New Methods & Non-Linear Measurements for Active Differential Devices

Joel Dunsmore

Agilent Technologies, 1400 Fountaingrove Parkway, Santa Rosa, Ca, 95403

Abstract — **This paper presents new results for non-linear measurements of active differential devices based on a novel source system. The system provides both true-differential and commom-mode stimulus for CW and modulated RF signals, and presents results of non-linear operation of differential devices driven with such signals, which are compared with the same devices driven at the same levels using single ended drive and calculating the differential response. A remarkable result is that the later method performs very well for devices having common-to-differential isolation.**

I. Introduction

Many wireless device topologies have moved to balanced (or differential) input drives from the traditional single-ended inputs and outputs. 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.

However, many active devices do not follow such a model for their behavior. For example, an amplifier might change it's bias current 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 for to create these signals, but it can be difficult to control and maintain balance from the hybrid port to the circuit connection. In test equipment applications, however, it may not be possible to control the interconnections sufficiently well to maintain desired balance. For linear circuits, this imbalance may be corrected for [3], but for circuits operating in a non-linear region, true-balanced drive may be necessary. For in-circuit applications, a balun (balanced to unbalanced transformer) is often used, and is placed in close proximity to the device to avoid introducing any phase offset due to connections between the device and the balun. However these baluns do not allow investigation of the device response to common-mode signals, nor do they allow measurements of common-to-differential mode conversion terms.

II. 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). The measurements section, which follows, will demonstrate that this fine level of control is a requirement if the actual active device characteristics are to be determined.

Fig. 1 shows a representative block diagram for the new source configuration. This first demonstration system makes use of three electronic signal generators (ESG) each of which have 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 the rear panel as a coherent carrier, as shown in the bottom ESG depicted in Fig. 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, 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 Fig. 1., where it also bypasses the internal source on the way to the vector output. For modulated signals, an arbitrary waveform generator (arb) is sent to

0-7803-7695-1/03/$17.00 © 2003 IEEE

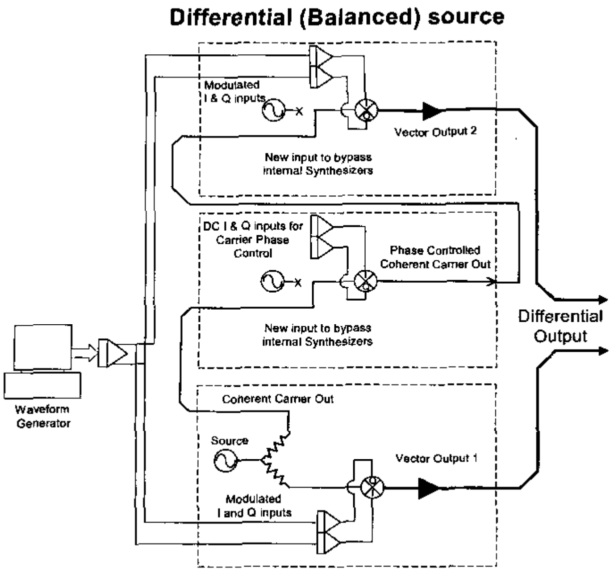

Figure 1: Block diagram for generating balanced modulated signals

each of the bottom and top ESGs, such that the output signals have the same modulation, but have phase control between the carriers. 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.

II. CALIBRATIN SOURCES & 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, the 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 to the VNA 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 frequency.

Fig 2 shows a measurement system with a differential DUT making CW measurements. 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 terminating first one input and measuring the resulting outputs, then terminating the second input and again measuring the output.

III. MEASUREMENT RESULTS

Figure 3 shows the result of measuring a differential amplifier using true-mode and single-ended measurements, presented as mixed-mode S-parameters, while sweeping input power. There are two remarkable aspects about the results shown. First, for the parameter Sdd in the upper left, the differential gain, there is no appreciable difference between single-ended and true-mode measurements, even at very high levels of gain compression. This indicates that single-ended measurements may be satisfactory for some devices in characterizing their non-linear performance. This result has been repeated for a second differential amplifier of a completely different design. Secondly, it is clear from the Sdc and Scc parameters (the common to differential mode conversion and the common mode gain, upper and lower right) that the common mode response is strongly dependent on the whether the device is driven in true-mode, or single ended. Consider an amplifier that has an input with good (low) common-mode to

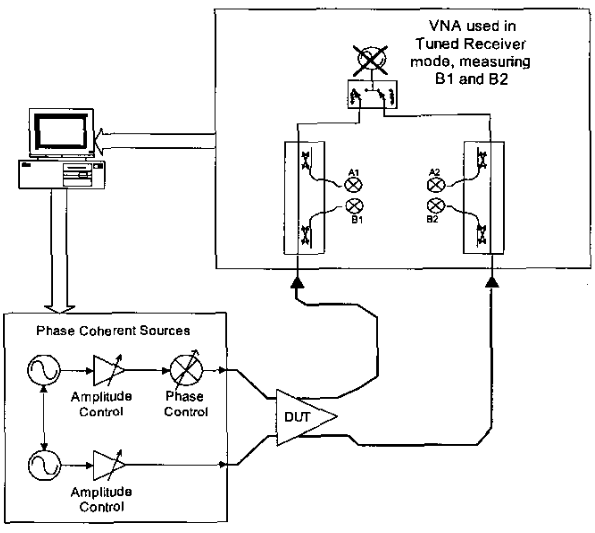

Figure 2: Measurement of a differential amplifier using a true-mode source and VNA

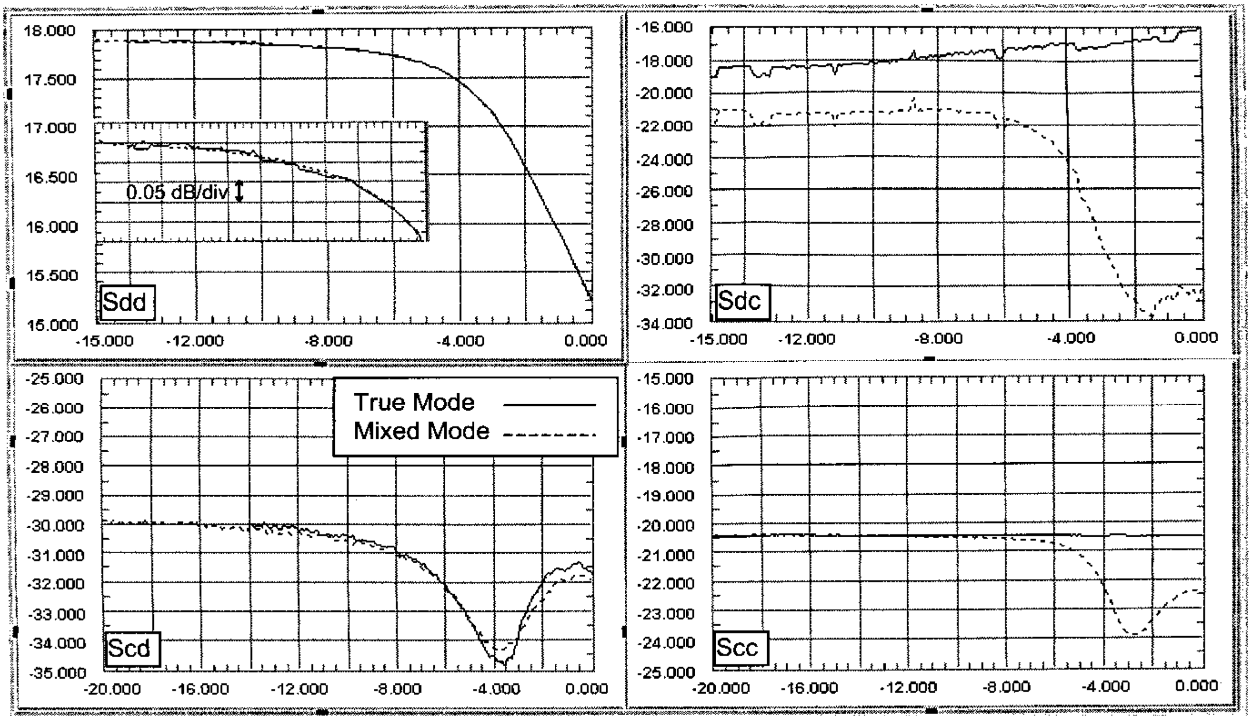

Figure 3: Power Sweep Measurement results for a differential amplifier using true mode (solid) and singled ended mixed-mode (dashed) measurement techniques. X-axis is power, Y-axis is gain.

differential conversion, then there will be little signal to drive the output stage. If the output stage is the principal cause of compression, then such an amplifier driven common mode will not see much compression, as shown for Sdc in the upper right corner of Figure 3. The same situation holds true for the Scc or common mode gain term. Conversely, for and amplifier driven in differential mode, the signal will nearly be the same in compressing the output whether one looks at the common mode output (Sdc) or the differential gain. One comment is important on drive level references: 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, for the same drive power setting of the source.

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

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

and from [1] the values of a and b can be found as

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

where one can see that for Scc and Sdd, 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

$$\begin{aligned} Sdc &= \frac{\sqrt{Z_c}}{\sqrt{Z_d}} \cdot \frac{V^-}{V^+},\ V^- = V_{d\,out},\ V^+ = V_{c\,in} \\ Scd &= \frac{\sqrt{Z_d}}{\sqrt{Z_c}} \cdot \frac{V^-}{V^+},\ V^- = V_{c\,out},\ V^+ = V_{d\,in} \end{aligned} \quad (3)$$

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

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

In this case the voltages are the measured values on the network analyze channels b, a and r. The small steps in the Scd term (upper right, figure 3) are due to small (0.05 dB, 0.1 degree) changes in the amplitude levels of the two input paths. Larger phase or amplitude uncertainties make the residual differential signal so large as to render the Scd term completely in error.

III. MODULATED MEASUREMENTS

The measurements shown in Figure 3 are CW non-linear measurements, but the differential sources can be configured to provide modulated signals as well. More complex tests such as Two-Tone intermodulation, EVM, ACLR etc., can be made in true-mode fashion if the drive signals are modulated. Measurements of these parameters require differential or common mode detection. Currently, there are no RF spectrum analyzers that provide for differential inputs. However, one can simulate that function by using a hybrid to separate out the differential and common mode responses to differential and common mode complex modulated input drives. Figure 4 shows the spectrum of a two-tone differential-drive signal measured for its differential and residual common-mode content. The measurement of the common-mode drive shows a similar differential residual. Figure 5 shows in the upper plot the TOI distortion measurement of the amplifier of Fig. 3 measured with a true-mode differential drive. The lower plot shows the same measurement driven from a single ended (+ input) drive. Remarkably, there is almost no difference in the result of these measurements, indicating that it may not be required to drive the amplifier with true-mode to get a reasonable answer for the differential TOI response. Figure 6 also shows a TOI measurement, but this time for a true-common-mode drive signal in the upper plot, and again a single-ended drive in the lower plot. Here it is clear that the true-mode drive shows no distortion created in the common mode, where the single ended drive shows substantial distortion being created. From this one might conclude that it is required to drive this amplifier in true-mode if the common-mode distortion is the desired measurement parameter.

V. CONCLUSION

This abstract shows the results from a new method for creating differential CW and modulated signals. The full paper will include the details of the source architecture used to create these signals. The results show that in some cases that single ended drive has good correlation with true-mode drive (for differential drive and response) but the single-ended drive sometimes yields quite different results, especially for large common mode drives in a differential amplifier.

REFERENCES

[1] D. E. Bockelman, W. R. Eisenstadt, "Combined Differential and Common-Mode Scattering Parameters: Theory and Simulation", IEEE Transactions on Microwave Theory and Techniques, Vol. 43, No. 7, July 1995, pp. 1530-1539

[2] D. E. Bockelman, W. R. Eisenstadt, Stengel, R "Accuracy Estimation of Mixed-Mode Scattering Parameter Measurments", IEEE Transactions on Microwave Theory and Techniques, Vol. 47, No. 1, January 1999, pp. 102-105

[3] D. E. Bockelman, W. R. Eisenstadt, "Calibration and Verification of a Pure-Mode Network Analyzer", IEEE Transactions on MTT, Vol. 46, No. 7, July 1998, pp. 1009-1

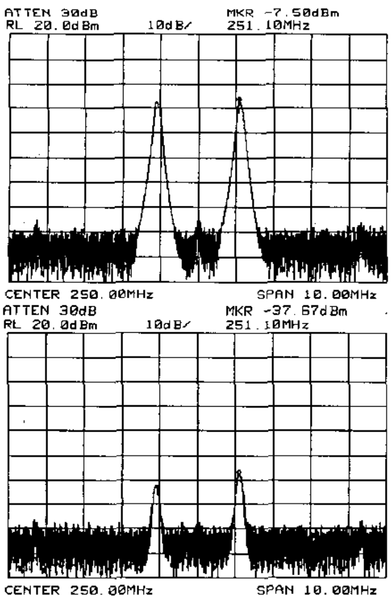

Figure 4 Upper: Differential input drive and Lower: residual common mode signal.

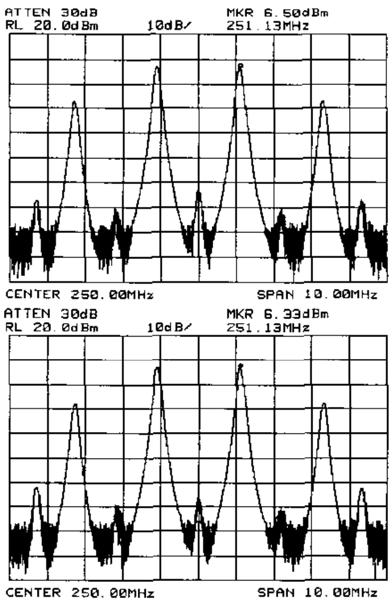

Figure 5 Amplifier output with (upper) true-differential-mode drive and (lower) single ended drive

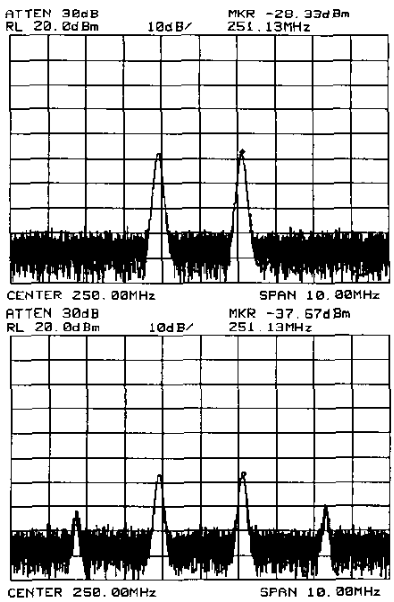

Figure 6 Amplifier output with (upper) true-common-mode drive and (lower) single-ended drive