X-parameter-Based Frequency Doubler Design

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***Abstract*—As a kind of superset of S-parameters, X-parameters are becoming increasingly popular in non-linear device simulation and measurement. Due to their good accuracy and convenient extraction procedures, X-parameter-based transistor device models have so far been mainly used in power amplifiers design. They have been limited to this kind of design up to now because the X-parameter models extracted are only suitable for fundamental frequency circuit design. In this paper, a new extraction method is described to allow the extracted model to be used to designing a frequency doubler, and verification through simulation results is presented.**

Keywords- X-parameter model; transistor modeling; load-pull; frequency doubler

I. Introduction

Transistor device modeling is an essential part of non-linear circuit design since a good semiconductor device model is very important for the efficient use of microwave and RF circuit CAD technology. As the development of transistor technology progresses, we can observe that the operating frequency, complexity of signal formats and power levels are rising steadily, increasing both the complication of the models, and the demand for good accuracy.

At the present time, many transistor device models have been presented mainly consisting of basic electrical elements such as resistors, capacitors, and inductors. However, construction of such models is complicated and time consuming. Careful and complex measurement procedures are required to extract the useful parameters from different part of the transistor's operating regime. An engineer might spend a year or more to develop and validate a useful model of this kind.

In view of these difficulties associated with traditional methods of transistor modeling, another approach to transistor modeling has become popular, based on so-called X-parameters, through which the model can be extracted by commercial simulation tools or by NVNA measurement equipment in the laboratory ([1]-[3]). It is then quite straightforward to extract the model, and the accuracy is also generally good. A further advantage is that this is a black box model, enabling, for example, easy IP protection.

Up to now, X-parameter transistor models have been mostly used to design power amplifiers [4][5]. In this paper, a different harmonic load pull method is presented to extract an X-parameter model, and then, this model is used to design a frequency doubler. In Part II, the extraction methodology and accuracy of the model are described. In Part III, the model will be used to design a frequency doubler. In Part IV, results will be presented, while conclusions are drawn in Part V.

II. Harmonic Load-Pull X-Parameter Model

X-parameter transistor models have been used to design power amplifier, with quite good accuracy. The models are able to describe the transistor nonlinearities very well, especially when the fundamental load-pull method [6] [7] was introduced for the extraction. The load-pull-based X-parameter model can include a complex sweep plan, power drive, frequency, load impedance, and bias. All of this makes the X-parameter model useful for a wide range of situations. Load dependent X-parameters for a two-port network are given in (1)

$$\begin{aligned} B_{pm} &= X^{F}_{pm}(DC,|A_{11}|,\Gamma_{21})P^{m} \\ &+\sum_{qn} X^{S}_{pm,qn}(DC,|A_{11}|,\Gamma_{21})P^{m-n}\bullet A_{qn} \\ &+\sum_{qn} X^{T}_{pm,qn}(DC,|A_{11}|,\Gamma_{21})P^{m+n}\bullet A^{*}_{qn} \end{aligned} \quad . \quad (1)$$

where $P = e^{j\Phi(A_{11})}$.

The incident (A) and scattered (B) waves have two indices, and so has the reflection coefficient (Γ). The first one is the port index, and the second is the harmonic index. The three X parameters (F, S, and T) depend on the available power A11, the output load at fundamental frequency, Γ21, and the DC bias.

However, if we want to use this X-parameter model to design a frequency doubler, a fundamental load pull method of this kind will not work very well. The reason is that the frequency doubler is working at the second harmonic while the X-parameter model is extracted only at the fundamental. So, if we want to use the model to design a doubler, we have to include second harmonic information of the transistor, which means using a second harmonic load-pull to extract the X-parameter model. The relevant expression of this method is given in (2)

$$B_{pm} = X^F_{pm}(DC, |A_{11}|, \Gamma_{22}) P^m + \sum_{qn} X^S_{pm,qn}(DC, |A_{11}|, \Gamma_{22}) P^{m-n} \bullet A_{qn} + \sum_{qn} X^T_{pm,qn}(DC, |A_{11}|, \Gamma_{22}) P^{m+n} \bullet A^*_{qn} \quad (2)$$

The main difference is that the X-parameter model depends on the second harmonic load rather than the fundamental load. Later, some simulation results are given to show the good accuracy of this method.

To illustrate the approach, we extract the model from a traditional circuit model through the Agilent's ADS simulation tool. The device under test (DUT) is a 10W GaN packaged transistor (CGH40010F) manufactured by Cree, and the equivalent circuit model used is also supplied by the manufacturer. The X-parameter model is extracted at 1 GHz, input power is 20 dBm, and the drain and gate bias voltages are 28V and -3.9V, respectively. The X-parameter model consists of 50 magnitude, and 90 phase divisions, forming a lattice of 4,500 load points covering the entire Smith chart. The maximum harmonic order that will be considered is 9.

The X-parameter model was extracted using the circuit as depicted in Fig.1,

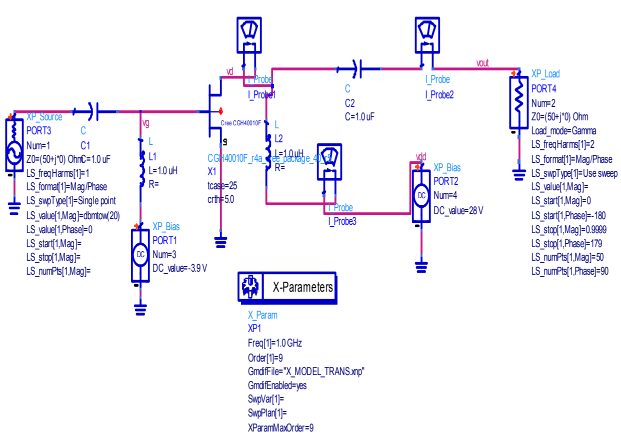

Figure 1. The circuit to extract the X-parameter model file

The extracted model is then used to perform second harmonic load pull simulation followed by a comparison between the X-parameter model and the original equivalent circuit model. Results are shown in Fig.2 and Fig.3.

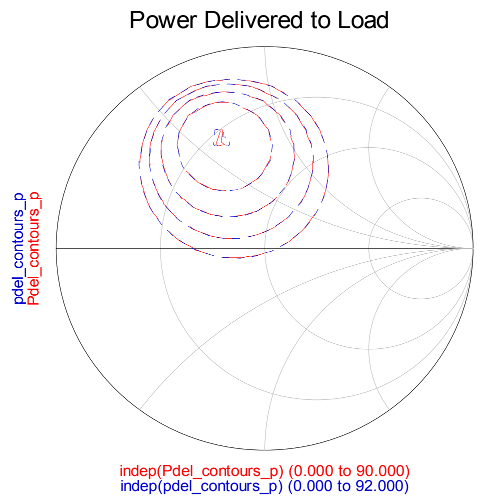

Figure 2. Comparision of second harmonic load pull simulation results of power delivered to the load between X parameter model (red) and circuit model (blue)

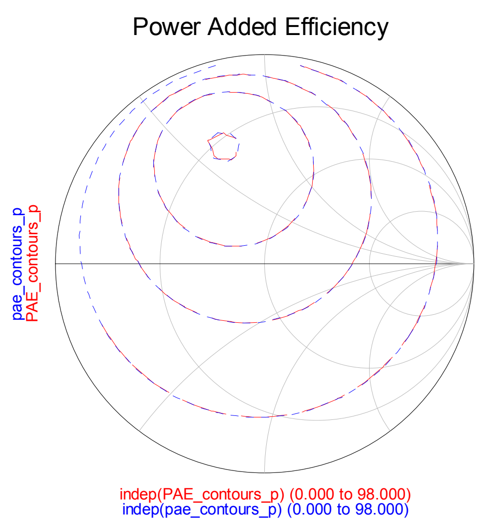

Figure 3. Comparison of second harmonic load pull simulation results of power added efficiency between X parameter model (red) and circuit model (blue)

Fig.2 shows the power delivered to the load contours. The red curves were generated using the X-parameter model, and the blue curves using the equivalent circuit model. Fig.3 shows the power added efficient curves. Again, the red one comes from X-parameter model, and the blue one comes from circuit model. The X-parameter model simulation results fit the equivalent circuit model data very well, which means the second harmonic load pull method gives good accuracy. This suggests that it is possible to use this method to extract an X-

III. HARMONIC LOAD-PULL X MODEL TO DESIGN FREQUENCY DOUBLER

As the development of high frequency wireless communication system progresses, a simple and effective method to generate high frequency signals become extremely important. Frequency multiplier is a commonly-used technique for the generation of such signal [8][9].

In this paper, we design a simple frequency doubler using the specific second harmonic load pull X-parameter model. Here, we set the fundamental reflection coefficient to -1, and at the same time sweep the reflection coefficient at the second harmonic frequency as before. This is just to make sure that the model is in a similar situation to that which will apply when it will operate as a doubler. The expression of this model is given in (3)

$$
\begin{aligned}
B_{pm} &= X^{F}_{pm}(DC,|A_{11}|,\Gamma_{21}=-1,\Gamma_{22})P^{m} \\
&+\sum_{qn} X^{S}_{pm,qn}(DC,|A_{11}|,\Gamma_{21}=-1,\Gamma_{22})P^{m-n}\bullet A_{qn} \quad .(3) \\
&+\sum_{qn} X^{T}_{pm,qn}(DC,|A_{11}|,\Gamma_{21}=-1,\Gamma_{22})P^{m+n}\bullet A^{*}_{qn}
\end{aligned}
$$

Here we can ignore the other harmonic waves reflected from the load back to the transistor, but cannot ignore the fundamental, because its magnitude is much larger than that of the other harmonics. It can be thought of as an additional large signal according to the X-parameter theory, and its presence will accordingly affect the nonlinear behavior of the model. If we ignore it, the accuracy will be significantly affected. This is the main difference compared with method described in the Part II.

IV. RESULTS

Then the X-parameter model was used to design a doubler. The bias, input power and operating frequency are the same as the model mentioned in Part II. The output frequency of the doubler is 2GHz. The circuit of the doubler is shown as Fig.4.

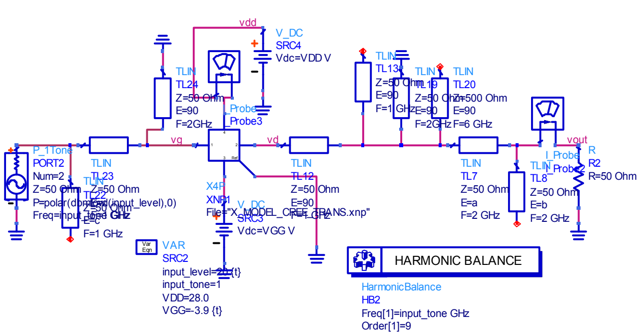

Figure 4. Equivalent circuit of X-parameter model doubler

Replacing the model with the original circuit model in the doubler, and then comparing the simulation results of the two models, we have results as showed in Fig.5, Fig.6, Fig.7, and Table1.

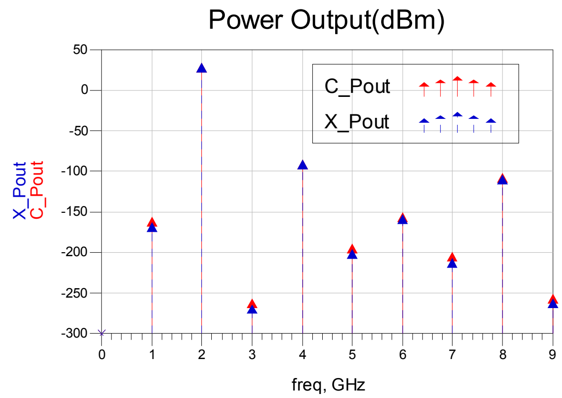

Figure 5. Comparision of second harmonic load pull simulation results of output power at load between X-parameter model (blue) and circuit model (red)

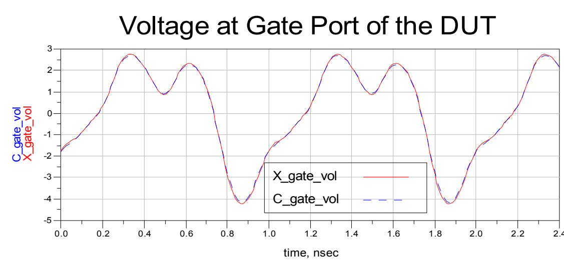

Figure 6. Comparision of second harmonic load pull simulation results of the voltage at gate port between X-parameter model (red) and circuit model (blue)

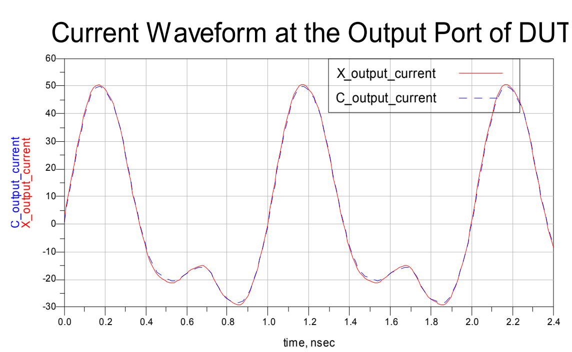

Figure 7. Comparision of second harmonic load pull simulation results of the current at output port of DUT between X-parameter model (red) and circuit model (blue)

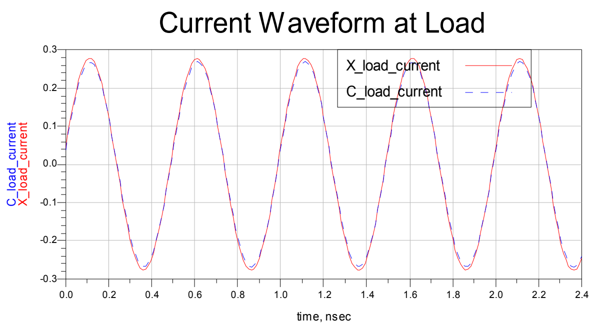

Figure 8. Comparision of second harmonic load pull simulation results of the current at load between X-parameter model (red) and circuit model (blue)

TABLE I. DOUBLER EFFICIENCY

Freq	Second harmonic efficiency at Load	
	X model doubler	***Circuit model doubler***
2.0GHz	36.160	35.565

Fig.5 shows the output power at the load, in dBm, from the fundamental to the ninth harmonic. The blue cures are the X model , and the red curves are the circuit model. As can be seen, the two results match quite well. Fig.6 is the voltage at the gate port of DUT. The red curve is generated using the X-parameter model, and the blue curve using the equivalent circuit model. Fig.7 and Fig.8 show current waveforms, Fig.7 is the current at output port, while Fig.8 is the current at load, we can see from the results that this model gives very high accuracy. Table 1 give the efficiency of the doubler, showing very good agreement between both methods.

V. DISSCUSION AND CONCLUSIONS

X-parameters are quite useful in transistor device modeling. As a behavior modeling technique, it can not only provide high accuracy , but it also helps protect IP. X-parameter model can be used to design both power amplifiers and frequency multipliers, giving good results.

It was shown in this paper that the specific harmonic load-pull X-parameter model can predict the detail of the transistor with high accuracy. This would be especially useful for some other circuit designs besides power amplifiers, such as frequency multiplexers.

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