My Understanding of X-Parameters

What can I offer that probably the readers cannot already find from the Internet? This was my thought when I was asked to contribute an article to Dreamcatcher's newsletter. Well, I could throw in some derivations with some explanations, just like any paper out there, and be done with this assignment. Or maybe just avoid contributing and hope nobody remembers. Oh wait, I have done that already! So it's back to the question. Like any radio-frequency (RF) engineers, I was thrown into this line of work unwittingly. Today, it's my 7th year as an RF engineer. So I thought, why not share on how I came to learn and understand some of the Really-Funny (my definition of RF) and somewhat interesting things in RF.

I vaguely remember when I first heard of the X-Parameters. It was probably around the time I was working on some power amplifier (PA) behavioral models for my Master's research project and was thrilled to hear about X-Parameters. X-Parameters, a registered trademark of Agilent Technologies, is a behavioral description of nonlinear Power Amplifiers. What is behavioral modeling? Today there are three ways to model amplifiers: creating physical device models, equivalent circuit transistor models and of course the behavioral models. Physical device models are based on the physics of the device. One needs to know, for example, the carrier transport physics of the underlying semiconductor of the device. The equivalent circuit models consist of electrical elements such as resistors, capacitors, inductors and nonlinear voltage or current sources, which can characterize the electrical properties of transistors. This is similar to the 2-port transistor model learned in basic electronics 101. Now behavioral modeling means a description of the input-output relationship of the amplifier. This method of modeling is popular as it avoids the complexity of the other two and allows for a simple integration of components at system level. RF engineers have been working with behavioral models for many years, namely with the S-Parameters.

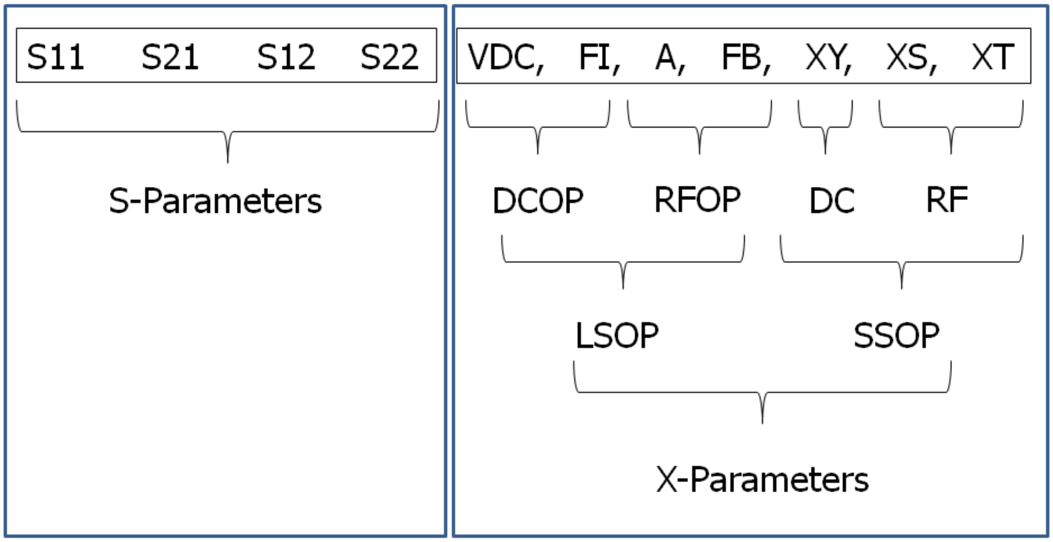

Figure 1: Components of S-Parameters and X-Parameters.

Let's turn our attention to the X-Parameters. An X-Parameter file consists of the terms that can be seen in Figure 1. It is the ensemble of the Large Signal Operating Point (LSOP) and Small Signal Operating Point (SSOP), with each operating point described by its own DC and RF terms. The S-Parameters, shown for comparison, consists of only 4 terms (for a 2-port device). The S-Parameters is valid at the biasing point it was measured and can be used to describe the device with any source/load terminations. So why do we need so many terms to describe a power amplifier? This question plagued me for awhile. Thus I decided to try and understand the behavior of a power amplifier first before diving into the X-Parameters definitions.

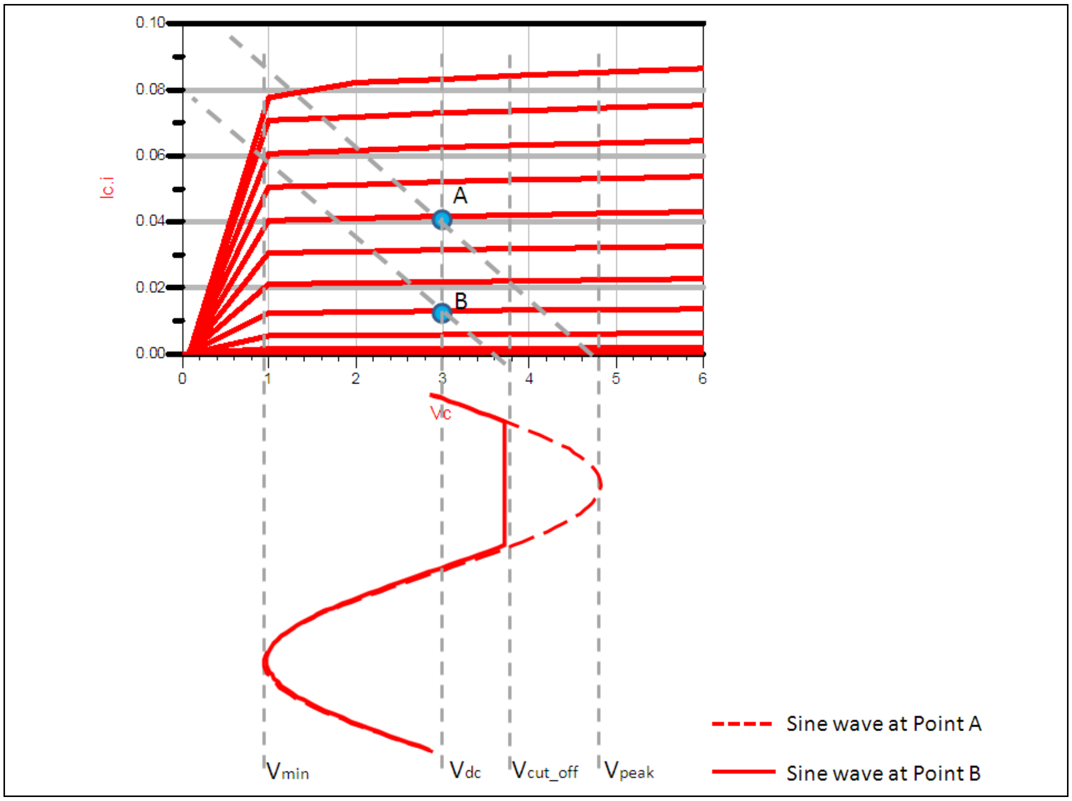

Figure 2: Voltage swing of Class A (red solid line) and Class AB (red dash line) Q-point.

Let's take a look at the IV curves of a typical amplifier (Figure 2). Here I simulated the IV curves of NEC's NE661M04 silicon RF BJT. In order to achieve good linearity, the class A operating mode is chosen. This means that the biasing point (Q-point) is selected at the center of the I-V curve (Point A). How is this, the most linear operation of any amplifier? Now imagine that you have to park in between two cars; one on your left and the other on your right. If you park exactly at the center, both you and your passenger can exit the car with a full swing of the car door open. Park a little to the right, and you will have a tight squeeze coming out as your door cannot swing in full. Similar to the bias point, the class A biasing point allows your sinusoidal signal to have a full swing in either directions without being clipped at either ends. Hence, no clipping means no harmonic distortions to your signal means a more linear operation. However, power amplifiers are hardly biased in class A.

To improve efficiency, a power amplifier is biased in class AB, B, C or switching classes where the biasing point is closer to the cutoff region of the amplifier (Point B). In this situation, half of the signal is limited to V_{cut_off} while the other still swings in full. Here is where it gets interesting. As you drive power (means increase the input RF power to the device), you'd notice the dc current increasing with this drive (Figure 3). This occurs as the average power is greater in the upper half of the sinusoidal signal and continues to increase as the RF input power increases, thus pushing the average dc current higher. So, what have we just observed? The DC operation of a power amplifier is dependent on the input RF power level!

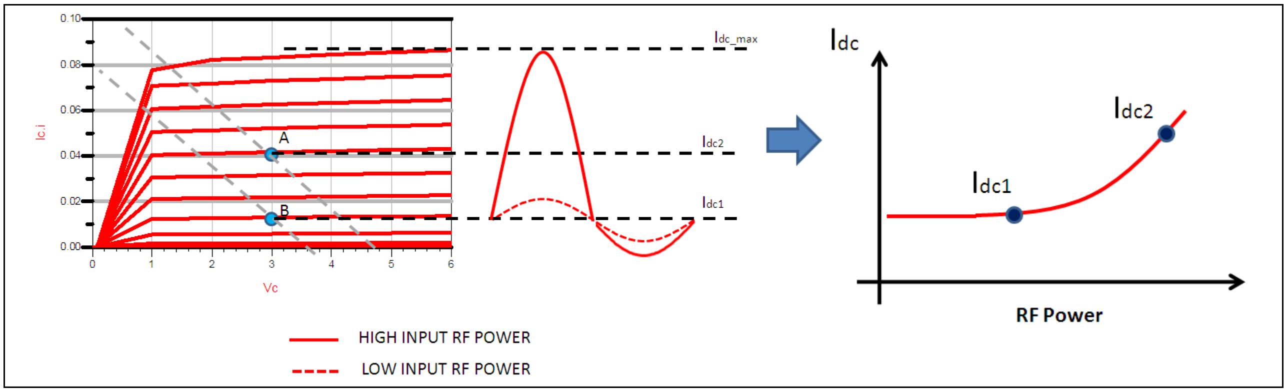

Figure 3: Current increase with input power, Pin.

What would happen if we now use the S-Parameters to describe the power amplifier? The input power in the forward direction would drive the amplifier's Q-point from Point B to point A (see Figure 3). Under these conditions, the S-Parameters, S11 and S21, is an accurate description of the amplifier. However, measuring the S-Parameters in the reverse direction would mean that the input power to the amplifier is no longer present and hence the S-Parameters, S22 and S12, are representing the amplifier at Point B. This is the problem. We now have an inaccurate description of the true behavior of both S22 and S12 under real large signal operation. To solve this problem, S22 and S12 are measured with the RF power still present at the input to the amplifier. The amplifier's bias point is at Point A and the reverse S-Parameters is thus valid. As this S-Parameter description is different from the typical S22 measurement, the name Hot-S22 (Figure 4) is given to denote the presence of the drive power when S22 is measured.

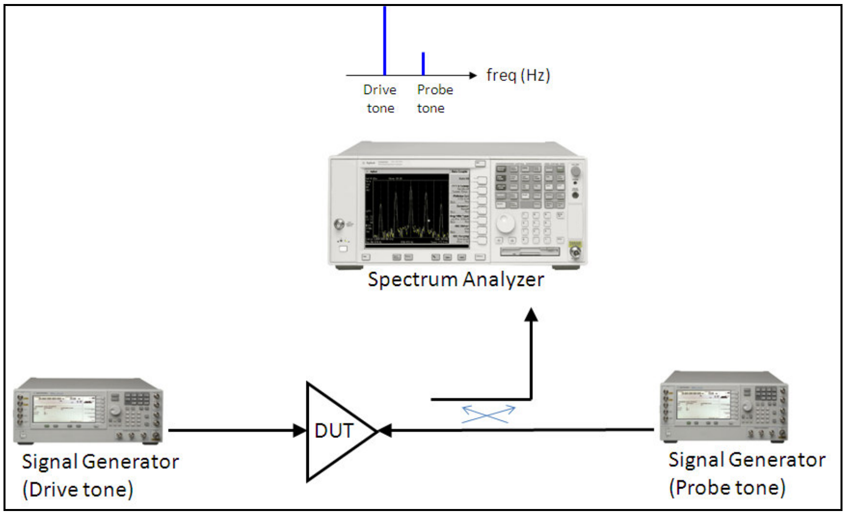

Figure 4: Simplified setup of a Hot-S22 measurement. The Drive tone sets the Large Signal Operating Point (LSOP) and the Probe tone is used to extract the S22. The Probe tone is usually 15-20dB smaller than the Drive tone.

By now we should be able to appreciate the motivation for having the Hot-S22 measurement. However, there is one significant drawback of Hot-S22. Before addressing that, what do we understand about the Third Order Intermodulation Product (TOI)? Amplifiers in the presence of 2 tones would generate third order intermodulation products. These are the $2f_2$-f_1 and $2f_1$-f_2 products. In Hot-S22, we are also subjecting the power amplifier to two tones. The only difference is that the magnitude of both tones is not equal. To illustrate this, the Hot-S22 simulation setup for the NE661M04 is shown in Figure 5 with the simulated result in Figure 6.

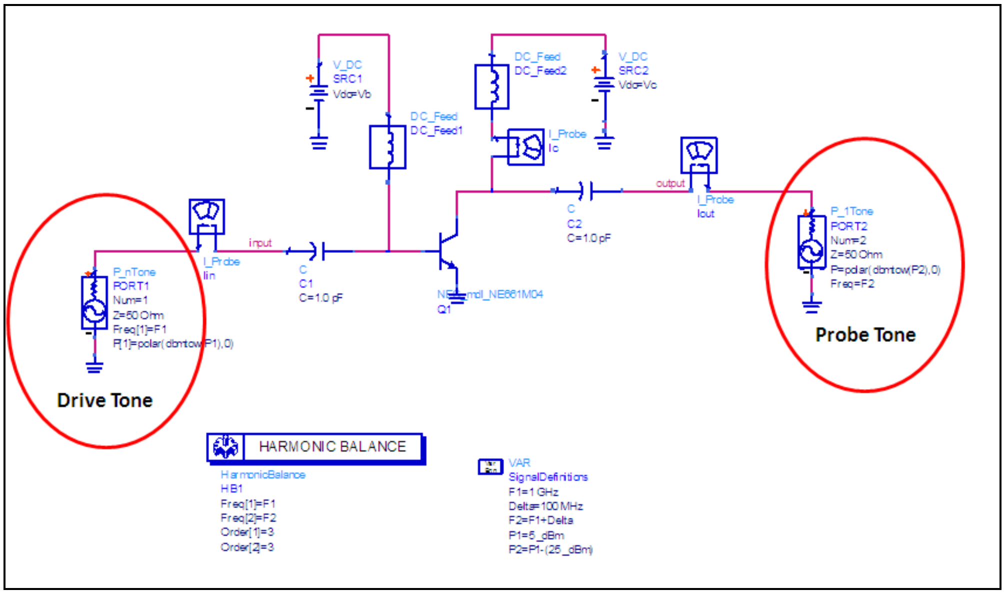

Figure 5: Hot-S22 simulation setup

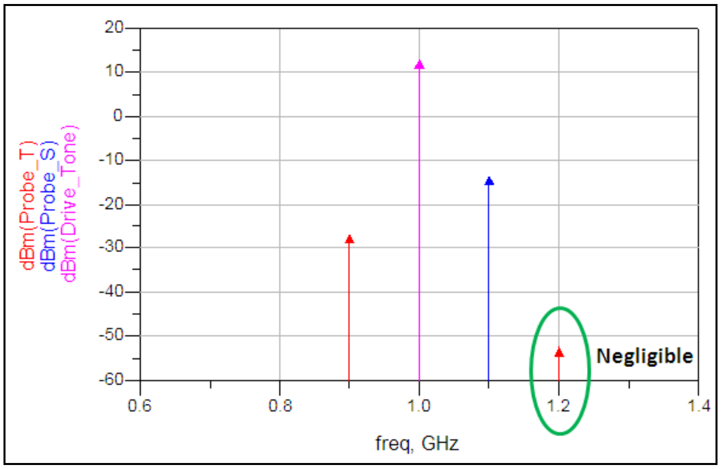

Figure 6: Hot-S22 Simulation. Drive tone is shown in Magenta, the Probe tone is shown in blue and the intermodulation product is shown in red.

Due to the presence of both the Drive tone at 1GHz and Probe tone at 1.1GHz, intermodulation products appear at 0.9GHz and 1.2GHz. What is noticeable is that the power of the intermodulation product at 1.2GHz is small and can be neglected. However, the intermodulation product at 0.9GHz must be taken into account. Failure to do so has resulted in poor behavioral models using Hot-S22.

Let's summarized what we have learned so far.

a) Power amplifiers dc current changes with the input power. The S-Parameters do not take into account dc voltages and currents. Hence, S-Parameters will not provide for a complete behavior of the power amplifier.
b) Hot-S22 introduced to overcome the large signal S-Parameter measurement problem introduces intermodulation products, hence reducing the accuracy of the behavioral model.

It is thus evident that S-Parameters are no longer a valid representation for a power amplifier. Let's now describe X-Parameters. The initial step in the characterization of a power amplifier includes defining its large signal operating point (LSOP). This is done in the following steps:

a) A DC voltage must be set. We call the constant voltage supply, **VDC**.

b) The operating point of the amplifier is defined by the RF input power to the amplifier. This is the drive tone and it is denoted as **A**. The term A is used primarily to denote A-waves going into the amplifier whereas the notation B is used to denote B-waves exiting the amplifier.

c) Subject to the level of the Drive tone the DC current will vary. This is the measured current and is denoted by **FI**. The notation 'I' is used to denote current and the notation 'F' is to denote frequency. FI_2 would mean the current due to the harmonic number 2.

d) We also need to capture the response of the drive tone. Thus, the **FB** terms are used to represent the transmitted and reflected power due to the drive tone. 'B' to denote the B-waves exiting the amplifier and F to denote the frequency. The notation FB_p_m is used, where p stands for port number and m stands for harmonic index. For example, FB_1_2 is the reflected power of the second harmonic out of port 1.

This completes the definition of the LSOP. Note that in defining the LSOP, all parameters are measured as the absolute value. Why then would we not take the ratio of the transmitted and reflected powers to the incident RF input power in defining the LSOP? This is unlike the S-Parameters where ratio measurements are recorded. To answer this, we simply must understand what the large signal drive tone is doing. This is like when you hear sounds coming from your car at, let's say, 100km per hour. If you are driving below this limit, you will not hear sounds coming from your car. So how then would you test to see which location is the sound coming from? You drive your car at a 100km per hour and start searching for the sound. Driving your car to 100km per hour is similar in principle to the drive tone. We are setting the operating point of the power amplifier. When we are looking for the sound, this is akin to using the probe tone.

The Probe tone defines the small signal operation point (SSOP) of your amplifier. Note that in obtaining the SSOP, the ratio between the measured signal and the Probe tone power is taken. Unlike the Hot-S22, the SSOP is measured by sending a Probe tone to both the input and the output of the amplifier. The magnitude of this Probe tone is usually lower than the Drive tone by 15 to 20dB. The SSOP is measured in the following steps:

a) Place a Probe tone at either the input or the output. The measured transmitted and reflected power at the frequency of the Probe tone is compared to the original Probe tone power. This is denoted as the **XS terms**. It is common to give the notation XS_p_m_q_n where

    - p is the response port
    - m is the response harmonic
    - q is the excitation port
    - n is the excitation harmonic

    For example, XS_2_3_1_2 means we are measuring the transmitted third harmonic probe tone power at port 2 and comparing it to the probe tone power at the second harmonic incident on port 1.

b) As discussed, we need to take into account the tone due to the intermodulation product of the Drive tone and the Probe tone. In this case, we only measure the power of the significant intermodulation product which falls adjacent to the Drive tone as the intermodulation product adjacent to the Probe tone is negligible (see Figure 6). The measured and reflected power at the frequency of this intermodulation product is compared to the original Probe tone power and denoted as **XT**. It is common to give the notation XS_p_m_q_n where

- p is the response port
- m is the response harmonic
- q is the excitation port
- n is the excitation harmonic

For example, XT_2_2_2_3 means we are measuring the reflected second harmonic intermodulation tone power at port 2 and comparing it to the probe tone power at the third harmonic incident on port 2.

c) Subject to the level of the Probe tone the DC current will also vary and is denoted the **XY** terms.

We thus come to the end of the X-Parameters definition. Table 1 summarizes the X-Parameter terms.

Table 1: Terms and definition of the X-Parameter

Terms	**Definition**
VDC	DC **biasing voltage** of the amplifier.
FI	Measured **current drawn** from the amplifier **under the large signal condition** (i.e. due to the presence of the Drive tone at the input).
A	RF input power (Drive tone) used **to set the Large Signal Operating Point**. The absolute power is recorded in dBm.
FB	The **response** of the amplifier **due to the RF input power**. The absolute power of the transmitted and reflected signals at the fundamental and harmonics is recorded in dBm.
XY	Measured **current drawn** from the amplifier **under the small signal condition** (i.e. due to the presence of the Probe tone at the input).
XS	**Transfer function** representing the transmitted and reflected power of the **probe tone** to the power of the probe tone presented to the device.
XT	**Transfer function** representing the transmitted and reflected power of the **intermodulation product** to the power of the probe tone presented to the device.

X-Parameters are indeed a great innovation from Agilent Technologies. X-Parameters are possible today mainly because of advancements in the calibration and measurement techniques available in Agilent's PNA-X network analyzers. In my opinion, X-Parameters have certainly opened up many interesting areas for research and have enabled, for the first time, a true description of the behavior of a power amplifier. For more information regarding X-Parameters, please refer to www.agilent.com/find/powerofx

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