Agilent
Advanced Measurements and Modeling of Differential Devices

White Paper

Agilent Technologies

Abstract

This paper answers the question “Do I need a true differential signal to measure my non-linear amplifier.” In measuring the non-linear characteristics of many active differential circuits, it is sufficient to measure the single-ended, non-linear response and compute the differential response. This paper explores why even non-linear differential circuits can be correctly measured using single-ended techniques, discusses topology considerations in testing differential circuits, and provides experimental and simulated results to reinforce the concepts.

Introduction

Many wireless device topologies have moved from the traditional single-ended inputs and outputs to balanced (or differential) input drives. Previous work has shown that for passive devices or active devices operating in their linear region, it is sufficient to measure the individual single-ended responses from a balanced device and combine the results mathematically to obtain the differential or balanced response [1]. Here the linear region means the signals are small enough such that the device behavior does not change with signal level.

Many active devices, however, do not follow this model for their behavior. For example, the bias current of an amplifier might change between large signals and small signals. For such devices, it appears necessary to drive them with real-time signals that present the proper amplitude and phase relationships. These drive signals must be presented at the input ports (+ and –) of the DUT with the same amplitude and 180 degrees of phase difference, to be true differential signals. Previous work has shown that using true differential and common-mode drives (true-mode drives) may result in less uncertainty for linear systems [2], based on a stack-up of calibration residuals. For test equipment applications, hybrids may be used to create these signals, but it can be difficult to control and maintain balance from the hybrid port to the circuit connection. For linear circuits, this imbalance may be corrected for [3], but for circuits operating in a non-linear region, a true-balanced drive may be necessary. For in-circuit applications, a balun (balanced to unbalanced transformer) is often used. It is placed in close proximity to the device to avoid introducing any phase offset due to connections between it and the device. However, baluns do not allow for investigation of the device response to common-mode signals, nor do they allow for measurements of common-to-differential mode conversion terms. In order to unambiguously determine the non-linear response of circuits, it is necessary to develop a test system which has the capability to drive CW and modulated single-ended, differential, and common-mode signals without changing the termination conditions of the device under test (amplifier). Such a system, first proposed and reported in Microwave Symposium Digest [4], has the capability to measure the gain of differential devices with a variety of drive signals.

Creating a Differential Source Drive

The difficulties of creating differential or common-mode drive signals have been overcome with a novel signal-source architecture that allows creation of two CW or modulated source signals with arbitrary amplitude and phase control between the source outputs. These outputs can be electronically controlled with very fine resolution (less than 0.05 dB of amplitude control, and less than 0.1 degree of phase control). In the Calibrating Sources and Making Measurements section, which follows, we will demonstrate that this fine level of control is a requirement if the actual active device characteristics are to be determined.

Figure 1 shows a representative block diagram for the new source configuration. This first demonstration system makes use of three electronic signal generators (ESG) each with vector modulation capability. In this case, Agilent E4438B model ESGs were used, but with modifications made to two of the ESGs. This model of ESG provides a portion of the synthesizer (CW) signal-out to the rear panel as a coherent carrier, as shown in the bottom ESG depicted in Figure 1. The other two ESGs were modified to provide an input of a signal before the vector modulator, bypassing the internal source. The input for the middle ESG is the coherent carrier from the bottom ESG. This input is sent through the vector modulator of the middle ESG, where DC controls are used to modify the phase of the output signal (as well as amplitude, if desired). This output signal is coherent with the vector output of the bottom ESG, and phase controllable. This signal is sent to the third, top ESG in Figure 1 where it also bypasses the internal source on the way to the vector output. For modulated signals, an arbitrary waveform generator (ARB) sends signals to both the bottom and top ESGs, such that the output signals have the same modulation, but phase control between the carriers is still possible. The phase of the signal out of the second ESG is controlled to set the output signals to 180 degrees of phase difference, with the same amplitude. In practice, the internal arb of the first ESG is used to drive both the first and third ESGs.

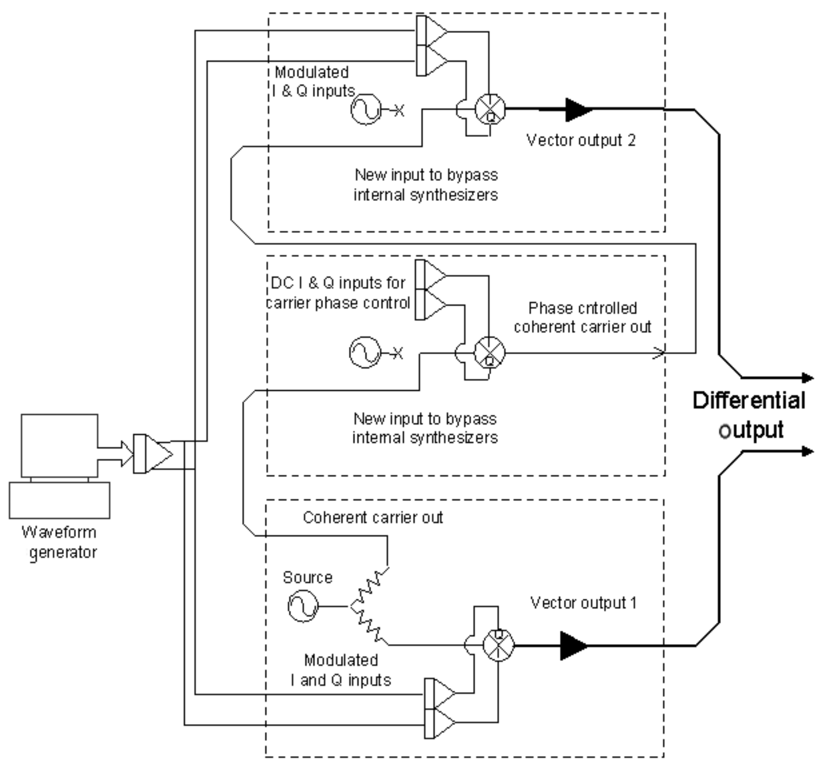

Figure 1. Block diagram for generating balanced modulated signals

Calibrating Sources and Making Measurements

For many practical applications of measurements, the balanced drive signal must be routed, often on PC board traces, to the final interface for the DUT. For CW measurements, true-mode signals can be calibrated using a two-step process with a vector network analyzer (VNA). The first step is to use a well-characterized power divider to provide a reference signal to the VNA in order to correct for phase and amplitude offset between the two input lines. Step two is to connect the differential outputs to the source, and characterize the amplitude and phase differences between the source outputs. This characterization should be done across power levels and frequencies.

Figure 2 shows a measurement system making CW measurements on a differential DUT. The VNA can measure both the power and the phase difference between the output ports. The mixed-mode S-parameters can be measured by first driving the DUT with a differential drive signal and measuring the resulting differential and common-mode output signals. Then, a common-mode input drive is applied and the common and differential outputs again are measured. This can be done for different power levels to determine the non-linear response of the DUT. An input reference signal, not shown, is routed to the VNA reference channel. Note that in this configuration, only the forward transmission (S21) terms are measured. But this is sufficient for many non-linear measurements of interest.

The same system can be used to measure the single-ended response of the amplifier, by first terminating one input and measuring the resulting outputs, and then terminating the second input and measuring the outputs.

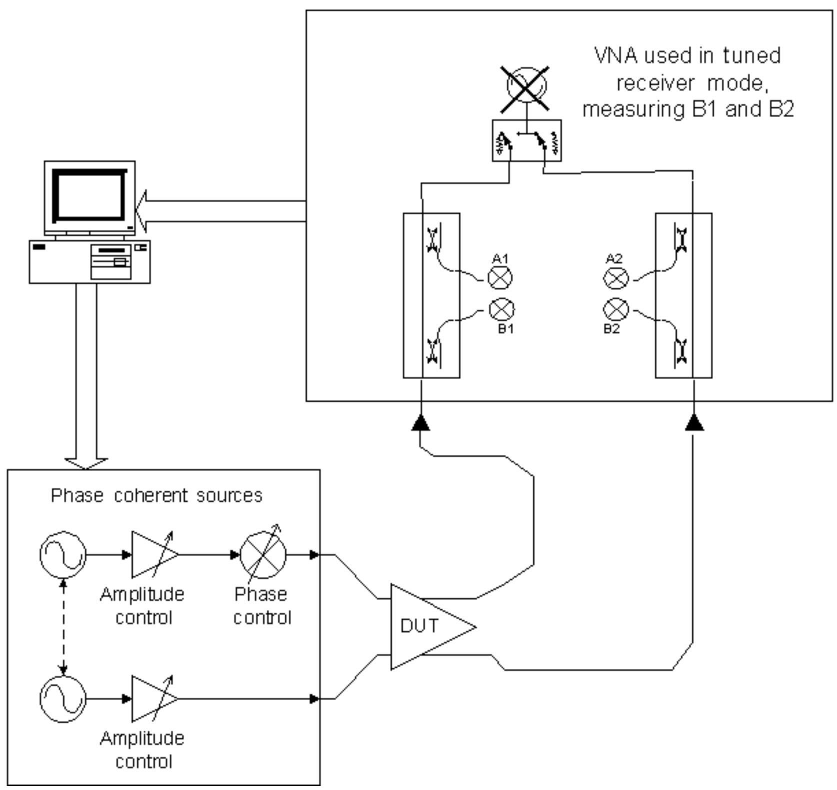

Figure 2. Measurement of a differential amplifier using a true-mode source and a VNA

For this system, the phase of the output signals can change with power level, so it is necessary to calibrate for the phase of each signal at every power level. Initially, this calibration was performed to reduce the phase error to less than 1 degree for differential and common-mode signals. The outputs of the signal generators were applied directly to the DUT. Figure 3 shows the resulting gains, including differential gain (SDD21), common-mode gain (SCC21), common-mode to differential conversion (SDC21), and differential to common-mode conversion SCD21). What is interesting about this result is that the single-ended mixed-mode measurements (light gray line in each display) do not converge with the true-mode measurements at low power. One would expect that the amplifier is perfectly linear at low power so the results should converge perfectly. However, the differential-drive result, especially for common-mode input/differential-mode output (upper right display) shows a large deviation, with a much higher value than the single-ended drive. It was discovered that this error is the result of a non-perfect source-match from the test system interacting with the input match of the amplifier under test. In this case, reflections from the amplifier, which was not perfectly matched, re-reflected from each of the source outputs, distorting the true-common-mode signal and adding a small amount of differential signal. Since the common-mode signal in this amplifier is suppressed by more than 20 dB, and the differential-mode signal is amplified by 20 dB, any error which introduces differential-mode signal at the input will cause substantial errors in the SDC21 term.

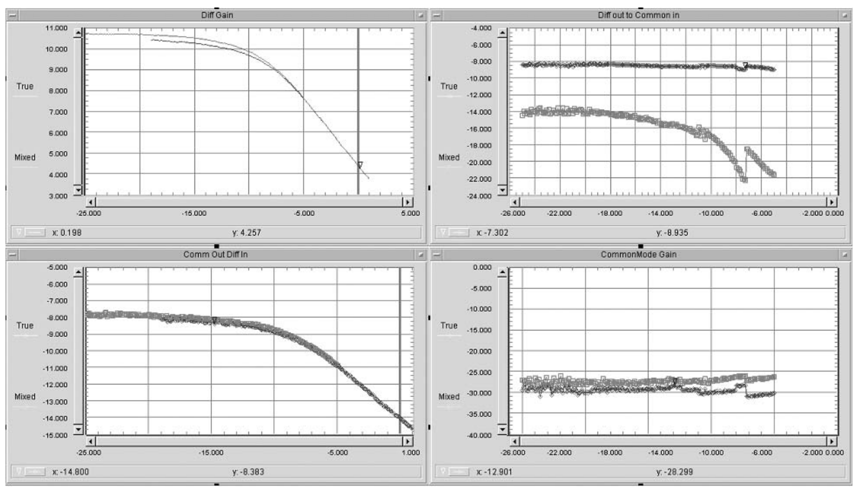

Figure 3. Mixed-mode and true-mode measurements of a non-linear amplifier -- first tests

Figure 4 shows the result when attenuators (pads) were added to the source drive inputs, improving the match to better than 35 dB. Note that the low power response from true-mode drive and mixed-mode drive are now identical for all four differential gain parameters. However, we see unusual behavior for SDC21, the common-mode to differential-mode conversion; there are discrete and abrupt changes in the response over changes in the source drive. This effect was postulated to be due to phase errors in the drive signal. Recall that the original drive signals were calibrated to ± 0.5 dB accuracy. This was chosen for convenience as the built in sources have 1 degree phase increments in their standard drive configuration. While this would seem to be adequate, the differential-mode error signal due to 1 degree of phase error in the common-mode signal amounts to an undesired differential input signal of –35 dB. This can be determined by taking 20log(tan(1 deg)). This may seem like a very small signal, but for this device it is amplified by 18 dB, whereas the common-mode signal is reduced by about 20 dB, creating a 38 dB enhancement to the output signal. Thus, the error signal causes an output that is in fact larger than the intended signal to be measured.

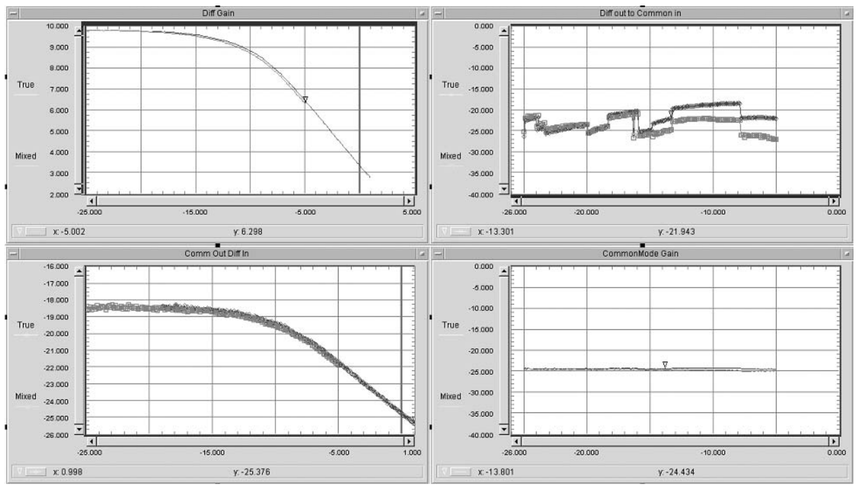

Figure 4. Mixed-mode and true-mode measurements of a non-linear amplifier – after improving source match using pads

To verify this result, the calibration algorithms were changed to provide 0.1 degree accuracy of the phase of the drive signals. Figure 5 shows the result of this improvement, where the size of the steps associated with the correction points are now much smaller. In this case, a different amplifier was used with greater common-mode suppression and high differential-mode gain. Even in this case, some artifacts of the 0.1 degree errors, although small, are still apparent in the SDC21 trace. Still, this system creates highly accurate, substantially pure, true differential-mode, common-mode, and single-ended signals.

What is truly remarkable about Figure 5 is that the differential mode gain, SDD21 in the upper left quadrant, measures exactly the same whether driven with pure differential-mode signals, or computed from mixed-mode parameters derived from single-ended measurements. This figure demonstrates that for this differential amplifier, it is not necessary to test it with a true differential-mode signal, even though it is in hard compression and behaving in an entirely non-linear way. Conversely, when the amplifier is driven with a common-mode signal, the non-linear behavior varies substantially, with the true-common-mode drive showing no non-linear behavior. One note, for these comparisons to be made accurately it is necessary to form a consistent reference for power; here we chose to compare signals with the same input drive when the small output signal is consistent. For signals driven in differential modes, it is necessary to change the X-axis (power axis) to reconcile the fact that the differential-drive signal is twice as large (6 dB higher) as the single-ended drive signal, for the same drive power setting of the source. That's why the plots for the differential drive start 6 dB higher than for the single-ended drive; given the same sources, the single-ended drive input power, in computing SDD21, is 6 dB lower than the equivalent input values of a true-differential signal.

For the cross-mode terms, such as SDC21 and SCD21, there must also be some adjustment to account for the proper impedance defined for each mode. In general, these terms (for S21 transfer characteristics) can be expressed as:

$$Sdc = \frac{b_d}{a_c},\ Scd = \frac{b_c}{a_d} \qquad (1)$$

and from (1) the values of a and b can be found as

$$a_c = \frac{V_c^+}{\sqrt{Z_c}},\ b_c = \frac{V_c^-}{\sqrt{Z_c}},\ a_d = \frac{V_d^+}{\sqrt{Z_d}},\ b_d = \frac{V_d^-}{\sqrt{Z_d}} \qquad (2)$$

where one can see that for Scd and Sdc, the impedance term cancels. The VNA measures the forward and reverse voltages (V^+ and V^-), so the values for the true-mode parameters must be adjusted from the normal measured voltage wave by:

$$Sdc = \frac{\sqrt{Z_c}}{\sqrt{Z_d}} \cdot \frac{V^-}{V^+},\ V^- = V_{d\ out},\ V^+ = V_{c\ in}$$

$$Scd = \frac{\sqrt{Z_d}}{\sqrt{Z_c}} \cdot \frac{V^-}{V^+},\ V^- = V_{c\ out},\ V^+ = V_{d\ in} \qquad (3)$$

and also from (1), the ratio of differential to common mode impedance must be 4:1, so the correction factor becomes:

$$Sdc = \frac{1}{2} \cdot \frac{V_{d\ out}}{V_{c\ in}},\ Scd = 2 \cdot \frac{V_{c\ out}}{V_{d\ in}} \qquad (4)$$

In this case the voltages are the measured values on the network analyzer channels b, a, and r. Thus, the power (X) axis must be renormalized by –3 dB in the Sdc case and +3 dB in the Scd case.

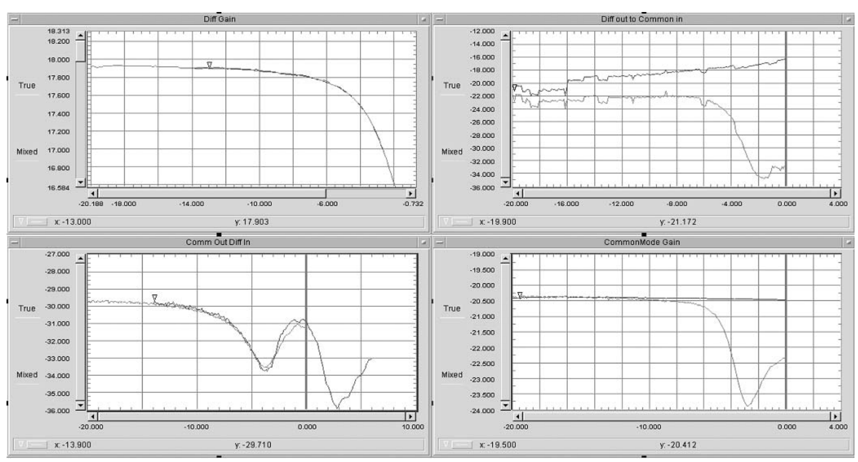

Figure 5. Mixed-mode and true-mode measurements of a non-linear amplifier – after improving phase calibration

Other measurements on non-linear devices

The previous tests were repeated for a new, limiting-type amplifier, with the results shown in Figure 6 [5]. In this case, the results are substantially different from those in Figure 5. In particular, the differential gain compression does not line up between single-ended and true-differential drive. Further, and somewhat more curious, the common-mode gain shows substantially more compression when driven with a true common-mode signal than when driven with a single-ended signal from which the mixed mode is calculated. Circuit topologies modeling the behavior of this amplifier, as well as the one measured in Figure 5 are proposed below.

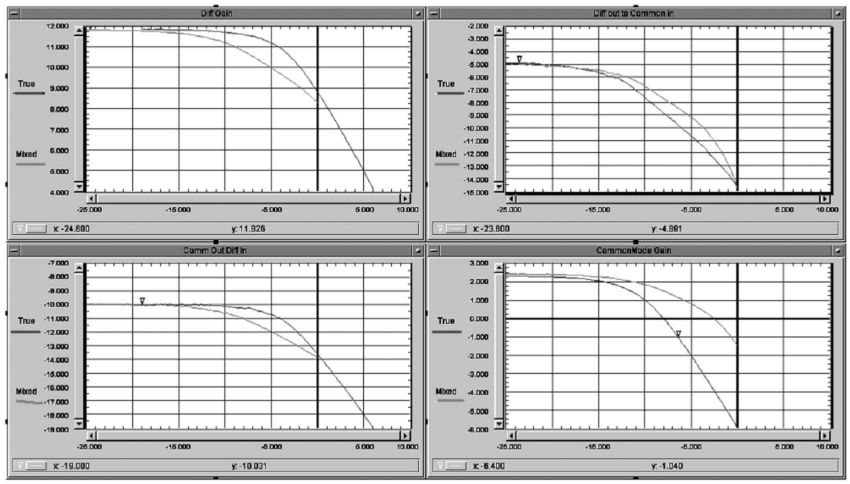

Figure 6. Mixed-mode and true-mode measurements of a limiting non-linear amplifier – Note the differential gain SDD21 is not the same when measured with a true-mode signal as compared with a single-ended mixed mode measurement

Circuit models to predict non-linear behavior

A single-ended signal can be thought of as being composed of a differential signal super-imposed on a common-mode signal as shown in Figure 7. Now consider this signal applied to an amplifier that has differential-mode gain and common-mode suppression. This is shown in Figure 8, and we can see that the output is mostly differential, even though a single-ended signal is applied. Figure 9 shows a dual-stage amplifier where the output stage also has common-mode suppression, and the output signal is nearly pure differential.

The non-linear behavior of the amplifier tested in Figure 5 can be explained by a model of the amplifier in Figure 9, where the non-linear behavior occurs in the output stage, after a differential input stage which has substantial common-mode suppression. Here the amplifier output stage clips the positive portion of the output waveform. In such a case the output signal of the first stage for a single-ended input is nearly identical to what one would see for a true-mode differential drive. When this signal drives the input to the final stage, where compression occurs, the output signal is compressed in the same way that the amplifier would behave if driven from a true-differential-mode signal, as shown in Figure 10. Also, interestingly, this amplifier creates more common-mode signal as it goes into compression, due to non-symmetrical clipping at the output. In general, this type of clipping is a sign of a non-optimized amplifier, as changing the bias level could increase the compression point for this amplifier. Figure 11 shows a similar amplifier but in this case, the output stage clips symmetrically, causing no common-mode signal at the output. Notice that a single-ended drive and a differential drive would give identical results. However, if the mixed-mode parameter SDC21 were computed from the single-ended drive, it too would show some compression. In contrast, Figure 12 shows the result of driving the amplifier with a large common-mode signal. Since the common-mode signal is suppressed, there is very little signal left to drive the output stage, so there is no compression. Here, we made the amplifier a little more interesting by adding some mode conversion, common-mode to differential-mode gain, in the first stage.

Now consider a model where the input stage compresses before there is any common-mode suppression, followed by an output stage which is differential, but has minimal compression. Such a model is shown in Figure 13, which is driven with a single-ended signal to an output differential level that causes compression in the first stage. In this case, the input stage is modeled as two separate amplifiers, but in practice this might represent a limiting or protection diode at the input to a differential-gain stage. Next consider the same amplifier model, but this time driven with a true-mode differential signal, to the same differential-output level, as shown in Figure 14. In this case, for the same nominal output voltage, the drive on each input is one half that of the single-ended input, and does not show compression when compared to Figure 13. In fact, one would expect that, relative to the output, the true-mode differential drive case would have 3 dB higher output power for the same gain compression. This is quite consistent with the results shown in the upper left portion of Figure 6. Finally, it should be clear that for true common-mode drive, there would be substantial compression. This is in contrast with the earlier cases where the circuit topology suppressed the common-mode signal before any compression could occur. Finally, note that this topology would predict substantial compression of the common-mode gain, in sharp contrast to the results shown in Figure 5 for SCC21, but completely consistent with the lower right plot of Figure 6.

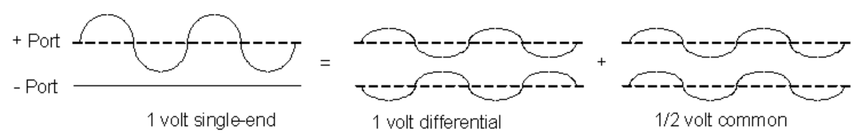

Figure 7. Single-ended signals can be thought of as being comprised of a differential signal and a common-mode signal

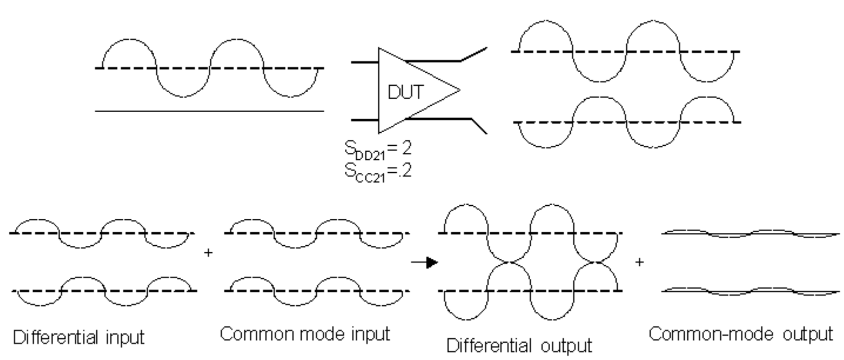

Figure 8. A single-ended signal applied to a differential DUT will result in a substantially differential signal at the output

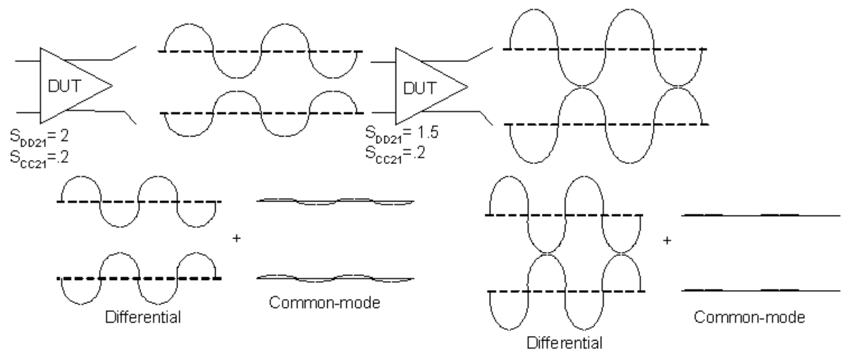

Figure 9. Here a two-stage amplifier is stimulated with a single-ended signal, and the output is nearly pure differential

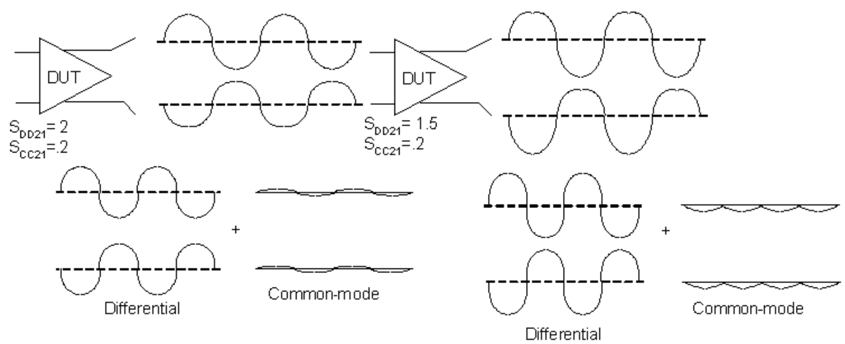

Figure 10. Here a two-stage amplifier is driven with a single-ended signal, and the output stage compresses by clipping the positive half of the output signal. This clipping causes the common-mode signal to increase as compression increases

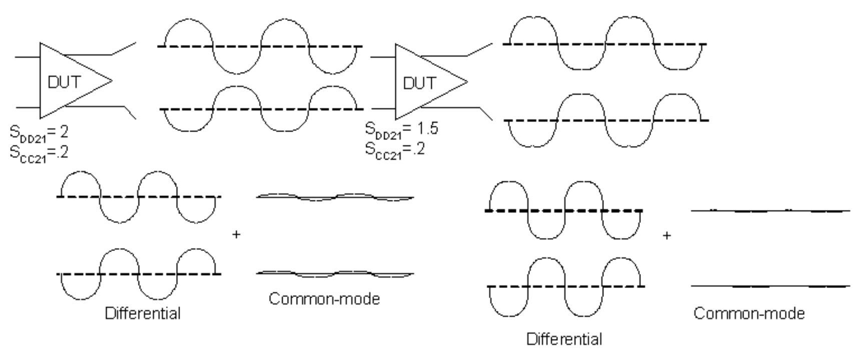

Figure 11. Here the output stage clips the output signal symmetrically; the common-mode signal is suppressed in this case

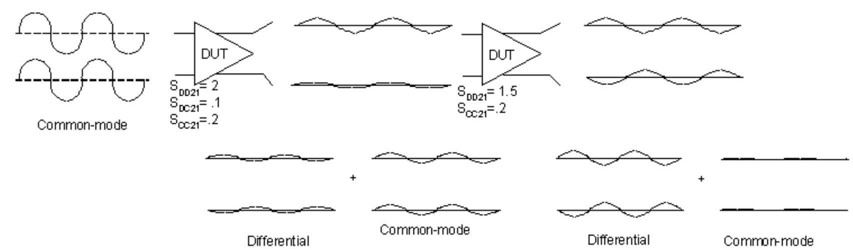

Figure 12. Here we drive the amplifier with a true-common-mode signal. Since the first stage suppresses the common-mode, there is very little signal to drive the output stage so no compression occurs

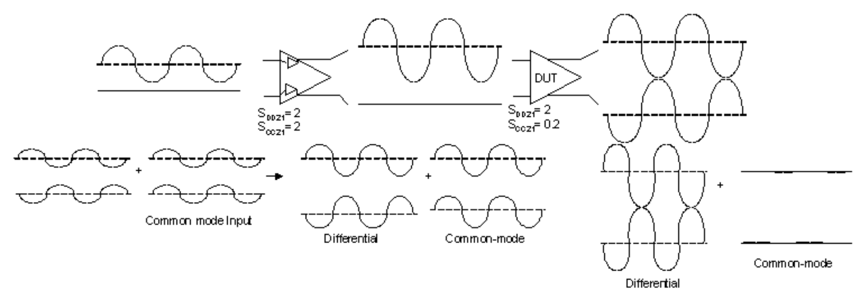

Figure 13. The first stage of this amplifier does not have common mode suppression, though the second stage does. Here input stage compresses on the positive half-cycles. Note that the single-ended signal causes compression, for a given nominal differential output voltage

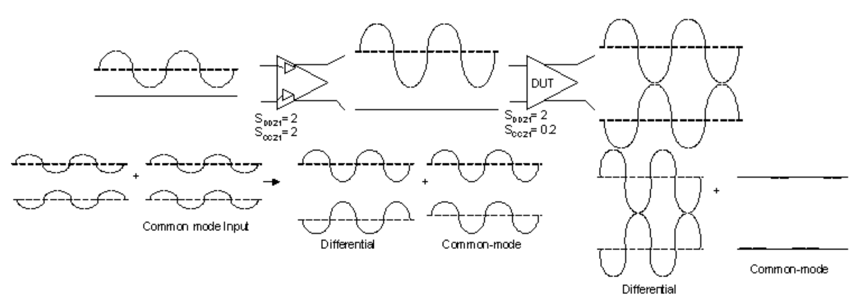

Figure 14. A limiting amplifier driven by a true-differential-mode signal does not show compression

Using circuit based simulation to confirm results

To evaluate the effects of drive on the operating points of an amplifier, a model of a high-frequency differential amplifier circuit was created and evaluated with various input drive signals as well as changes to circuit topology. The basic circuit is shown in Figure 15; an amplifier with two stages of differential gain followed by a low impedance output driver. Several test cases using different drives were simulated for this circuit. One example is shown in Figure 16, with four graphs. The upper two are for true differential drive, the lower two are for single-ended drive. The left plots are for the inputs to the plus and minus input, the outputs are at the output of the first differential stage, before any of the high-power stages. From this figure, it is very clear that for this device, even though there is substantial distortion and compression, the output from the first stage is nearly identical regardless of the input drive. In this case, the input circuit is sensitive only to the differential voltage at the input, and not to the common-mode voltage. Thus it is clear that the distortion is substantially from the output. The differential voltage input in both cases is identical. An additional experiment was performed where a single limiting diode was added *across* the input, as shown in Figure 17, and the experiment repeated. The results are shown in Figure 18, with the middle graph showing the differential input voltage, that is, the difference between Vin-plus and Vin-minus.

Here it is clear that the input waveform is distorted due to the non-linearity at the input. Remarkably, even with a strong non-linearity at the input, the output of the first stage is identical between true-mode drive and single-ended drive. Looking at the differential voltage, that is, taking the difference between the input plus and input minus, shows that both drives have the same *differential* voltage at the input, and the output non-linearity is sensitive only to the differential signal (common-mode signals will not stimulate the non-linearity, due to the common-mode suppression of the first-stage of the amplifier). A third experiment was conducted where a diode limiter was placed from each of the inputs to ground. The input voltage was driven hard enough to turn on the diodes for the single-ended input, whereas only half that value was used for each input of the differential signal to maintain a constant output. The results are shown in Figure 20, with the differential output graph in the middle overlaid with the true-mode and single-ended differential voltage, for easier comparison. Here, finally, we see a difference in the output waveform, due to the compression of the single-ended signal and not the true-mode signal. Thus, from these experiments, we can further refine when true-mode drive is required for testing of non-linear differential circuits.

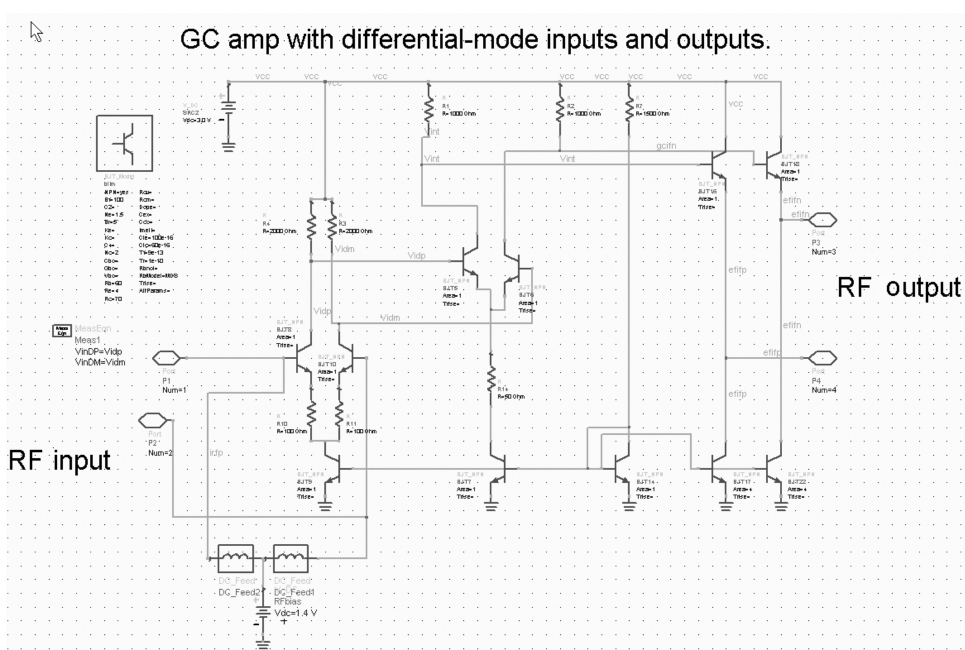

Figure 15. Gilbert-cell differential amplifier used in simulations

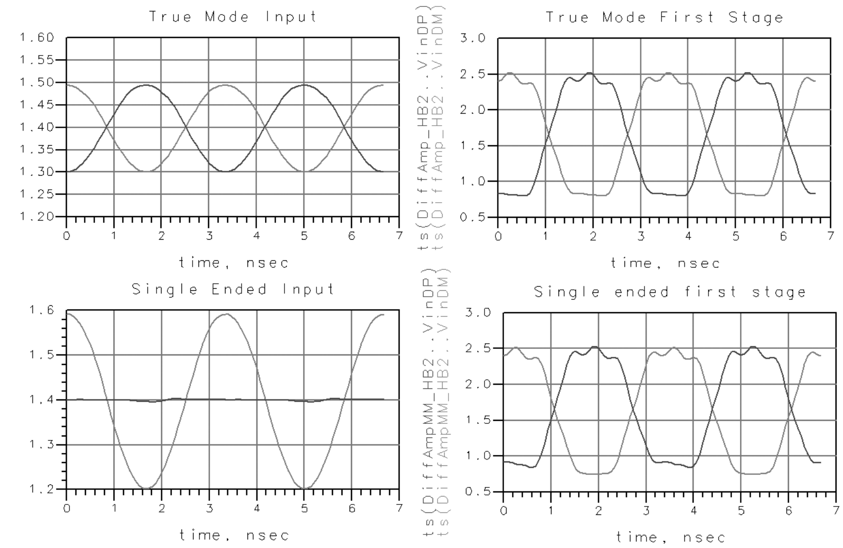

Figure 16. True-mode (upper) and Single-Ended (lower) Inputs (left) and outputs (right)

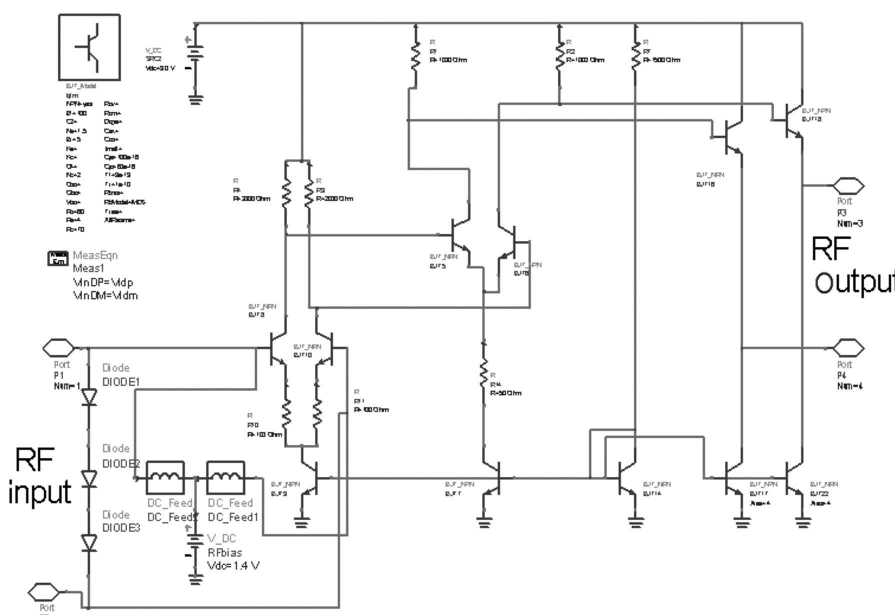

Figure 17. Schematic of a non-linear differential amplifier with a diode limiter across the input

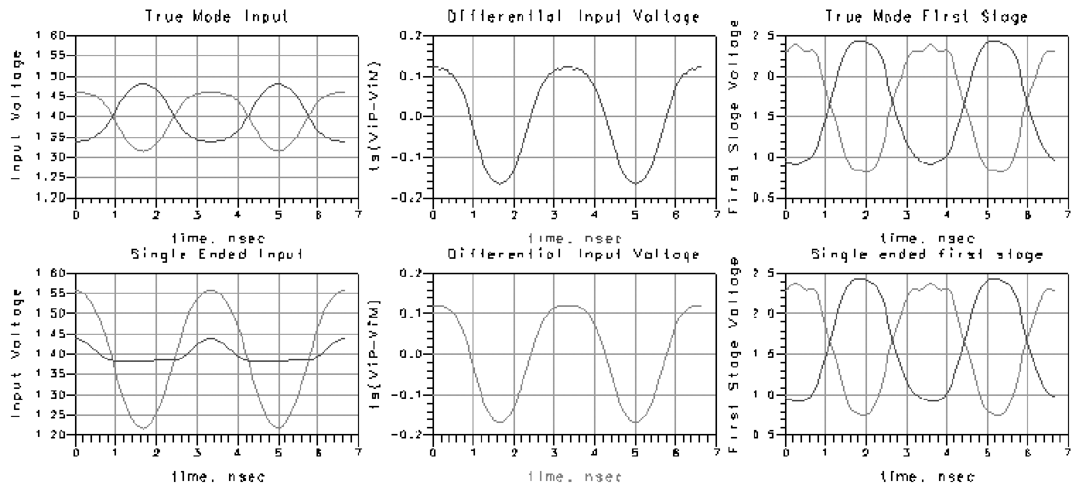

Figure 18. Inputs (left), differential input (middle) and outputs (right), of an amplifier with diodes across the inputs. Upper is true mode, lower is single ended

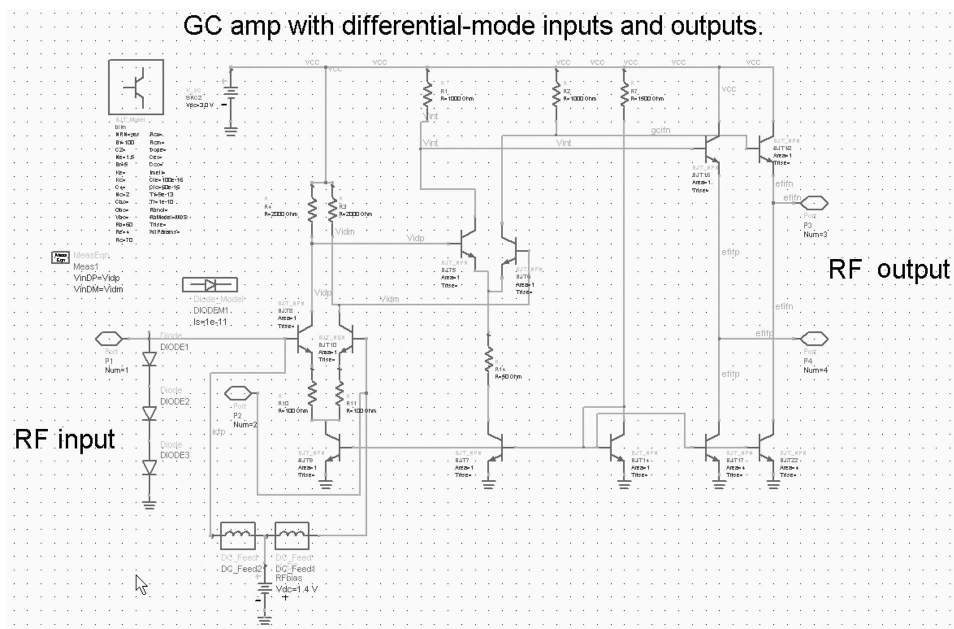

Figure 19. A differential amplifier with diodes to ground on the input

Modulated (two-tone) measurements

Using the same circuits used to create Figure 17 and Figure 19, a two-tone source was applied at the input, with both true-mode differential drive and single-mode drive. Figure 21 and Figure 22 show the two-tone response for the circuits in Figure 17 and 19 respectively. Here we see some difference in the output waveforms. The input signals were adjusted to result in the same differential output power. The differential input voltage is clearly somewhat different for the case of the circuit in Figure 19, as shown in Figure 21 (middle) due to the single ended clipping. Figure 23 shows the two-tone spectrum. We can see that the single-ended drive shows about 1 dB different TOI for the same output signal (in this case, the input level of the single-ended drive signal was increased to produce the same output level in the main tones as the true-mode drive signal). Note that for all of the other cases except diodes-to-ground on the input, the two-tone response was identical between true-mode and single-ended drive. The result from this simulation for normal differential amplifiers, that is, amplifiers that have common-mode suppression in a stage before any stage which compresses, is that two-tone or modulated distortion results will be identical whether driven with a single-ended drive or a true-differential-mode drive. These simulated results confirm the measured results reported in Microwave Symposium Digest [4].

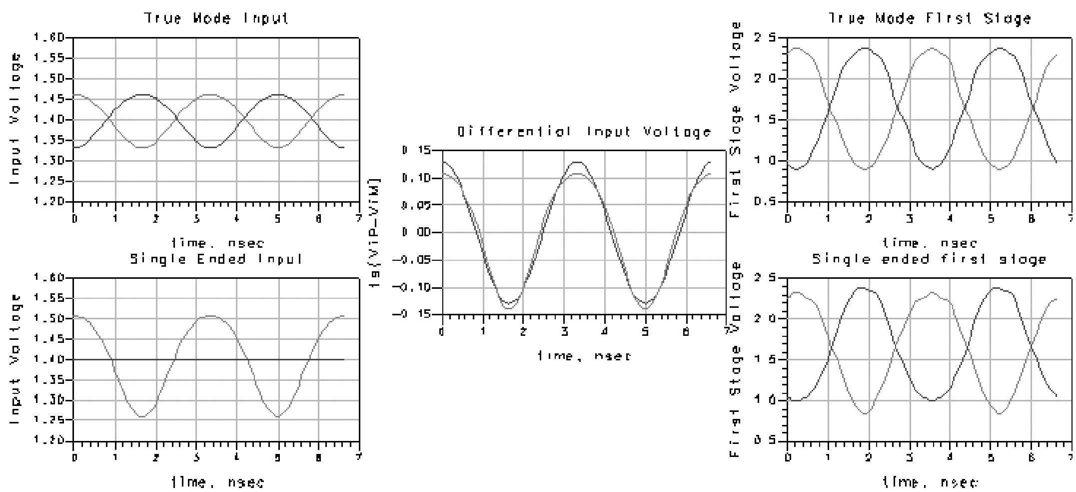

Figure 20. Single-ended inputs (left), differential input (middle) and outputs (right), of an amplifier with diodes from input to ground. The middle plot has differential input voltage for true-mode (higher peaks) and single-ended (lower peaks) overlaid

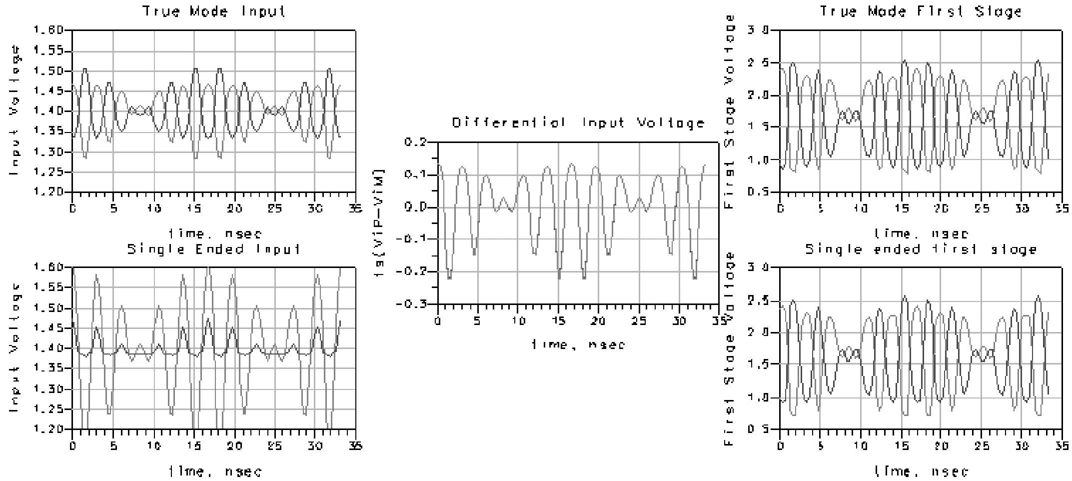

Figure 21. Single-ended inputs (left), differential input (middle) and outputs (right), of an amplifier with diodes across the inputs, drive with two-tones. Upper is true mode, lower is single-ended. Note that the output is identical

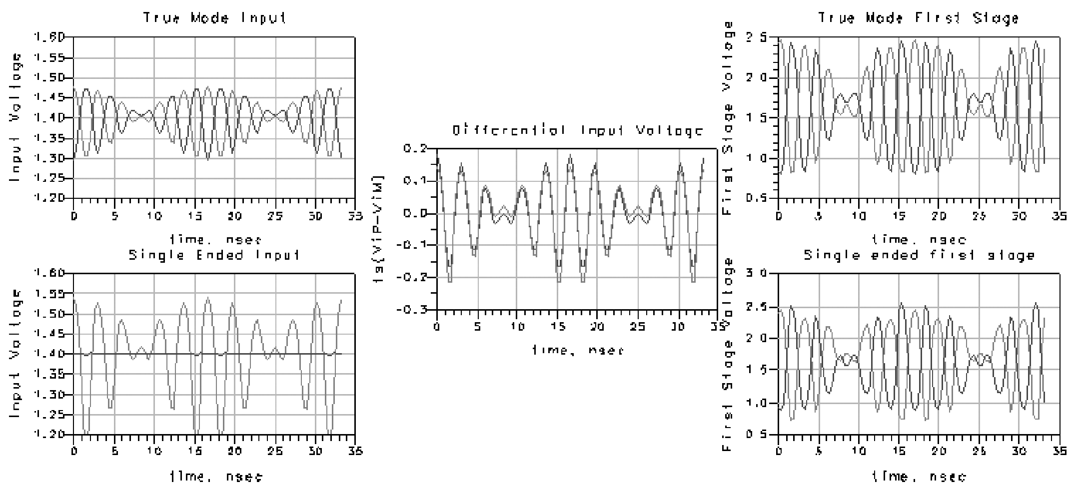

Figure 22. Inputs (left), differential input (middle) and outputs (right), of an amplifier with diodes from inputs to ground, drive with two-tones. Upper is true mode, lower is single ended

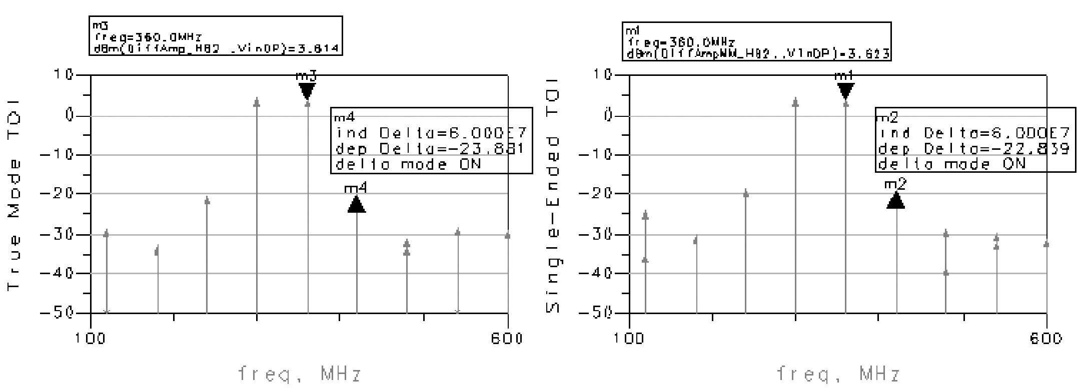

Figure 23. TOI spectrum of an amplifier with diodes from inputs to ground, driven with two-tones. Left is true mode, right is single ended

Conclusions

This paper shows the results from a new analysis of true-mode differential and mixed-mode single-ended drive on various configurations of differential amplifiers. In the cases where the non-linearity of the amplifier followed a differential stage, or where the input non-linearity was differential in nature, there was no substantive difference between the results for single-ended or true-mode drive. Only in the case where the input of the amplifier was both non-linear and not differential, with the non-linearity between the input and ground, was there any observed difference between single-ended drive and true-mode drive. This was true for CW and modulated (two-tone) signals. Even in the case where there was a difference, when normalized to the output, the difference amounted to 1 dB change in a –23 dBc TOI signal. From these results, it appears that the non-linear characteristics of differential amplifiers can be determined from only single ended measurements.

Reiterating the key points:

- The correlation between true-mode drives and single-ended mixed-mode measurements depends strongly on the circuit topology.
- For most circuits, the non-linear response will be identical.
- Only in circuits where the non-linear element occurs before a balanced stage, will single-ended measurements give different results... And only if the non-linearity is NOT differential.
- If a device is a *normal* differential device (non-linearity occurs after a balanced stage), true-mode and single-ended measurements will give IDENTICAL results.

Final comments about measurement systems

Above we conclude that for normal differential devices, those that have a non-linear stage following a stage with common-mode suppression, it is sufficient to measure with a single-ended measurement system and compute the mixed-mode parameters. If, however, one has a device that has a limiting stage at the input, such as that measured in Figure 6, a true-mode drive may be required. But, the true-mode drive must really produce a true-mode signal, and normal error-correction techniques, such as computing the source and load match and post processing the data to correct for non-ideal instruments, will not produce the correct results as the DUT behavior depends upon the actual voltage applied to the input terminals. Further, this voltage depends upon the characteristics of the DUT and the test instrumentation. This implies that a true-mode test system must have either ideal match, as was created in the system of Figure 2, or must provide for amplitude and phase control to actively modify the drive signal in response to reflections from the DUT.

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