Why Network Analyzer Signal Levels Affect Measurement Results

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When measuring a circuit or device with our network analyzers, engineers generally inject a signal and believe that the measured results reflect that of a small-signal AC measurement. Many of us have been taught to keep the signals “very small”. This raises the questions, “how small is very small” and “is this an issue with my network analyzer”? SPICE based circuit simulators use partial derivatives to perform small-signal analysis, and therefore, are not sensitive to the signal level; regardless of the AC magnitude the results are linearized and scaled. So how big can an injected signal be before it significantly impacts a measurement? Let’s investigate the answer via a simple test.

We can start the investigation by first characterizing the device we want to measure. We will use a transistor because a transistor has a known emission coefficient (N=1), thus removing N as an unknown parameter. The voltage of a silicon junction is given by Eq.1:

$$V_F = \ln\left(\frac{ID+IS}{IS}\right) * N * VT + ID * Rs \qquad \text{Eq.1.}$$

Differentiating V_F with respect to ID results in the junction impedance given by Eq.2:

$$Rj = \frac{1}{ID+IS} * N * VT + Rs \qquad \text{Eq.2.}$$

If we assume the junction temperature of the device to be 25°C, knowing the Boltzmann constant, K, and the elementary charge, Q, we can solve VT as shown in Eq.3:

$$VT = K * \frac{Temp_K}{Q} = 1.38 * 10^{-23} * \left(\frac{273+25}{1.602*10^{-19}}\right) = 0.026\,V \qquad \text{Eq.3.}$$

We can also assume the forward biased current, ID, is much greater than the saturation current, IS, and the junction impedance, Rj, is much greater than the series resistance, Rs. Substituting in, Eq. 4 gives the familiar small signal junction impedance, Rj:

$$Rj = \frac{0.026*N}{ID} \qquad \text{Eq.4.}$$

Next, we can derive an equation that defines the maximum input power allowed to obtain a result that is within 10% of the exact small signal solution as a function of the DC bias, the signal's source impedance, and the device emission coefficient. This is given by Eq.5:

$$Pin\_dBm(ID, RS, N) = 10 * \log\left\{\frac{\left[\left(\frac{1.11*RS}{\frac{VT*N}{ID}}+1\right)*\left(0.207*ID*\frac{VT*N}{ID}\right)\right]^2}{RS*0.001}\right\} \qquad \text{Eq.5.}$$

Since we know the emission coefficient of a transistor is 1, and our network analyzer source impedance is specified to be 50 ohms, we can determine the maximum allowable input power level for a range of bias conditions.

$$Pin\_dBm(.0001,50,1) = -30.69\ dBm$$

$$Pin\_dBm(.001,50,1) = -22.447\ dBm$$

$$Pin\_dBm(.005,50,1) = -11.027\ dBm$$

$$Pin\_dBm(.01,50,1) = -5.387\ dBm$$

All cabling and board parasitics must be eliminated from the measurement by calibrating the analyzer to ensure these maximum signal levels are accurate.

Next let's confirm these signal level calculations using the Agilent E5061B network/impedance analyzer. The collector and the base of a 2N3904 transistor are tied together as shown in Figure 1 and the voltage bias should be adjusted until the DC current bias is 1mA. This can be monitored after each impedance sweep in the E5061B software and can be toggled on in the top right corner of the screen.

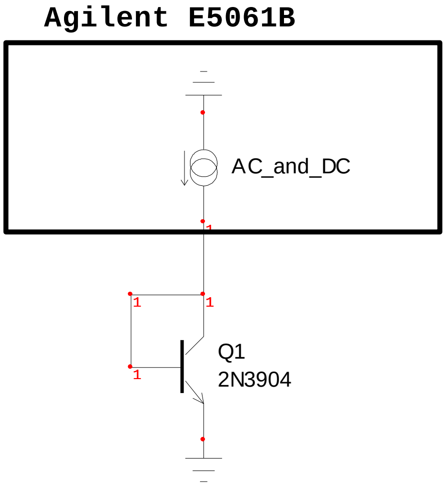


Figure 1 – 2N3904 Connection.

Two impedance measurements are then made; one at an injection level of -23dBm, and one with a level of -13dBm.

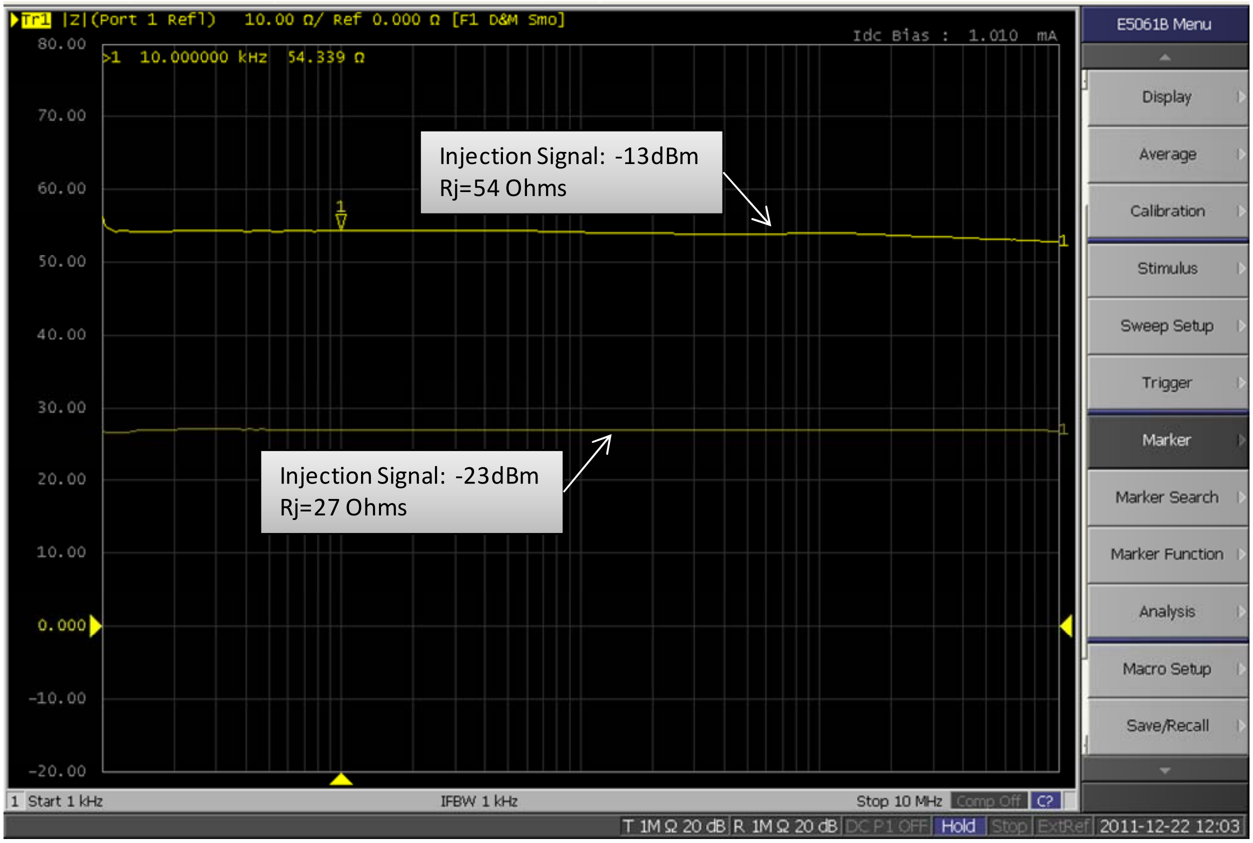


Figure 2 – 2N3904 impedance with -23dBm injection (thick line) and -13dBm injection (thin line).

Figure 2 shows us that the correct result of 27.8ohms is measured with a -23dBm signal, while with a -13dBm signal, the result reflects a 100% error.

To take this one step further, we can use the harmonic balance (HB) engine in the Agilent ADS simulator to confirm the effects of input signal power on the junction impedance. Like a small signal simulation in SPICE, harmonic balance yields a steady state solution and analyzes the circuit in the frequency domain. Unlike SPICE which uses a small-signal approach, HB uses a large signal solution to correctly model signal effects on all components in the simulation.

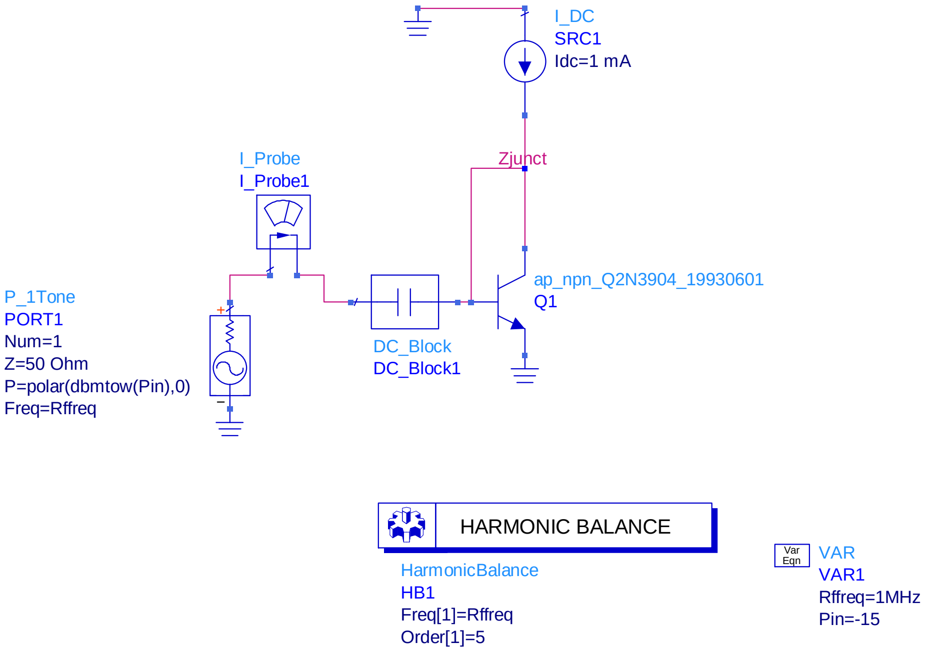


Figure 3 – Harmonic Balance Simulation in ADS

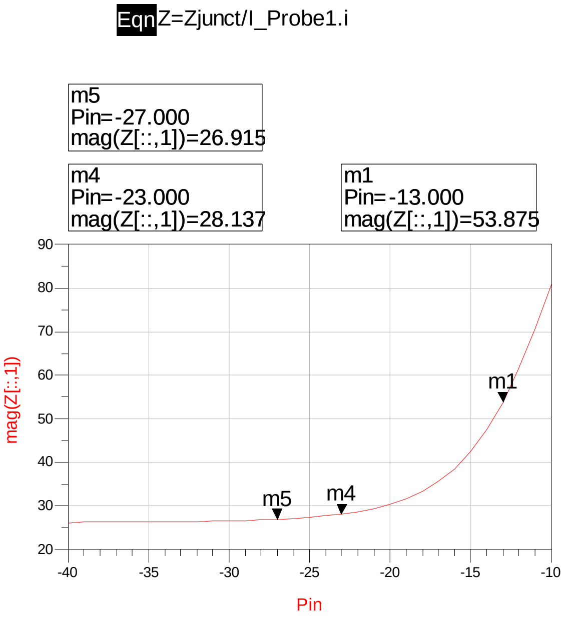
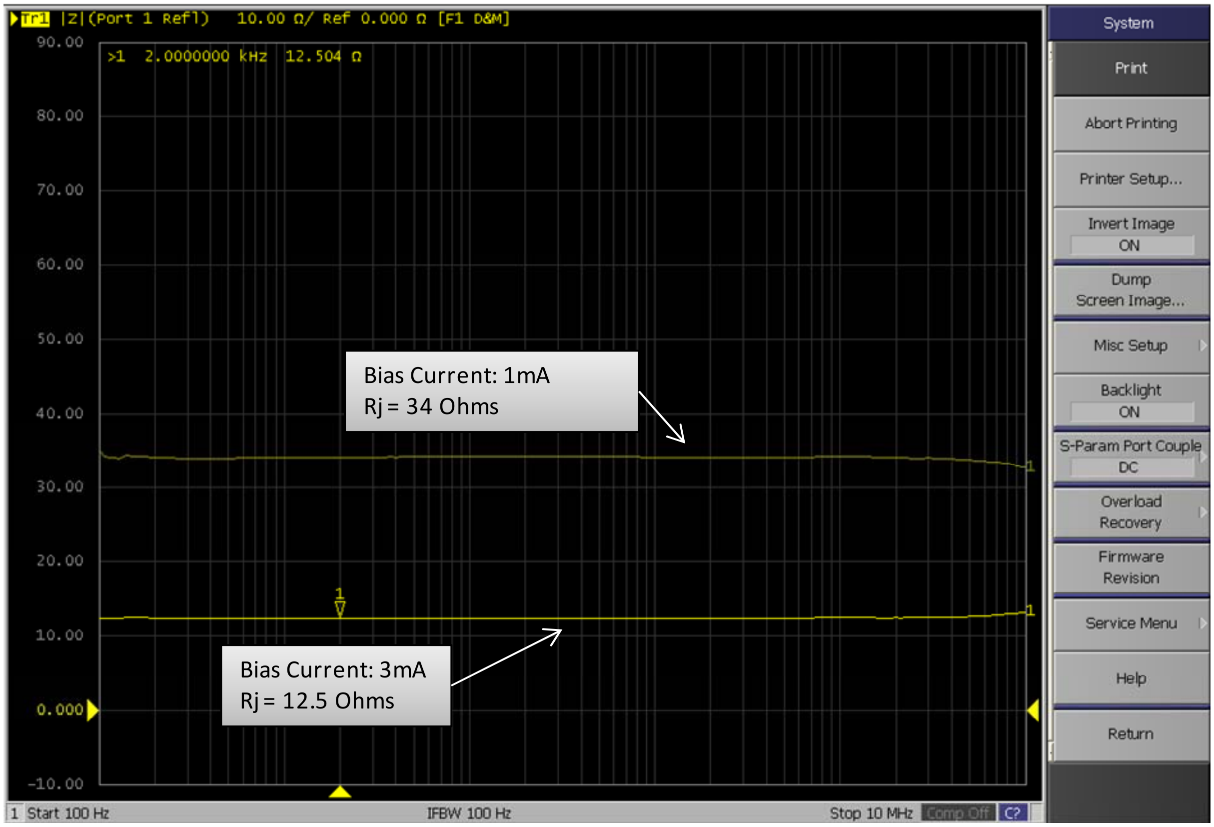


Figure 4 – Simulation results of junction impedance vs. input signal power

Marker m4 in Figure 4 shows the operating condition where the impedance deviates 10% from the actual value, which is at -23dBm. The simulated impedance at that point is 28ohms which is in excellent agreement with the bench result at that injection level of 27.8ohms. Further validating evidence is that the incorrect impedance obtained with an injection level of -13dBm which is approximately 54ohms in both the measurement and the simulation. This confirms our calculated 10% error input signal level of -23dBm. By changing the bias condition on the device in Eq.5, we can observe an exceptionally large swing in allowable input signal level. Looking back at Eq.2 we see that bias current changes the impedance of the junction, so from this equation we know that IS, N, RS and to a smaller degree, temperature, can all affect the junction impedance. The Agilent E5061B can be used to extract all of these parameters and in a similar method to measuring the transistor, we can determine the allowable input signal power for proper measurement. Assessing the calculation using a diode provides a verification of the significance of the emission coefficient in determining the maximum signal level. Since the emission coefficient, N, is not necessarily 1 for a diode, we must take multiple measurements and calculate N from the measured impedance at different bias levels using Eq.2.

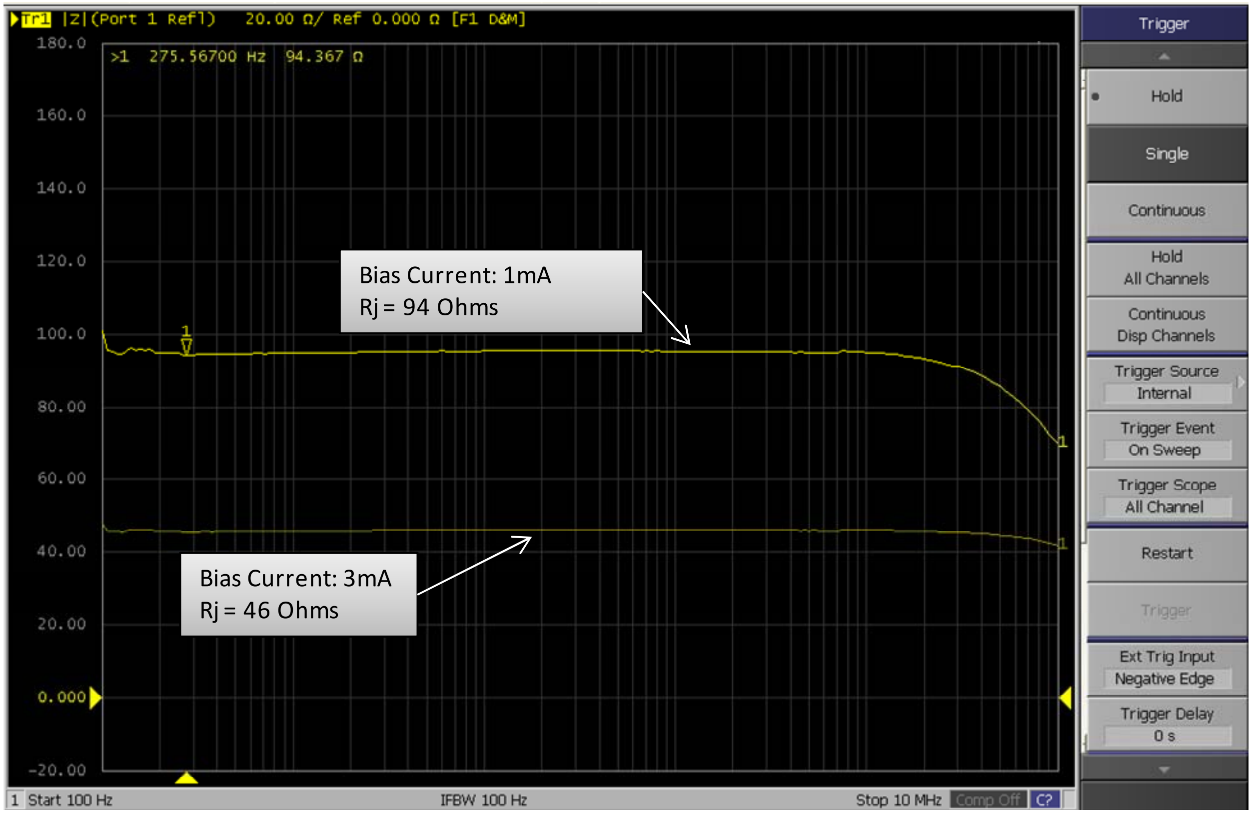


Bias Current: 1mA
Rj = 34 Ohms

Bias Current: 3mA
Rj = 12.5 Ohms

Figure 5 – MUR110 diode impedance, -27dBm injection level with a 1mA and 3mA bias.

The emission coefficient of a diode is not necessarily 1 as with a transistor, but can be calculated from this impedance measurement. Using Eq.4, we see this particular diode has an emission coefficient of approximately 1.26. A diode with a low emission coefficient is chosen to further show the impact of signal level on the measured impedance.



Tr1 |Z|(Port 1 Refl) 20.00 Ω/ Ref 0.000 Ω [F1 D&M]

>1 275.56700 Hz 94.367 Ω

Bias Current: 1mA
Rj = 94 Ohms

Bias Current: 3mA
Rj = 46 Ohms

1 Start 100 Hz IFBW 100 Hz Stop 10 MHz

Figure 6 – 1N5711 diode impedance, -27dBm injection level with a 1mA and 3mA bias.

Figure 6 shows the 1N5711 diode impedance measurement with 1mA and 3mA bias. The effective resistance is approximately 40 Ohms, while Eq.4 shows N is approximately 0.89. More than one measurement must be taken to confirm the emission coefficient of the diode, as the signal level, even at its minimum of -27dBm, is large enough to affect the measurement results.

From all of the preceeding we can see that there is in fact a finite allowable signal level when using your analyzer. This is not due to the network analyzer, but a real phenomenon related to the large signal effects of the semiconductors. It is important to always remember that a SPICE simulation is ONLY solving for a small-signal problem, and that oversized injection amplitudes can result in drastically wrong test results.

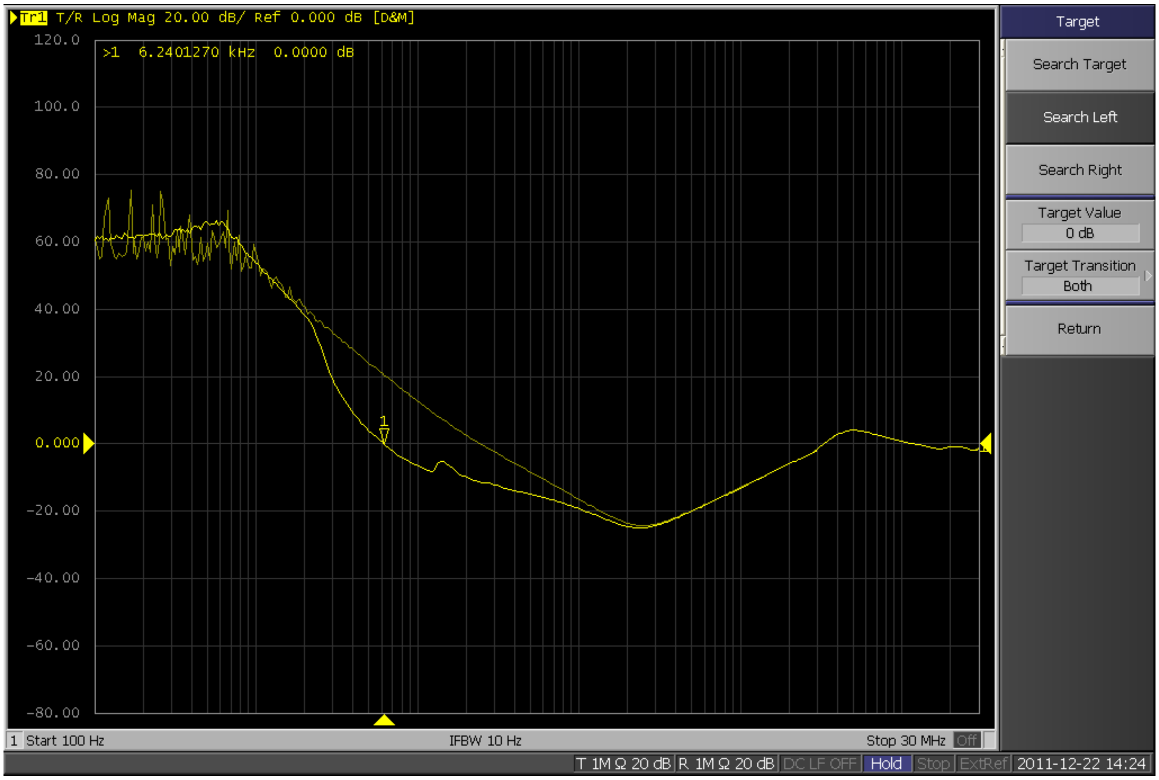
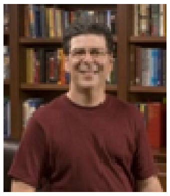


Fig 8 – LM137 Voltage Regulator Bode Response 3.3V/50 Ohm resistive Load 27uF Aluminum output cap using -37dBm (thin line) and -20dBm (thick line) signal level.

About the Authors:



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