ECE 451

Automated Microwave Measurements Laboratory

Experiment 11 - Generating X-parameter from circuit models with ADS

1 Introduction

In a typical RFIC design flow for modern communication systems we often see a tradeoff in simulation accuracy, allotted design time and IP protection. In traditional design flow a foundry would create a SPICE model for a transistor in a given process technology and then hand it over to an IC design house. This IC design house is the team that will actually design the circuit and send it back to the foundry for fabrication. Circuits are always designed for a particular application and have to meet certain specification pertaining to that application. The system engineers whose task is to meet their customer's needs typically set design specifications. Often the end customer, foundry, IC design house and the system engineers/system integrators are disparate entities and can even be competing firms thus Intellectual Property (IP) protection is a big concern today.

Most significant advantage of X-parameters over other network parameters as well as standards like IBIS-AMI is that they provide complete IP protection by characterizing any given circuit's linear as well as non-linear behavior. X-parameters significantly speed up simulation times and allow the system integrators to characterize the entire system with a true black-box approach. This paradigm shift protects the IP of the IC design house, as they no longer need to share the circuit level design details with the system integrators. System engineers can take the X-parameter model in the form of a '.xnp' file and accurately capture the small-signal linear behavior as well as all the non-linearities, amplitude/phase perturbations on all harmonics during large signal behavior. The X-parameter models are not only capable of describing circuits at a schematic level but are also able to characterize packaged components including the effects parasitics. Furthermore, the ability to cascade X-parameters allows the system integrators to speed up the analysis and design time without compromising on accuracy like they do today while using traditional behavioral modeling techniques.

In this experiment, we will use Keysight ADS to generate X-parameters from a circuit-level design of a Power Amplifier (PA). We will then be using these X-parameters in simulation to extract 1-dB compression point and third-order intercept (TOI) points via 2-tone Harmonic Balance (HB). Our aims are to develop an intuitive understanding of how X-parameter system level simulations compare with the circuit level SPICE simulations and demonstrate how powerful the X-parameter formulism is in characterizing an entire system by a 'black-box' design approach. This experiment will demonstrate how to characterize an entire circuit using a 'black-box' approach by generating X-parameters from a transistor-level circuit schematic of a PA and then using ADS to simulate its small-signal linear as well as the large-signal non-linear behavior.

2 Background

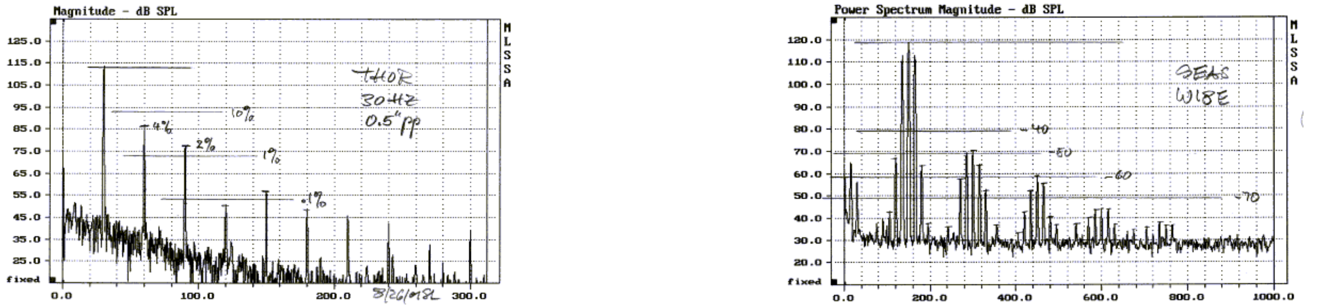
Non-linear effects

Nonlinear effects in RF circuits can be roughly categorized into 02 groups: the harmonic distortion (HD) and the intermodulation distortion (IMD). We will now go through some simple yet sufficient mathematical derivations to demontrate the nonlinear effect of 02 types. Any nonlinearity can be approximated by a Taylor series (though its convergence is a complicated issue, needs considering with care). Let's now consider a third-order nonlinear system, for instance:

$$v_{out}(t) = a_1 v_{in}(t) + a_2 v_{in}^2(t) + a_3 v_{in}^3(t)$$

Let $v_{in}(t) = V_0 \cos(\omega_0 t)$, it is trivial to obtain:

$$v_{out}(t) = \frac{a_2 V_0^2}{2} + \left(a_1 V_0 + \frac{3 a_3 V_0^3}{4}\right) \cos(\omega_0 t) + \frac{a_2 V_0^2}{2} \cos(2\omega_0 t) + \frac{a_3 V_0^3}{4} \cos(3\omega_0 t)$$



(a) HD for one-tone excitation. Image coutersy of http://www.linkwitzlab.com

(b) HD and IMD for multi-tone excitation. Image coutersy of http://www.linkwitzlab.com

Figure 1: Typical nonlinear distortion

A typical HD spectrum is shown in 1a. 1b shows a typical general nonlinear distortion, each "lobe" is a high-order nonlinear HD in which IMD surrounding the harmonic frequency. HD usually appears out of band, it might interfere with other systems at higher frequencies, but is easily resolved by filters.

IDM, on the contrary, usually poses more serious problems to signal integrity because some of them appear in-band and would interrupt with the desired signals. Let $v_{in}(t) = V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t)$, with no loss of generality, $\omega_2 > \omega_1$. The output expression is now much more complicated. Let's summarize the terms using Table 1, for simplicity, assuming $V_1 = V_2 = V_0$.

A more visual way to represent Table 1 is in Figure 2. There are plenty of important observations in this example. The even (such as second) order IMD appears well above or below the input tones, they are not a problem to in-band signals. However, odd (specifically in this case, third) order IMD interferes directly with the fundamental tones as well as the in-band signals. Removing of them is usually infeasible with the use of filters. The third order IMD is the strongest, closest to the signals that it originates from. Thus, it is often the most troublesome.

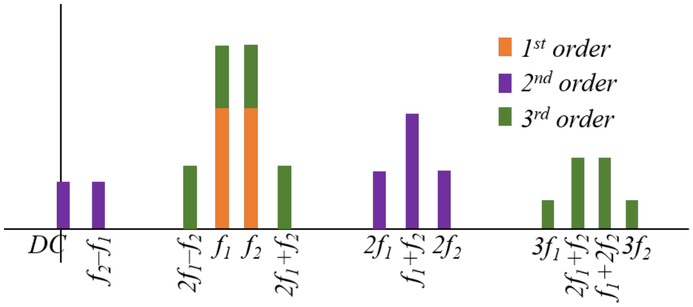


Figure 2: HD and IMD effects for the 2-tone excitation

The amplitude behaviors of each order nonlinear effect are plotted in terms of input versus output power in log scale in Figure 3. As the excitation is small, the linear response dominates, we have a constant gain. As the excitation becomes larger, the third order IMD on the fundamental tones becomes dominant, the linear gain starts to compress. Therefore, ***1dB compression point***, where the actual *linear* gain (blue solid line) drops below its linear trend (blue dash line) by 1dB is the first measure to quantify the nonlinear effect. As explained above, the third order IMD poses more serious unavoidable problems, the ***third-order intercept*** point ***(TOI***, aka ***IP3)*** provides a simple and meaningful way to predict the distortion at the operation frequency. The ***TOI*** is defined by the intersept between the linear extrapolation of the fundamental and that of the third harmonic component and is given by

$$OTOI = P_{out} + \frac{IMD3}{2}$$

or

$$ITOI = P_{in} - \frac{IMD3}{2}$$

The ***TOI*** measurement/calculation should be made in conditions such that the DUT operates well below 1dB compression point, but the 3rd order output power is well above noise level [1].

Frequency	Amplitude	HD product	IMD product
0	$a_2V_0^2$	0 (DC)	2
$\omega_2 - \omega_1$	$a_2V_0^2$	–	2
$2\omega_1 - \omega_2$	$\frac{3a_3V_0^3}{4}$	–	3
ω_1	$\frac{a_1V_0}{4} + \frac{9a_3V_0^3}{4}$	1	3
ω_2	$\frac{a_1V_0}{4} + \frac{9a_3V_0^3}{4}$	1	3
$2\omega_2 - \omega_1$	$\frac{3a_3V_0^3}{4}$	–	3
$2\omega_1$	$\frac{a_2V_0^2}{2}$	2	–
$\omega_1 + \omega_2$	$a_2V_0^2$	–	2
$2\omega_2$	$\frac{a_2V_0^2}{2}$	2	–
$3\omega_1$	$\frac{a_3V_0^3}{4}$	3	–
$2\omega_1 + \omega_2$	$\frac{3a_3V_0^3}{4}$	–	3
$\omega_1 + 2\omega_2$	$\frac{3a_3V_0^3}{4}$	–	3
$3\omega_2$	$\frac{a_3V_0^3}{4}$	3	–

Table 1: Output frequency components of a third-order nonlinear system under 2-tone excitation

For circuits with bias, ***power added efficiency (PAE)*** is introduced as a figure of merit of the design as

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}}$$

In PA design, for instance, a PAE above 45% indicates a good design.

In addition, there are ***adjacent channel power ratio (ACPR)***, ***noise-power ratio (NPR)***, ***AM-AM***, ***AM-PM conversion*** and many more other measures to characterize non-linear effects. But they are beyond the scope of this experiment, we will just focus on P1dB and TOI.

Harmonic Balance (HB) technique[2]

HB is a frequency-domain analysis technique for simulating distortion in nonlinear circuits and systems. It is an iterative method and based on the assumption that for a given sinusoidal excitation there exists a steadystate solution that can be approximated to satisfactory accuracy by means of a finite Fourier series. The HB solution is approximated by truncated Fourier series and this method is inherently incapable of representing transient behavior. You are strongly recommended to refer to [2] for a brief introduction on the math behind HB as well as for a better understanding about the parameters that you will input to the HB solver from Keysight ADS.

X-parameter[3]

In the lecture, you have been introduced to XFB which carries the infomation about the large-signal operating point (LSOP) and XS and XT which carries the information about the small-signal harmonic on top of the LSOP, used to describe the RF response. In order to correctly take into account for the DC effects, now you are introduced to XFV (for current bias), XFI (for voltage bias) which carries the interaction at LSOP and XY (for DC current response), XZ (for DC voltage response) which carries the information about the small-signal harmonic on top of the LSOP.

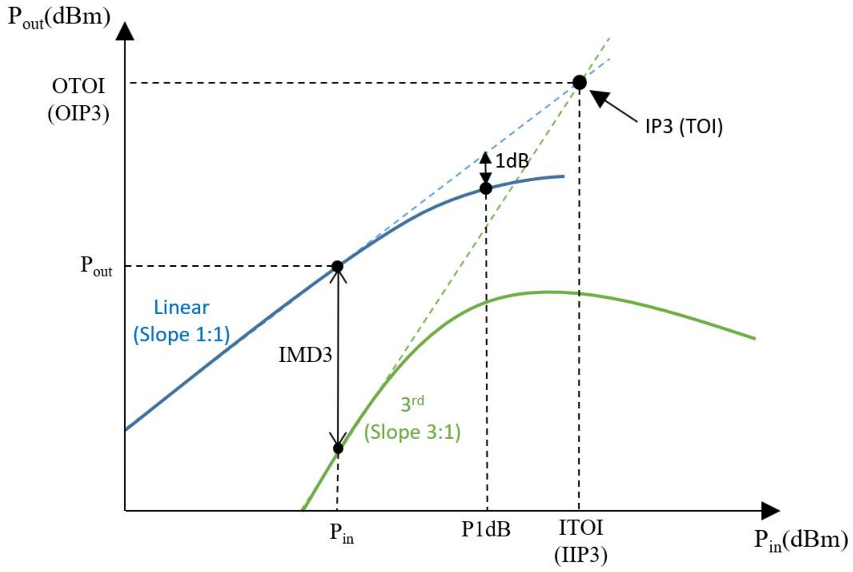


Figure 3: Harmonic power and intercept point (IP)

Figure 4 illustrates the contribution of different types of X-parameter to the output. Notice that in X-parameter framework, contradictory to S-parameter case, the large-signal also disturbs the DC bias port, so responses at these bias ports will be no longer as simple as a DC bias voltage or current as in the small-signal case. The bias ports' responses will have a rich spectrum of all frequencies got excited within the system.

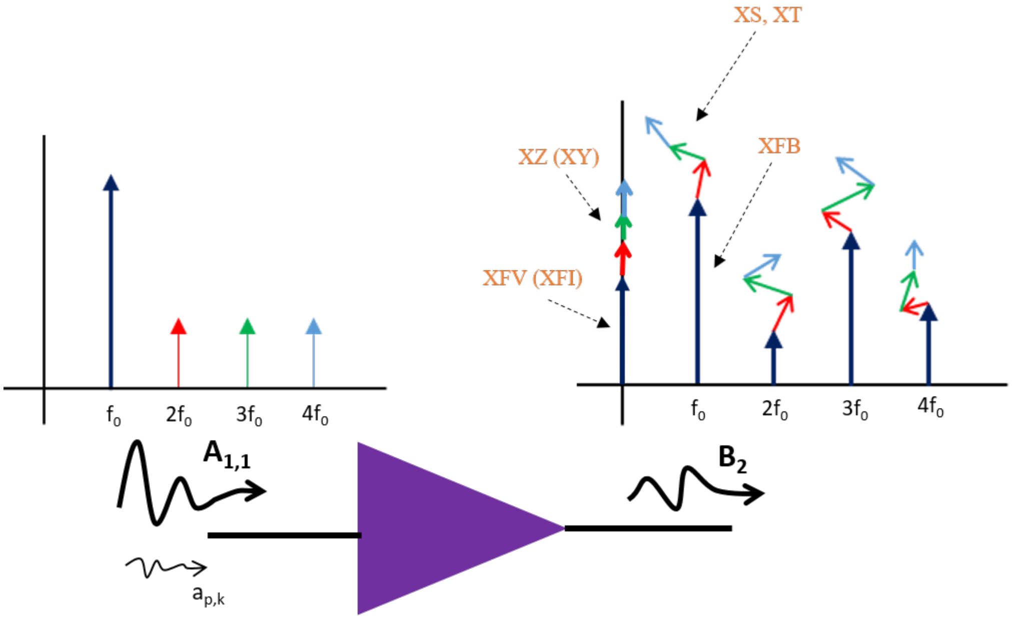


Figure 4: Illustration of output spectrum contributions from various types of X-parameter

Useful link

- X-parameter generation by Keysight

3 Pre-lab

1. A device is excited under a 2-tone excitation. The output spectrum measurement obtained from a spectrum analyzer screen is shown in Figure 5. Four markers are located from left to right in order: M3, M1, M2, M4. Given that the linear gain of this device is $G = 7$dB. Calculate the TOI (i.e. identify both IIP3 and OIP3) of this device?

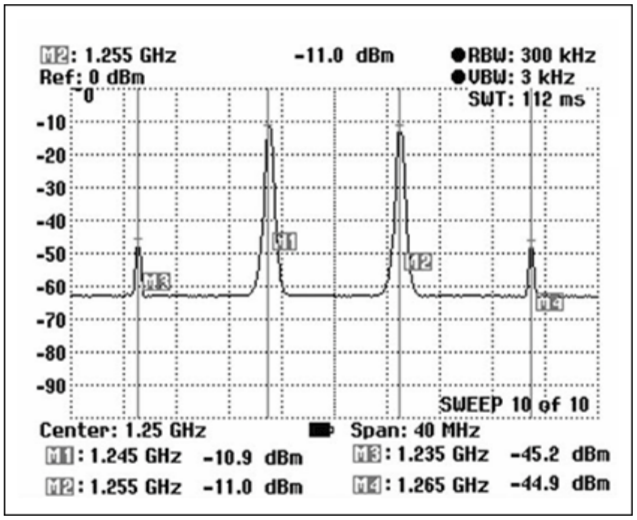


Figure 5: A 2-tone excitation response spectrum

2. What is X-parameter? How many types of X-parameter are there?

3. How many tones are needed in the excitation to identify P1dB?

4 Equipment

- Keysight ADS
- PA circuit level schematic

5 Procedure

5.1 1-tone excitation characterization

1. We will first generate 1-tone X-parameter and prove that 1-tone X-parameter is sufficiently equivalent to 1-tone characterization of nonlinear circuits using any other simulation techniques, such as 1-tone HB simulation. The fundamental tone is swept from 500MHz to 1.5GHz, 11 points. For each fundamental tone value, the power level is swept among 26 points from −20dBm to 5dBm. Bias voltage is set to 12V. We will first request for 3 harmonics when generating X-parameter (**'XParamMaxOrder = 3'**). In the upper left pallet, select '**Simulation-X_Param**'. You will find all the components needed for the X-parameter generation schematic shown in Figure 6 under this pallet. Save this schematic as '**a0_Xpar_Sim**' and run the simulation.

   You can export the simulated data to .xnp file by checking the **"Output GMDIF file"** box and choosing a file name in the X-parameter engine setting. However, the .ds file generated after running the simulation is sufficient to replace it in the following steps. Later you will see that the XNP component (used for macromodeling with X-paraemeter) accepts both .xnp and .ds file so in this section, we will not export the .xnp file to save I/O time. In practice, you will need to export the .xnp file to exchange with vendors or customers replacing your circuit level schematic as you will do in the next section.

2. Now create a new schematic and recreate the schematic shown in Figure 7. We will perform a frequency sweep for the circuit level PA as well as the X-parameter model of the PA using HB. Save this schematic by

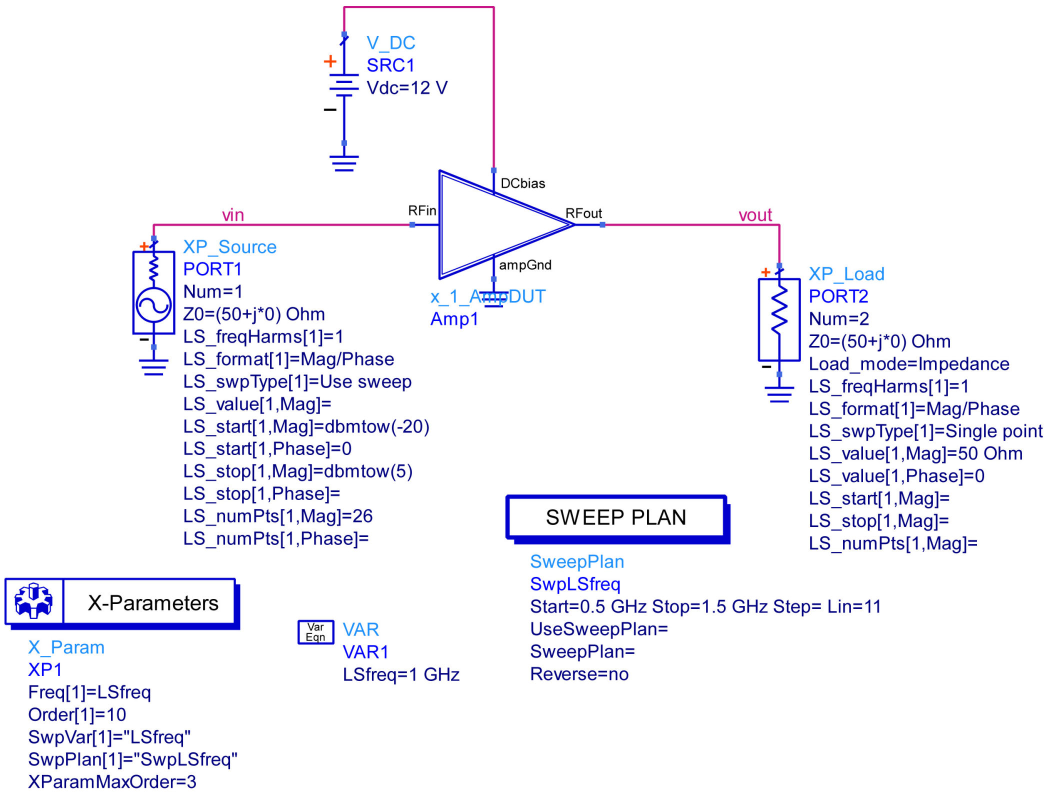


Figure 6: 1-tone X-parameter generation

the name ‘**a1_FreqSweep**’. You will find the ‘**P_1Tone**’ from the drop-down pallet named ‘**Sources-Freq Domain**’ and find the HB simulator under ‘**Simulation-HB**’. Finally, select the ‘**X MODEL**’ component under ‘**Data Items**’ pallet, rename the instance from ‘**XNP**’ to ‘**X2P**’ (2 port X-parameter), the terminals will appear. You then can import the *‘a0_XparSim.ds’* dataset into the X2P component, make sure that in ‘File type’ drop-list, “Dataset” is selected. Pay attention to the fact that the third terminal of X2P component must be grounded. Simulate the schematic and compare the plots for dbm and phase curves for all harmonics (there are only 5 harmonics in the result, why?). The last index of ‘mdl_vout’ (or ‘ckt_vout’) is for different harmonics, for example, `dbm(mdl_vout[::,1])` gives you the dbm of the first harmonic from ‘mdl_vout’ while `phase(ckt_vout[::,3])` gives you the phase of the third harmonic from ‘ckt_vout’.

Comment on the result from X-parameter model compared to that from the PA circuit model. Elaborate the meaning of the plots you just obtain by using them and constructing the output spectrum of the PA when an 810MHz, −10dBm excitation is sent to the PA. You should have something ***similar*** to that shown in Figure 8, which again shows that X-parameter provides the exact same amount of information the circuit model could under the same HB simulation set up.

Do you get exact same result as in Figure 8? If not, what could be the issue here? Fix the issue and calculate the expected result.

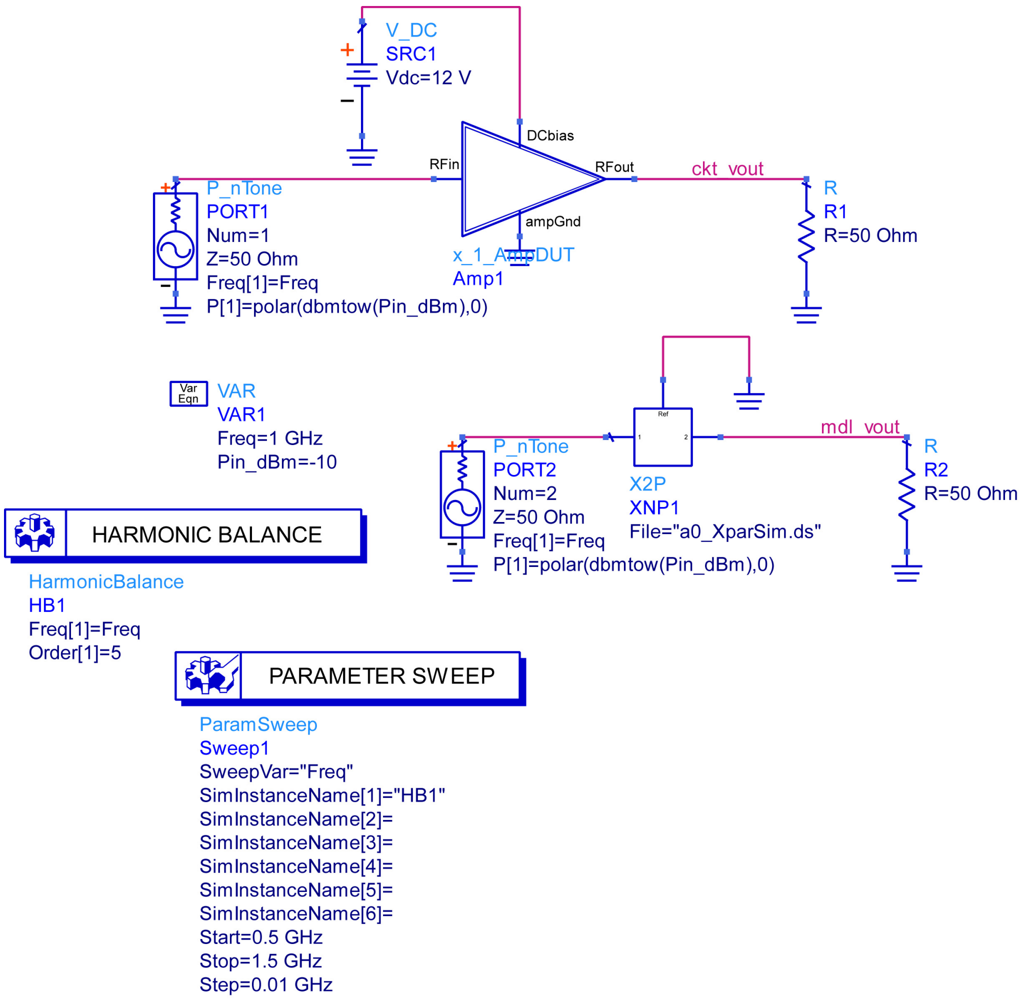


Figure 7: Frequency sweep using HB simulation

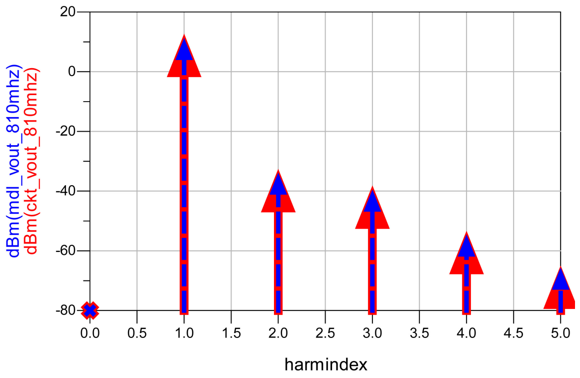


Figure 8: Output spectrum of the given PA excicited by a −10dBm, 810MHz tone

3. Repeat step 2 (you can skip the 810MHz tone test) but now change the frequency sweep of HB simulation in Figure 7 from 0.5 − 1.5GHz range to 0.05 − 2GHz range. Comment on the result and explain any discrepancies if any. What is your conclusion about the accuracy of X-parameter model and the requirement for it to be able to give same information as the circuit model?

4. We will calculate 1dB compression point of the given PA by performing a power sweep HB simulation at 1GHz. Create a schematic as in Figure 9, name it '**a2_PowSweep**', the gain is computed for both the

circuit level design and the X-parameter model. Compare the results between 2 models. Identify P1dB?

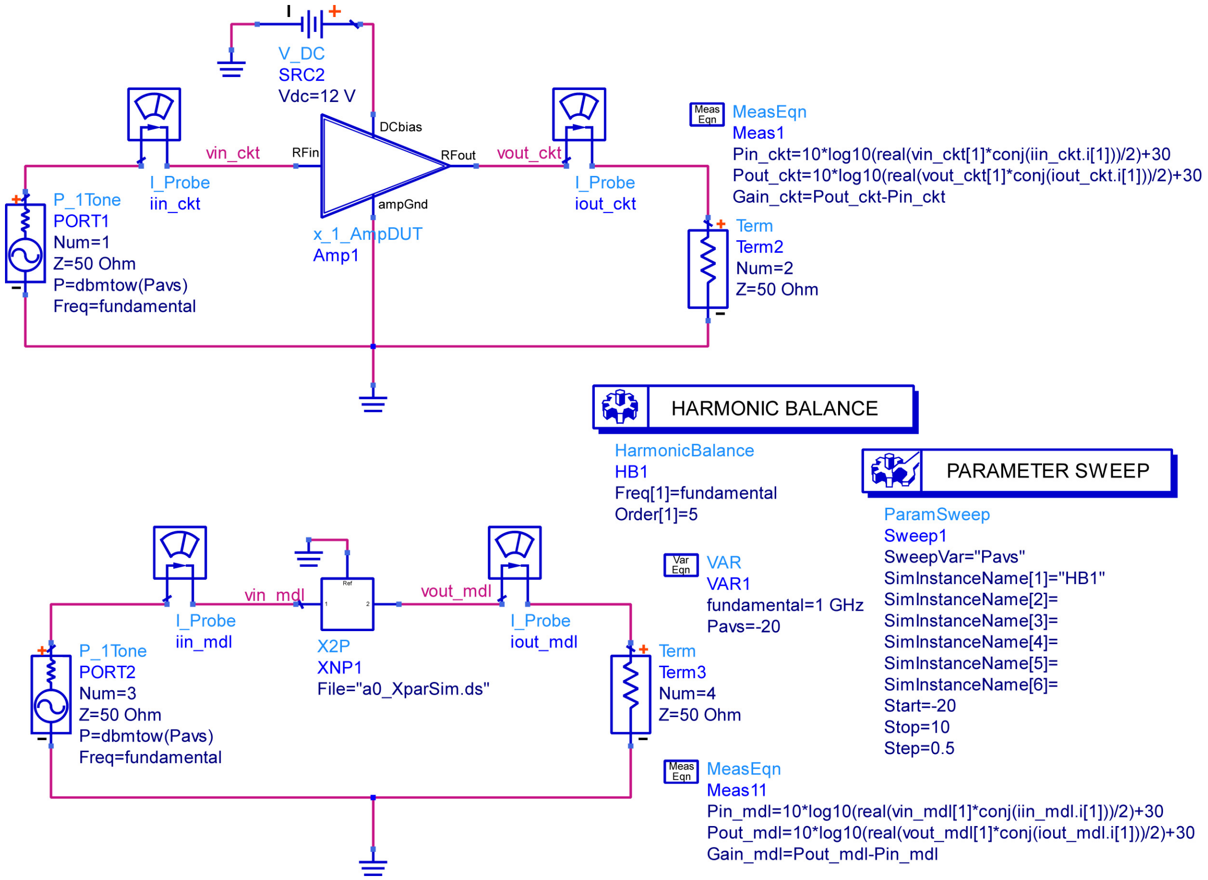


Figure 9: HB frequency sweep simulation using 1-tone X-parameter

5. Now change the operating frequency to2GHz and repeat the power sweep HB simulation. Comment on the results this time.

6. Assume now the PA is needed biasing with a different DC voltage, say $V_{bias} = 10$V. The *'a0_Xpar_Sim.ds'* was generated when $V_{bias} = 12$V and RF input and RF output terminals are the only 2 ports get defined when generating X-parameter. It doesn't contain any information about how the system will behave if changing the bias. So now we will learn how to defined an additional port to do so. The DC types of X-parameter are now introduced. Modify the X-parameter generation schematic as in Figure 10. '**XP_Bias**' component can also be found in '**Simulation-X_Param**' pallet. You will see that the X-parameter now includes extra terms. It is now a **three**-port model. Repeat step 4 with different bias voltages of your choice to verify that X-parameter models, if appropriately generated, is sufficient to replace circuit models. Make sure to rename '**XNP**' to '**X3P**' so the data can be processed correctly.

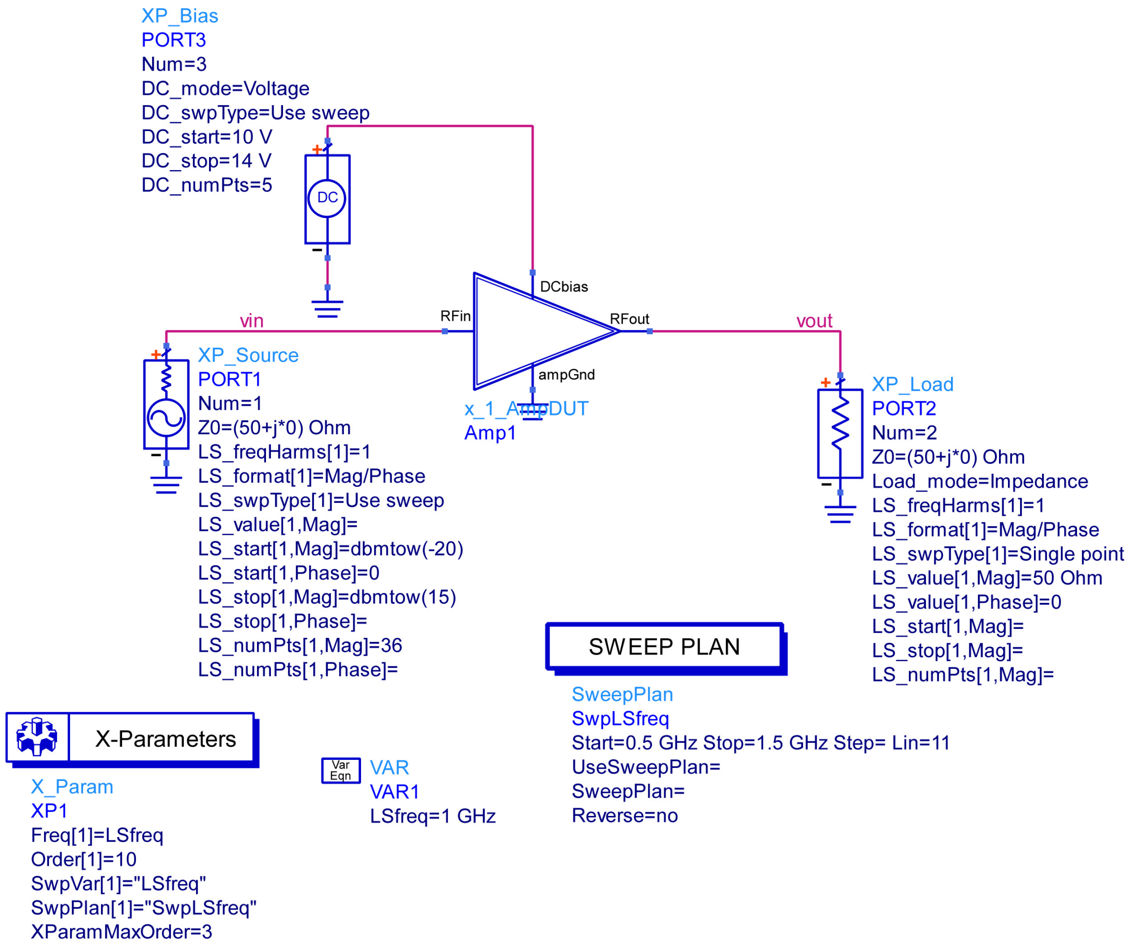


Figure 10: 1-tone X-parameter generation with DC sweep

5.2 2-tone excitation characterization

1. Let's now study the PA under 2-tone excitations. It is known that using 2-tone excitation, we could calculate TOI, one of the

   Create a schematic named '**b0_TwoTones_HB**' as shown in Figure 11. Run the simulation to verify that 1-tone X-parameter does not provide the accurate behavior of the PA under a 2-tone excitation.

2. We will generate X-parameter of the PA using two closely spaced large signal tones. Create a new schematic similar to that shown in Figure 12 to generate the 2-tone X-parameter model. Name it '**b1_XparSim_2LSswp**'. As shown, we sweep the power level of 2 tones from −30dBm to 0dBm, the DC bias is defined as a port but we only collect data at a single value $V_{DC} = 12$V because in the following experiments, we would not change DC bias. The distance from the 2-tone to the center frequency, 1GHz, is varied among 0.1MHz, 1MHz and 5MHz. This time, export the X-parameter to .xnp file named '**XfileTOI.xnp**'.

3. We now have 2-tone X-parameter, the earlier experiment in this section is expected to work with this new data set. Go back to '**b0_TwoTones_HB**' and modify the X-parameter model as shown in Figure 13. Since in the previous step, we generated the 2-tone X-parameter including a sweep of '**deltaFreq**'. So we need to specify the value of '**deltaFreq**' we want to run the X-parameter model with.

   Now, recall that our goal is to find the TOI of the PA. Adjust the frequency range in the spectrum plot to around the center frequency, i.e. 1GHz then compute the output TOI, input TOI of the PA. Using data from both circuit model and X-parameter model and compare results between them. You should have a plot similar to that of Figure 14. Explain why even though the TOIs calculated from 2 models are sufficiently close but the spectra from 2 models are not the same.

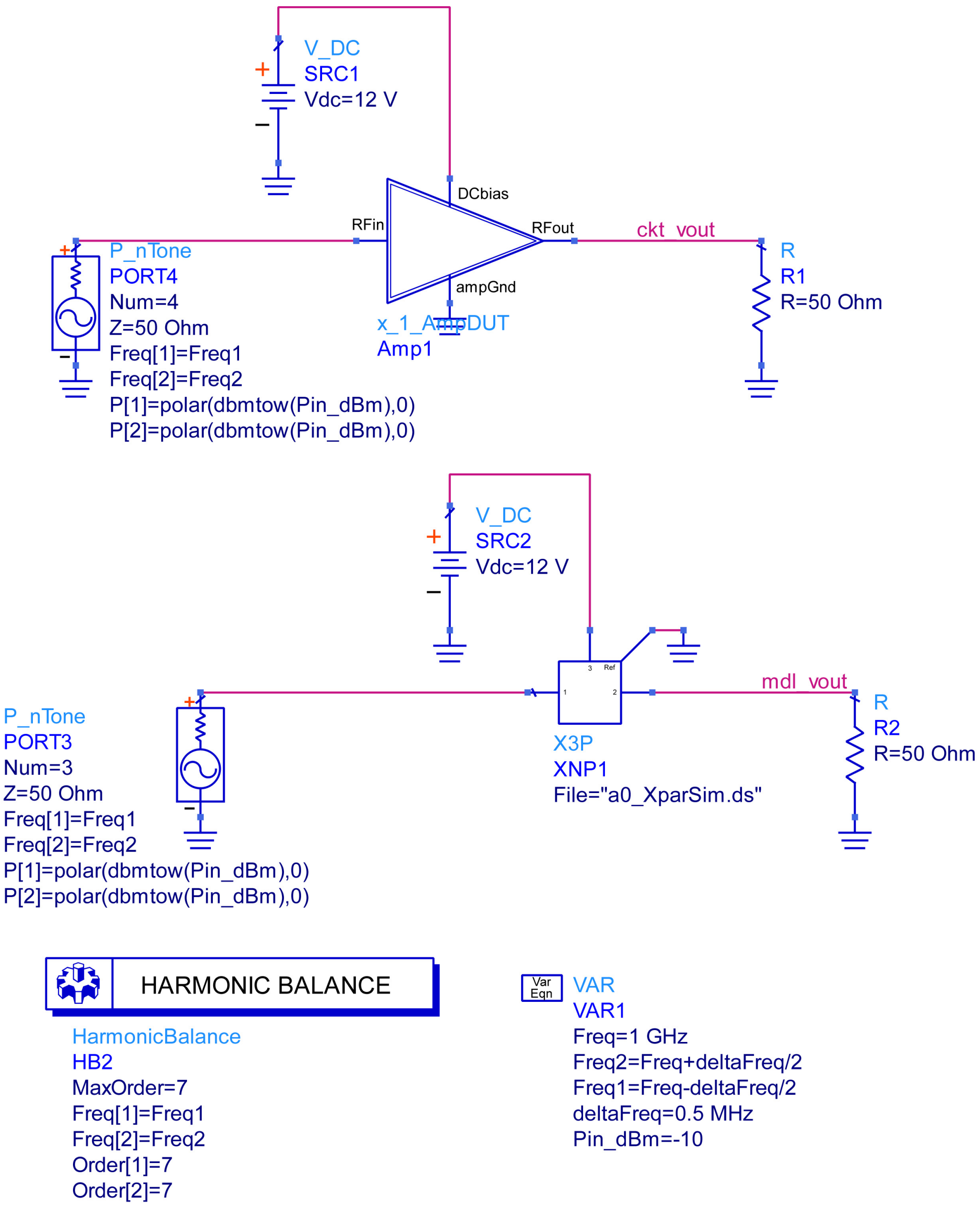


Figure 11: 2-tone HB simulation using 1-tone X-parameter

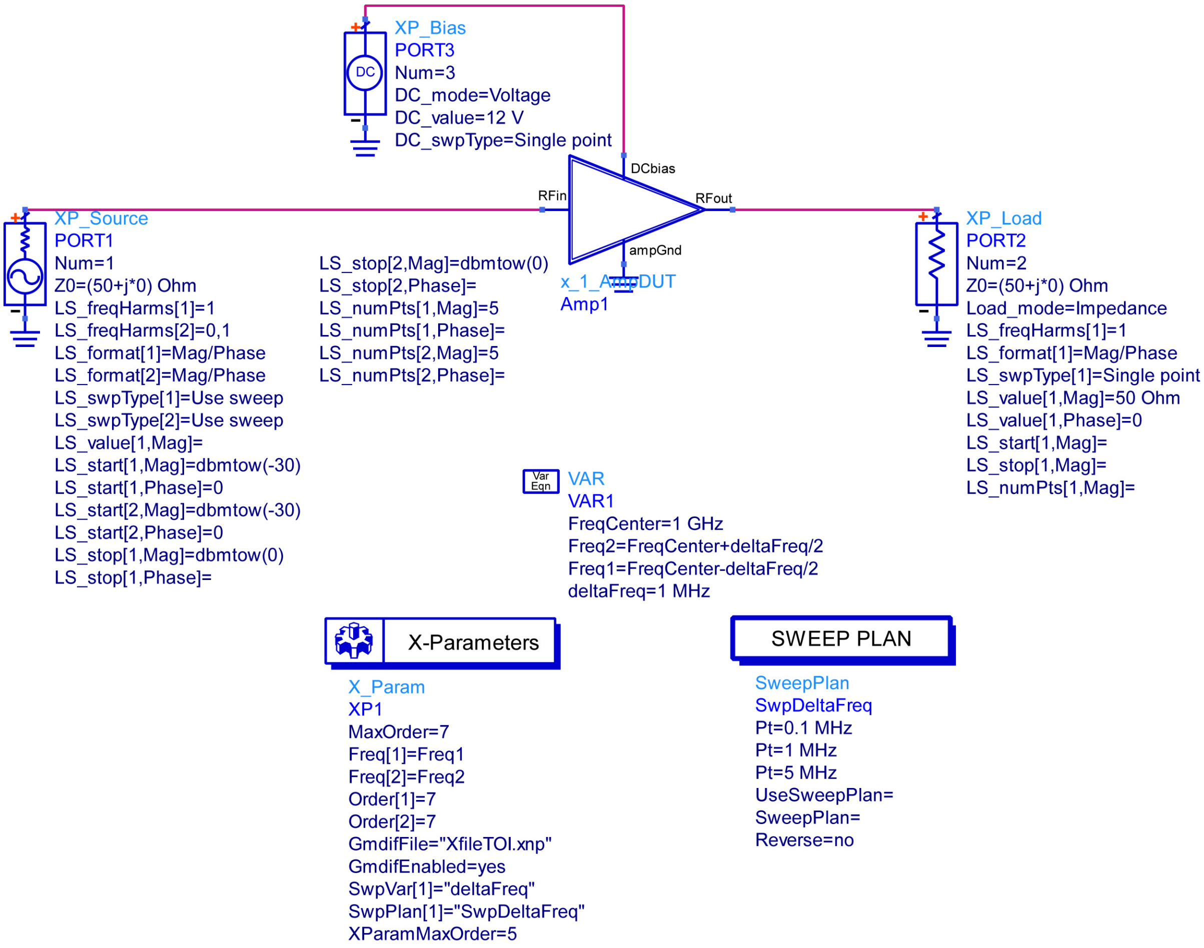


Figure 12: 2-tone X-parameter generation

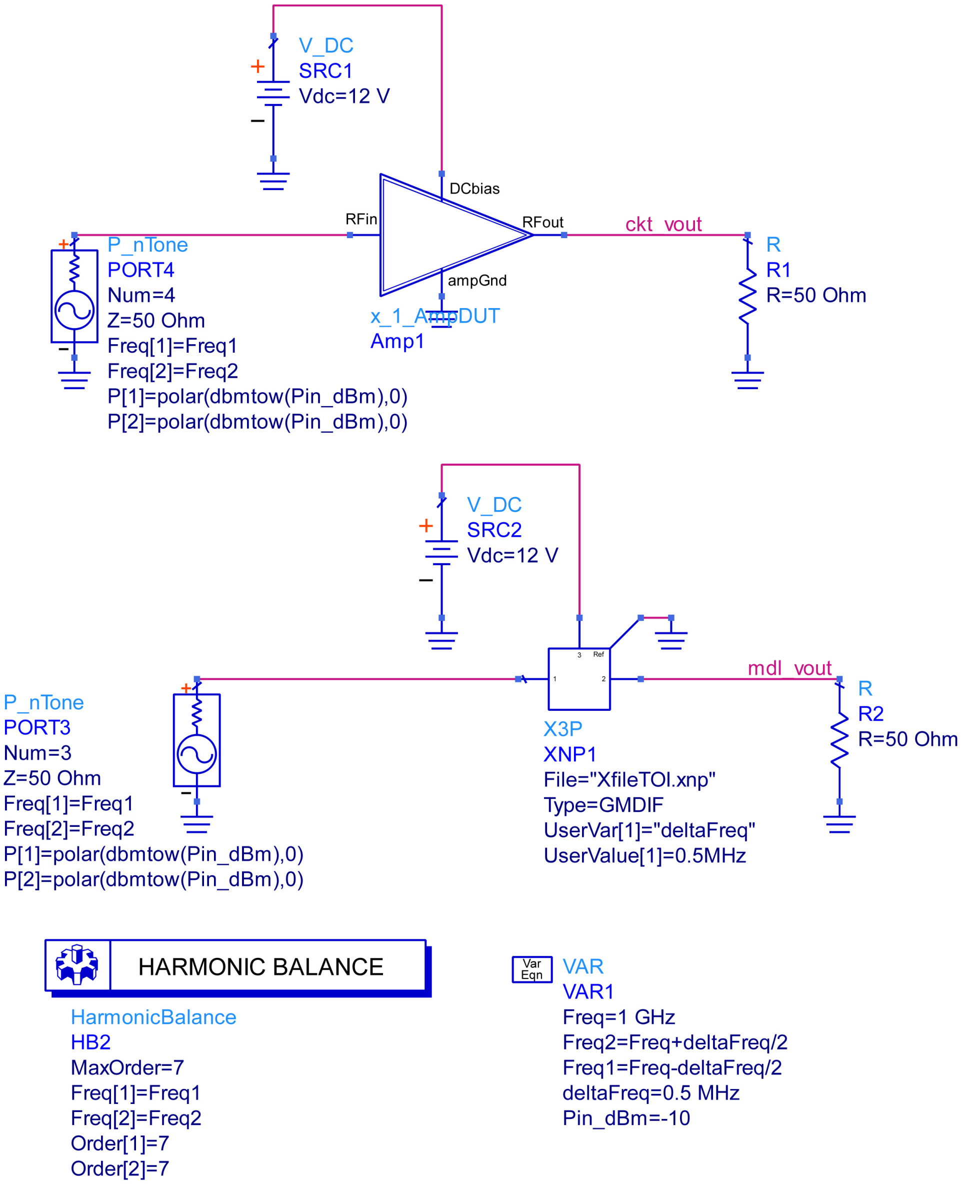
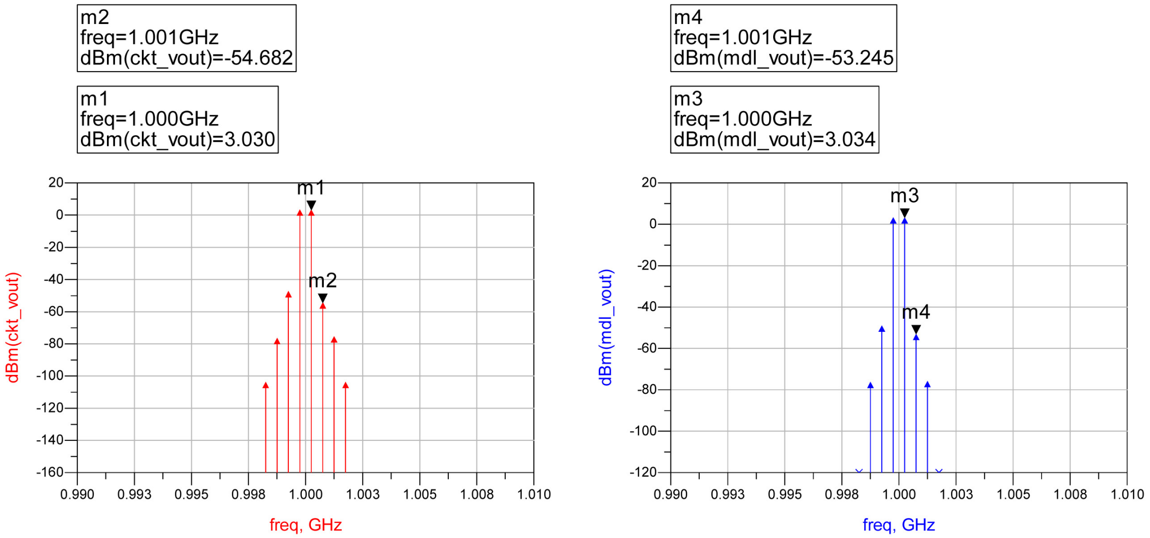


Figure 13: 2-tone HB simulation using 2-tone X-parameter



Eqn OTOI_ckt_dBm = m1+(m1-m2)/2

Eqn OTOI_mdl_dBm=m3+(m3-m4)/2

OTOI_ckt_dBm	OTOI_mdl_dBm
31.886	31.173

Figure 14: OTOI calculations using circuit model and X-parameter model

6 Conclusion

1. Comment on the overall use of X-parameter in providing a complete IP protection pipeline for system level simulation via the experiments you have done above?
2. What are the potential limitations of using X-parameter?

References

[1] Anritsu, "Intermodulation Distortion (IMD) Measurements Using the 37300 Series Vector Network Analyzer."

[2] Keysight Technologies, Inc., "Harmonic Balance Simulation."

[3] D. E. Root, J. Verspecht, J. Horn, and M. Marcu, *X-Parameters: Characterization, Modeling, and Design of Nonlinear RF and Microwave Components.* Cambridge University Press, 2013.