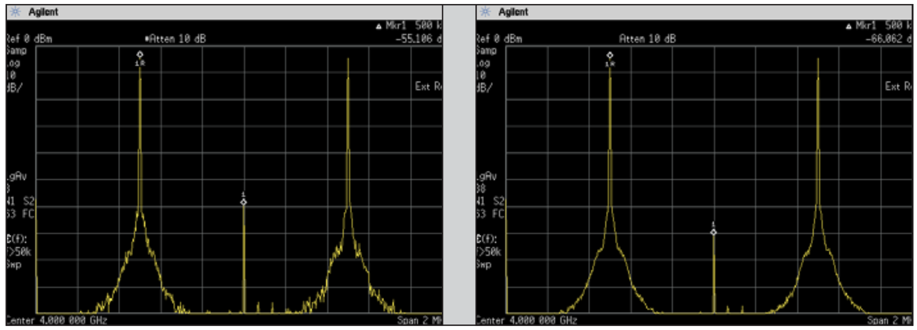

Figure 15 · Carrier feedthrough before and after DC offset adjustment.

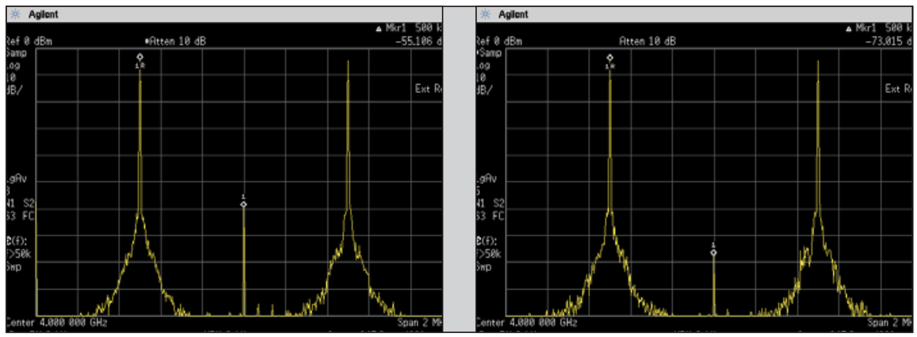

Figure 16 · Carrier feedthrough before and after predistortion.

Advanced predistortion techniques are also being employed to generate a canceling tone at the carrier frequency that is 180 degrees out of phase with the carrier feedthrough signal component. The example shown in Figure 16 indicates an 18 dB carrier suppression was achieved after predistortion. This is an additional 7 dB improvement over manually adjusting the DC offset. Predistortion techniques are more effective, but again, only temporarily due to dependence on time, temperature, frequency, and output power variation. Even so, an almost 20 dBc suppression improvement considerably reduces measurement uncertainty and may be worth the effort. Corrections can be re-initiated once the carrier creeps back up to an unacceptable level.

Non-Linear Distortion

Both intermodulation distortion (IMD) and harmonics occur as a result of the signal passing through components and devices with nonlinear transfer functions. IMD is a particular type of non-linear distortion resulting from unwanted intermodulation between the various frequency components that comprise a signal. IMD and harmonics are the primary cause of in-band and out-of-band spectral regrowth in the test stimulus. This degrades measurement system performance and may also interfere with neighboring channels.

Nonlinear distortion cannot be corrected using simple equalization techniques as this only works with linear phenomena. However, new product introductions for multitone and NPR test stimulus generation now utilize advanced predistortion algorithms to virtually eliminate IMD in an automated fashion. This makes repeatable high quality distortion test stimulus generation conveniently and easily realized using a single vector signal generator. This approach can even remove IMD caused by additional devices in the test setup, including booster amplifiers that are notorious for degrading the distortion performance of the test stimulus. The examples shown in Figures 17 and 18 indicate the remarkable improvements in distortion performance that are achievable using predistortion methods. Harmonics on the other hand can typically be dealt with using external filters.

In-band IMD refers to the intermodulation products that fall within the channel bandwidth of the generated signal. This type of distortion is particularly undesirable since it cannot be filtered and directly interferes with the signal of interest. Similar to removing carrier feedthrough, this predistortion technique generates a canceling tone at the IMD frequency that is 180 degrees out of phase with the distortion product. This approach uses a spectrum analyzer to measure the IMD of the original test stimulus. Based on these measurements, a predistorted waveform is created to remove the in-band, as well as the out-of-band IMD products. As shown in the before and after predistortion measurements of Figure 17, exceptional distortion suppression is achievable. For this test stimulus, an over 40 dB improvement was obtained.

As the bandwidth of arbitrary waveform generators continues to increase, out-of-band non-linear distortion can be addressed in a similar manner. This level of performance substantially reduces the measurement uncertainty contributed due to the effects of the test stimulus non-linear distortion. The example in Figure 18 shows an 8-tone test stimulus with 1 MHz tone spacing. The spectrum analyzer display is set to 100 MHz to show the IMD products generated by the signal generator. After predistortion, that same 8-tone test stimulus is virtually free of distortion products. For accurate characterization of the device under test, this is a clear advantage.

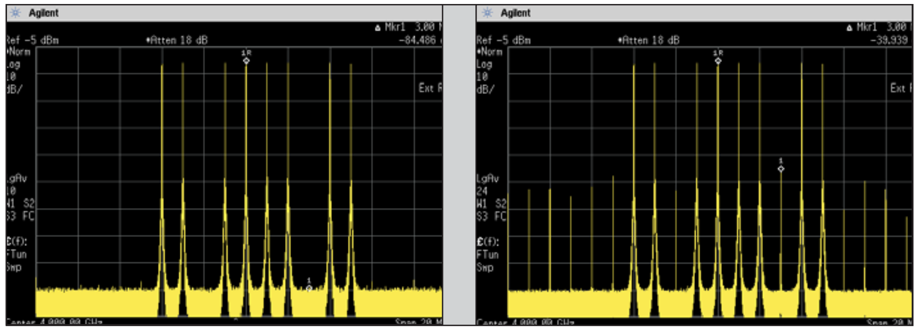

Figure 17 · In-band non-linear distortion.

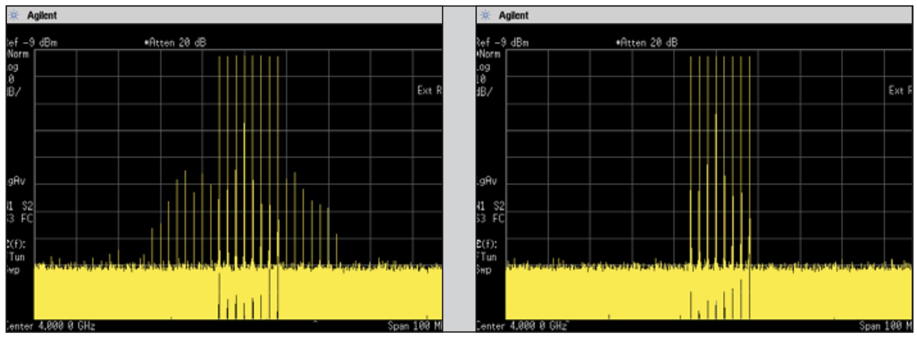

Figure 18 · Out-of-band non-linear distortion.

Next Month in Part 2

This article continues with Part 2 in the next issue, discussing the additional performance problem areas of group delay, peak-to-average power ratio, level accuracy, burst overshoot and droop, RF amplitude flatness and instrument-dependent corrections.

Author Information

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